Network Analysis Fundamentals

January 2017

KEYSIGHT TECHNOLOGIES

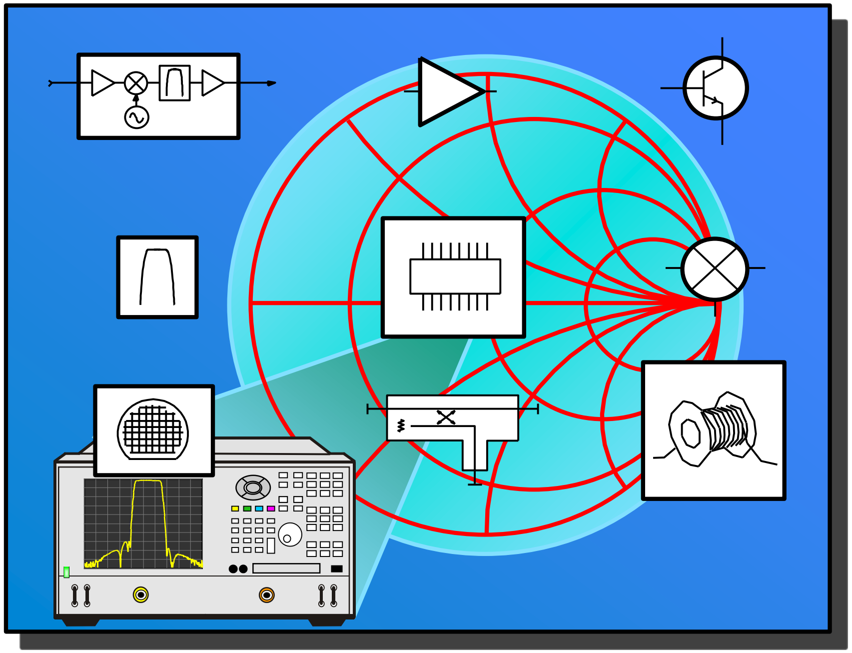
KEYSIGHT HOTSPOTS
Where Technologies and Experts Meet

Objectives

– Review RF basics

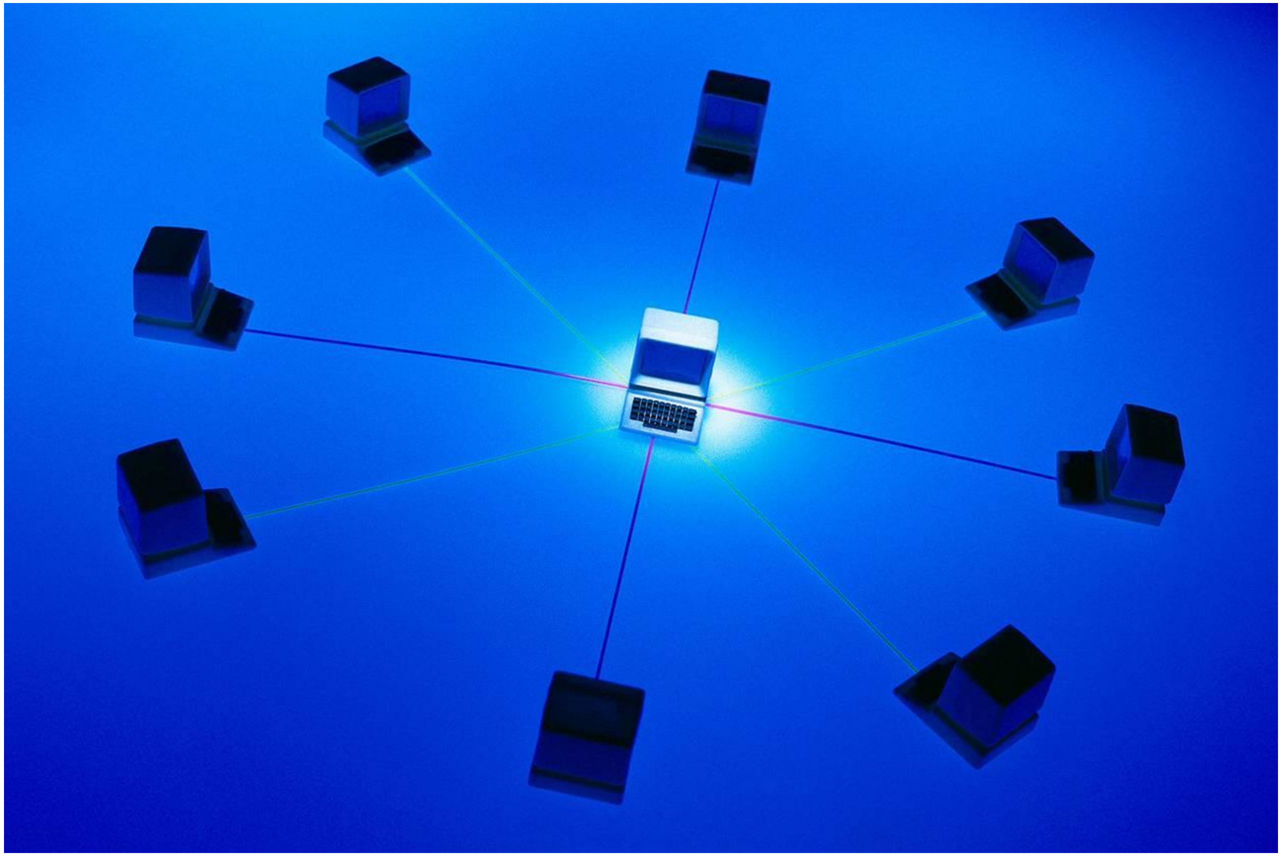
– Understand fundamentals on S-parameter measurements

– Examine architectures and calibrations of VNAs



So...what is a Network Analyzer?

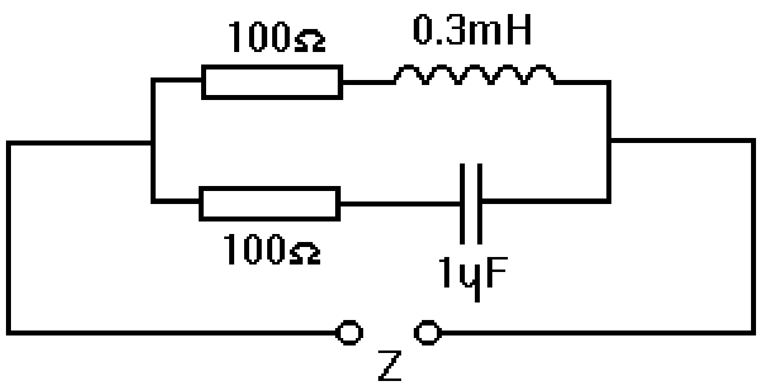
Network Analysis is NOT the analysis of…



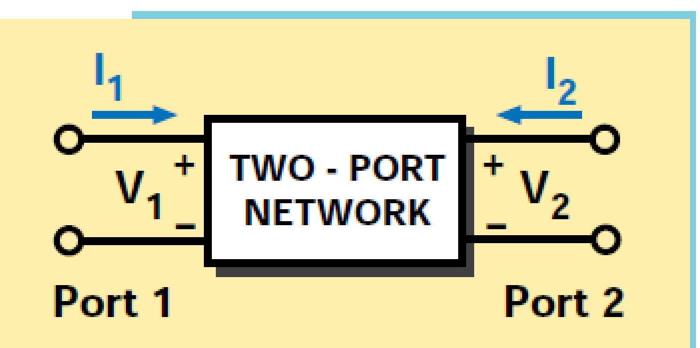
Computers
Network/protocol performance etc…

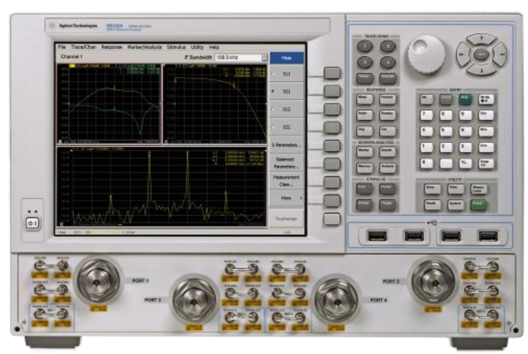
What is a Network Analyzer?

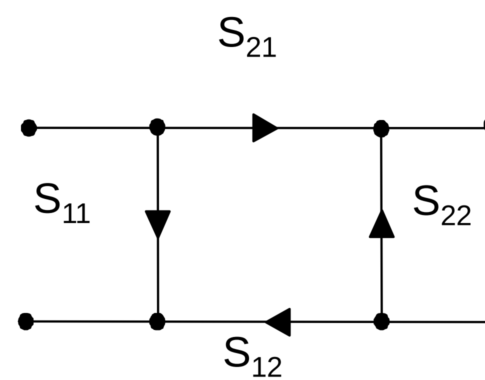
A *network analyzer* is an instrument that measures the network parameters of electrical networks.



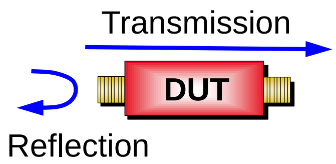
Electrical Network

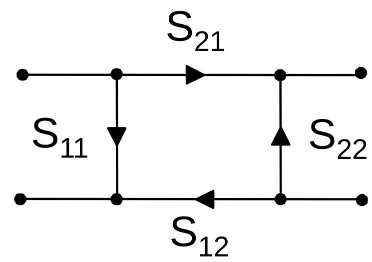




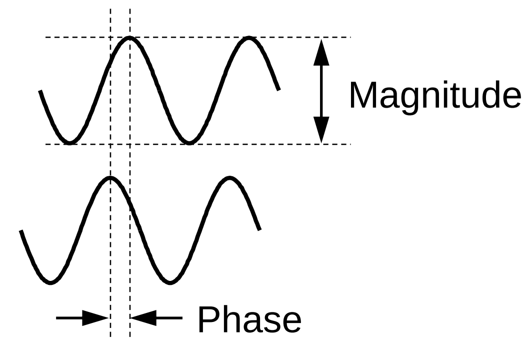


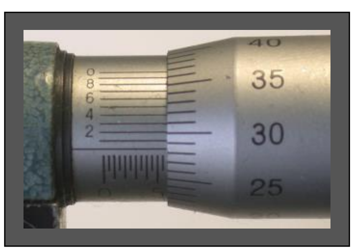
What Are Vector Network Analyzers?

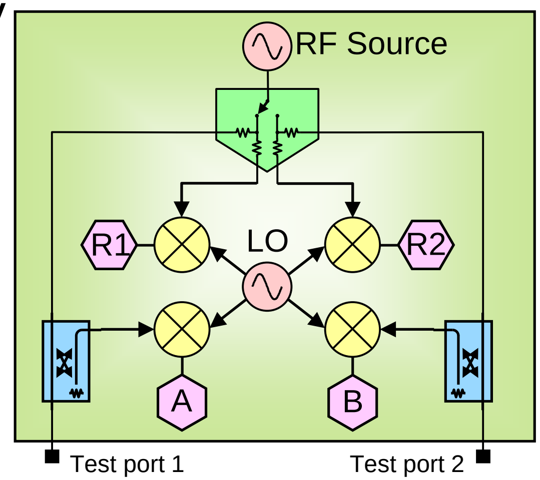




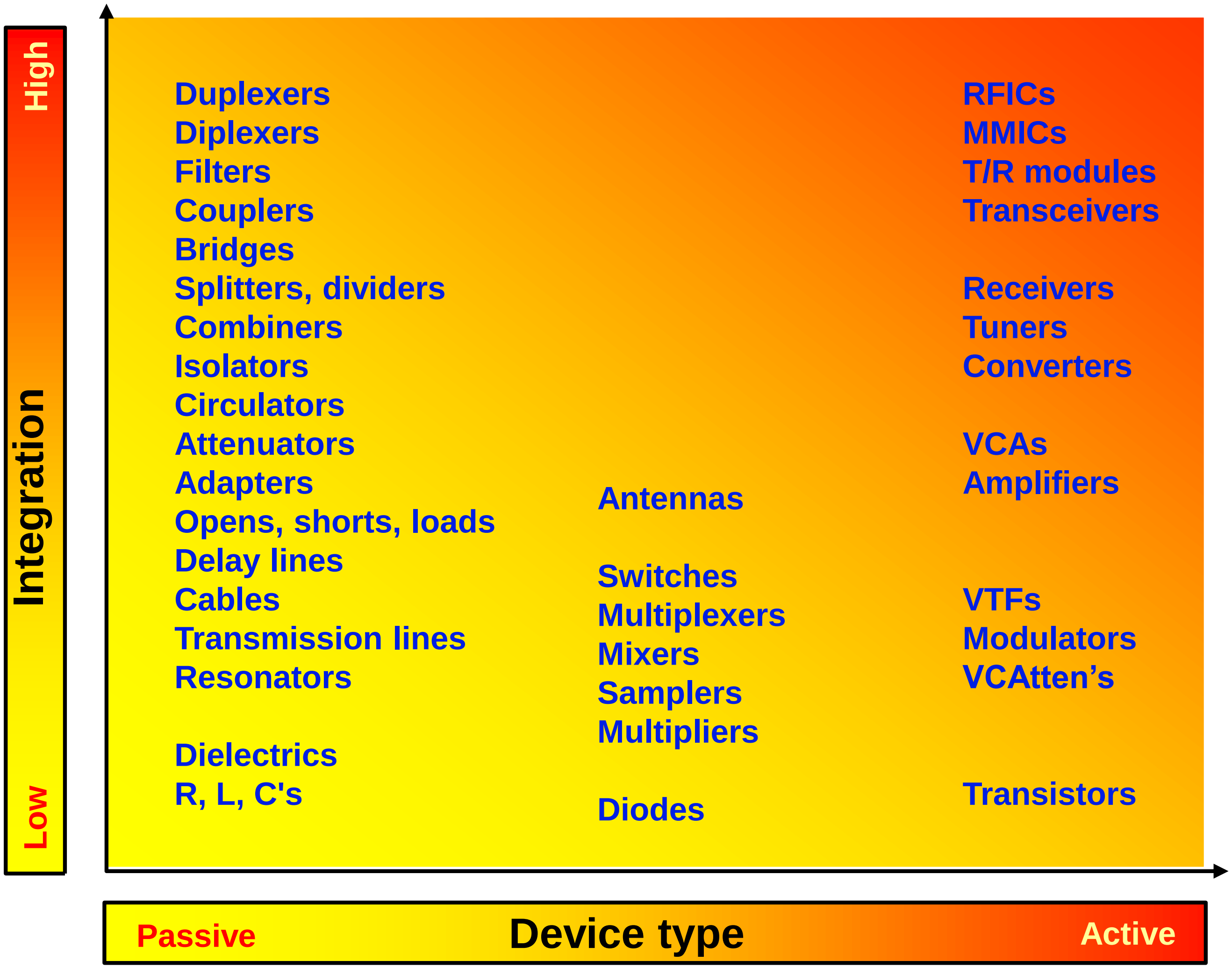
- Are stimulus-response test systems
- Characterize forward and reverse reflection and transmission responses (S-parameters) of RF and microwave components
- Quantify linear magnitude and phase
- Are very fast for swept measurements
- Provide the highest level of measurement accuracy



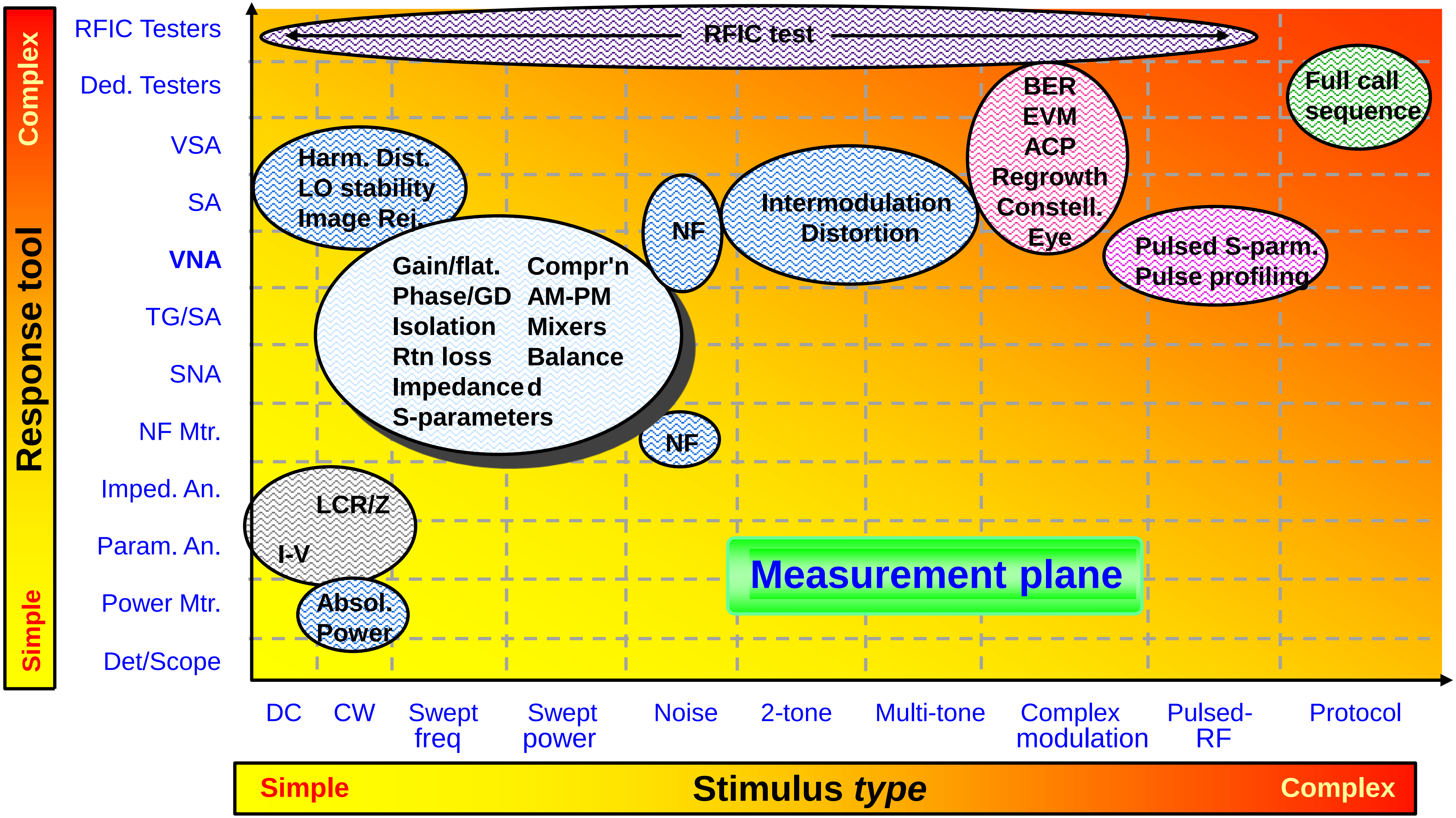




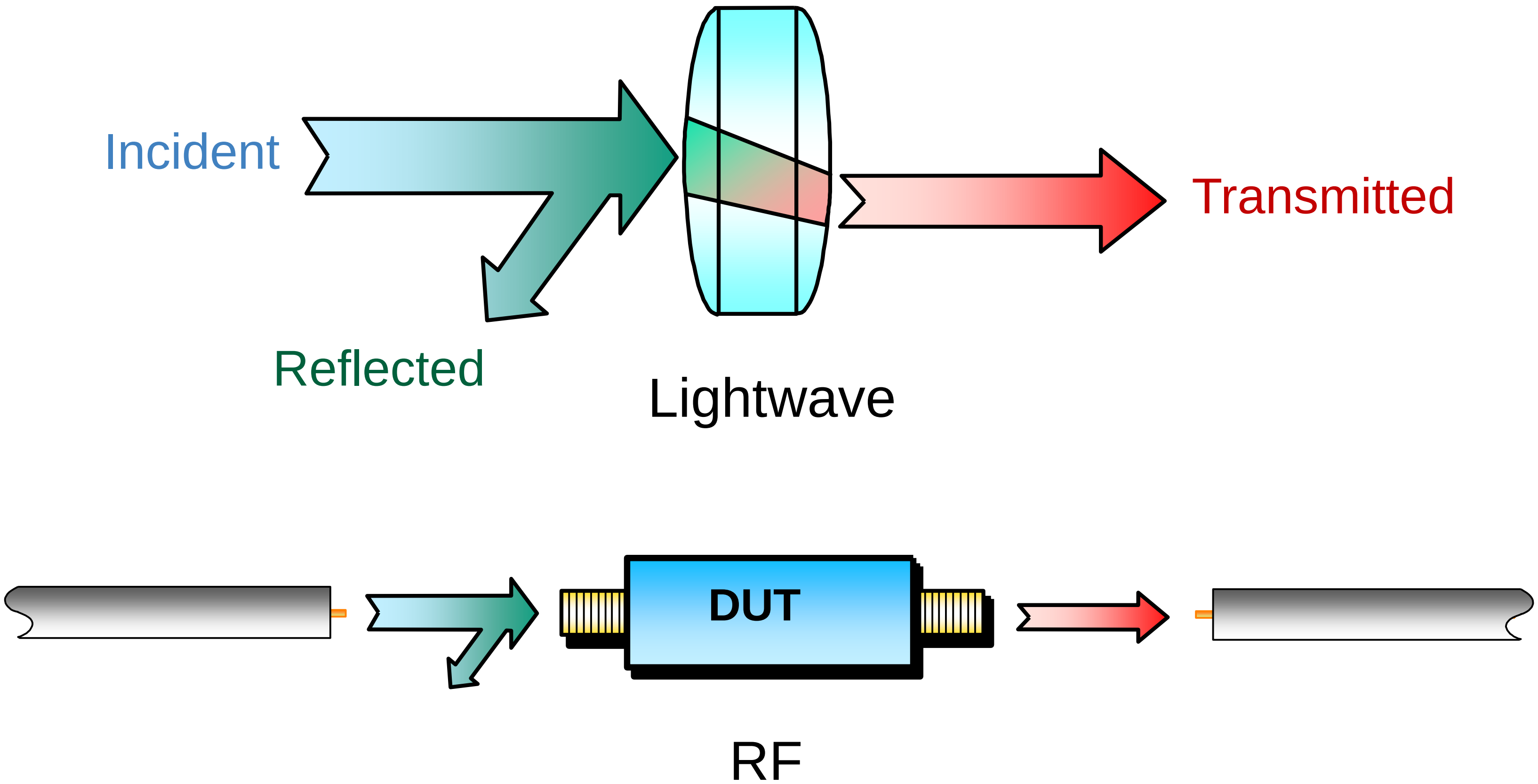
What Types of Devices are Tested?



Device Test Measurement Model



Lightwave Analogy to RF Energy



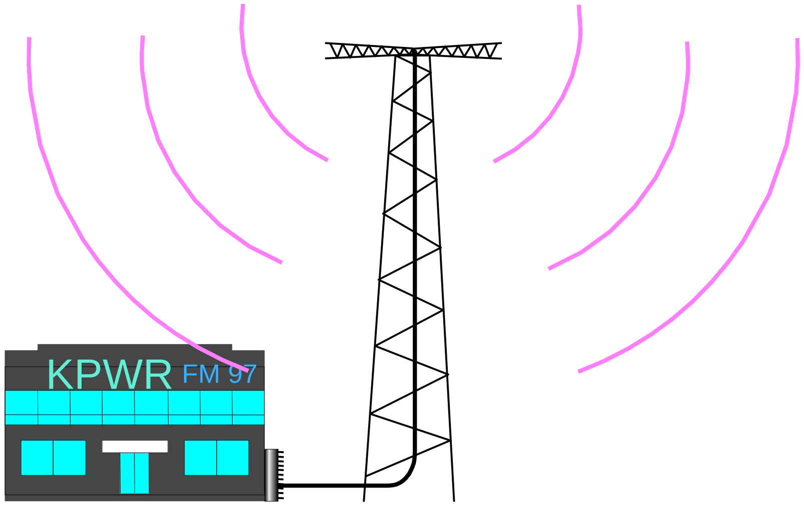
Why Do We Need to Test Components?

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

– Ensure distortionless transmission of communications signals

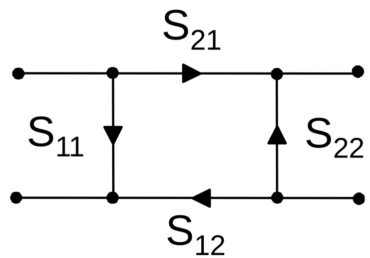
- Linear: constant amplitude, linear phase / constant group delay
- Nonlinear: harmonics, intermodulation, compression, X-parameters

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

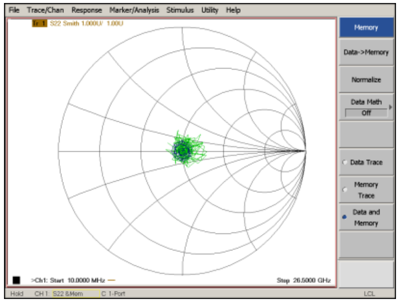


The Need for Both Magnitude and Phase

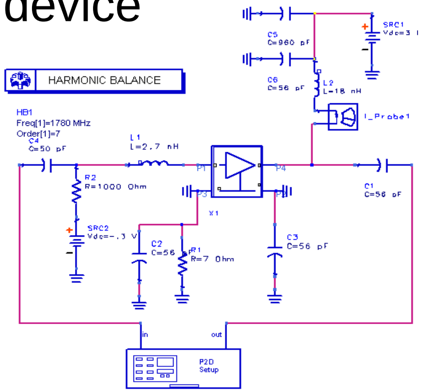
1. Complete characterization of linear networks



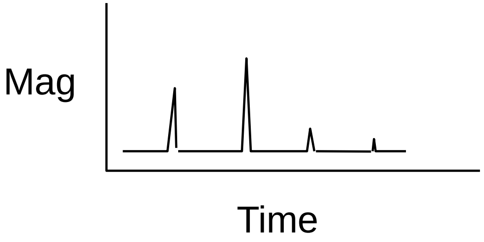
2. Complex impedance needed to design matching circuits



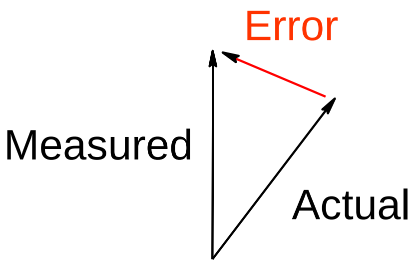
3. Complex values needed for device modeling



4. Time-domain characterization



5. Vector-error correction



6. X-parameter (nonlinear) characterization

Agenda

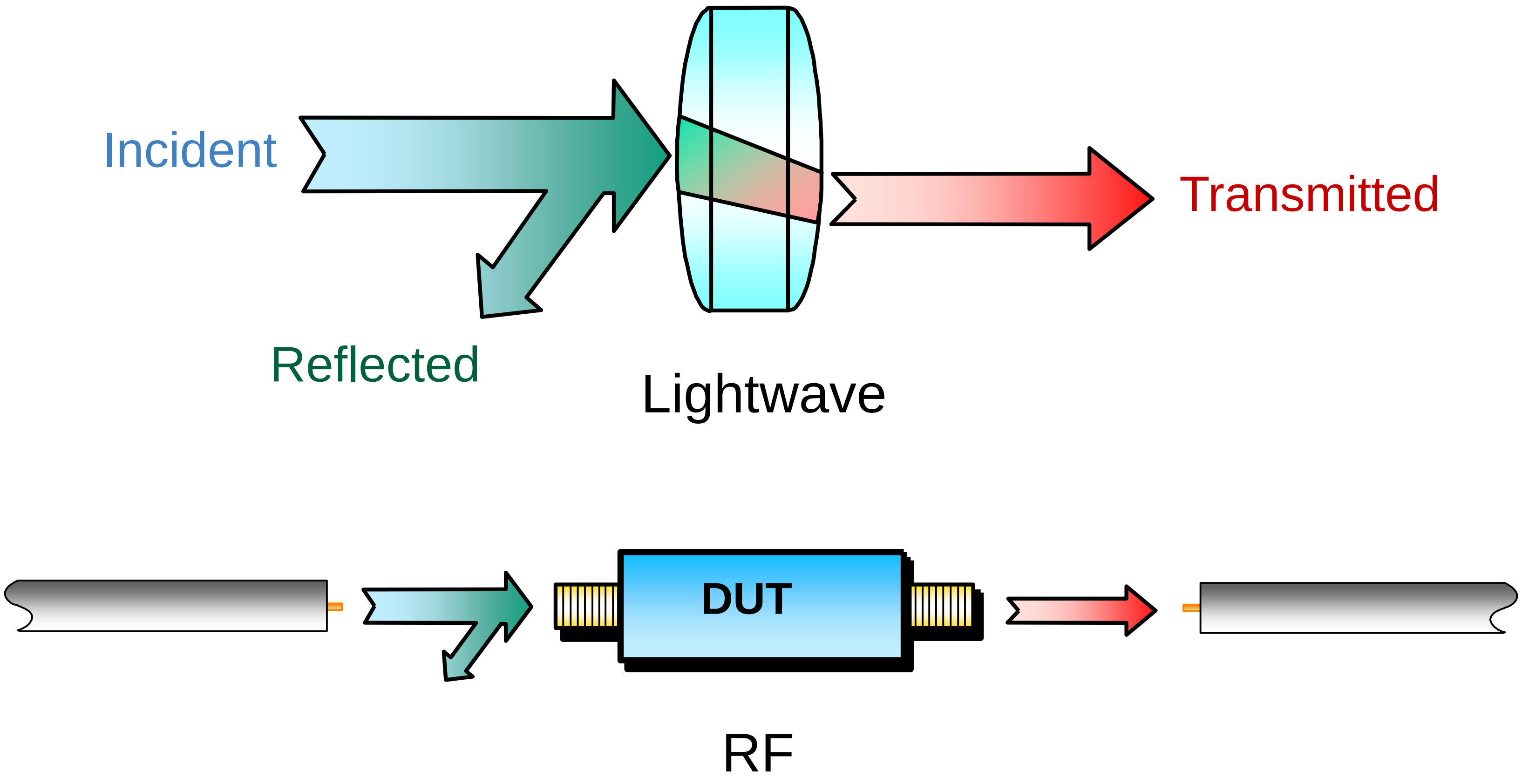
– What measurements do we make?

– Network analyzer hardware

– Error models and calibration

– Additional measurements

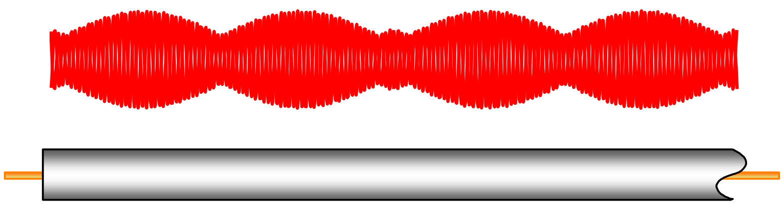
Lightwave Analogy to RF Energy



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

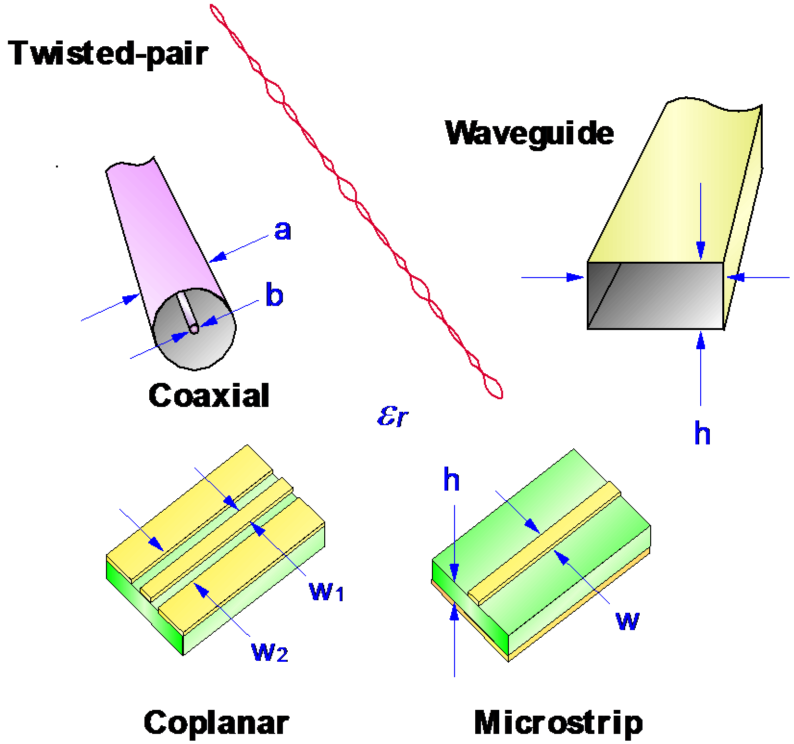


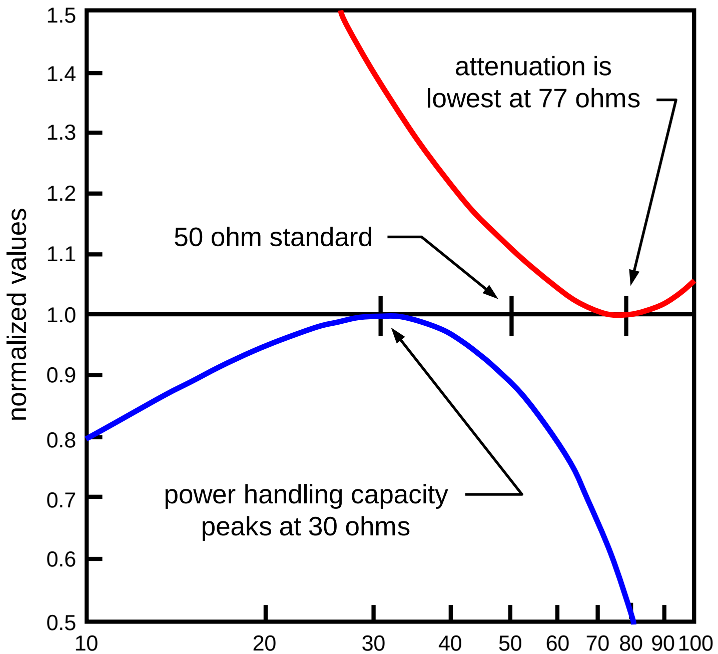
High frequencies

- 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

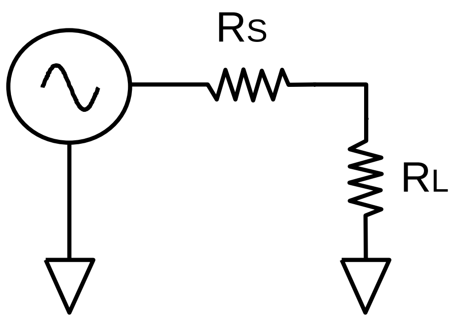
- Z_o determines relationship between voltage and current waves
- Z_o is a function of physical dimensions and ε_r
- Z_o is usually a real impedance (e.g. 50 or 75 ohms)

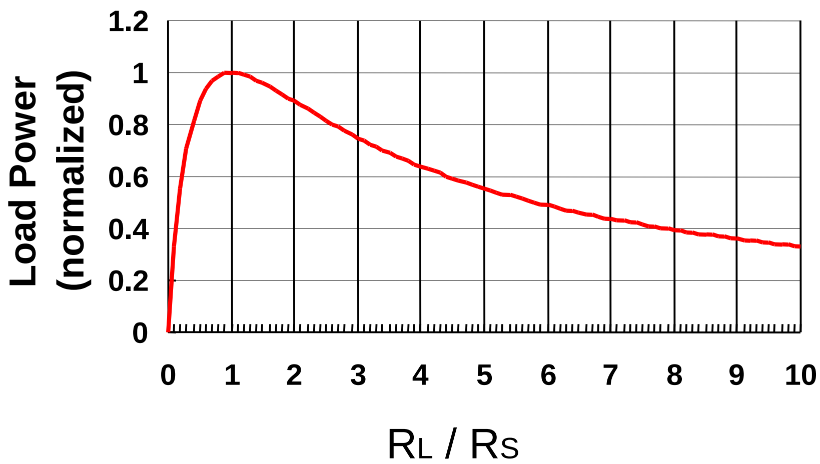




Characteristic impedance for coaxial airlines (ohms)

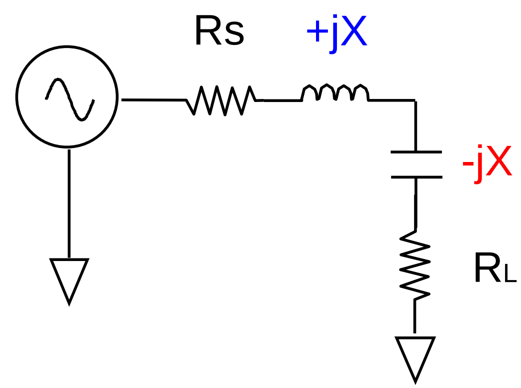
Power Transfer Efficiency



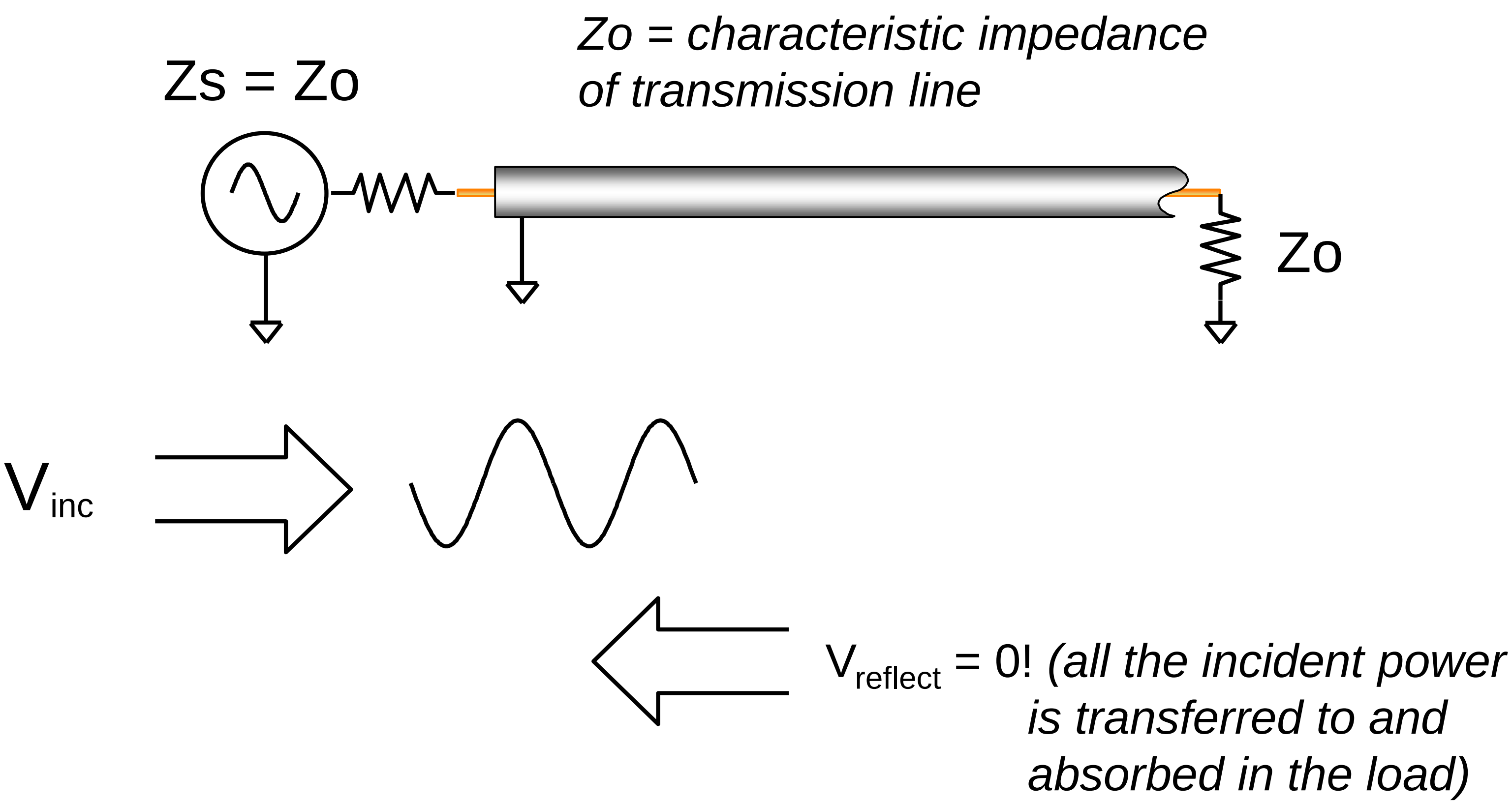


Maximum power is transferred when $R_L = R_S$

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

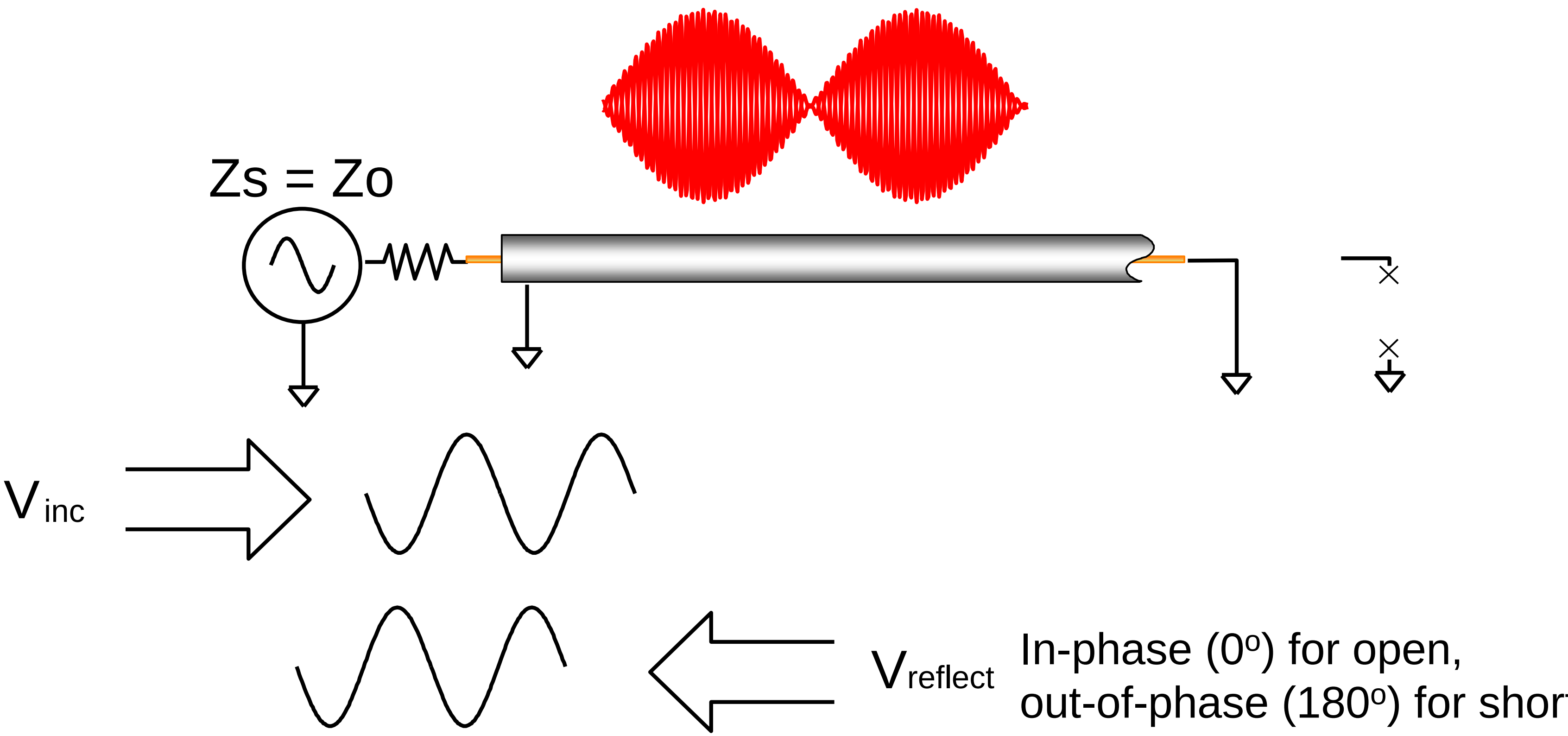


Transmission Line Terminated with Zo



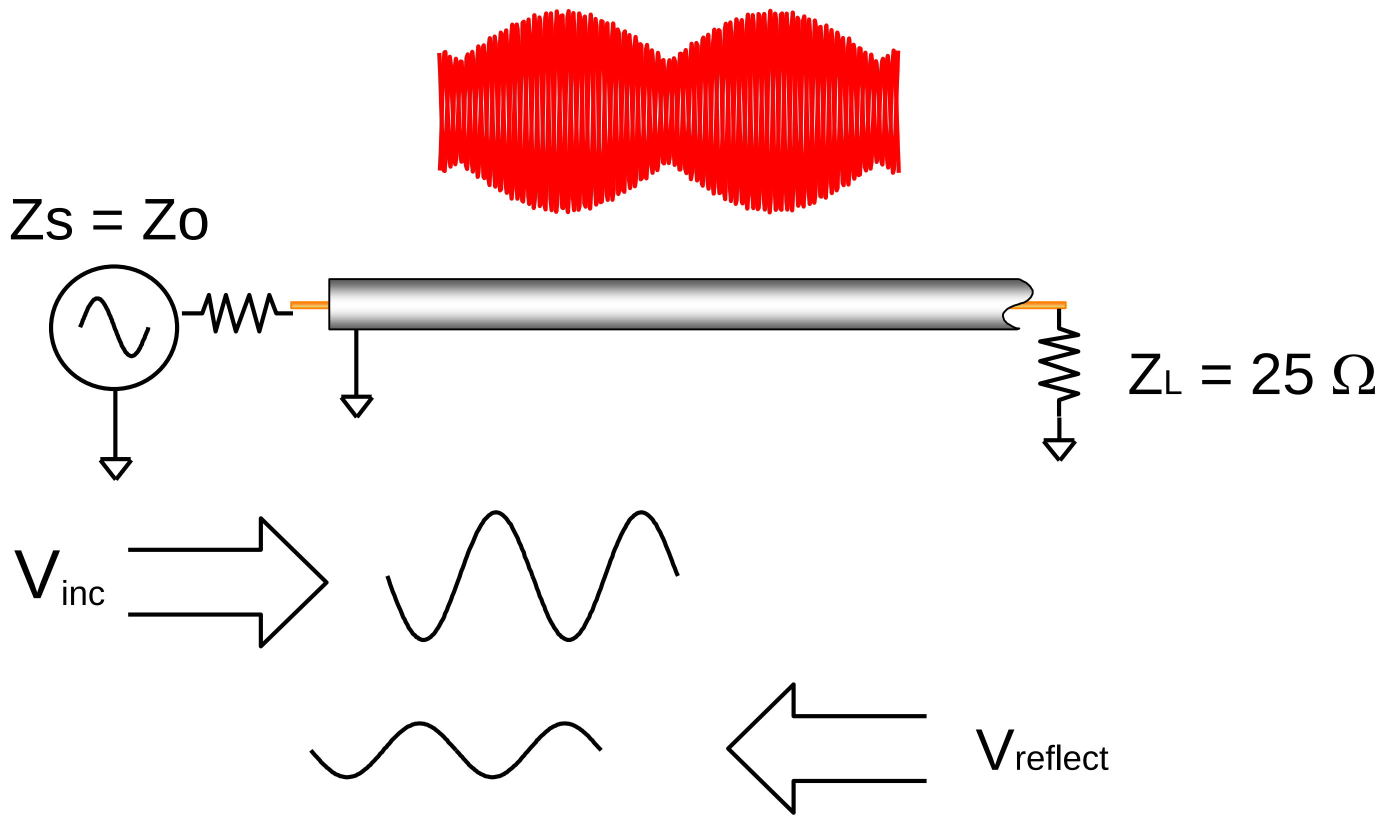
For reflection, a transmission line terminated in Zo behaves like an infinitely long transmission line

Transmission Line Terminated with Short, Open



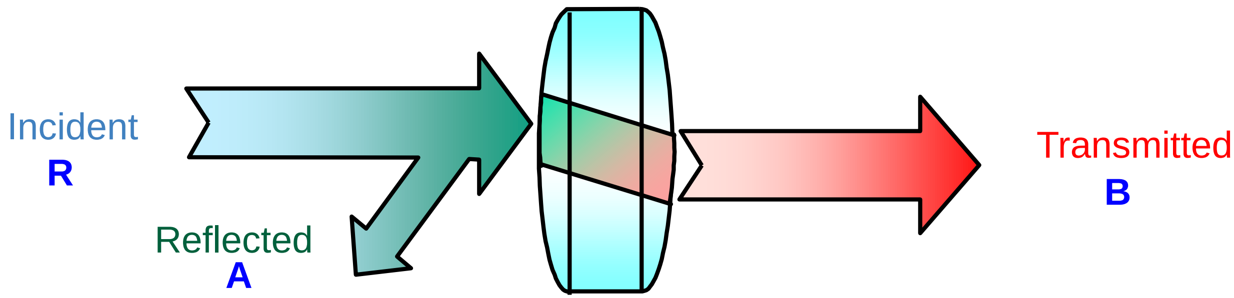
For reflection, a transmission line terminated in a short or open reflects all power back to source

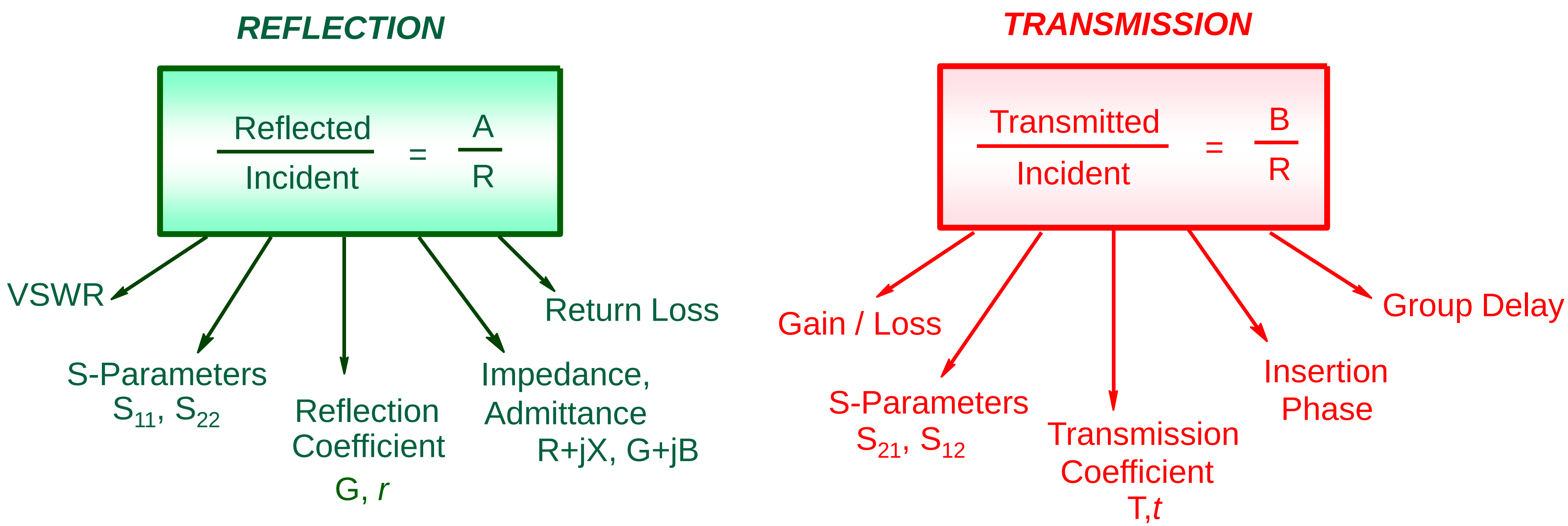
Transmission Line Terminated with 25 Ohms



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

High-Frequency Device Characterization

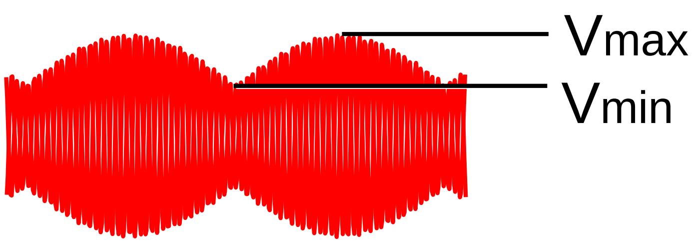




Reflection Parameters

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

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



Voltage Standing Wave Ratio

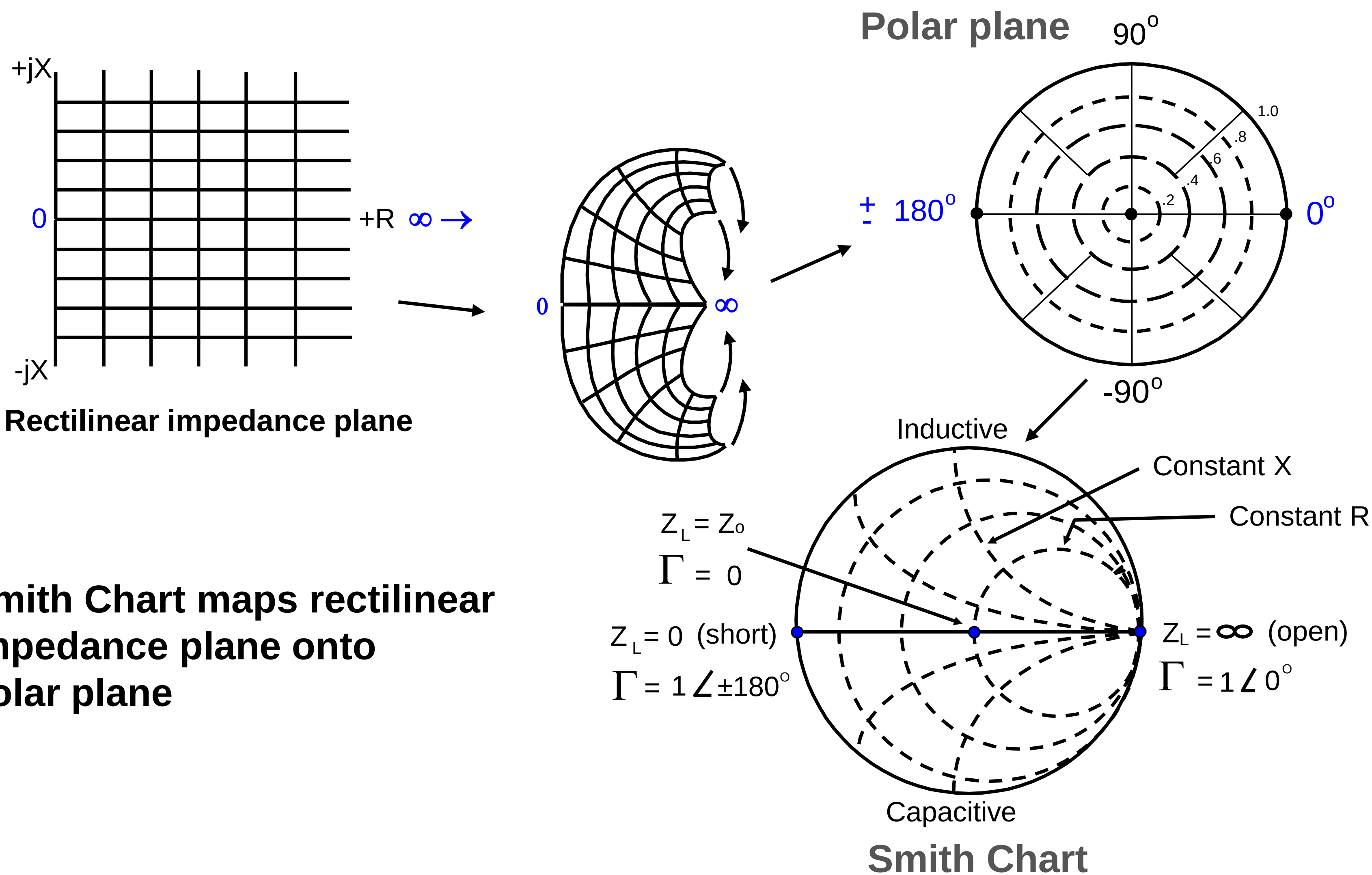
VSWR $= \dfrac{V_{max}}{V_{min}} = \dfrac{1+\rho}{1-\rho}$

No reflection (ZL = Zo)

Full reflection (ZL = open, short)

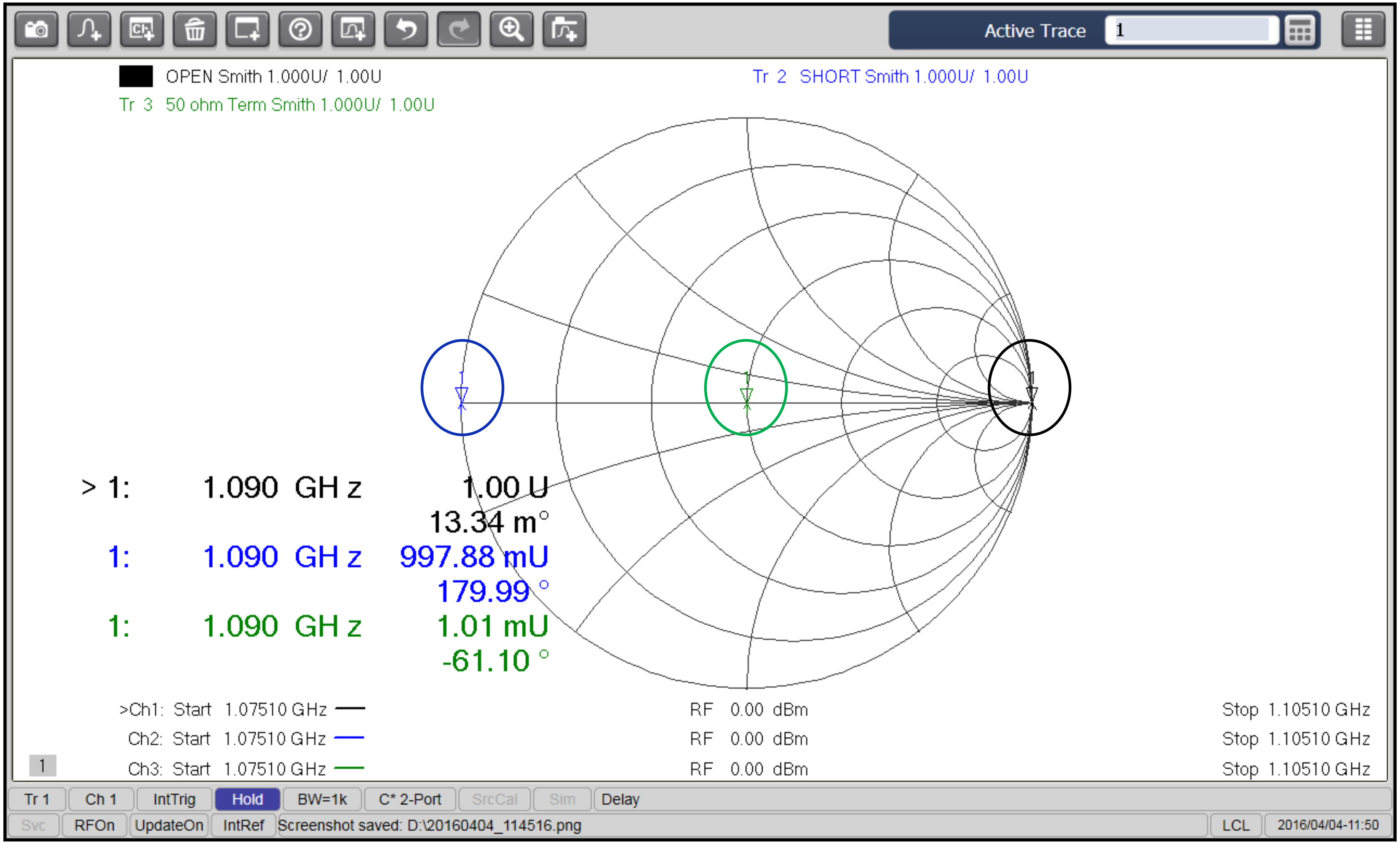
No reflection	Parameter	Full reflection
0	ρ	1
∞ dB	**RL**	0 dB
1	**VSWR**	∞

Smith Chart Review

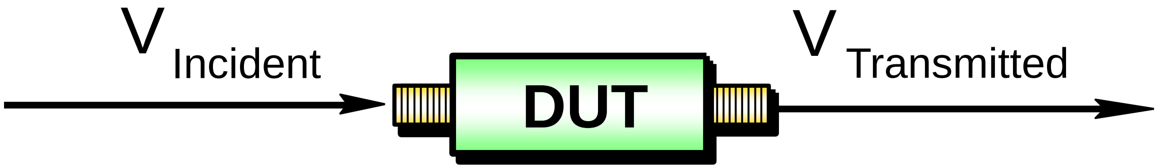


Smith Chart maps rectilinear impedance plane onto polar plane

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



Transmission Parameters



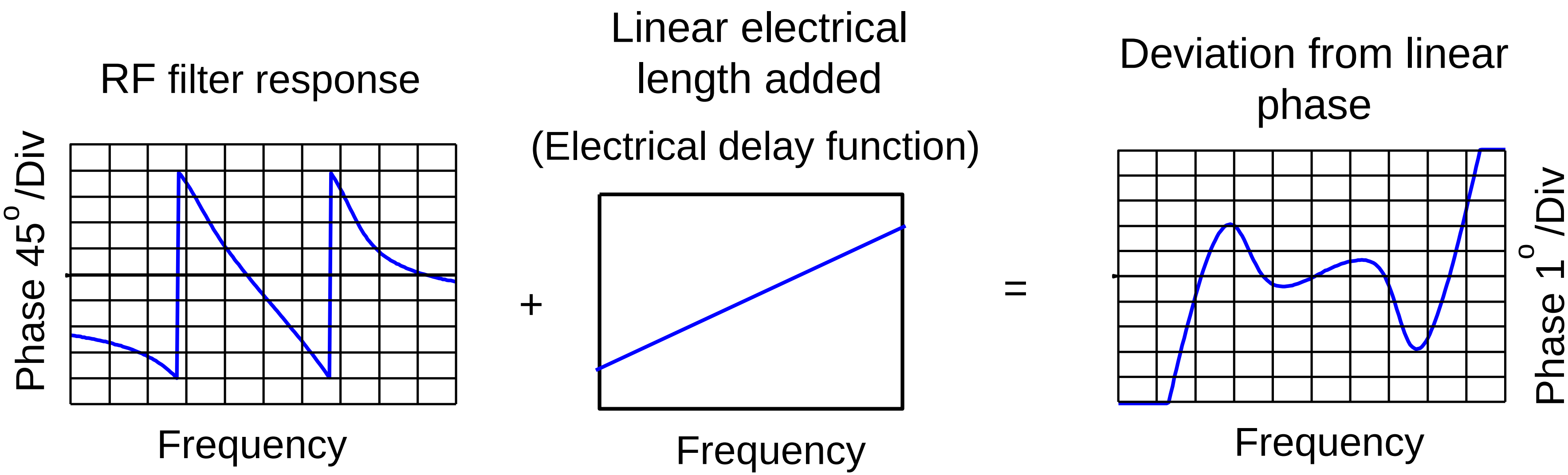
$$\text{Transmission Coefficient} = T = \frac{V_{Transmitted}}{V_{Incident}} = \tau \angle \phi$$

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

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

Deviation from Linear Phase

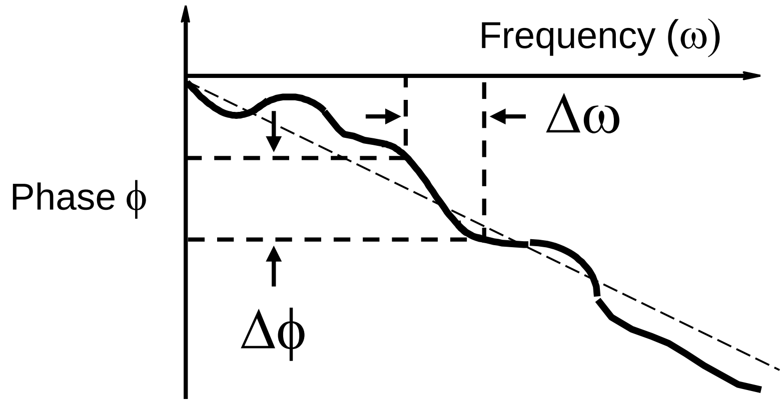
Use electrical delay to remove linear portion of phase response

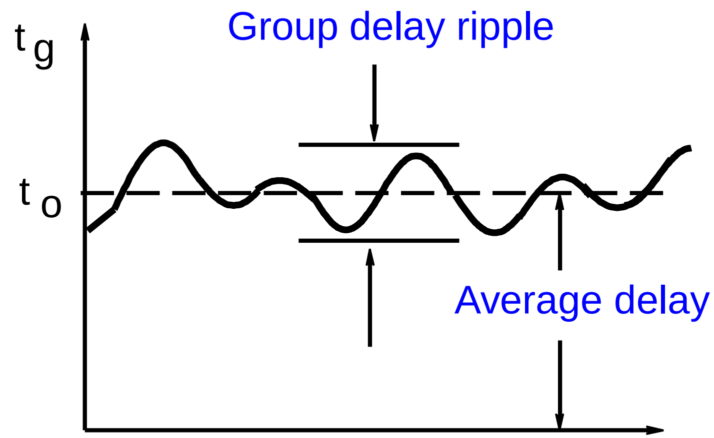


Low resolution

High resolution

Group Delay





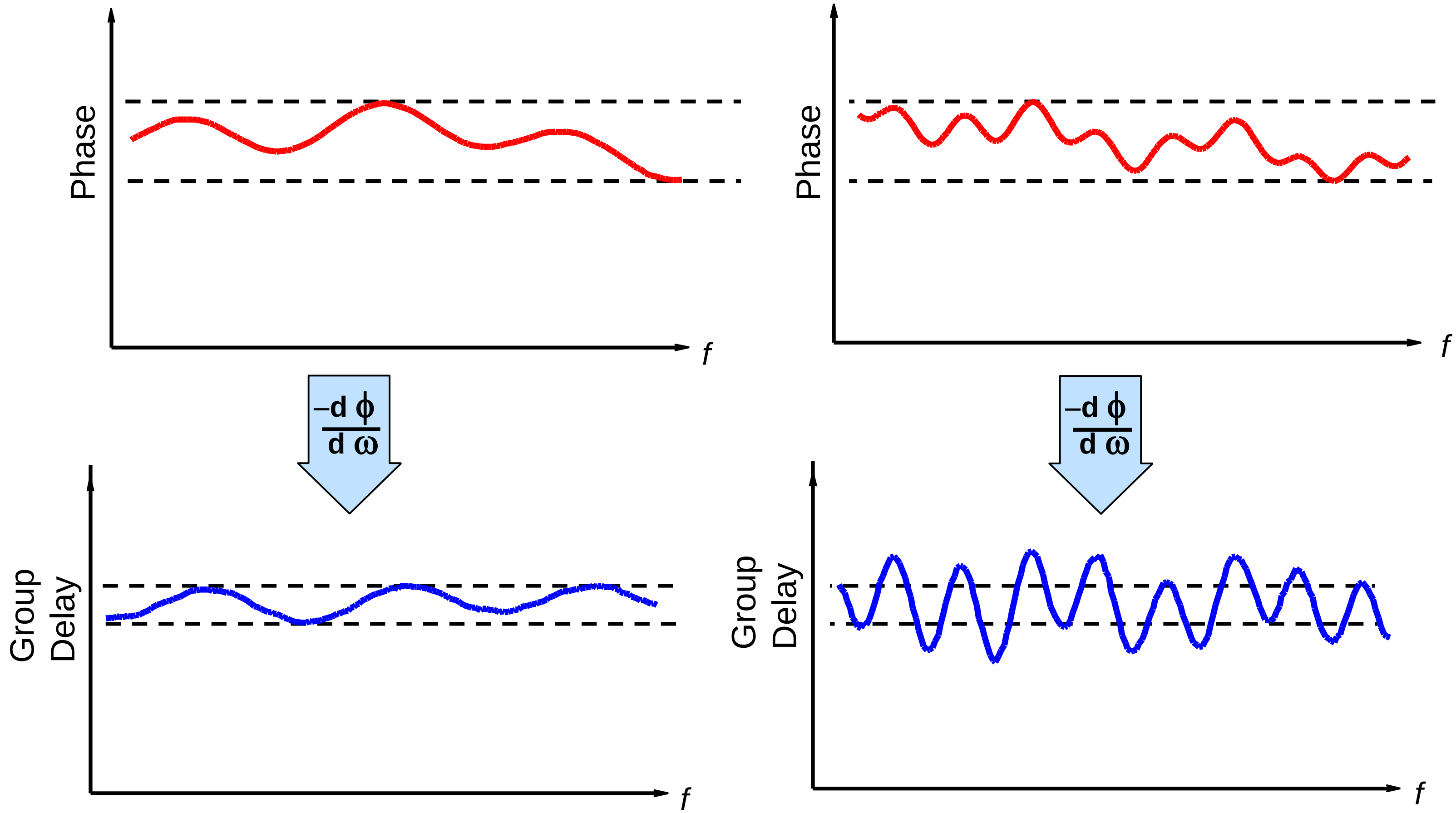
Group Delay= (t_g)

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

- 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 (Δω) of measurement is very important

Why Measure Group Delay?



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

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

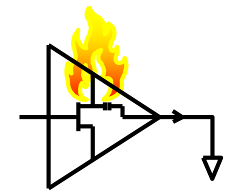
$V_1 = z_{11}I_1 + z_{12}I_2$

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

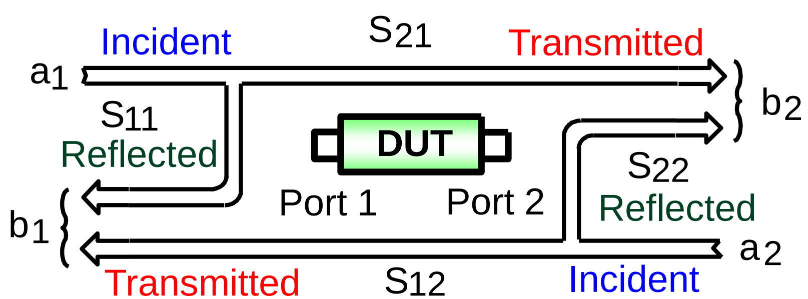
$$h_{11} = \left.\frac{V_1}{I_1}\right|_{V_2=0}$$ *(requires **short circuit**)*

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

Why Use S-Parameters?



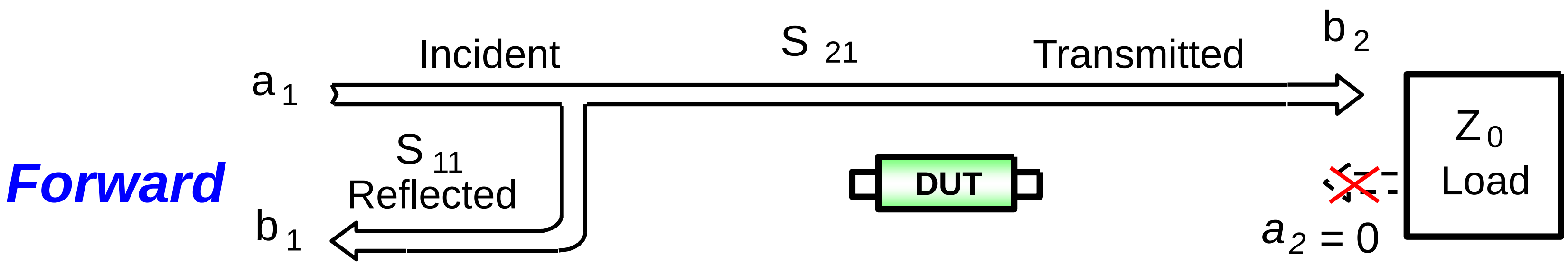
- Relatively easy to **obtain** at high frequencies
  - Measure voltage traveling waves with a vector network analyzer
  - Don't need shorts/opens (can cause active devices to oscillate or self-destruct)
- Relate to **familiar** measurements (gain, loss, reflection coefficient ...)
- Can **cascade** 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



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

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

Measuring S-Parameters

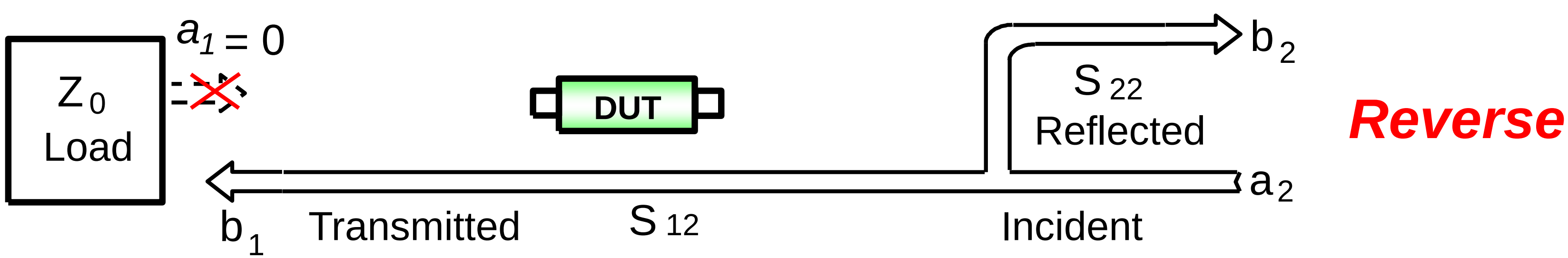


$$S_{11} = \frac{\textit{Reflected}}{\textit{Incident}} = \frac{b_1}{a_1}\Bigg|_{a_2 = 0}$$

$$S_{21} = \frac{\textit{Transmitted}}{\textit{Incident}} = \frac{b_2}{a_1}\Bigg|_{a_2 = 0}$$

$$S_{22} = \frac{\textit{Reflected}}{\textit{Incident}} = \frac{b_2}{a_2}\Bigg|_{a_1 = 0}$$

$$S_{12} = \frac{\textit{Transmitted}}{\textit{Incident}} = \frac{b_1}{a_2}\Bigg|_{a_1 = 0}$$



Equating S-Parameters With Common Measurement Terms

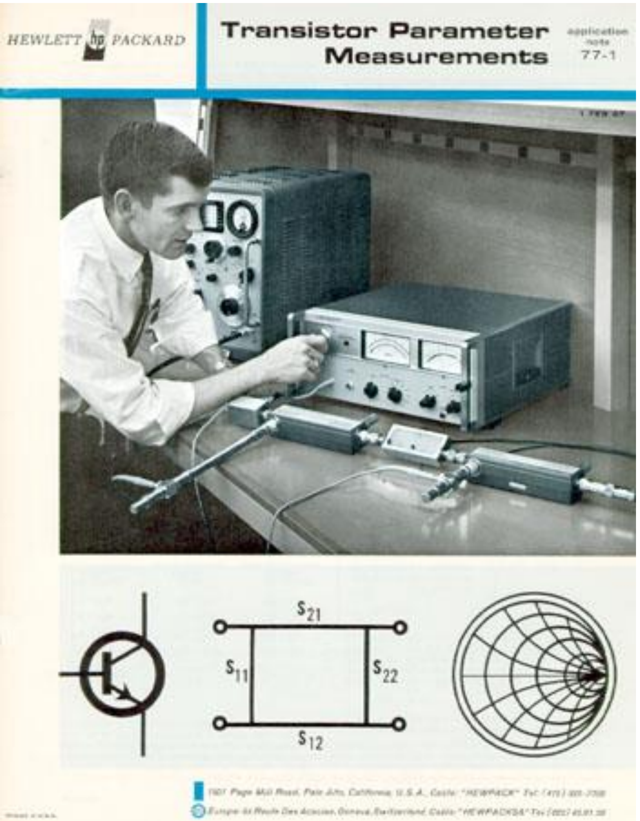
S_{11} = forward reflection coefficient ***(input match)***

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

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

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

S-parameters is not very new…



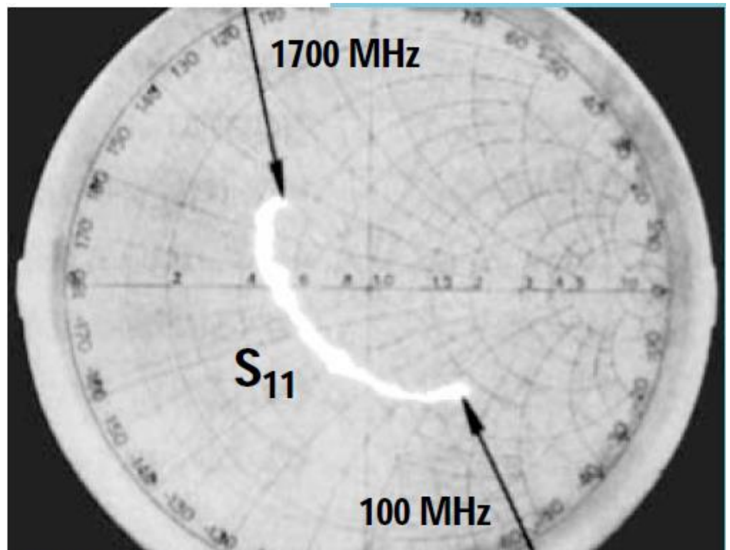


Figure 4a

s_{11} of a 2N3478 transistor measured with the classic HP 8410A network analyzer. Outermost circle on Smith Chart overlay corresponds to $|s_{11}| = 1$. The movement of s_{11} with frequency is approximately along circles of constant resistance, indicative of series capacitance and inductance.

Figure 1. 8410 network analyzer

The Network Analyzer make the S-parameter design simple, affordable and accurate!!

Agenda

– What measurements do we make?

– Network analyzer hardware

– Error models and calibration

– Additional measurements

Keysight Technologies
Over 45 Years of Network Analyzer Innovations

1967
8410A

Figure 1. 8410 network analyzer

1975
8542A Automation V

Figure 2. 8542 automatic network analyzer system

1984
8510A set the industry standard

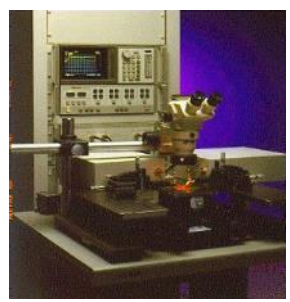
Figure 3. 8510 network analyzer

1986
8753 Series New economy entry into RF market

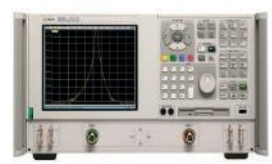
1988
8720 Series New economy entry into the Microwave

1991
8711 Series Low Frequency

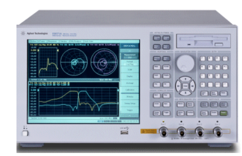
1996
8510XF Single sweep up 110GHz



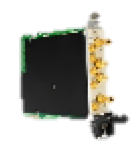
2000
PNA: New standard of performance



2001
ENA



2014
PXI VNA



2007
PNA-X

2008
FieldFox

2015
E5080A

Broadband Passive Components for Microwave Network Analysis

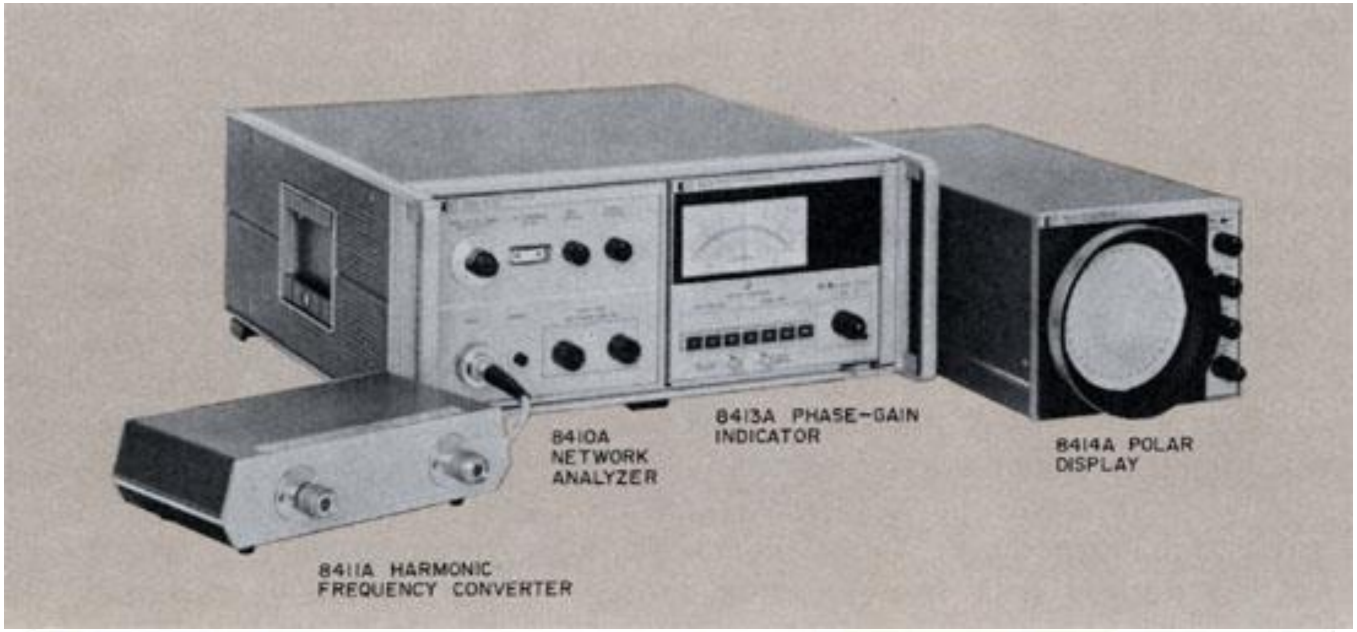
It takes more than an advanced network analyzer to make accurate, broadband device-parameter measurements. You can't do it without precision, broadband hardware—things like directional couplers, line stretchers, switches, and transmission lines. It also helps to have everything in one instrument.

By Stephen F. Adam, George R. Kirkpatrick, and Richard A. Lyon

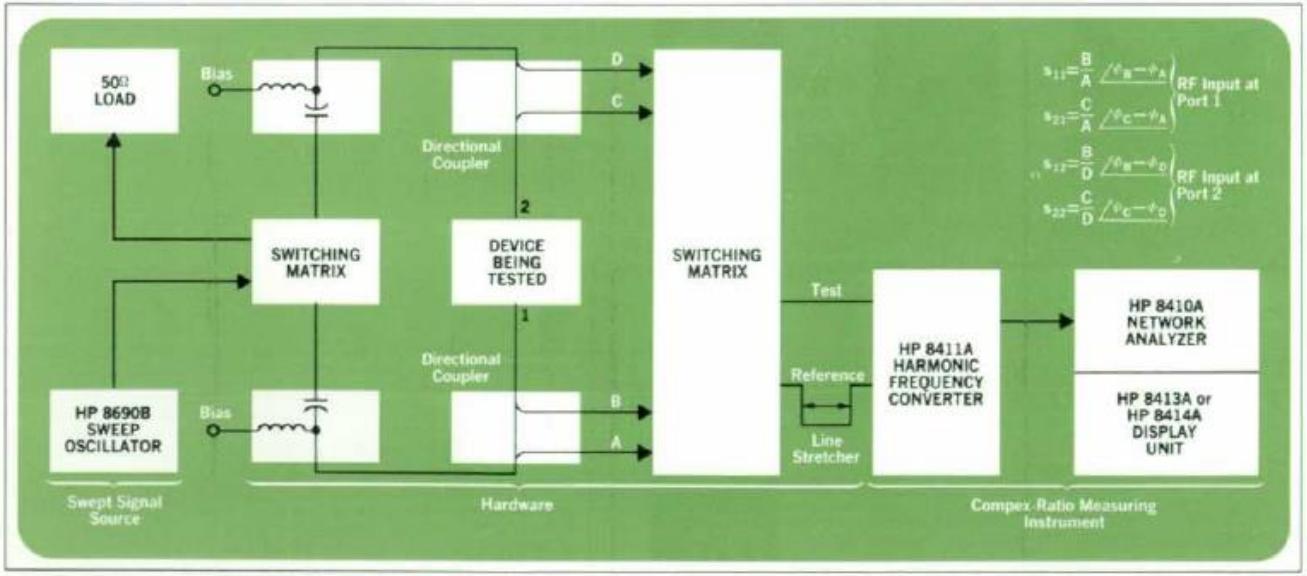
THERE WAS A TIME, not very long ago, when microwave transmission and reflection measurements were nearly always magnitude-only measurements. People were interested in phase, of course, and it would have been most desirable to have a system that could measure magnitude and phase looking into or through any two-port device. But a system that could do this, and do it over very broad frequency ranges, conveniently and accurately, would have been extremely expensive and complex.

At Hewlett-Packard, the key to broadband microwave measurements proved to be a dc-to-12.4-GHz sampling device, developed in 1966.[1] Using the device as a harmonic mixer, a network analyzer system, Model 8410A, was developed and introduced in 1967.[2] The network analyzer is basically an instrument which measures and displays the complex ratio of two signals. Specifically, it measures the complex reflection and transmission coefficients, or s-parameters, of active and passive devices.[3] These parameters characterize the device completely.

Besides the network analyzer, two other elements are needed to measure network parameters. One is a swept signal source, and the other is a collection of passive components for interfacing the signal source and the network analyzer with the device being tested. Fig. 1 illustrates the three elements and their relationships. The passive components take the signal from the sweep generator, isolate part of it for use as a reference signal, and direct the rest to one of the ports of the device being

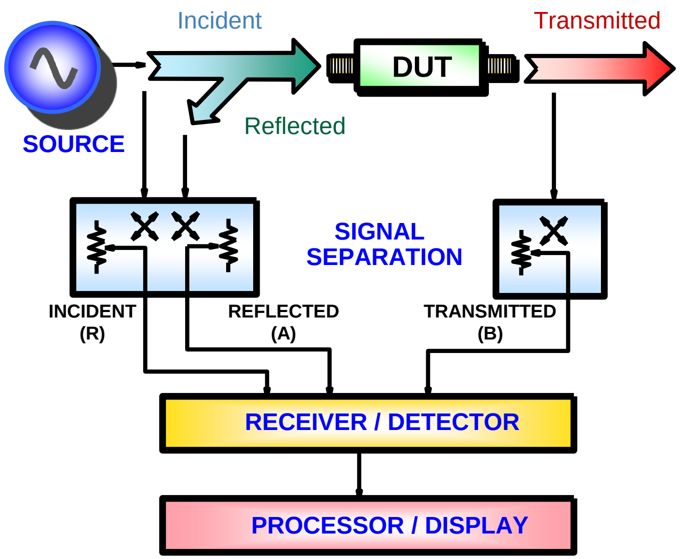


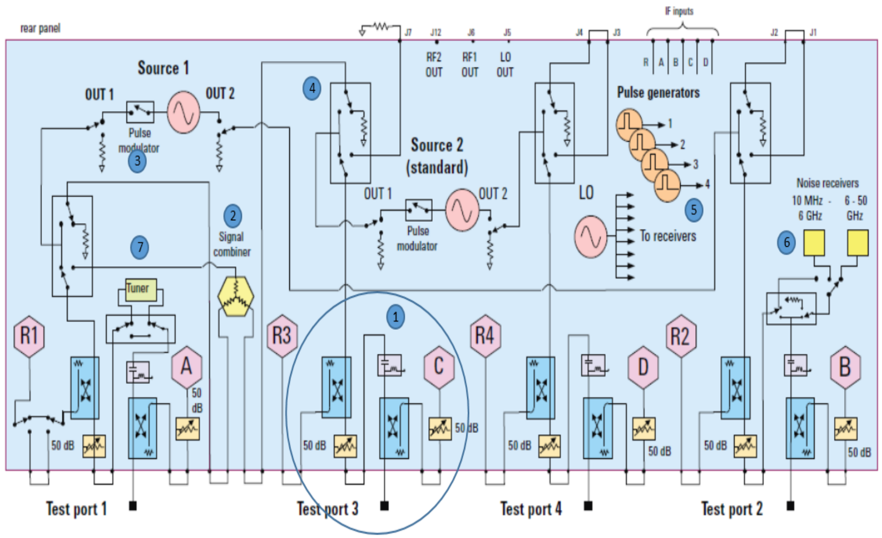
8410A NETWORK ANALYZER
8413A PHASE-GAIN INDICATOR
8414A POLAR DISPLAY
8411A HARMONIC FREQUENCY CONVERTER

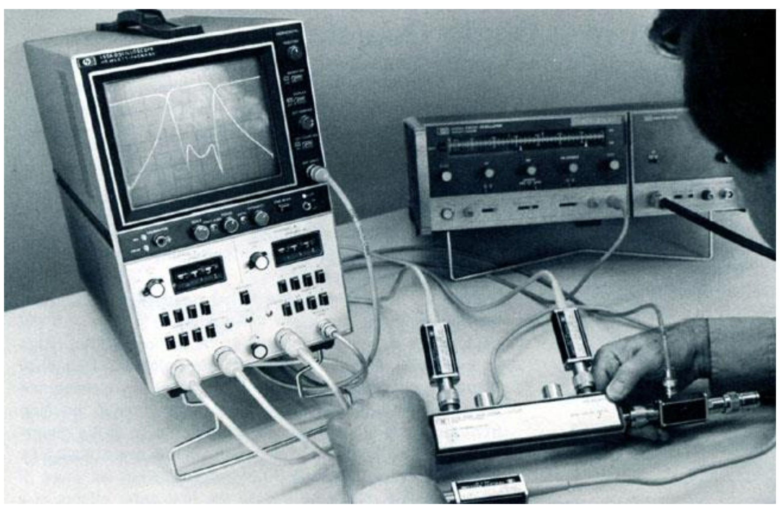


50Ω LOAD
Bias
Directional Coupler
D
C
2
SWITCHING MATRIX
DEVICE BEING TESTED
1
SWITCHING MATRIX
Directional Coupler
B
A
Bias
HP 8690B SWEEP OSCILLATOR
Test
Reference
Line Stretcher
HP 8411A HARMONIC FREQUENCY CONVERTER
HP 8410A NETWORK ANALYZER
HP 8413A or HP 8414A DISPLAY UNIT
$s_{11}=\frac{B}{A}\angle\phi_B-\phi_A$
$s_{21}=\frac{C}{A}\angle\phi_C-\phi_A$
RF Input at Port 1
$s_{12}=\frac{B}{D}\angle\phi_B-\phi_D$
$s_{22}=\frac{C}{D}\angle\phi_C-\phi_D$
RF Input at Port 2
Swept Signal Source
Hardware
Compex-Ratio Measuring Instrument

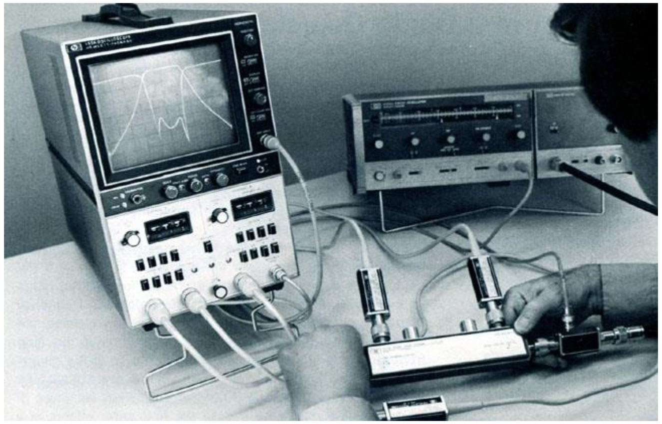
Network Analyzer Block Diagram: Yesterday and Today





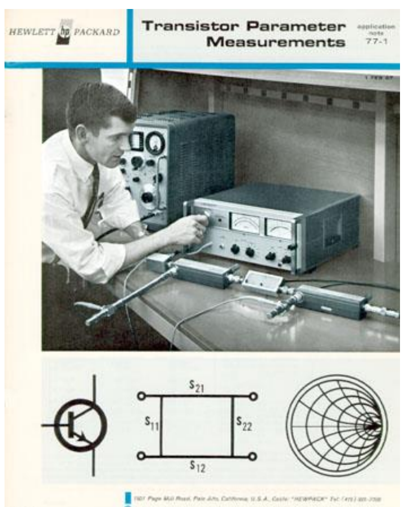


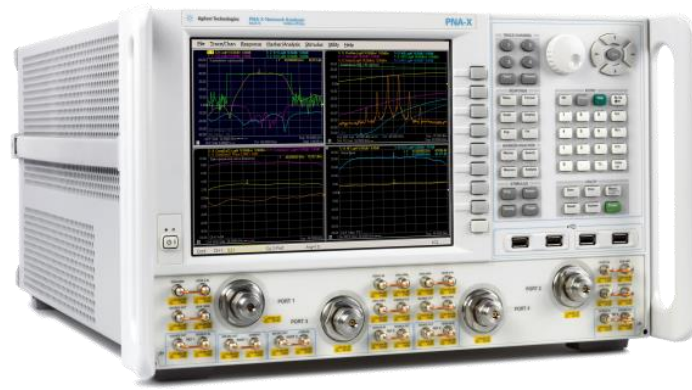
Network Analyzer Block Diagram: Yesterday and Today



Measurements:

- ✓ **CW S-parameters**

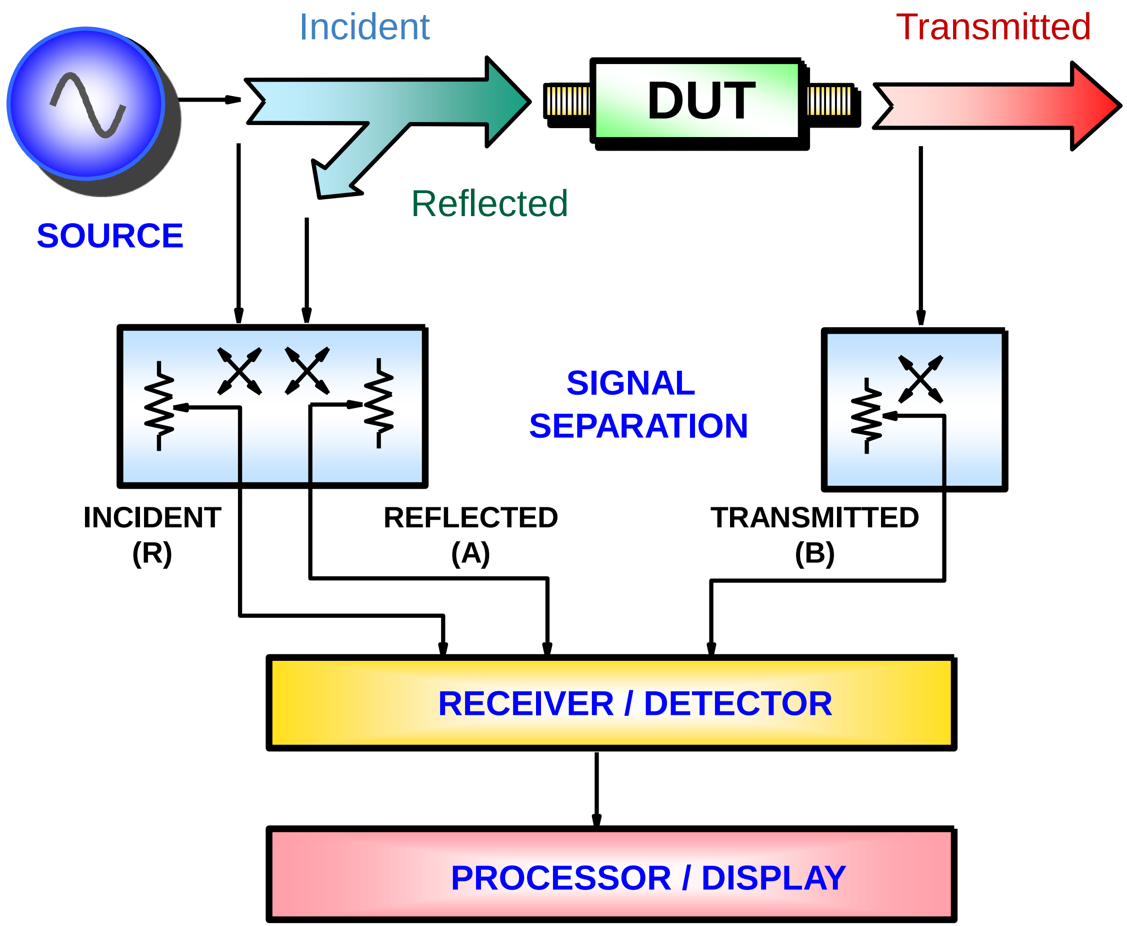




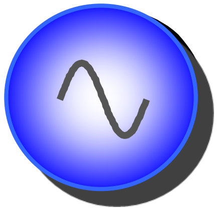
Measurements:

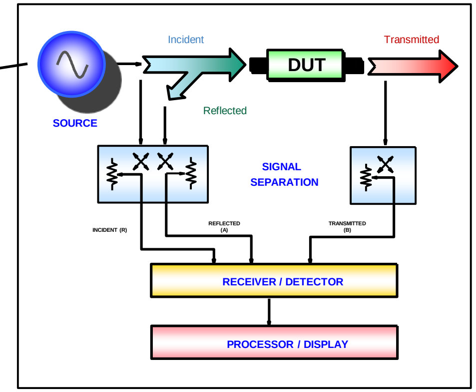
- ✓ **CW S-parameters**
- ✓ **Pulsed S-parameters**
- ✓ **Gain compression**
- ✓ **AM-to-PM conversion**
- ✓ **Harmonics**
- ✓ **Intermodulation distortion**
- ✓ **Noise Figure**
- ✓ **Hot-S-parameters**
- ✓ **Phase versus drive**
- ✓ **True-mode differential stimulus**
- ✓ **Spectrum Analysis**

Generalized Network Analyzer Block Diagram (Forward Measurements Shown)

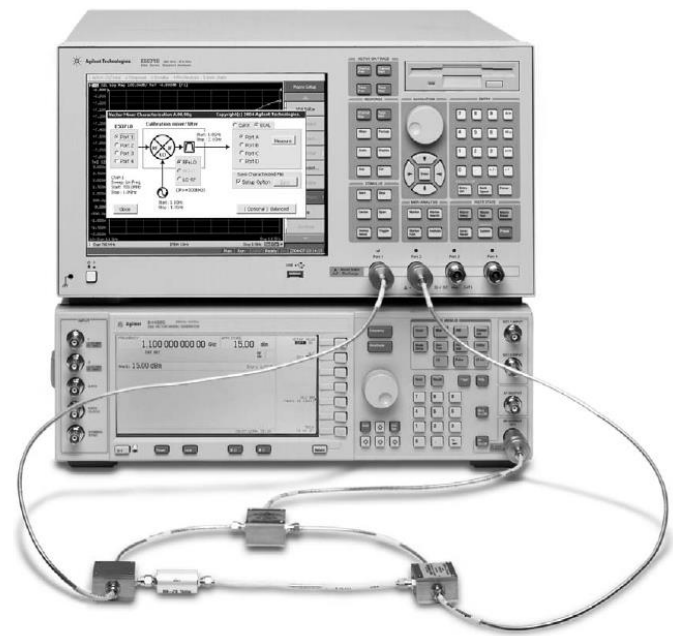


Source





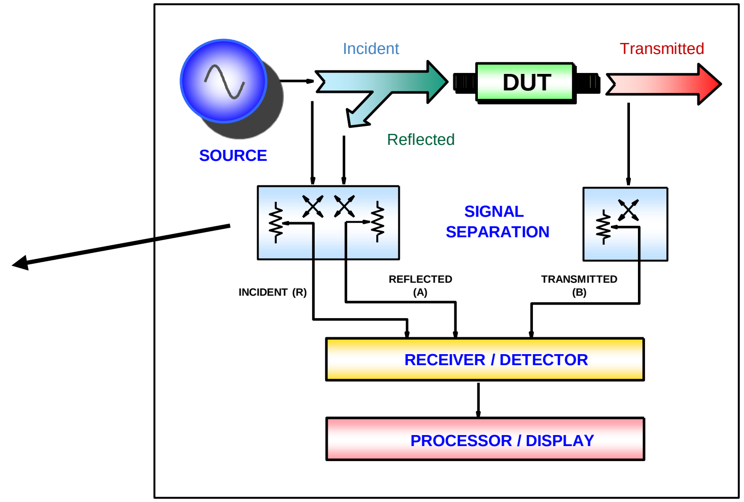
- Supplies stimulus for system
- Can sweep frequency or power
- Traditionally NAs had one signal source
- Modern NAs have the option for a second internal source and/or the ability to control external source
  - Can control an external source as a local oscillator (LO) signal for mixers and converters
  - Useful for mixer measurements like conversion loss, group delay

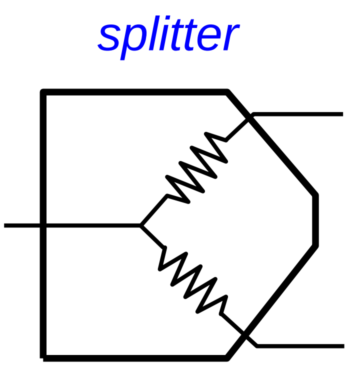


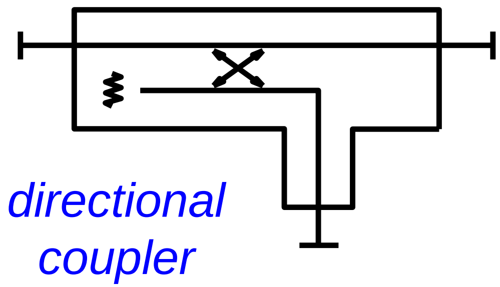
Signal Separation

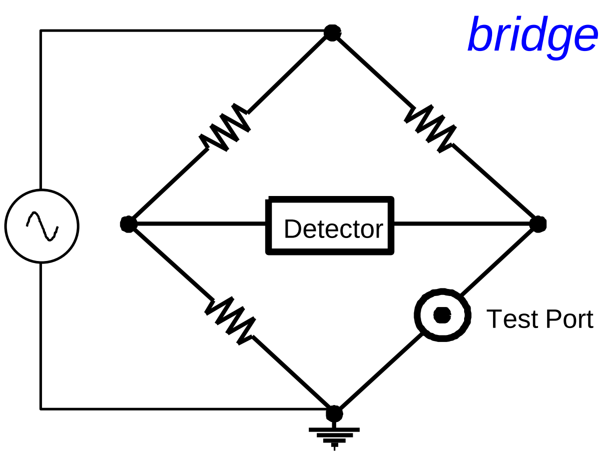
– Measure incident signal for reference

– Separate incident and reflected signals

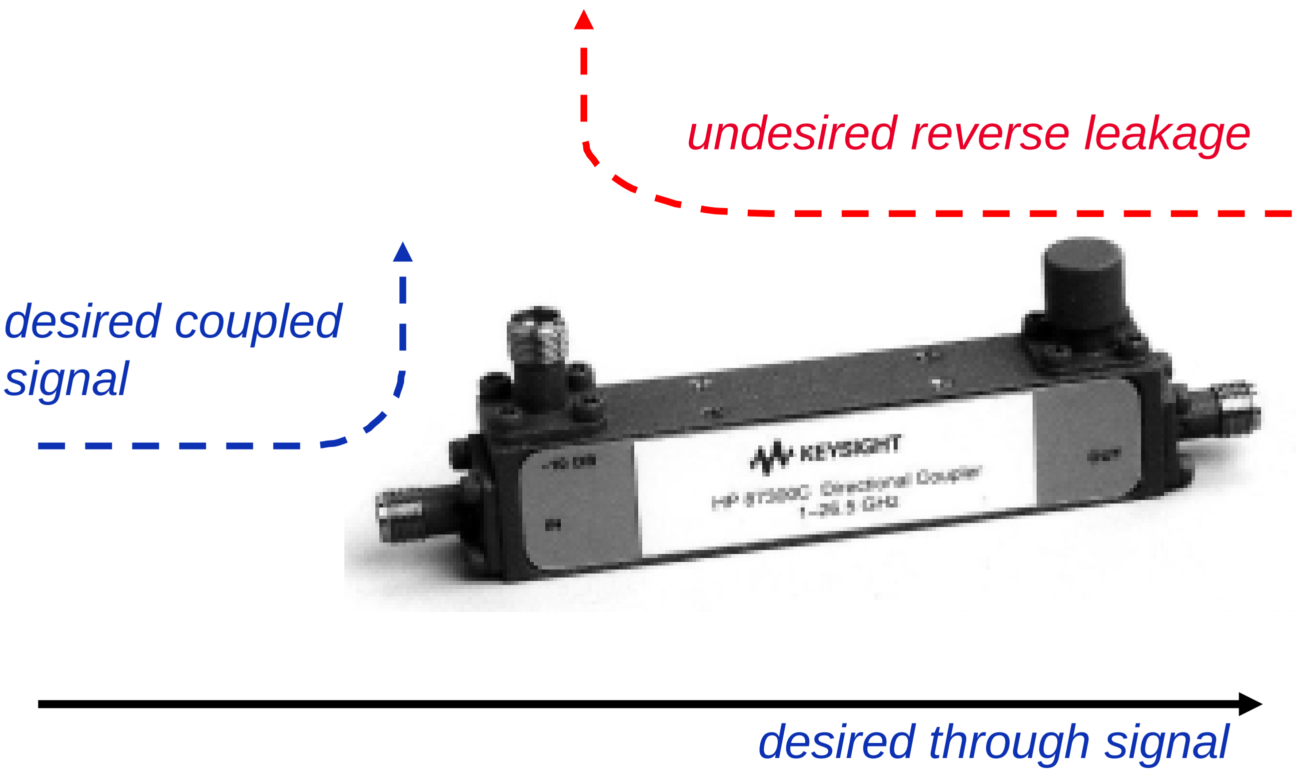






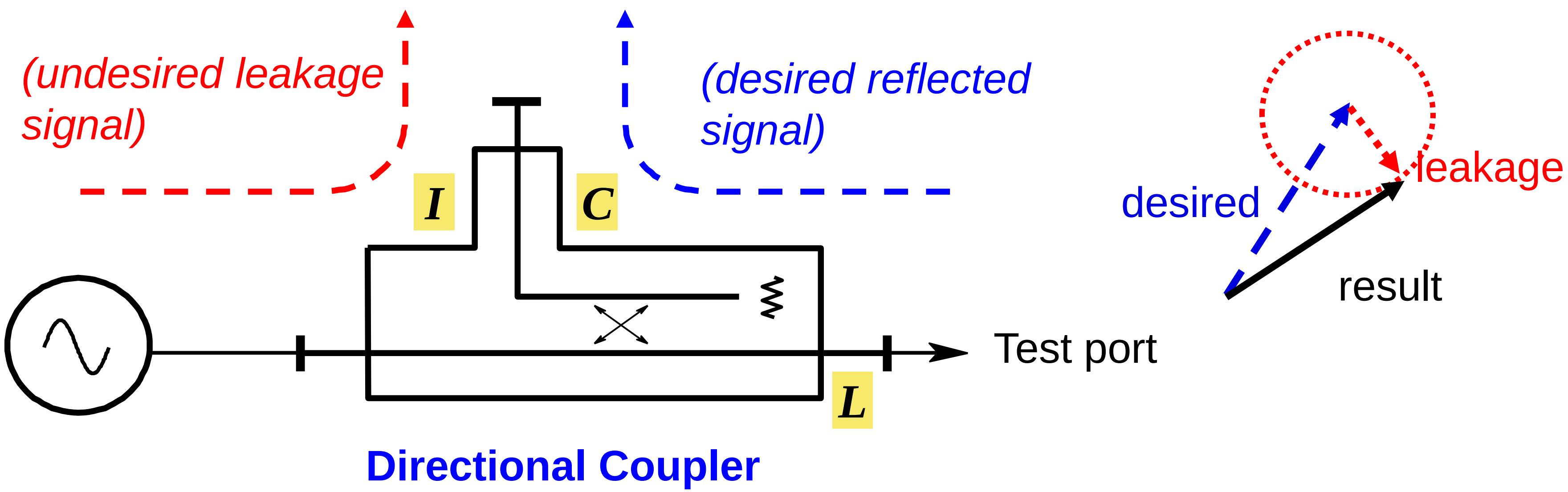


Directional Coupler



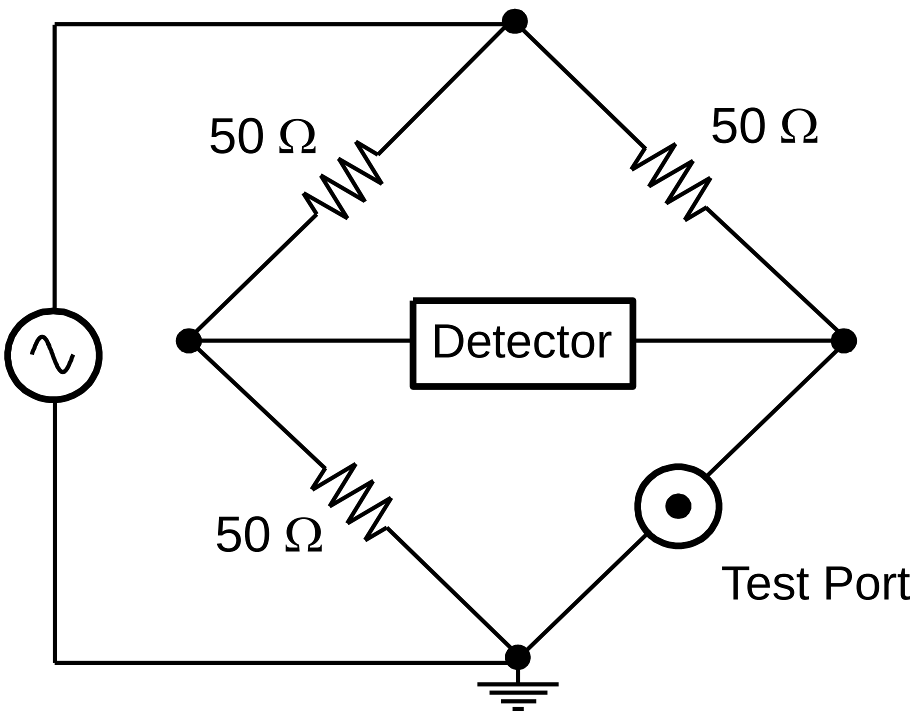
Directivity

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



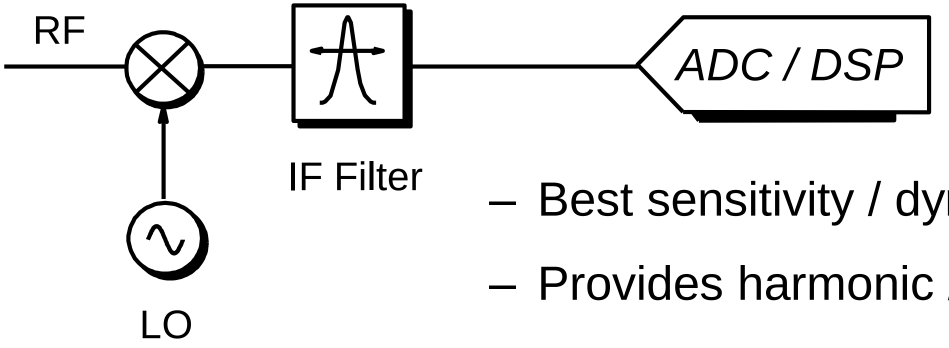
Directivity = Isolation (I) - Fwd Coupling (C) - Main Arm Loss (L)

Directional Bridge

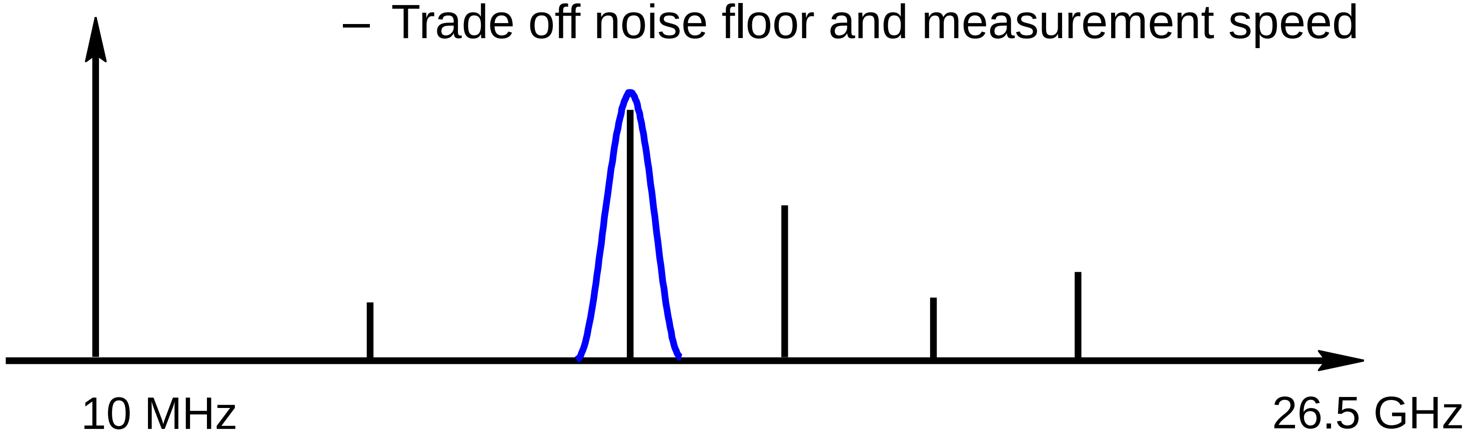


- 50-ohm load at test port balances the bridge -- detector reads zero
- Non-50-ohm load imbalances bridge
- Measuring magnitude and phase of imbalance gives complex impedance
- "Directivity" is difference between maximum and minimum balance
- Advantage: less loss at low frequencies
- Disadvantages: more loss in main arm at high frequencies and less power-handling capability

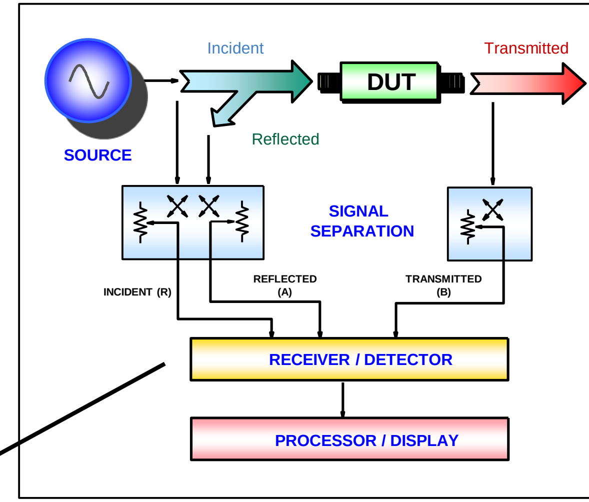
Detector:
Narrowband Detection - Tuned Receiver

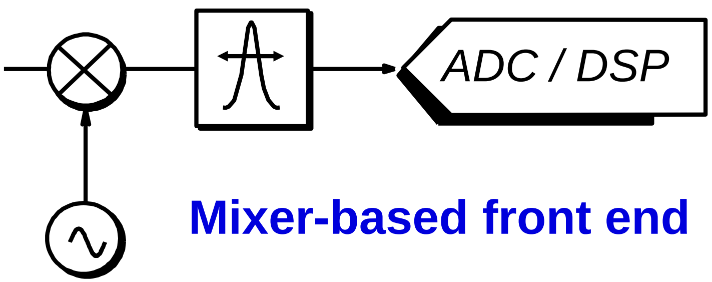


– Best sensitivity / dynamic range
– Provides harmonic / spurious signal rejection
– Improve dynamic range by increasing power, decreasing IF bandwidth, or averaging
– Trade off noise floor and measurement speed



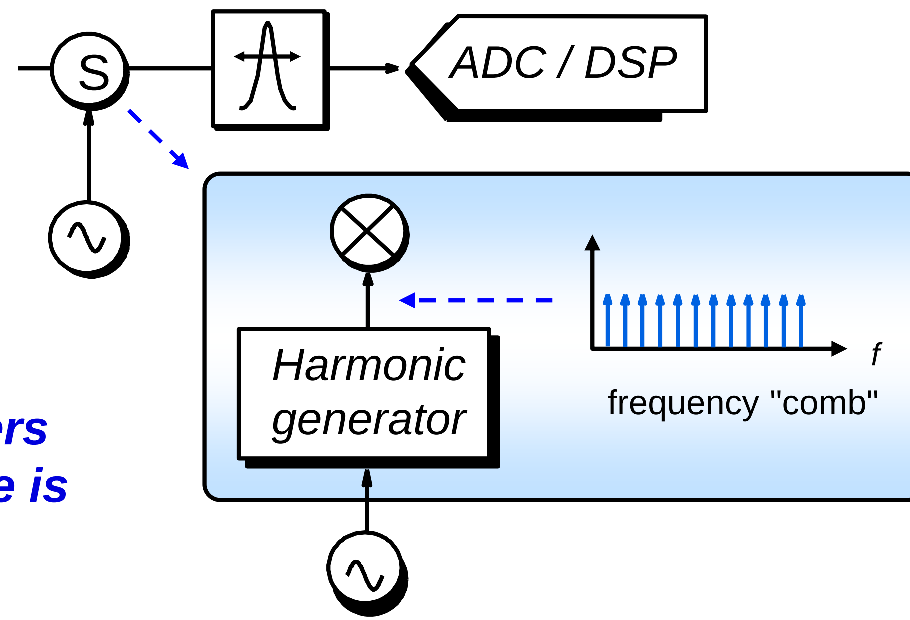
Tuned Receiver Front Ends: Mixers Versus Samplers





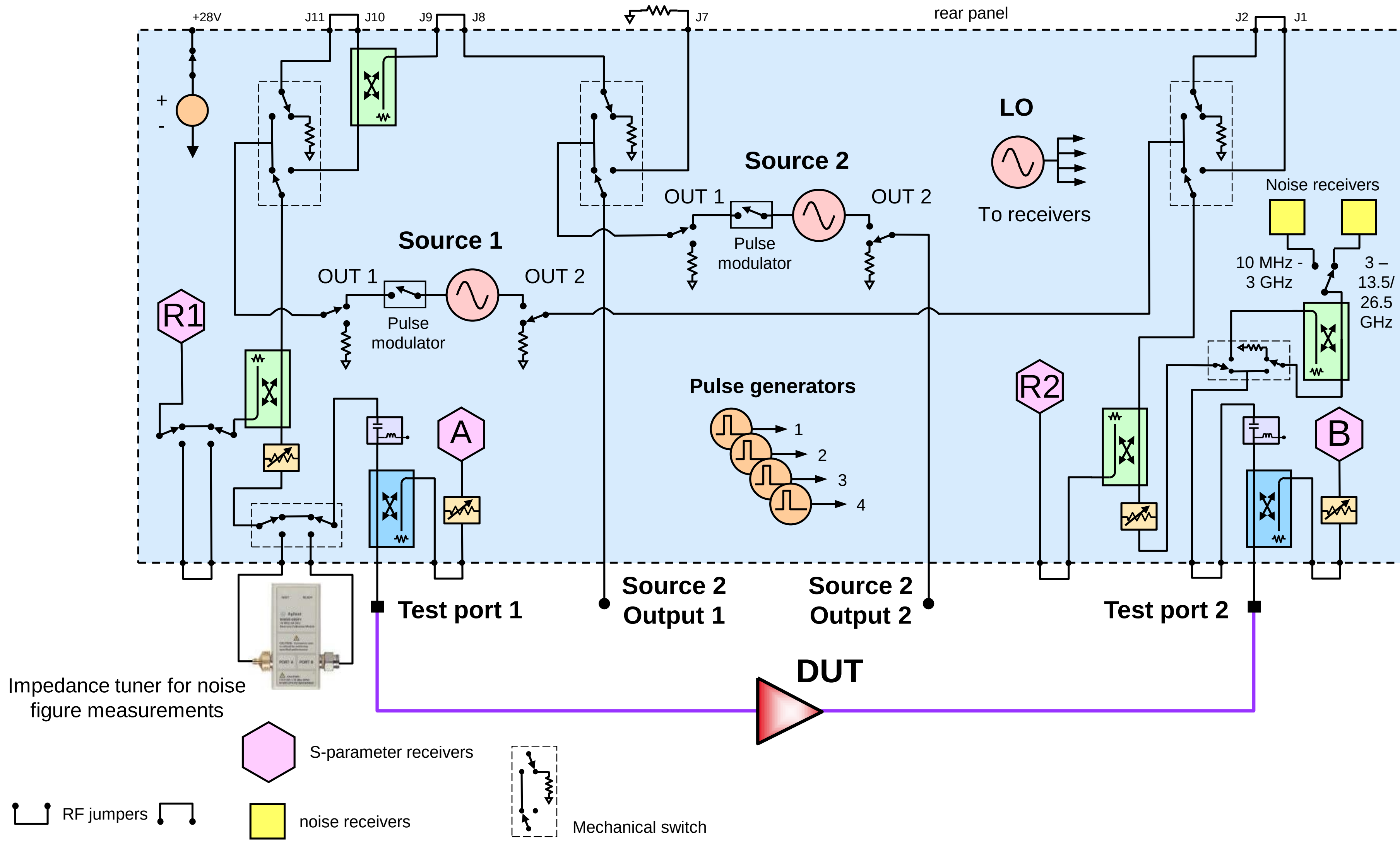
Mixer-based front end

Sampler-based front end

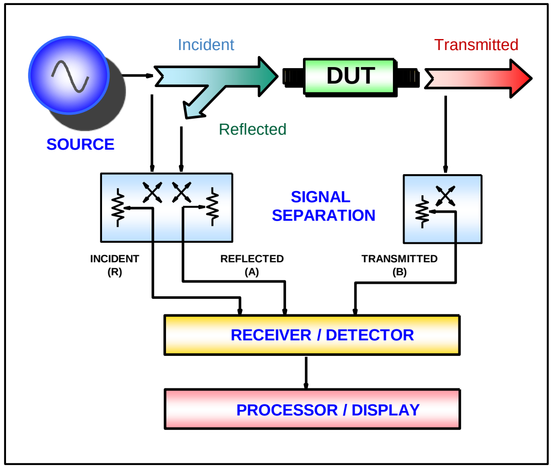


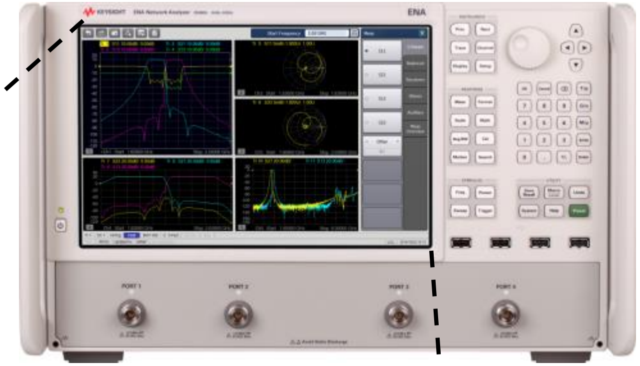
It is cheaper and easier to make broadband front ends using samplers instead of mixers, but dynamic range is considerably less

Modern VNA Block Diagram (2-Port PNA-X)

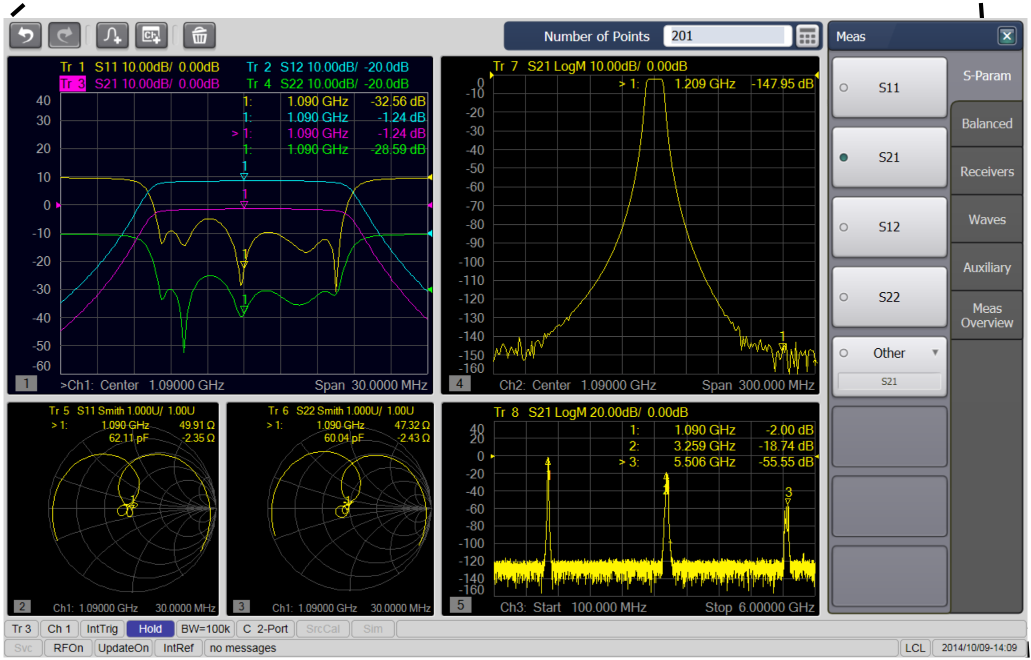


Processor / Display



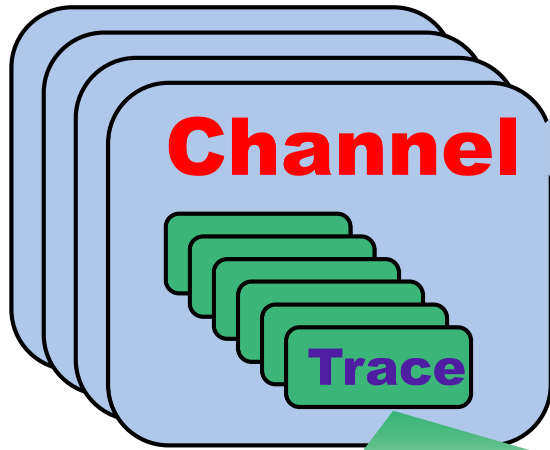


E5080A ENA

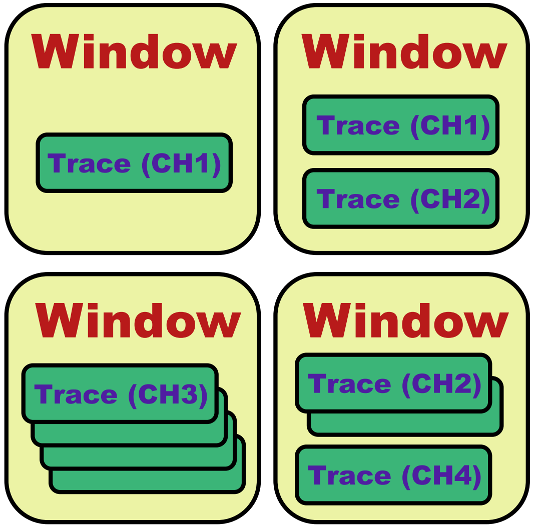


– Markers
– Limit lines
– Pass/fail indicators
– Linear/log formats
– Grid/polar/Smith charts
– Time-domain transform
– Trace math

Achieving Measurement Flexibility (PNA and E5080A)

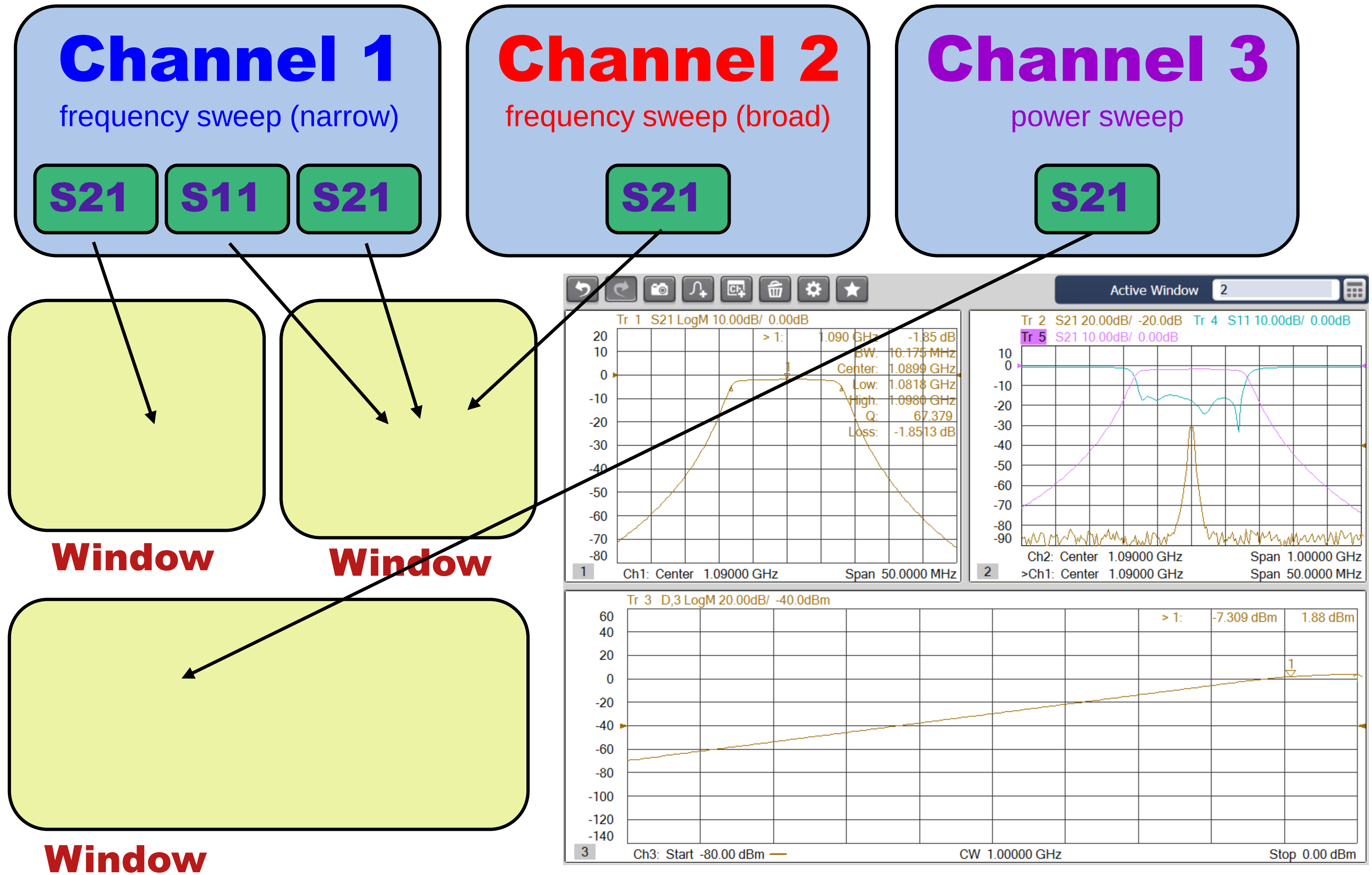


Channel
- Sweep type
- Frequencies
- Power level
- IF bandwidth
- Number of points
- Trigger state
- Averaging
- Calibration



Trace
- Parameter
- Format
- Scale
- Markers
- Trace math
- Electrical delay
- Phase offset
- Smoothing
- Limit tests
- Time-domain transform

Three Channel Example (PNA and E5080A)



Agenda

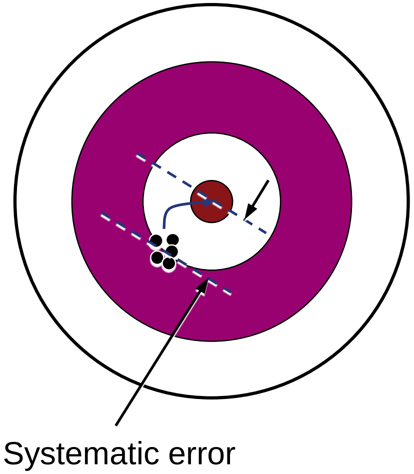
- What measurements do we make?
- Network analyzer hardware
- Error models and calibration
- Additional measurements

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***

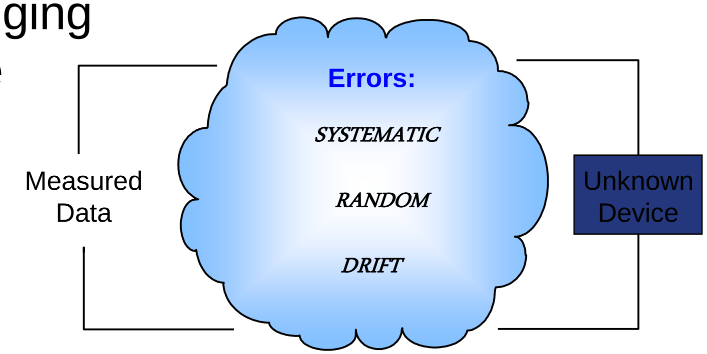
- Due to imperfections in the analyzer and test setup
- Assumed to be time invariant (predictable)
- Generally, are largest sources or error

– ***Random errors***

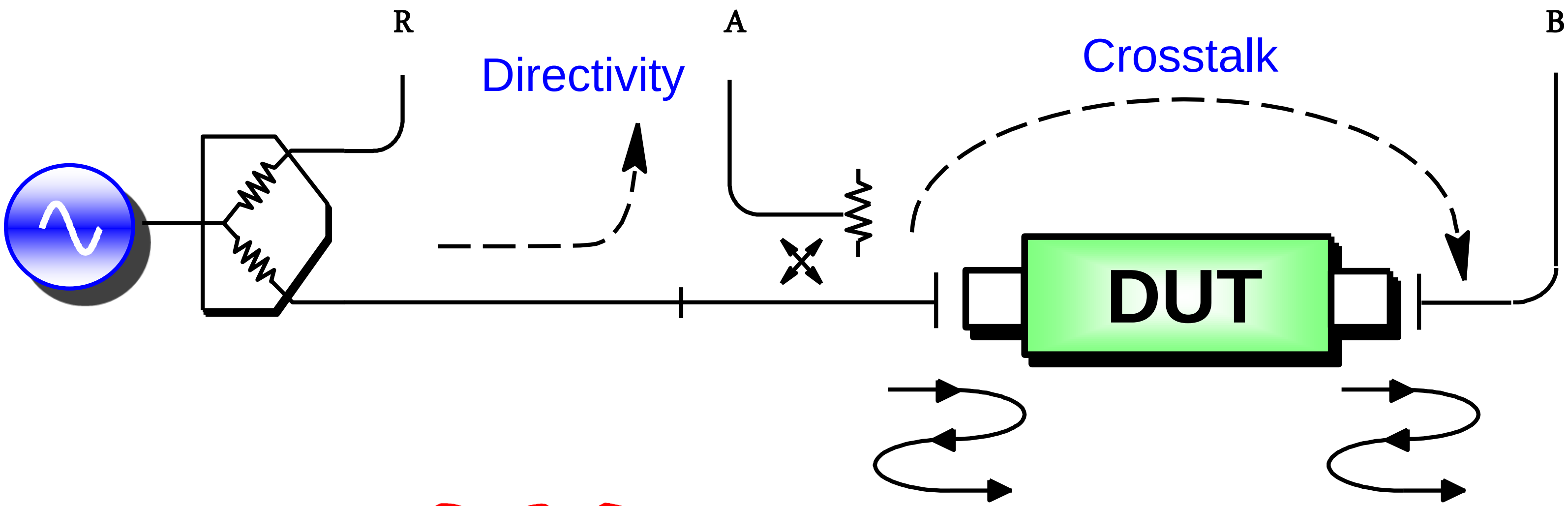
- Vary with time in random fashion (unpredictable)
- Main contributors: instrument noise, switch and connector repeatability

– ***Drift errors***

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



Systematic Measurement Errors

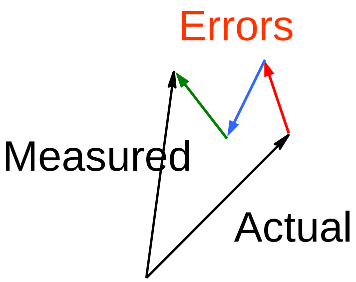


Frequency response

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

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

What is Vector-Error Correction?



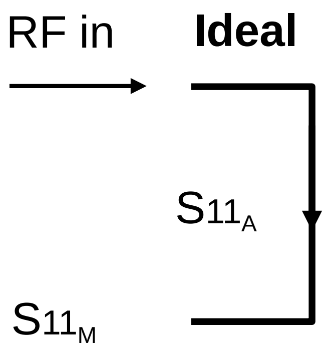
– **Vector-error correction…**
  - Is a process for characterizing systematic error terms
  - Measures known electrical standards
  - Removes effects of error terms from subsequent measurements

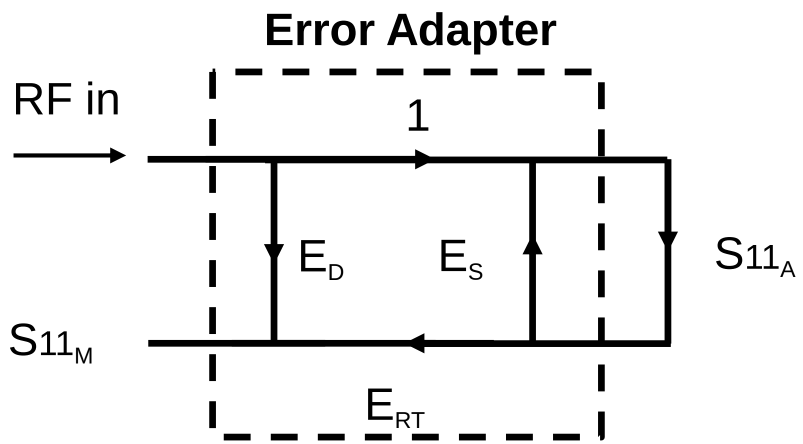
– **Electrical standards…**
  - Can be mechanical or electronic
  - Are often an open, short, load, and thru, but can be arbitrary impedances as well

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

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

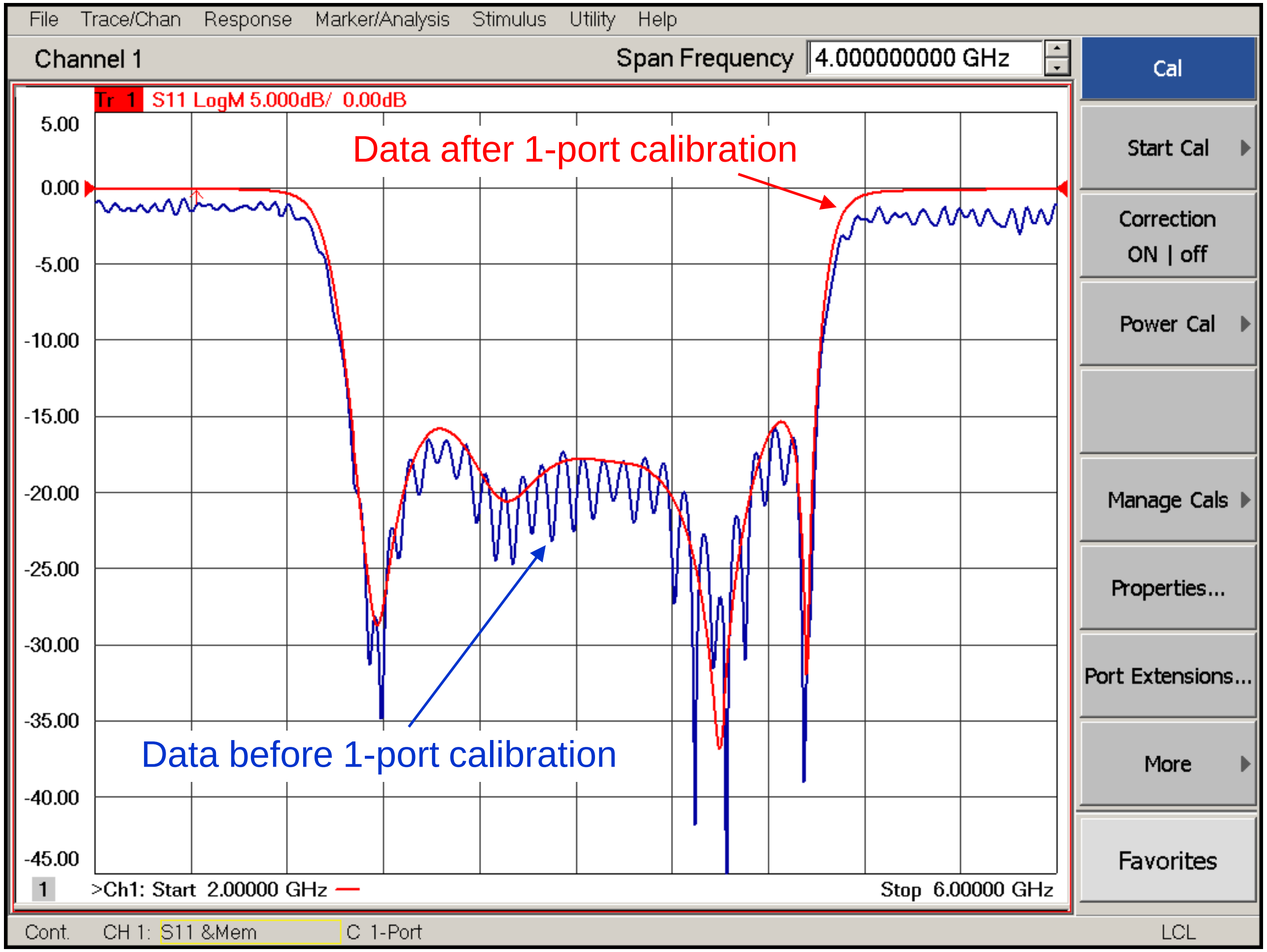
$$S11_M = E_D + E_{RT}\left[\frac{S11_A}{1 - E_S\ S11_A}\right]$$

– Assumes good termination at port two if testing two-port devices

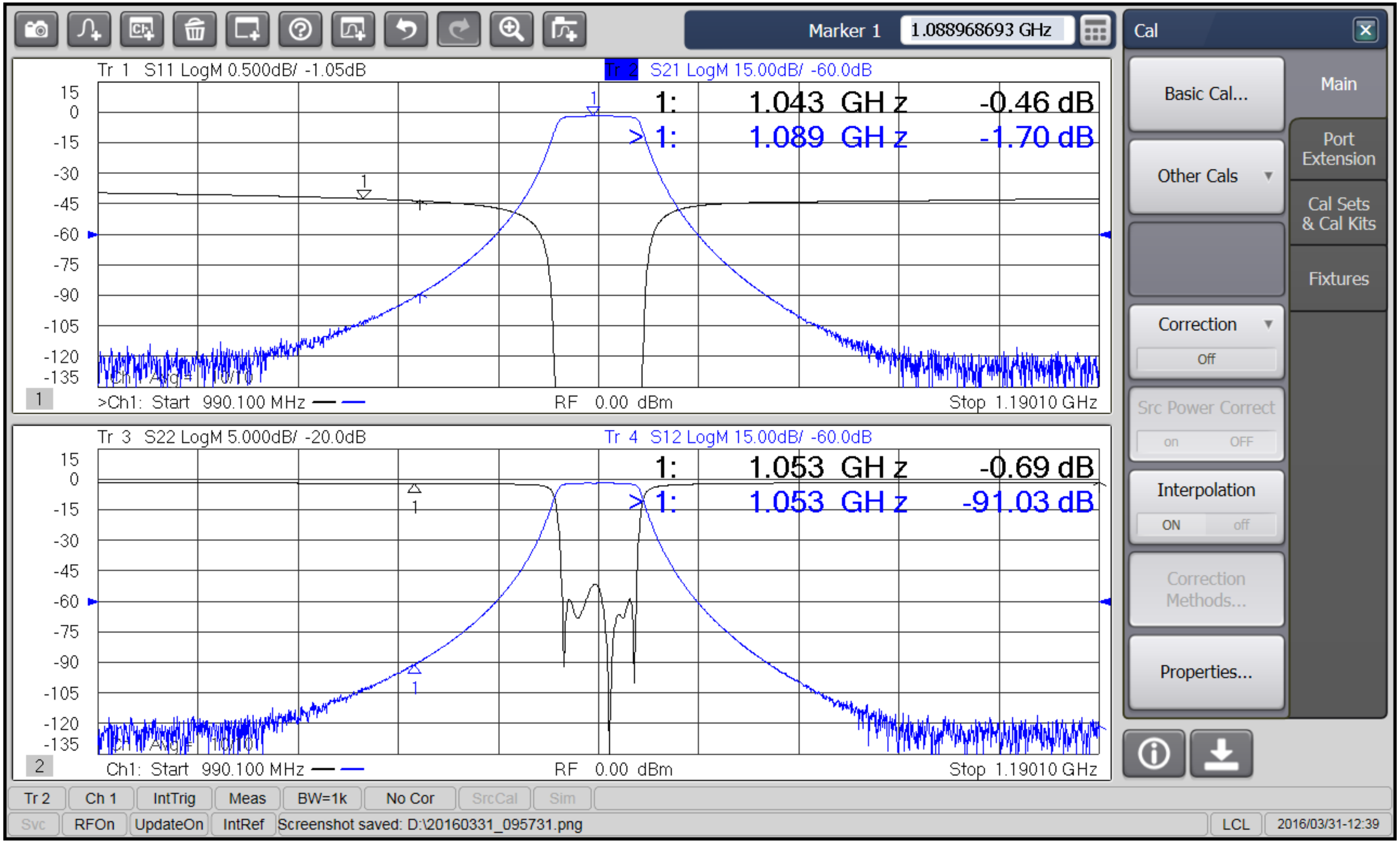
– If using port two of NA *and* DUT reverse isolation is low (e.g., filter passband):

- Assumption of good termination is not valid
- Two-port error correction yields better results

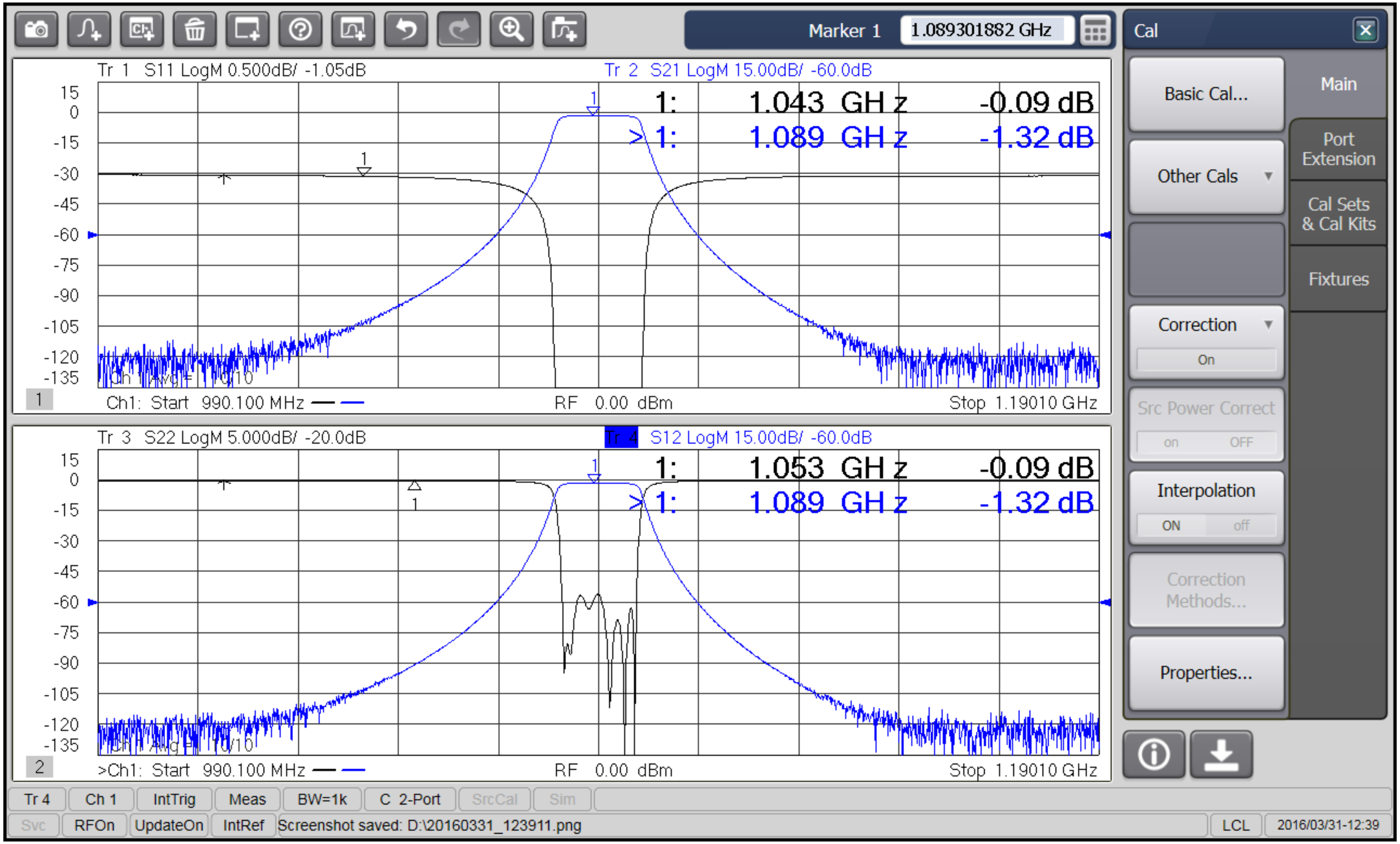
Before and After A One-Port Calibration



Demonstration
4 S-Parameters with Correction Off

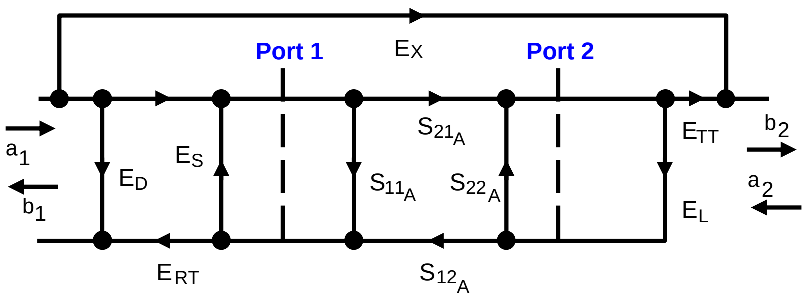


Demonstration
4 S-Parameters with Correction On

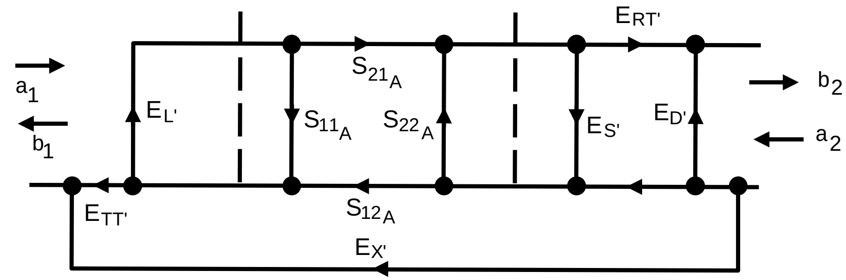


Two-Port Error Correction

Forward model



Reverse model



E_D = fwd directivity
E_S = fwd source match
E_{RT} = fwd reflection tracking

$E_{D'}$ = rev directivity
$E_{S'}$ = rev source match
$E_{RT'}$ = rev reflection tracking

E_L = fwd load match
E_{TT} = fwd transmission tracking
E_X = fwd isolation

$E_{L'}$ = rev load match
$E_{TT'}$ = rev transmission 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!!!

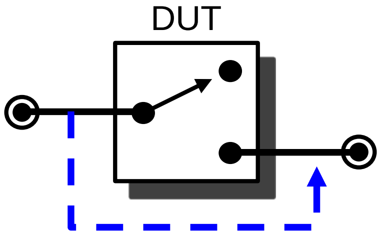
$$S_{11a} = \frac{\left(\frac{S_{11m}-E_D}{E_{RT}}\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right) - E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}{\left(1+\frac{S_{11m}-E_{D'}}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right) - E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{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

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

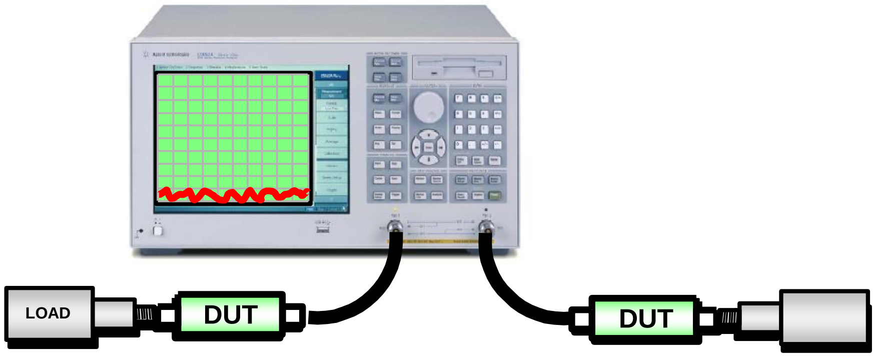
$$S_{12a} = \frac{\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}(E_S-E_L')\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right) - E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

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

Crosstalk: Signal Leakage Between Test Ports During Transmission

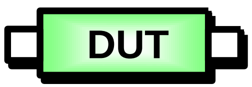


- Can be a problem with:
  - High-isolation devices (e.g., switch in open position)
  - High-dynamic range devices (some filter stopbands)
- Isolation calibration
  - Adds noise to error model (measuring near noise floor of system)
  - Only perform if really needed (use averaging if necessary)
  - If crosstalk is **independent** of DUT match, use two terminations
  - If **dependent** on DUT match, use two DUTs with termination on output



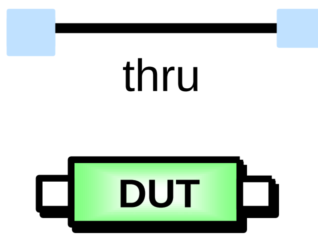
Errors and Calibration Standards

UNCORRECTED



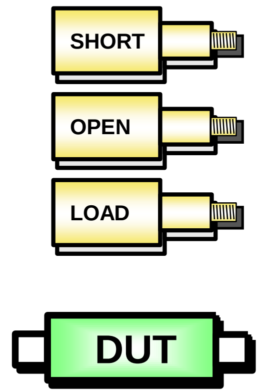
- Convenient
- Generally not accurate
- No errors removed

RESPONSE



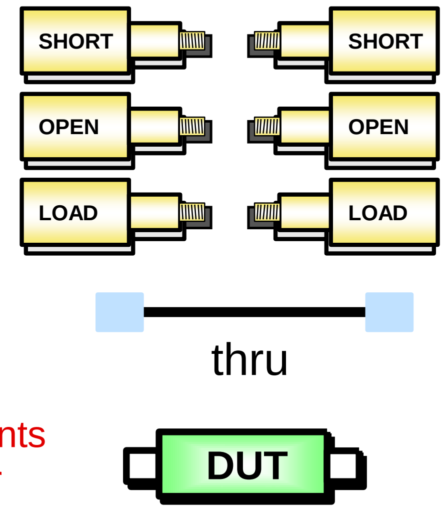
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

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



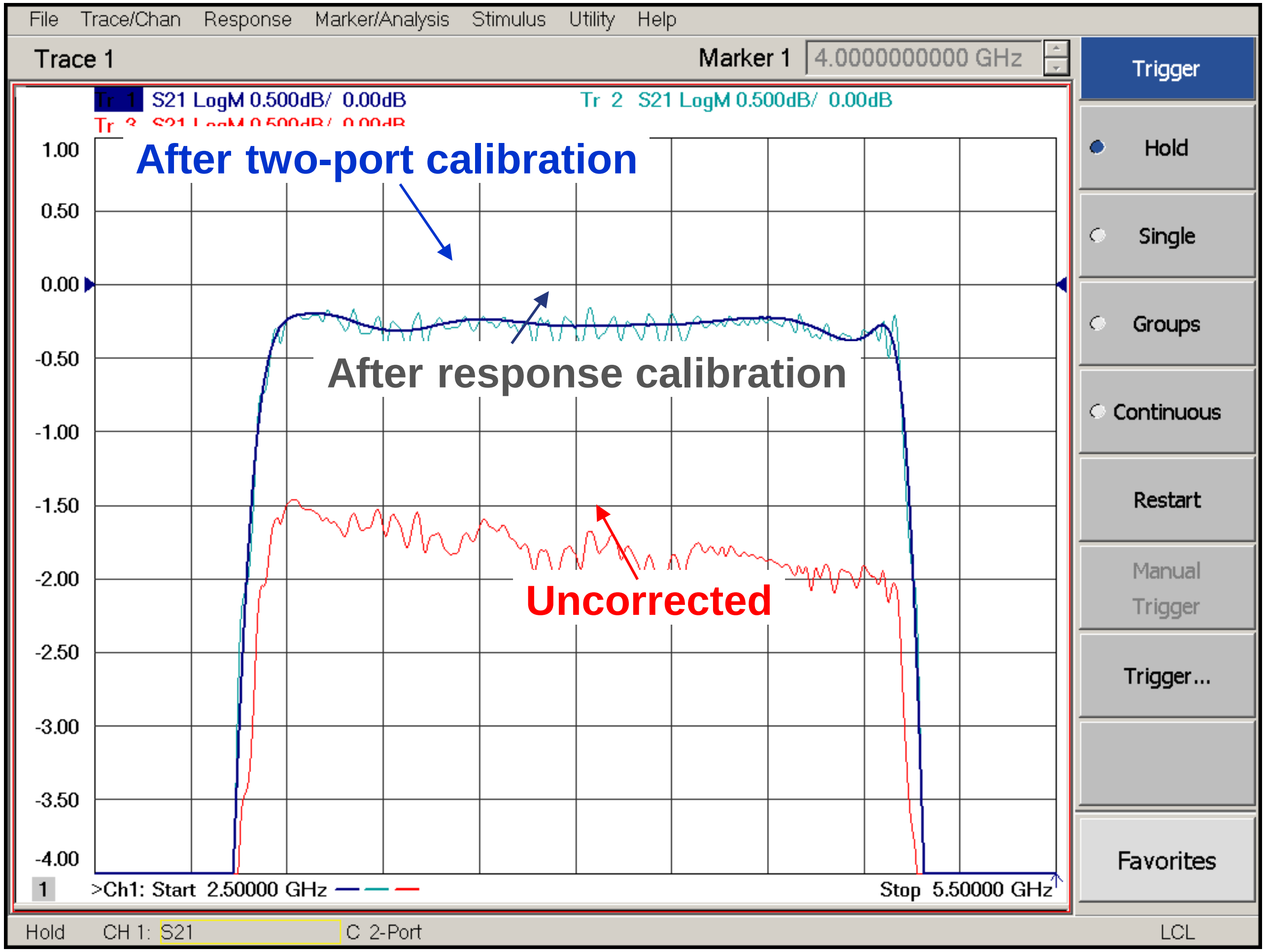
- Highest accuracy
- Removes these errors:
  - Directivity
  - Source, load match
  - Reflection tracking
  - Transmission tracking
  - Crosstalk

ENHANCED-RESPONSE

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

Response versus Two-Port Calibration

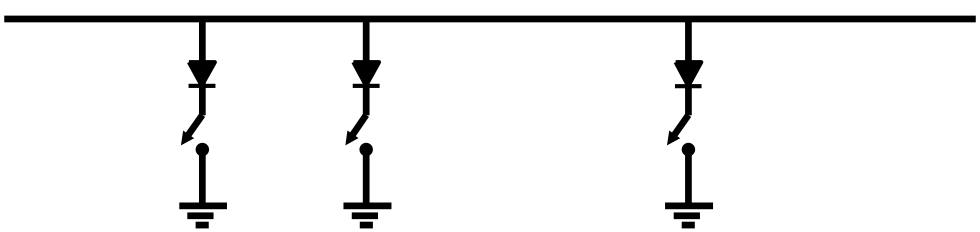
Measuring filter insertion loss



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

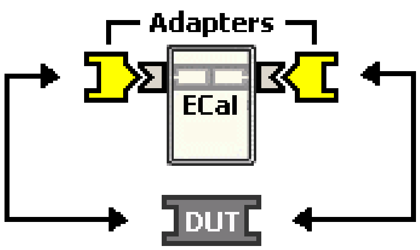
USB controlled



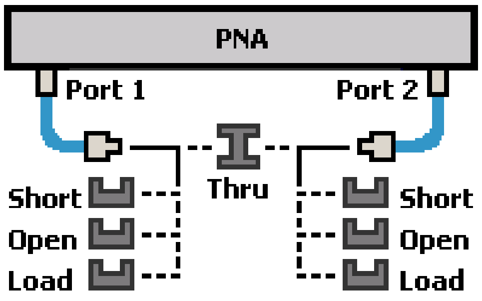
Microwave modules use a transmission line shunted by PIN-diode switches in various combinations

ECal User Characterizations

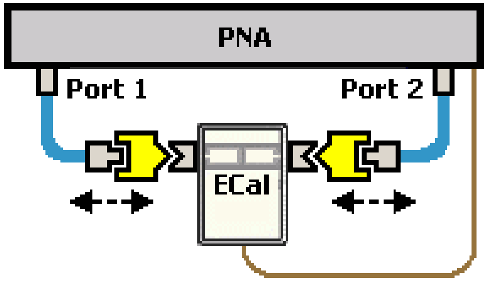
1. Select adapters for the module to match the connector configuration of the DUT.



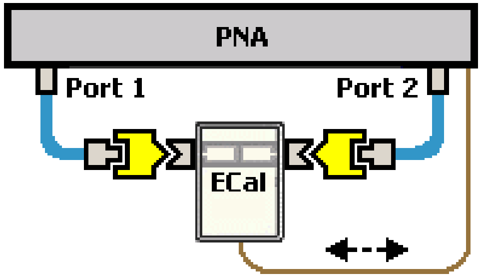
2. Perform a calibration using appropriate mechanical standards.



3. Measure the ECal module, including adapters, as though it were a DUT



4. VNA stores resulting characterization data inside the module.



Unknown Thru Calibration Requirements

1) The systematic errors, directivity, source match and reflection tracking, of each test port can be completely characterized.

2) The "unknown thru" must be reciprocal, $S_{ij} = S_{ji}$.

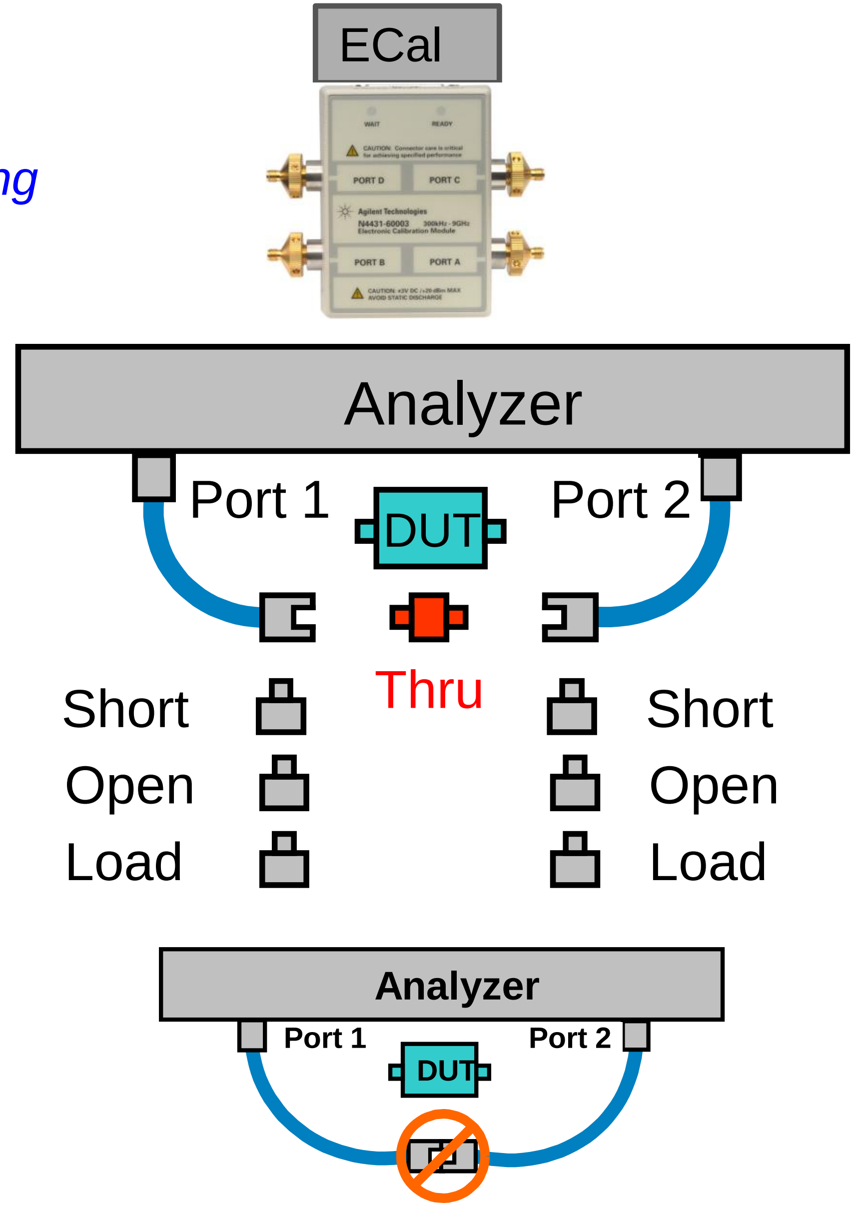
3) The phase response of the "unknown thru" must be known to within a quarter of a wavelength.

4) VNA signal path switch errors can be quantified.

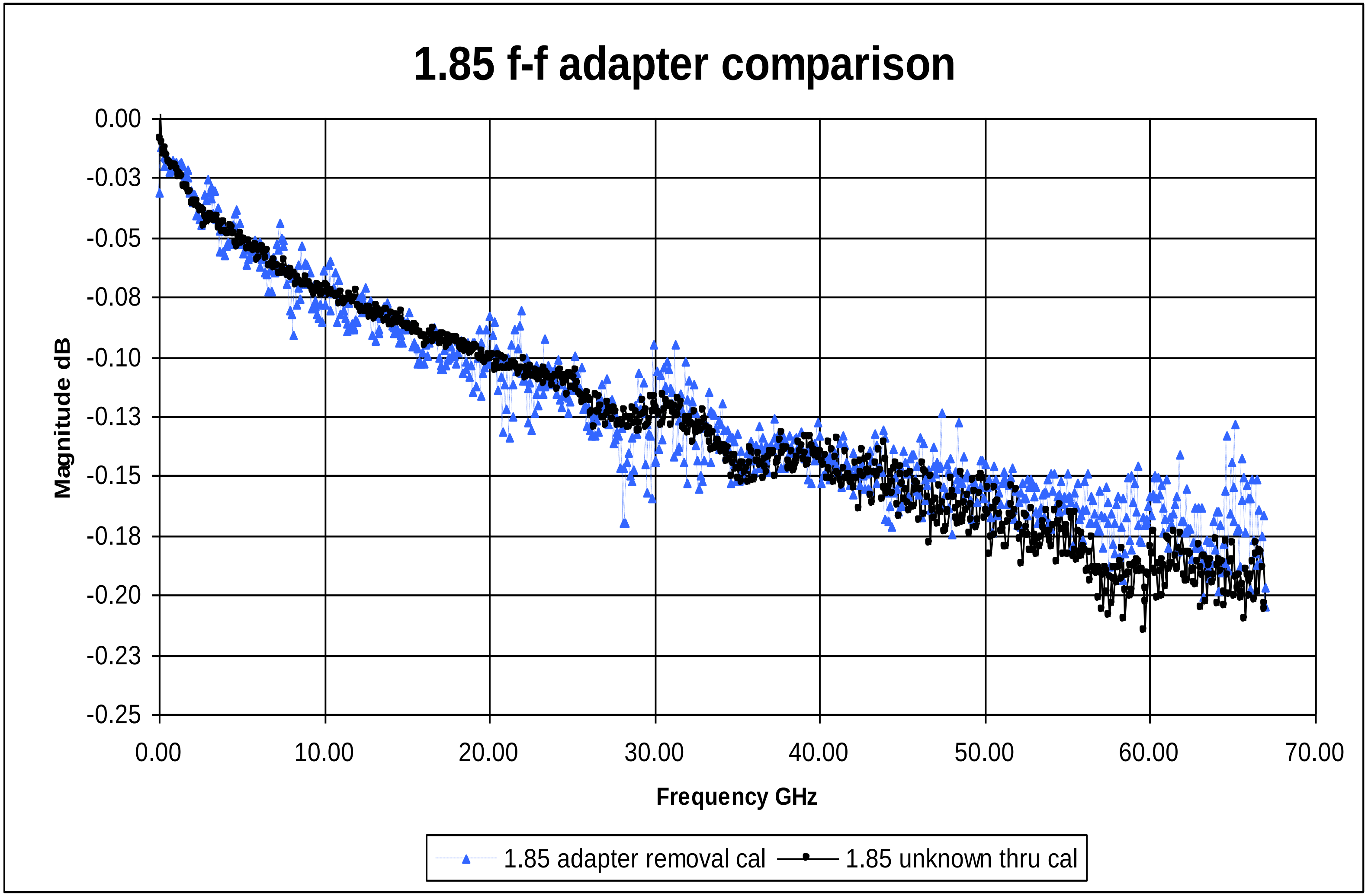
Unknown-Thru Calibration

Cal Methods are listed in order of ascending accuracy (most accurate first):

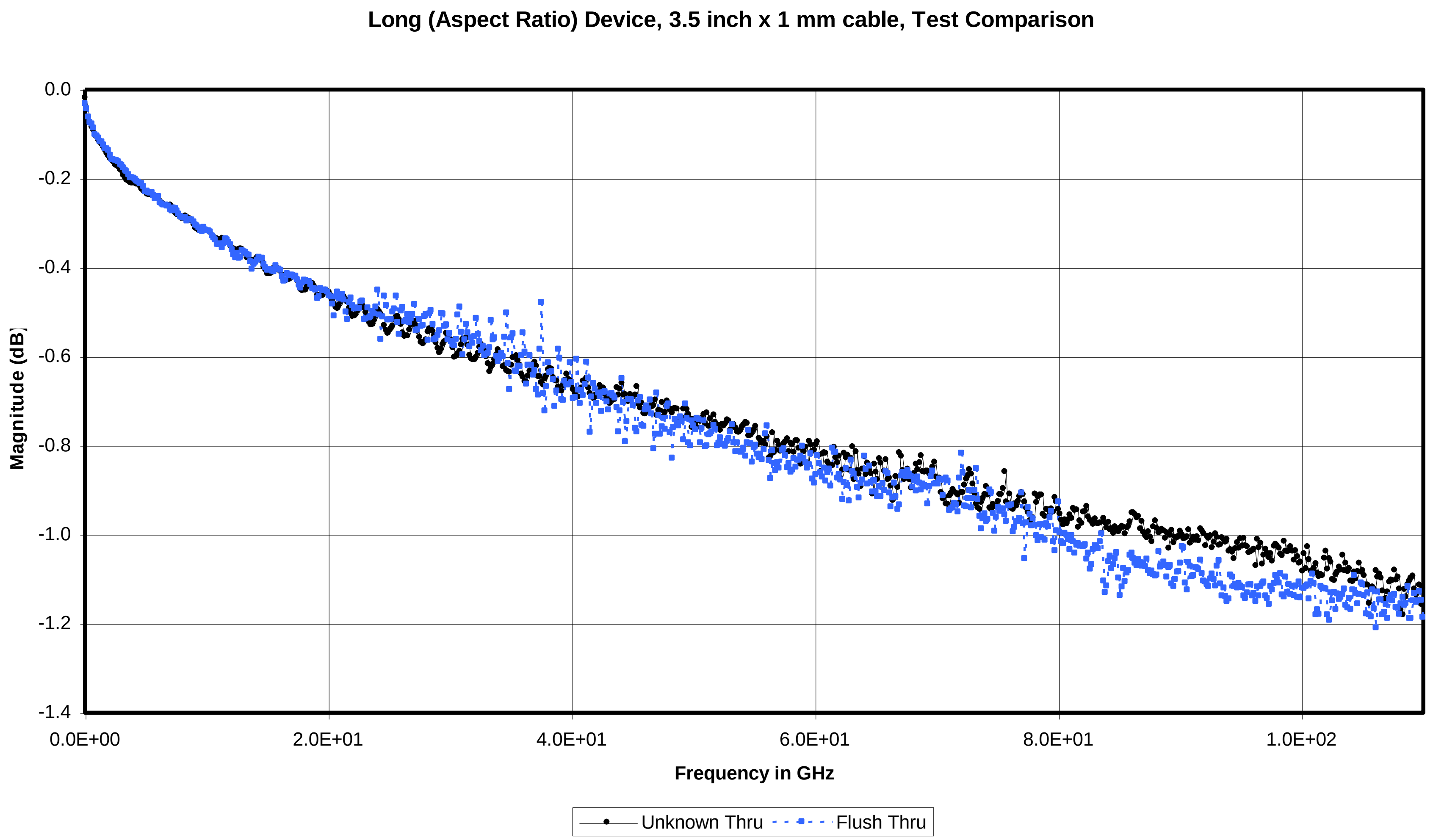
- *ECal with Unknown Thru*
- *Adapter Removal*
- *Mechanical with Unknown Thru Cal*
- *Electronic Calibrator (ECal)*
- *Uncharacterized Thru Adapter*



Unknown Thru and Adapter Removal Compared (PNA)



Unknown Thru and Flush Thru Compared (PNA)



KEYSIGHT TECHNOLOGIES

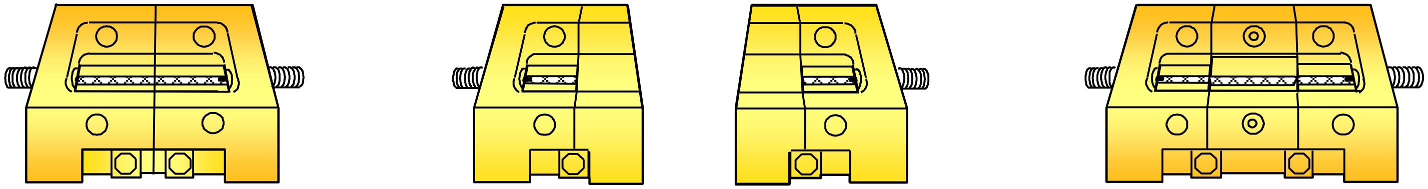
KEYSIGHT HOTSPOTS
Where Technologies and Experts Meet

Thru-Reflect-Line (TRL) Calibration

We know about Short-Open-Load-Thru (SOLT) calibration... What is TRL?

- A two-port calibration technique
- Good for non-coaxial environments (waveguide, fixtures, wafer probing)
- Characterizes same 12 systematic errors as the more common SOLT cal
- Uses practical calibration standards that are easily fabricated and characterized
- Other variations: Line-Reflect-Match (LRM), Thru-Reflect-Match (TRM), plus many others

TRL was developed for **non-coaxial microwave** measurements



Agenda

– What measurements do we make?

– Network analyzer hardware

– Error models and calibration

– Additional measurements

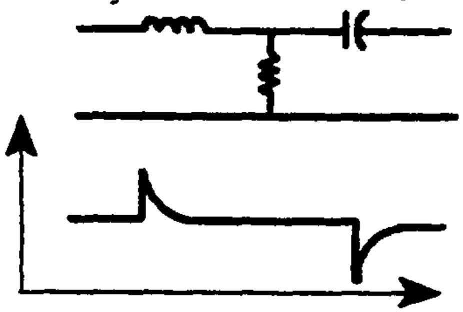
Additional measurements

- Time domain analysis
- Gain compression
- Three and four ports S-parameter measurement
- Mixed-mode S-parameter measurement

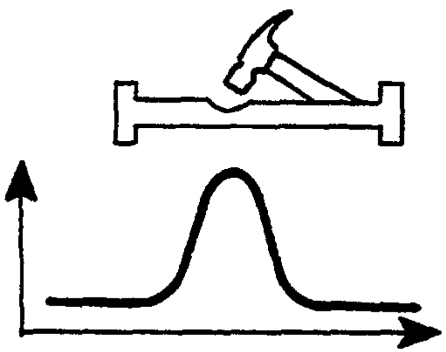
Why the Time Domain?

With the time domain information we can:

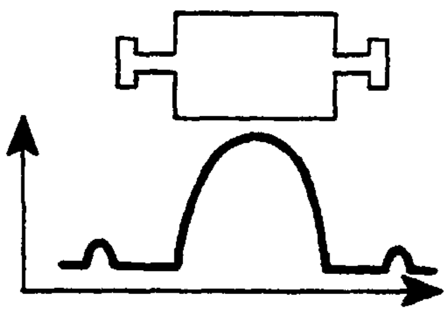
Identify Circuit Elements



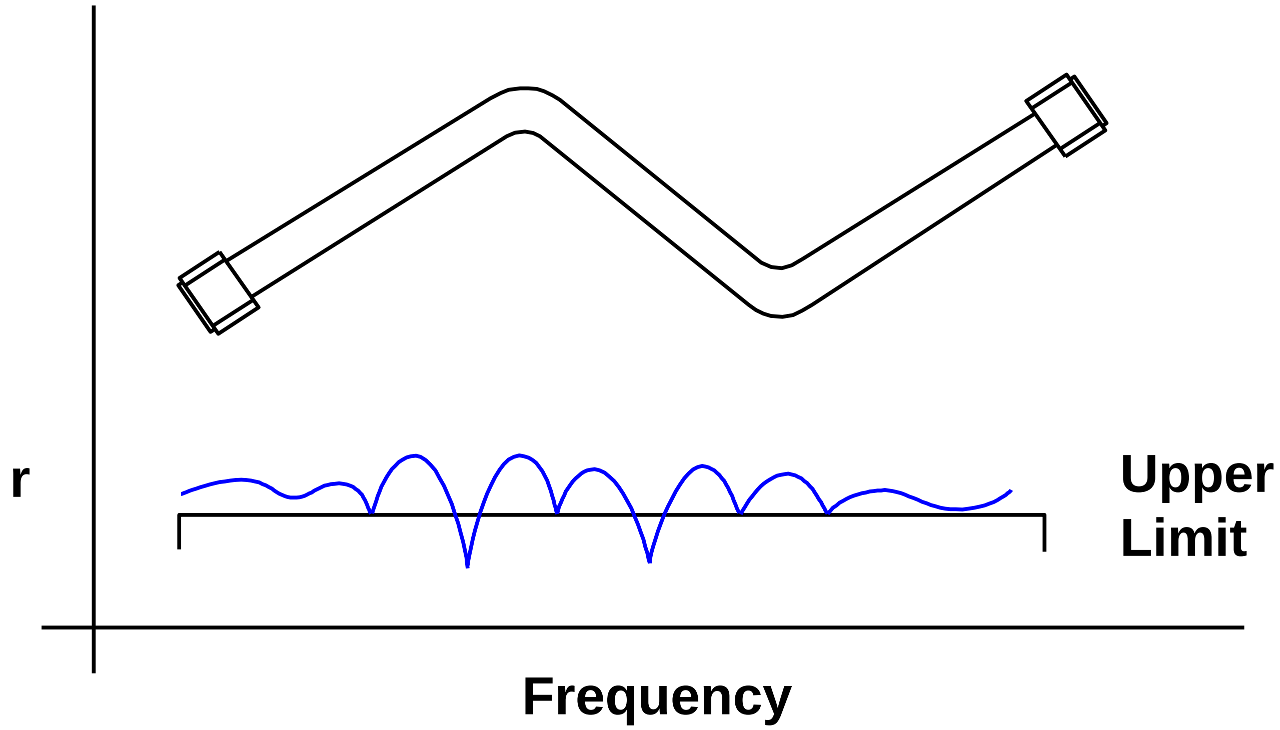
Locate Faults



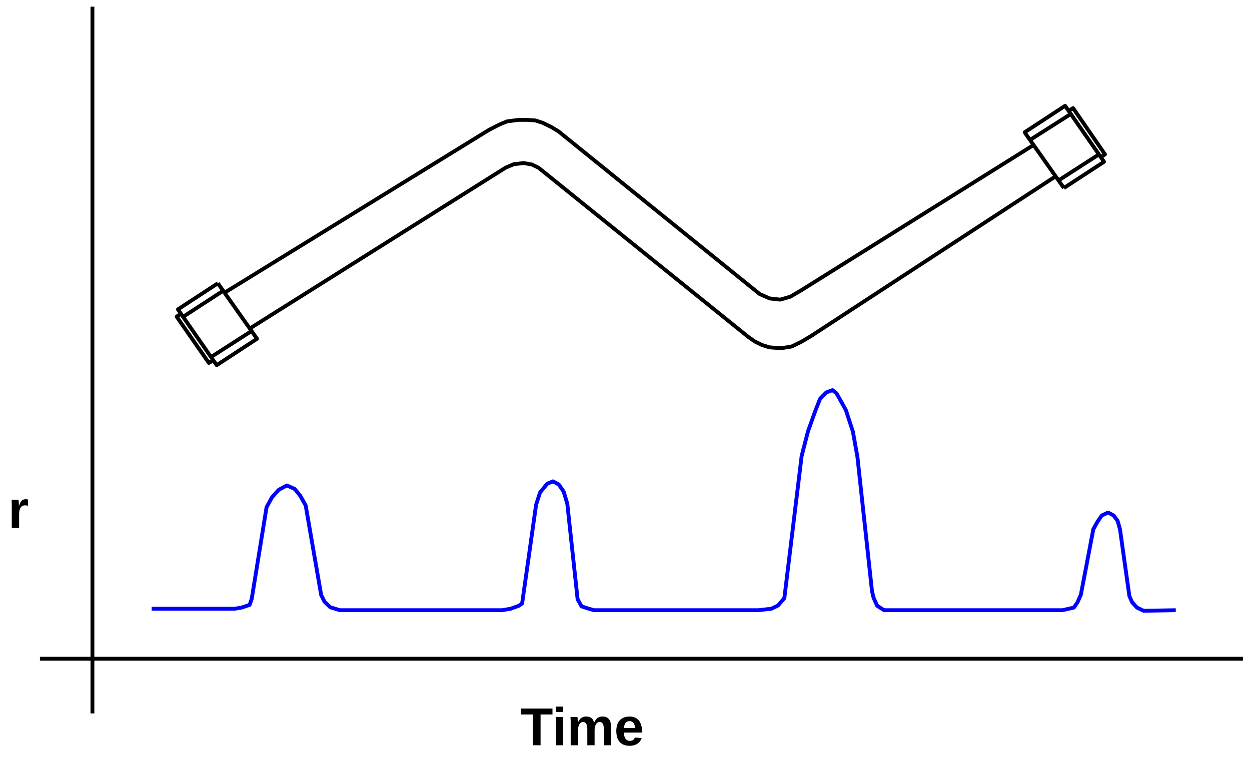
Identify and Remove Unwanted Responses



Frequency Domain S_{11} Response of Semi-rigid Coax Cable



Time Domain S_{11} Response of Semi-rigid Coax Cable



To Increase Alias Free Range

- **Increase the number of points**
- **Decrease frequency span**

- **AFR = (Number Points - 1) / Span**

Range Resolution

- **The ability to locate a single response in time**

- **Range Resolution** $= \dfrac{\text{Time Span}}{\text{Points} - 1}$

Range Calculation Example

$$\text{Range (s)} = \frac{1}{\Delta f} = \frac{\text{Points}-1}{f_{SPAN}} \quad \Delta f, \quad f_{SPAN} = \text{Hz}$$

$$= \frac{400}{2.5\,\text{GHz}}$$

$$= 160\,\text{ns}$$

$$\text{Range (m)} = \frac{\text{Points}-1}{f_{SPAN}} \; * \; 2.9979 \times 10^{8}\,\text{m}$$

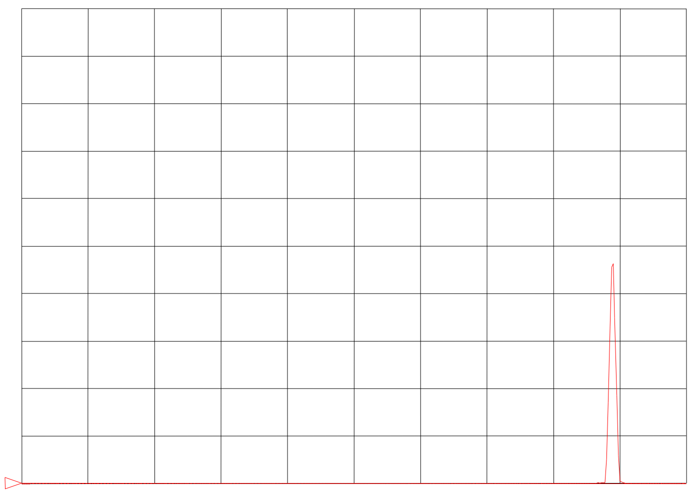
$$= \frac{400}{2.5\,\text{GHz}} * 2.9979 \times 10^{8}$$

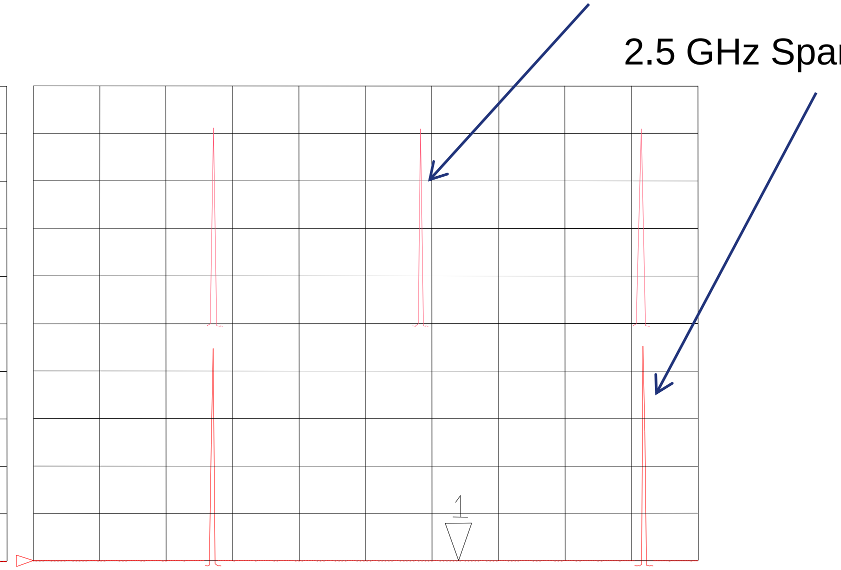
$$= 48\,\text{m}$$

Fault Location Range Example: 10m cable

Effects of Changing Frequency Span

Band Pass Mode, 401 Points, Span changed from 5.0 GHz to 2.5 GHz Range = 160 ns (48 m)



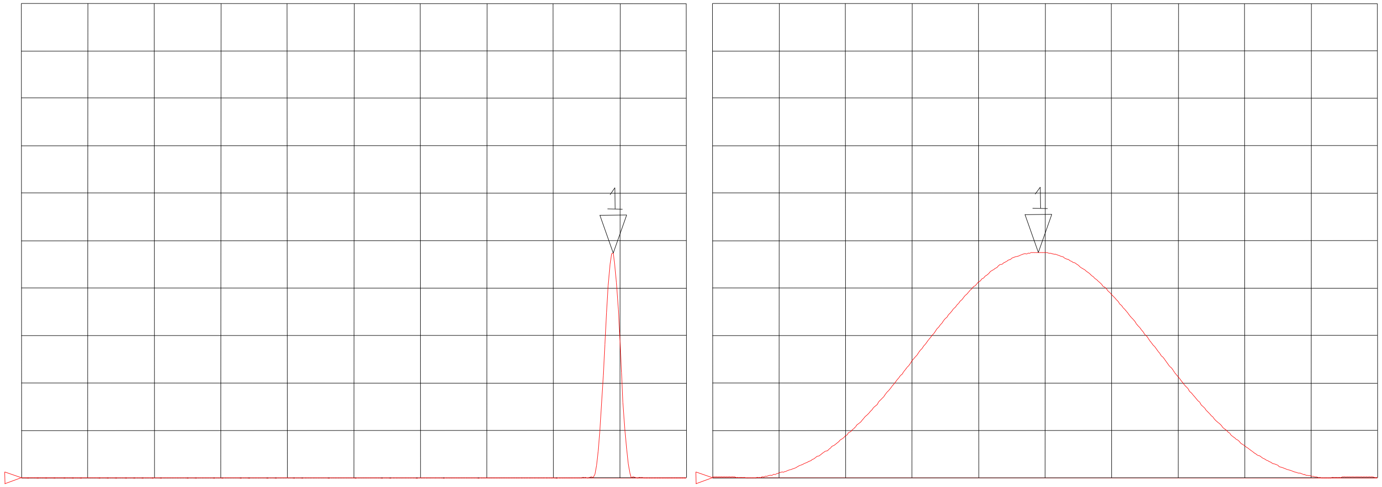


Range Resolution Example - narrow time span

S11 LINEAR
REF 0.0 Units
D 10.0 mUnits/
1 47.571 mU

S11 LINEAR
REF 47.62 Units
1 5.0 mUnits/
Ñ 47.621 mU

MARKER 1
13.3425 ns
4.0 m



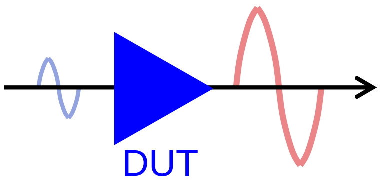
START 0.0 s
STOP 15.0 ns

CENTER 13.3425 ns
SPAN 384.0 ps

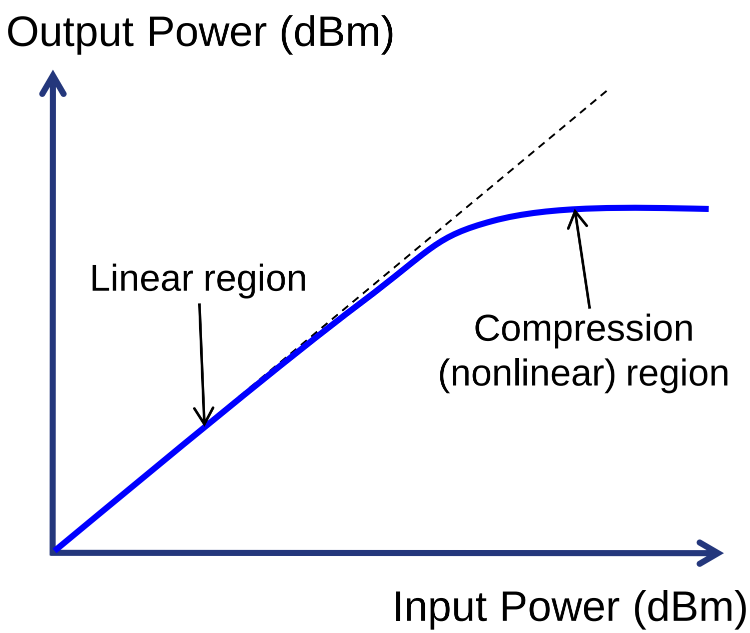
Additional measurements

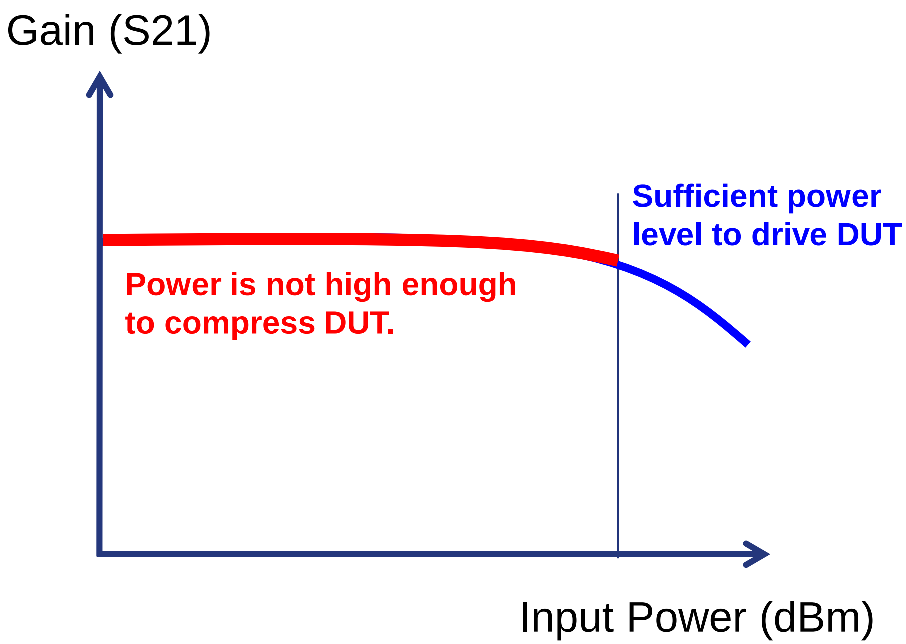
- Time domain analysis
- Gain compression
- Three and four ports S-parameter measurement
- Mixed-mode S-parameter measurement

What is gain compression?



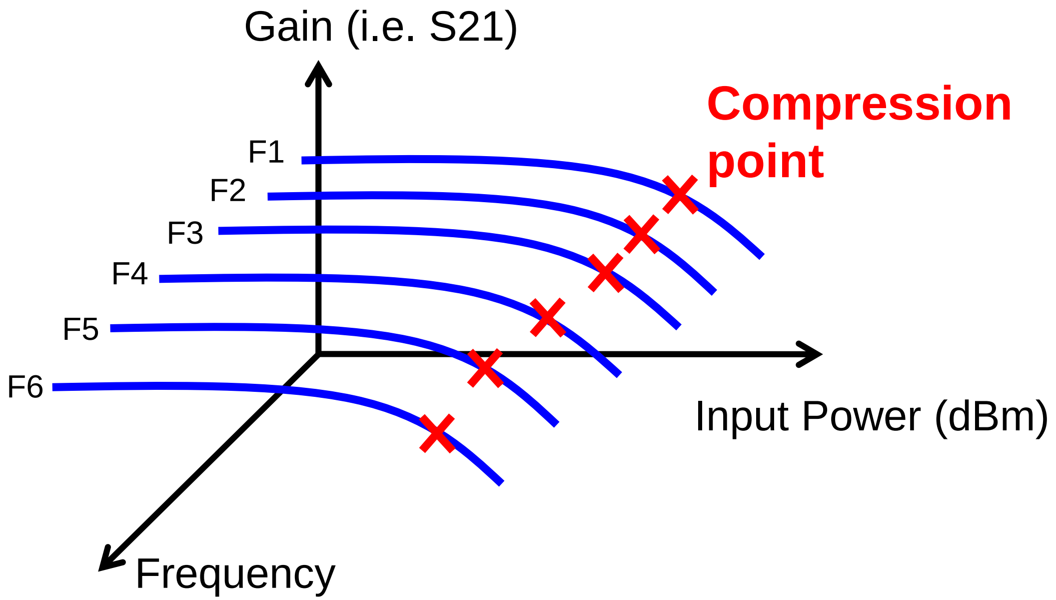
- Parameter to define the transition between the linear and nonlinear region of an active device.
- The compression point is observed as x dB drop in the gain with VNA's power sweep.

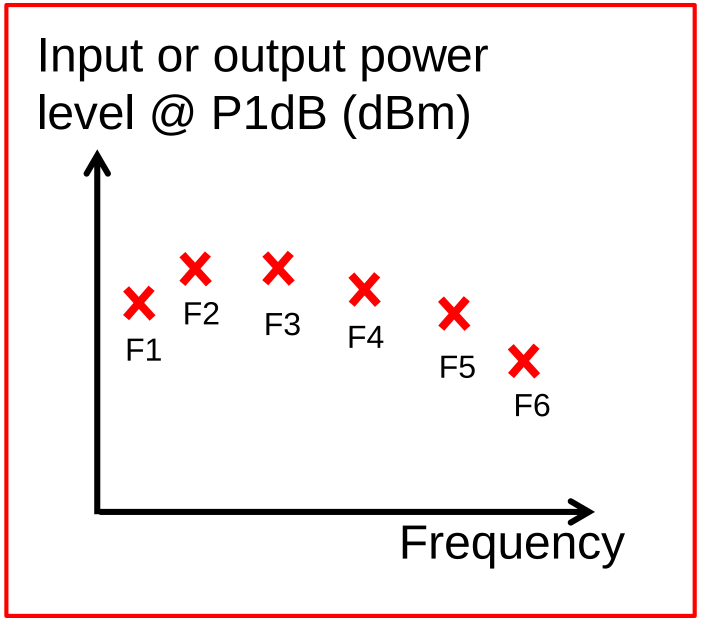




Enough margin of source power capability is needed for analyzers.

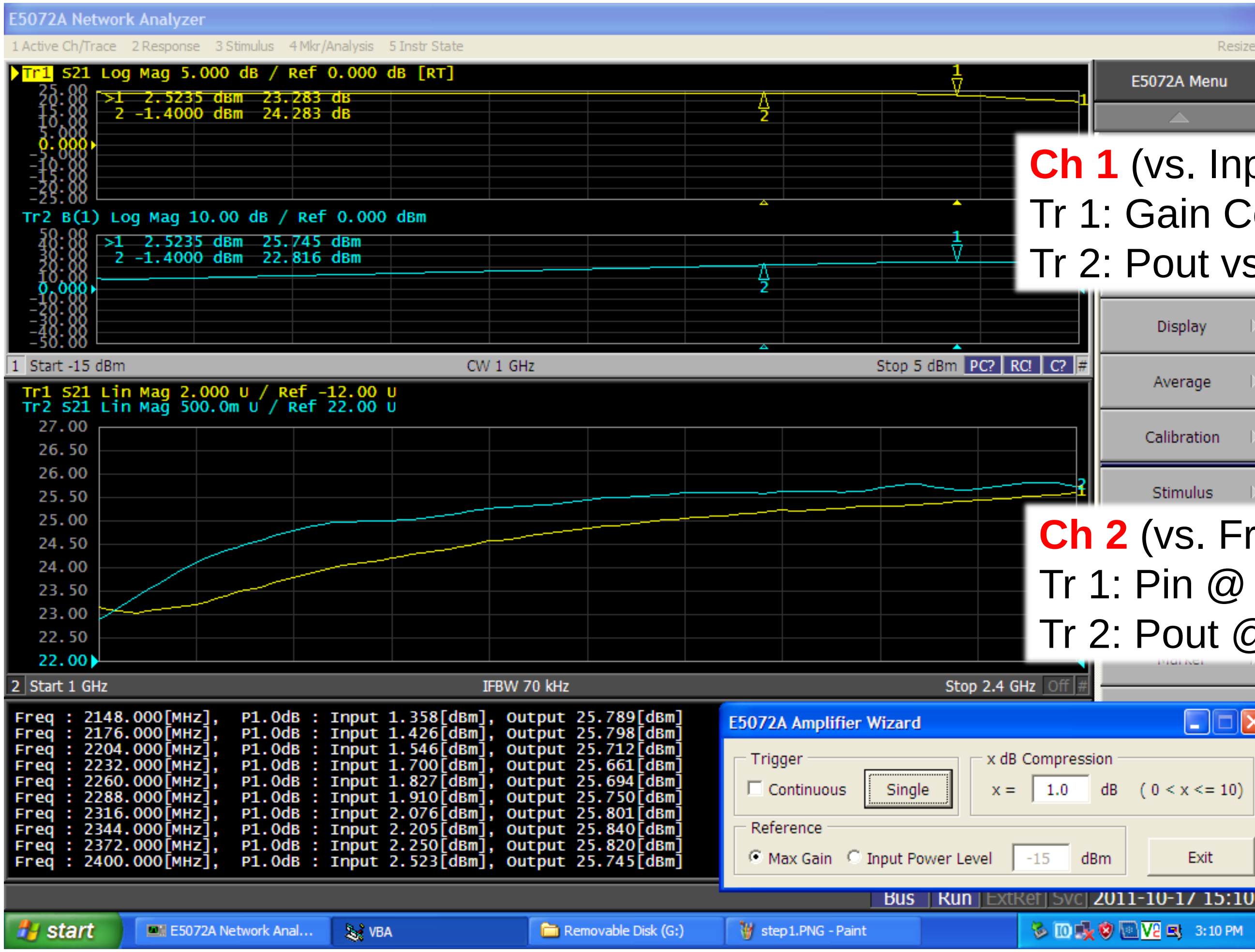
Gain compression over frequency





Gain compression over frequency

Gain compression measurement example



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

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

RF amplifier test

Stability (K-factor)

Calculates stability (K-factor) from all S-parameters with equation editor

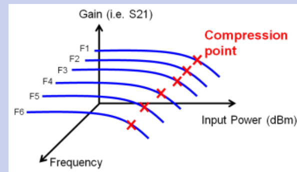
$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|}$$

where

$$\Delta = S_{11}S_{22} - S_{12}S_{21}$$

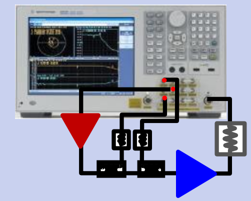
Gain compression

Sweeps both frequency and input power level at PxdB



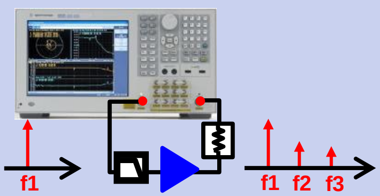
High-power test

Performs accurate tests with high-power input / output of DUT



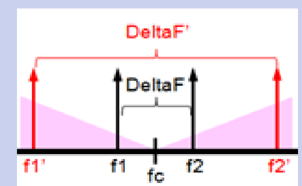
Harmonic Distortion

Performs real-time harmonics test over frequency or input power



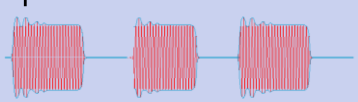
Swept IMD

Performs IMD analysis over an entire range of frequencies



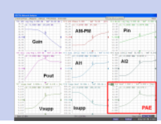
Pulsed-RF

Characterize pulsed performance of devices



Efficiency (PAE)

Calculate power-added efficiency (PAE)

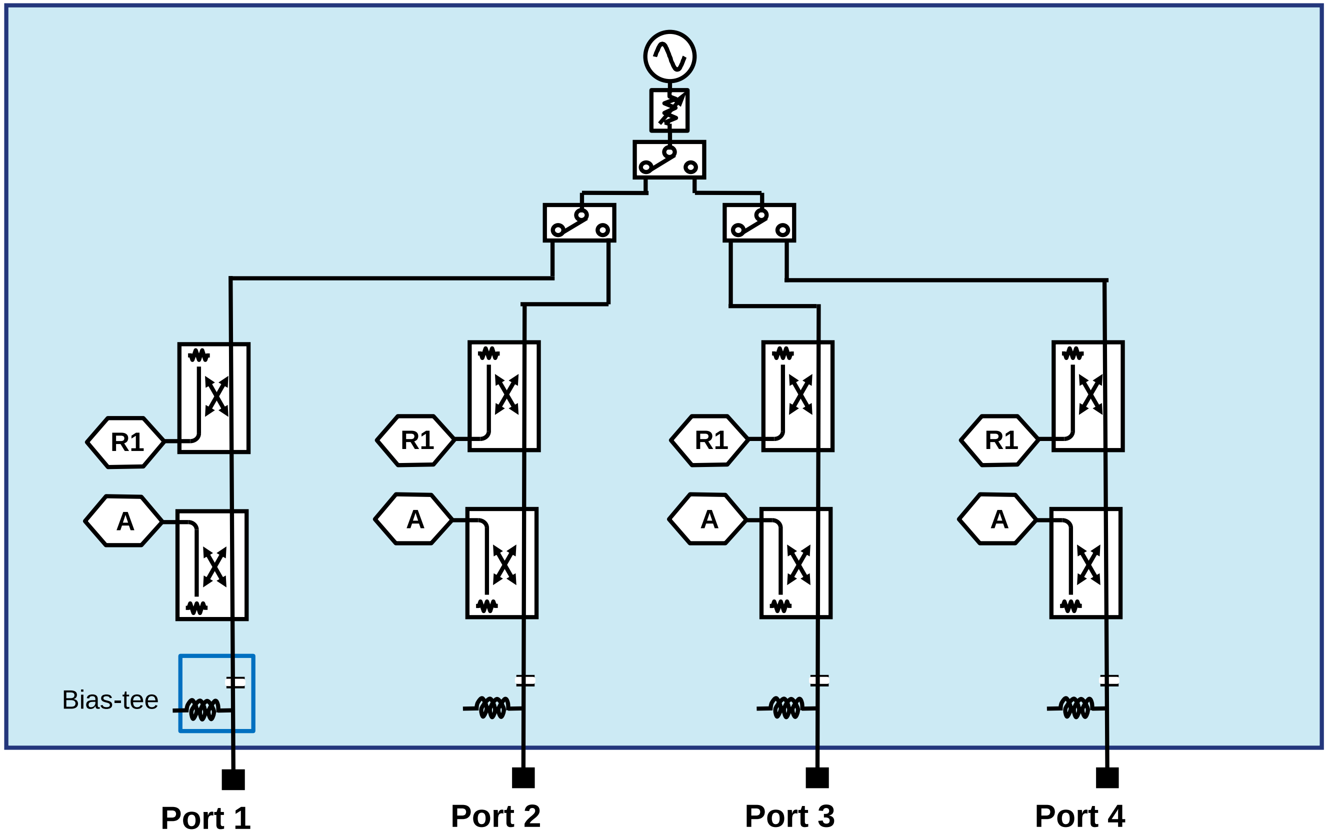


The modern VNA is a more suited solution for many parametric tests of RF amplifiers.

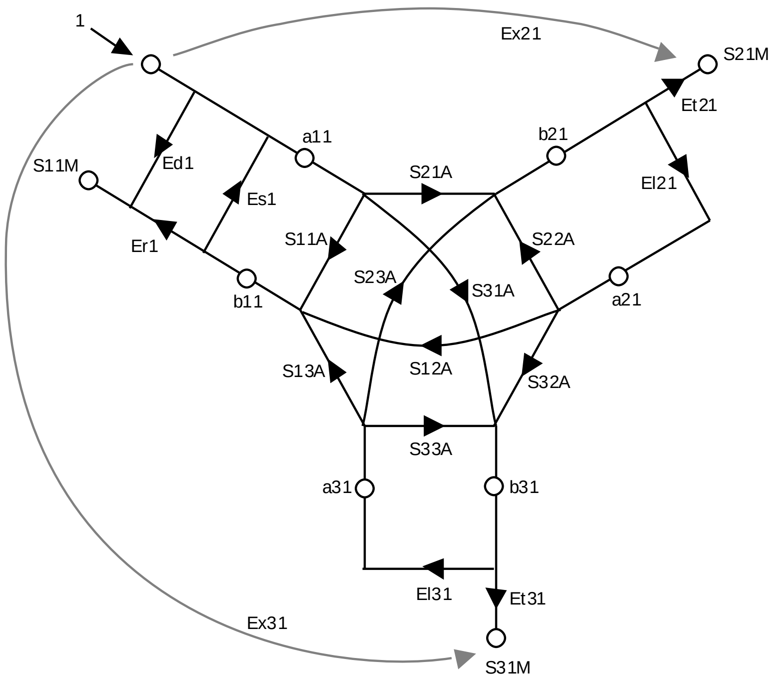
Additional measurements

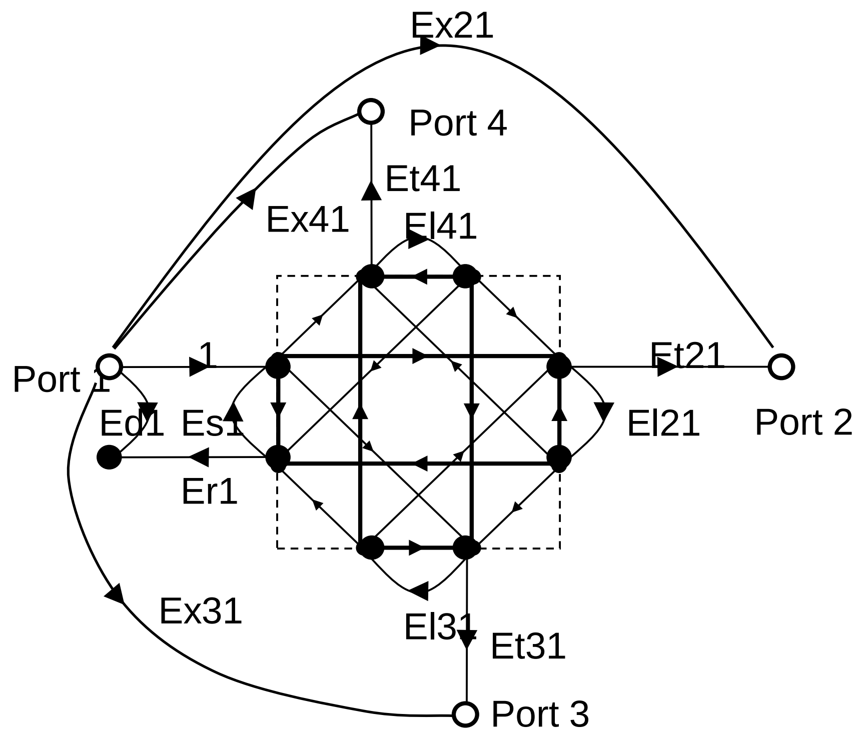
- Time domain analysis
- Gain compression
- Three and four ports S-parameter measurement
- Mixed-mode S-parameter measurement

4-port VNA Block Diagram (E5080A)



Full 3 and 4-Port Error Correction





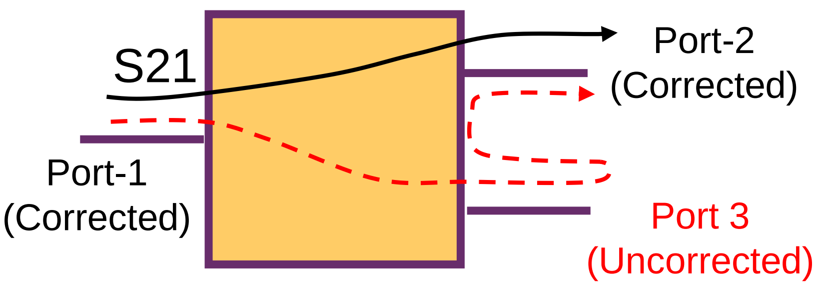
Total number of Error Terms:
3N+3N*(N-1) = 3N^2

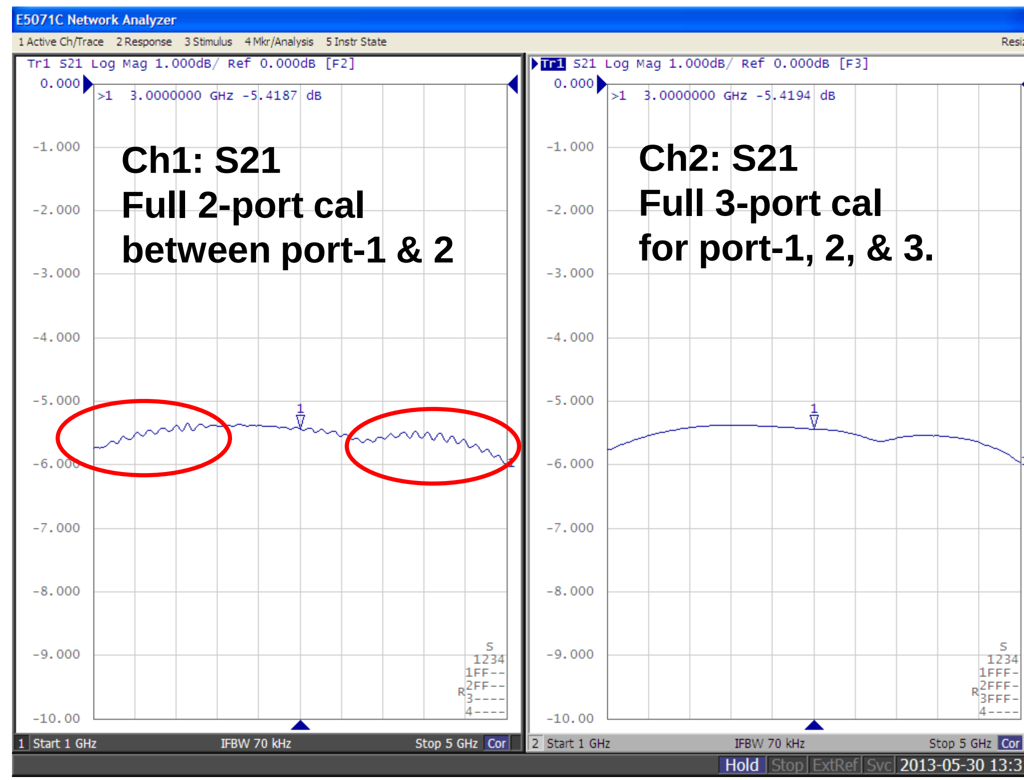
2-port Error Terms :	3*2^2 = 12
3-port Error Terms :	3*3^2 = 27
4-port Error Terms :	3*4^2 = 48

When full 3 and 4-port cal required?

- Reflection from uncorrected test port affects measurement.
- Measure mixed-mode S-parameters

Ex) 2-way power divider (isolation between output ports=13 dB)



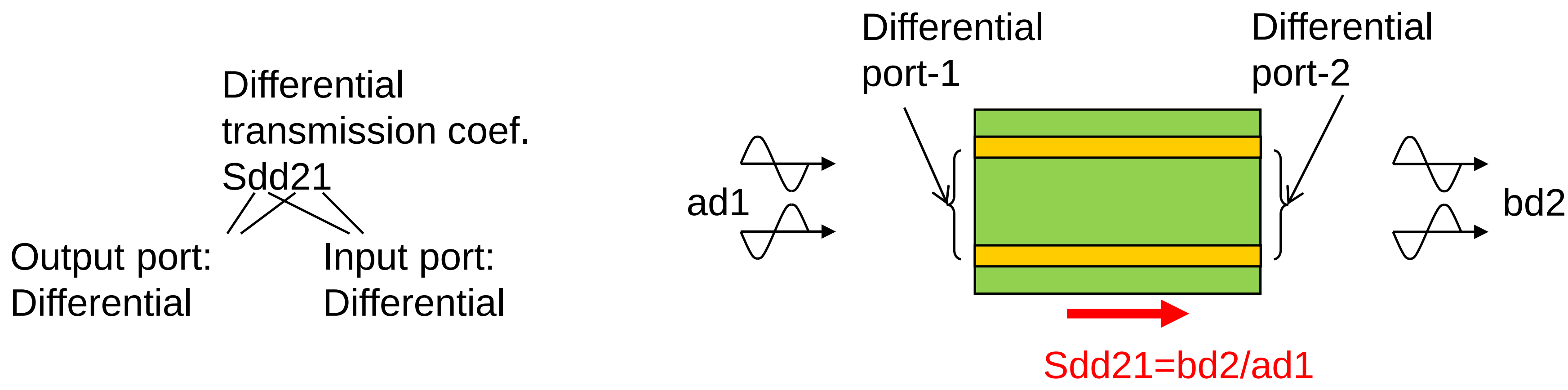


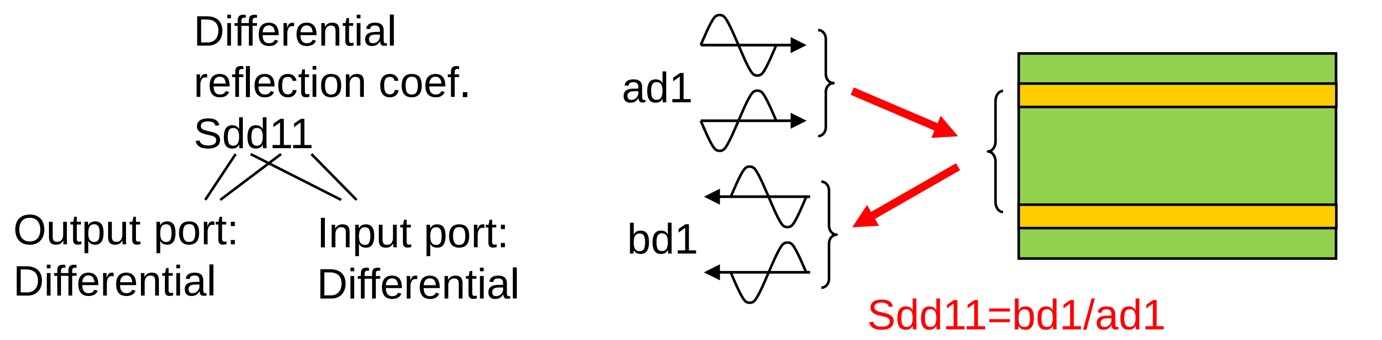
Reflection at uncorrected port-3 affect measurement at port-2.

Additional measurements

- Time domain analysis
- Gain compression
- Three and four ports S-parameter measurement
- Mixed-mode S-parameter measurement

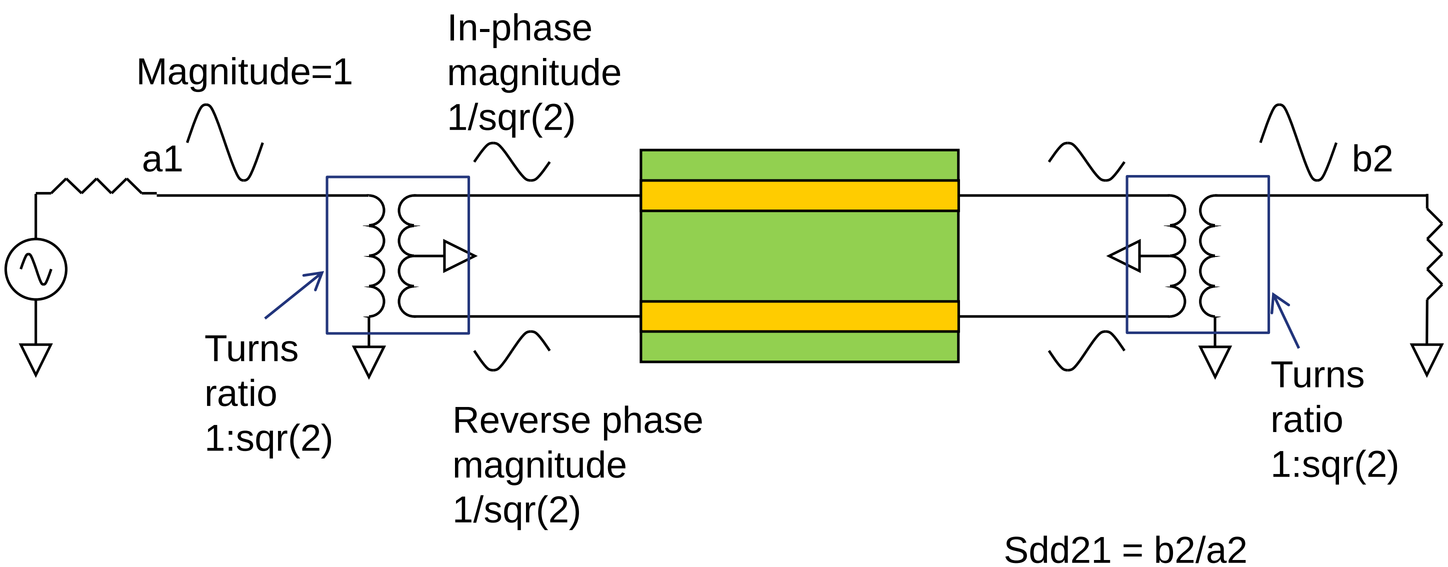
Differential S-parameter measurement



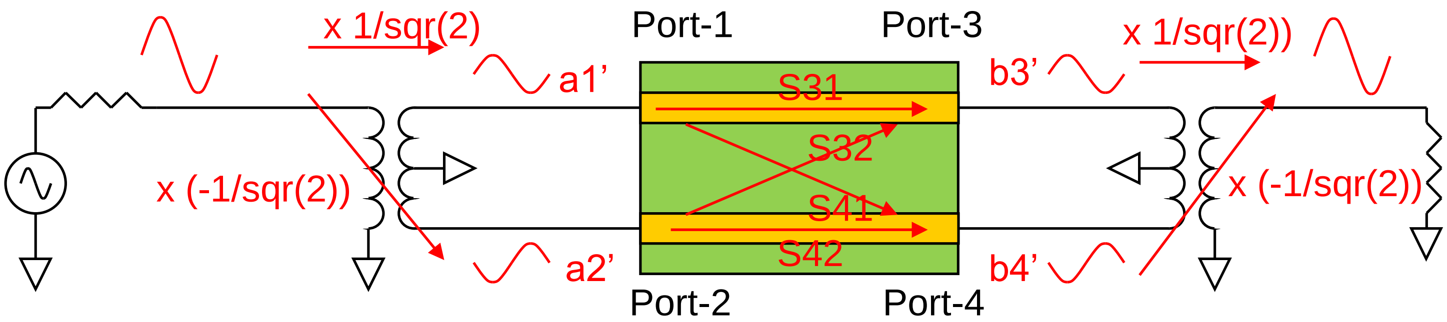


Differential S-parameter measurement

Sdd21 measurement using ideal balun transformers



Differential S-parameter measurement



We consider transmission characteristic of four signal paths;

S31 path: (1/sqr(2)) x S31 x (1/sqr(2)) = (1/2) x S31

S41 path: (1/sqr(2)) x S41 x (-1/sqr(2)) = (-1/2) x S41

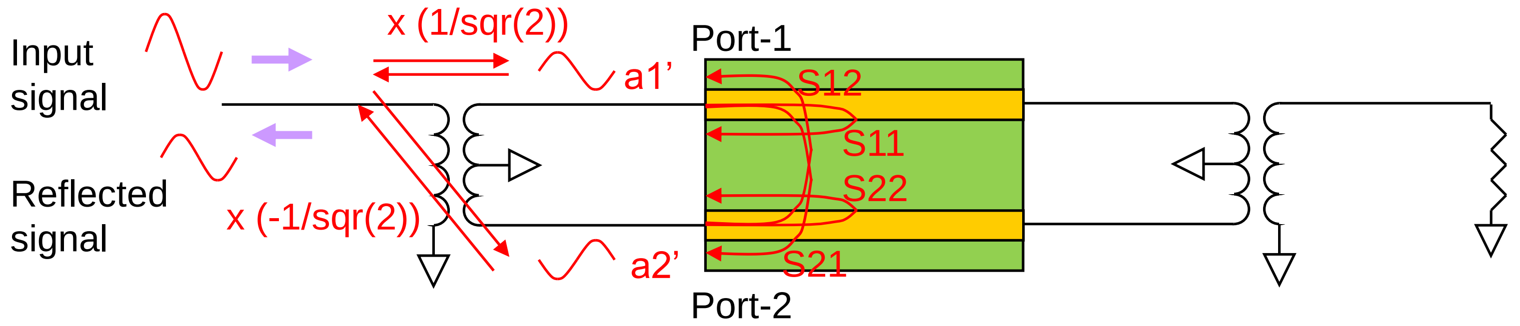
S32 path: (-1/sqr(2)) x S32 x (1/sqr(2)) = (-1/2) x S32

S42 path: (-1/sqr(2)) x S42 x (-1/sqr(2)) = (1/2) x S42

By superimposing above four equations, we can obtain Sdd21;

Sdd21 = (1/2)*(S31-S32-S41+S42)

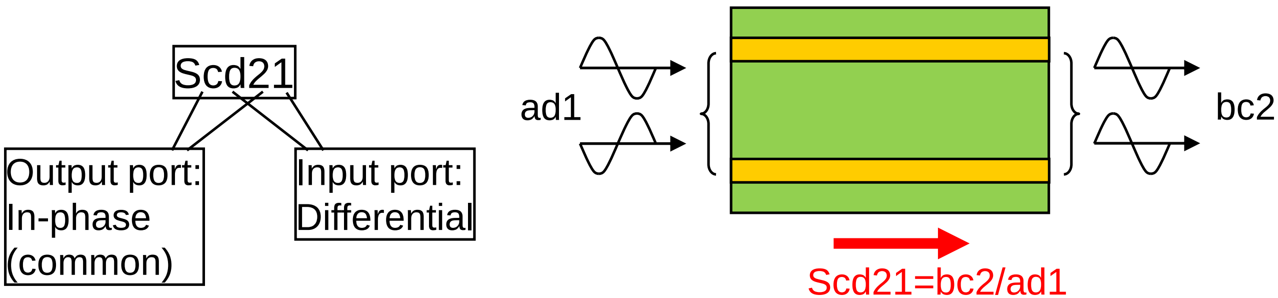
Differential S-parameter measurement

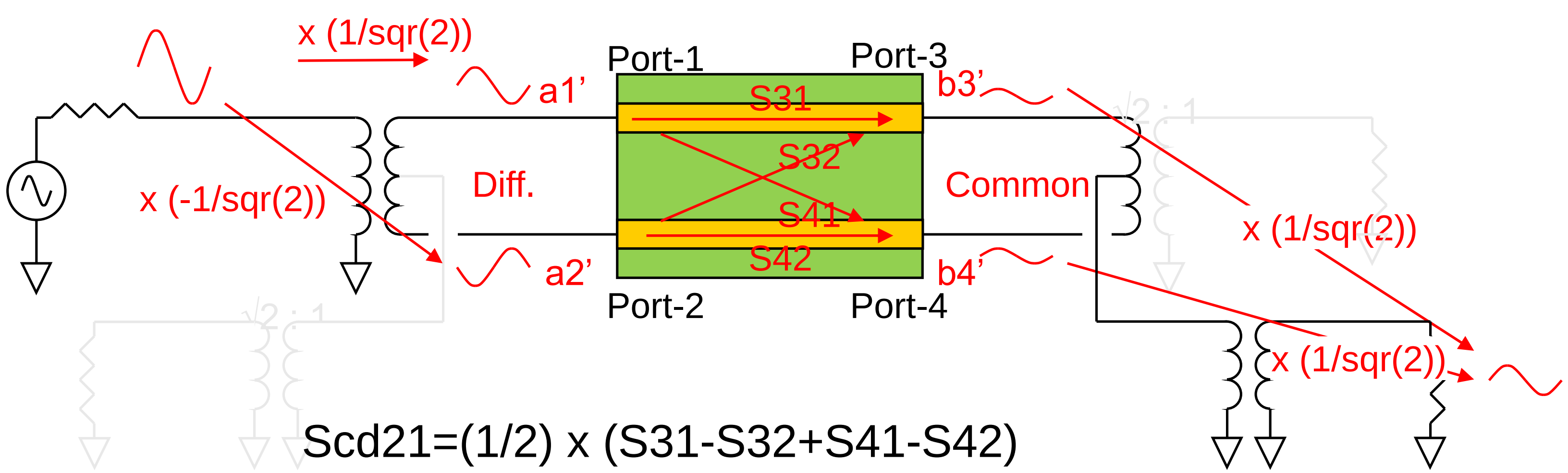


Sdd11 can be derived by superimposing transmission characteristics of S11, S12, S21, and S22 signal paths;

$$Sdd11 = (1/2)*(S11-S21-S12+S22)$$

Differential-Common S-parameter measurement

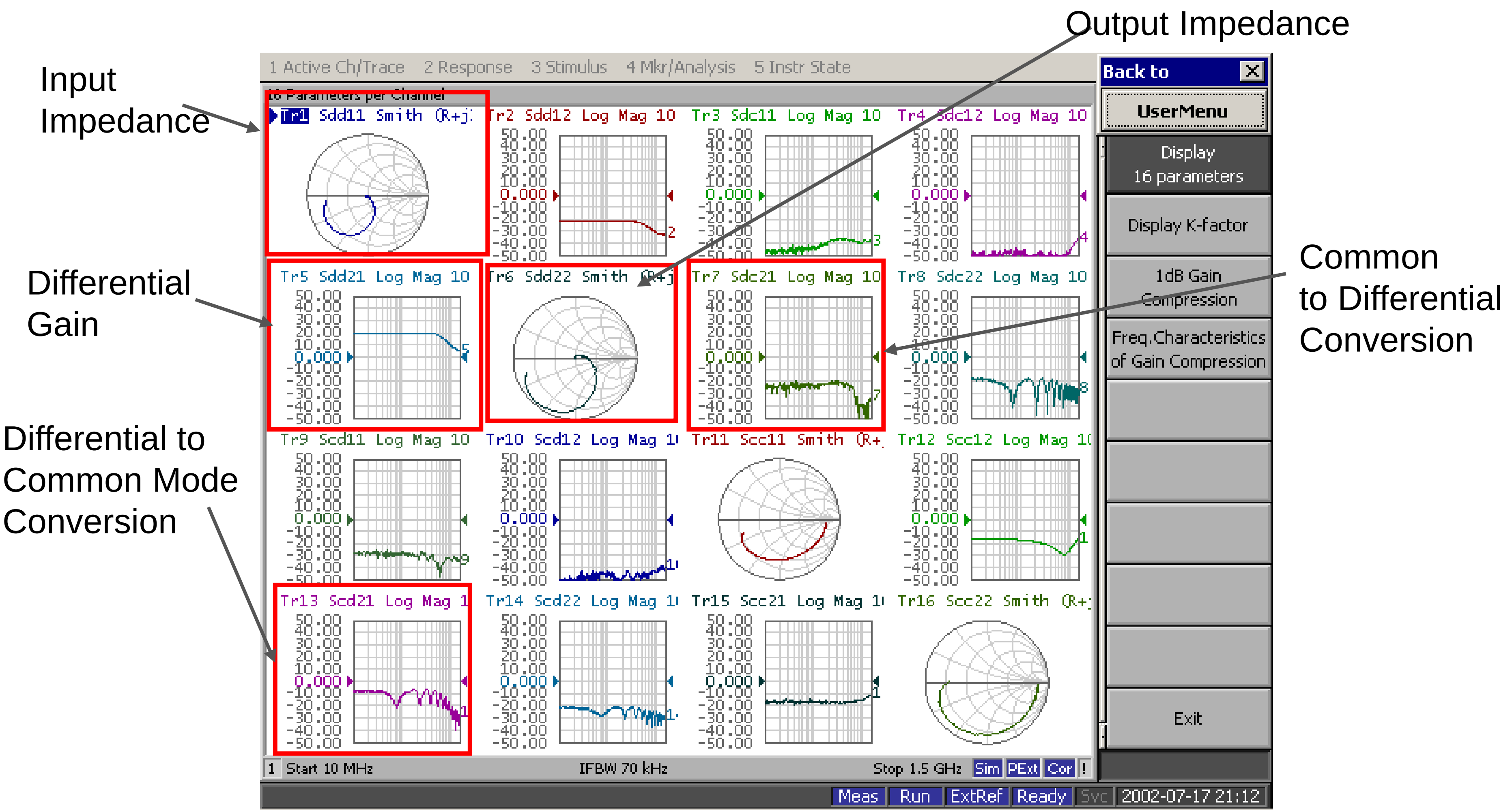




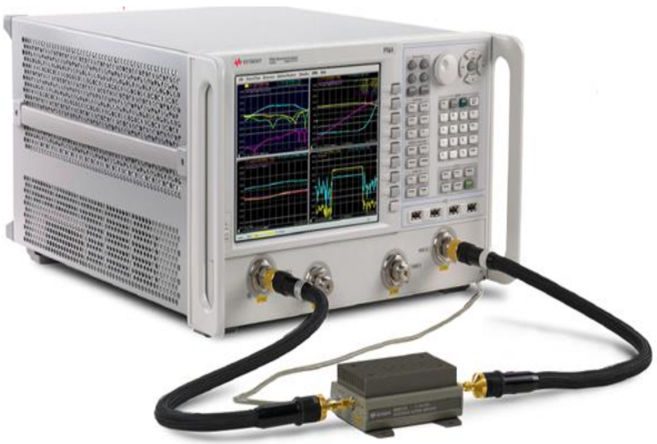
$$Scd21=(1/2) \times (S31-S32+S41-S42)$$

Mixed-mode S-parameter Measurement Example

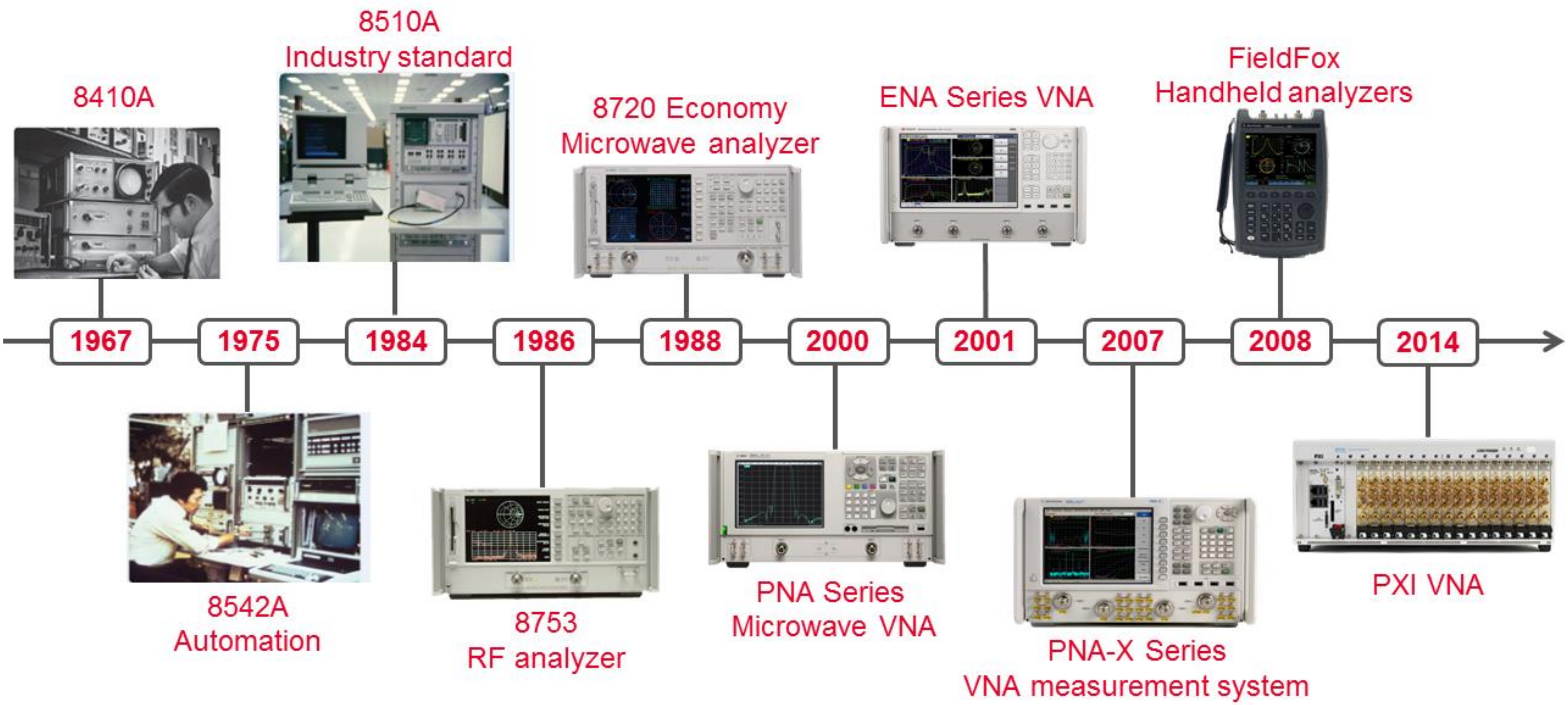
- Differential amplifier



Keysight VNA Portfolio



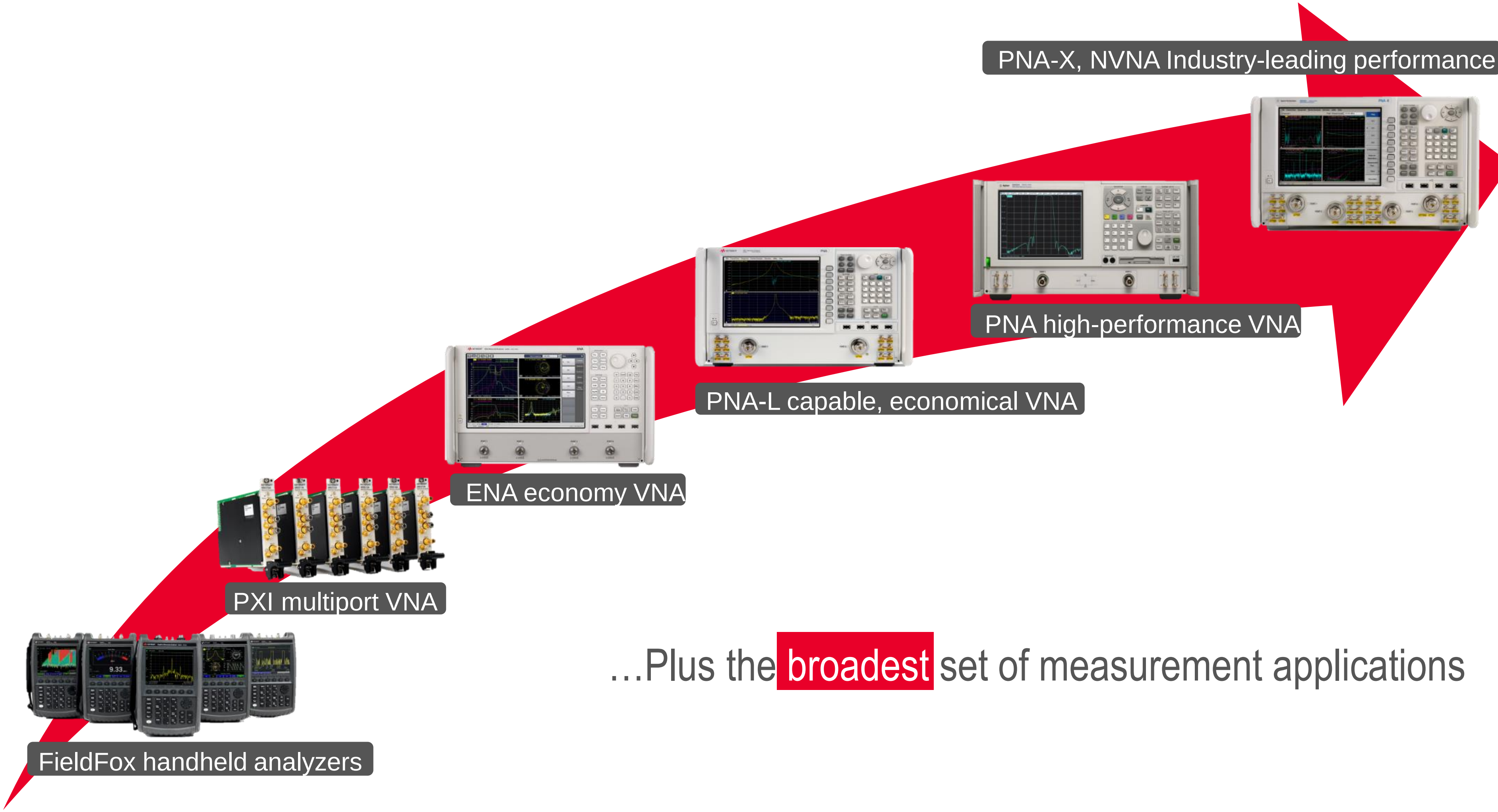
Leader in RF and Microwave Network Analysis



50 Years of Network Analyzer Innovations !

Keysight Vector Network Analyzers

Industry's broadest price / performance choices



…Plus the broadest set of measurement applications

FieldFox Handheld Analyzers

Carry precision with you

FieldFox Handheld Analyzers

Carry precision with you

Configurable as:

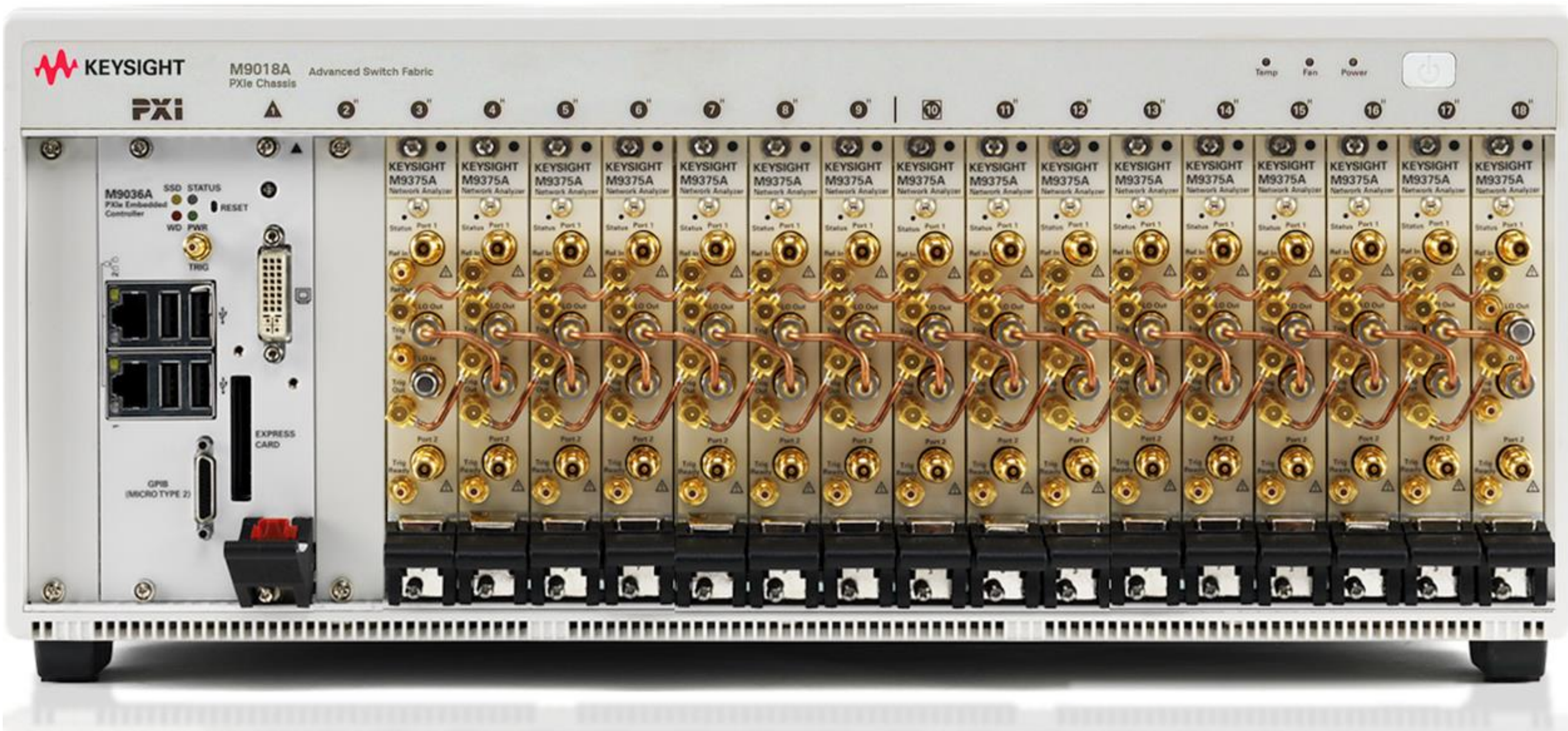
- ✓ Cable and antenna testers
- ✓ Vector network analyzers
- ✓ Spectrum analyzers
- ✓ All-in-one combination analyzers
- ✓ Frequency ranges from 2 MHz to 50 GHz

PXI Vector Network Analyzers

- ✓ Full 2 port VNA in a single PXI slot
- ✓ Six Frequency ranges: 300 KHz to 4,6.5,9,14,20 or 26.5 GHz

PXI Vector Network Analyzers

- ✓ True Multiport VNA
- ✓ Up to 32 ports



PXI Vector Network Analyzers

- ✓ High Performance Multiport VNA
- ✓ True Modular for customized Applications

ENA Series Vector Network Analyzer

- ✓ Industry standard in RF Network analysis
- ✓ Widely used in Manufacturing test and R&D Application

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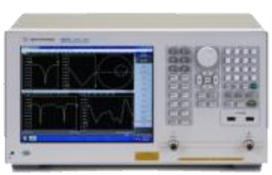


***E5063A*: Low cost RFNA**
100 kHz to 4.5 /8.5/18 GHz

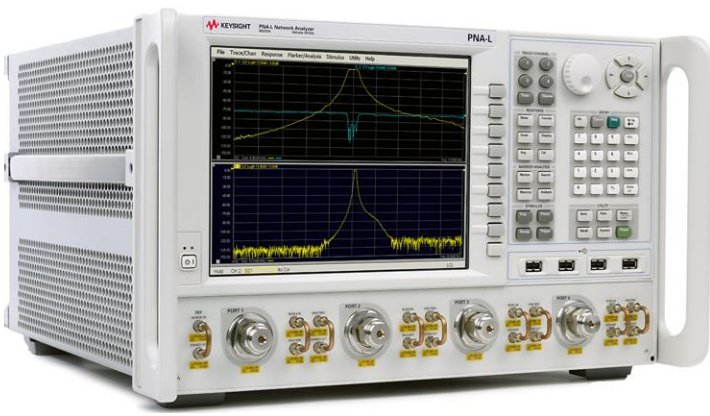
***E5061B:* LF-RF NA option**
5 Hz to 3 GHz
Impedance analysis option
RF NA options
100 kHz to 1.5/3 GHz
50 Ω & 75 Ω

***E5072A:* ENA with Configurable Test Set**
30 kHz to 4.5/8.5 GHz

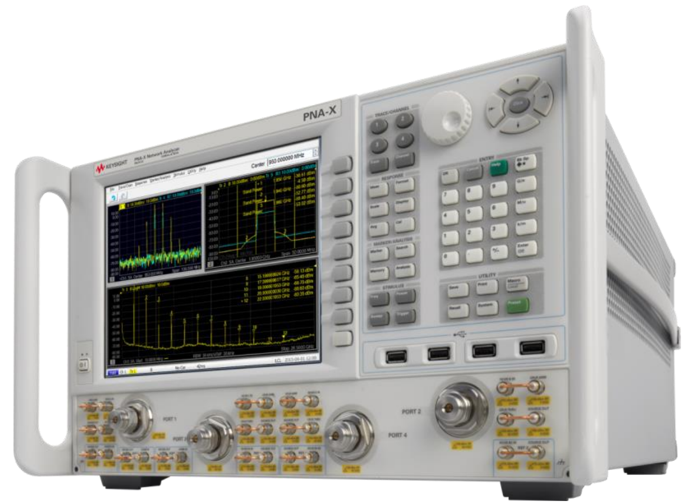
***E5071C:* Industry standard RF NA**
9/100 k to 4.5/6.5/8.5 GHz
300 k to 14/20 GHz, 2 & 4-port
TDR option

***E5080A:* The next generation ENA**
9 kHz to 4.5/6.5/9 GHz, 2 & 4-port

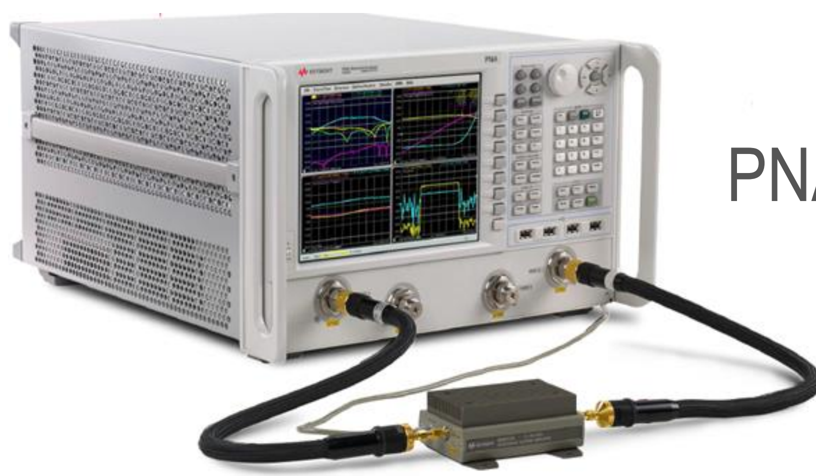
PNA Series Vector Network Analyzer



PNA-L



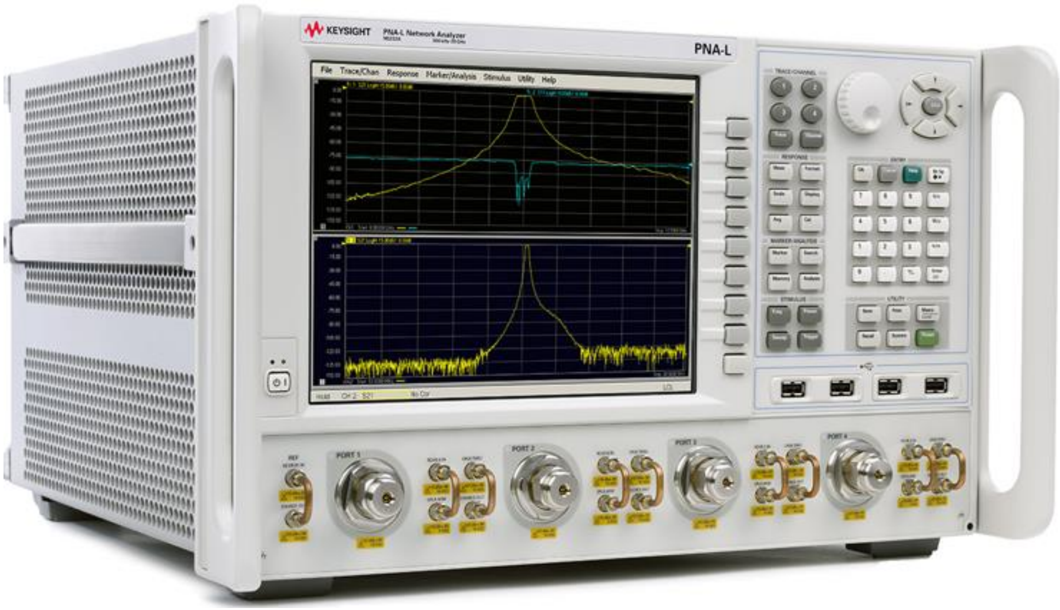
PNA-X



PNA

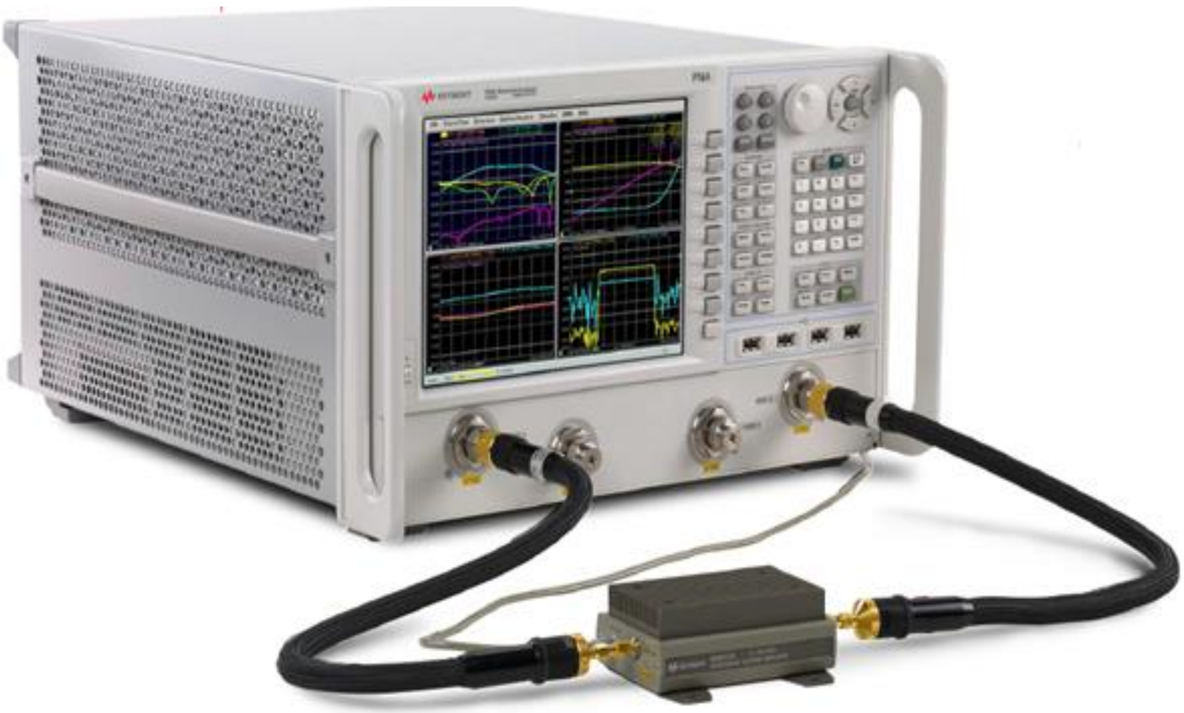
PNA-L Series Vector Network Analyzer

- ✓ Excellent performance at a low price point
- ✓ Frequency ranges from 300 KHz to 8.5,13.5,20,43.5,50 GHz
- ✓ Achieve greater yields and tighter guard bands



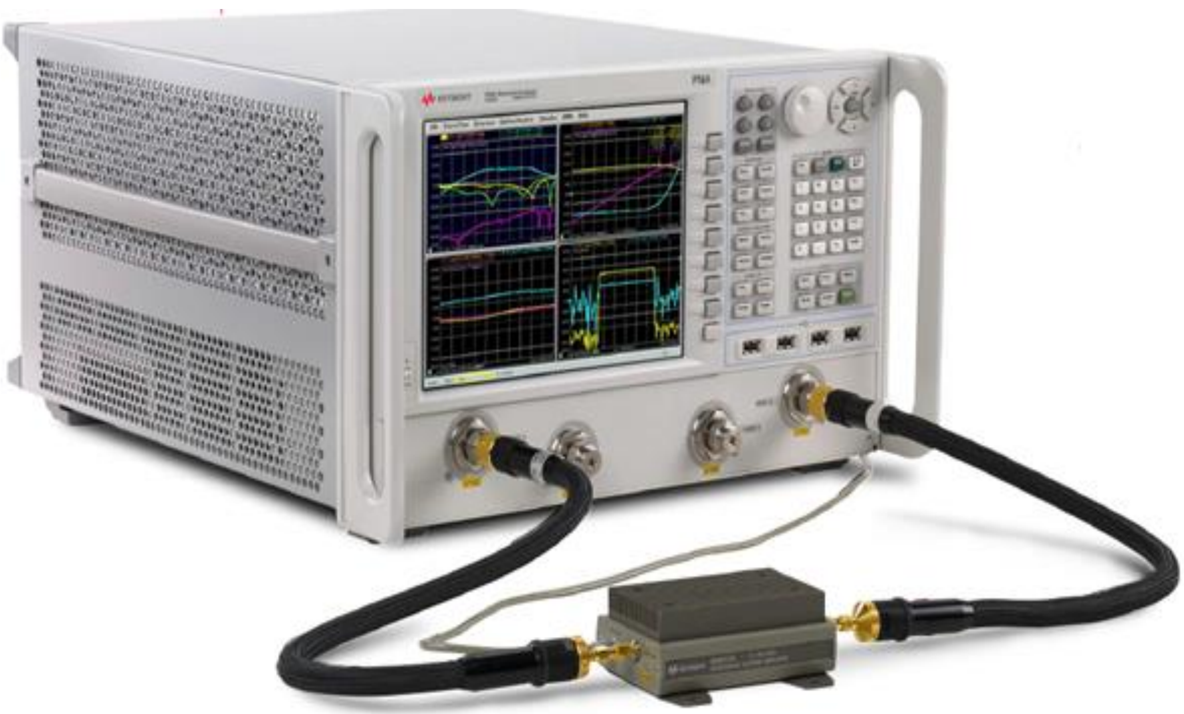
PNA Series Vector Network Analyzer

- ✓ Highest performing network analyzer for passive and active device test
- ✓ Five Frequency ranges up to 67 GHz
- ✓ Customize your PNA with the right performance and application to meet your needs



PNA-X Series Vector Network Analyzer

- ✓ Complete linear and non-linear component characterization
- ✓ Most integrated and flexible microwave network analyzer
- ✓ Unrivaled flexibility and configurability



Rich Set of Measurement Applications and Software Solutions

Optional Capabilities:

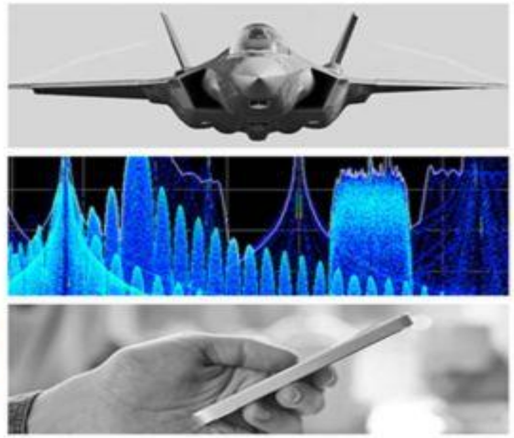
007 Automatic fixture removal
008 Pulsed RF measurements
010 Time domain
015 Dynamic uncertainty for S-parameters
021 Pulse modulators and pulse generators
028 Standard receiver NF measurements
029 Fully corrected noise figure measurements
080 Frequency offset measurements
082 Scalar calibrated converter measurements
083 Vector and scalar calibrated converter
084 Embedded LO measurements
086 Gain compression measurements
087 Intermodulation distortion measurements
088 Source phase control
089 Differential & I/Q device application
090 Spectrum analyzer capability
118 Fast CW mode
510 Nonlinear component characterization
514 Nonlinear X-parameters
518 Nonlinear pulse envelope domain
520 Arbitrary load impedance X-parameters
551 N-port calibrated measurements

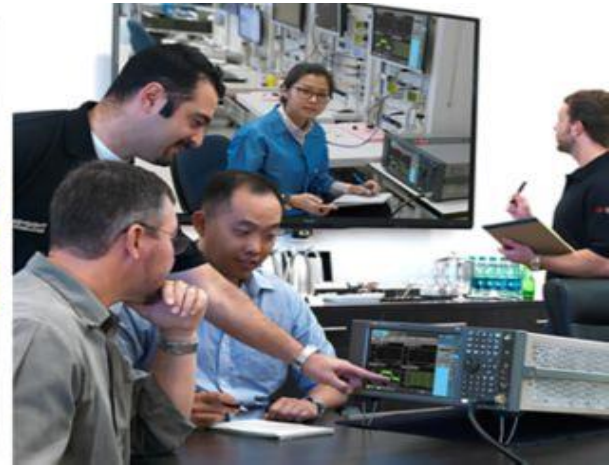
Applications:

Material measurements
Load-pull noise parameters
T/R module test
Satellite payload test
Antenna test
Lightwave component analysis
Mixer test
High power devices & components
Millimeter & Terahertz research
Amplifier test
Nonlinear modeling
Metrology
Signal integrity
Atomic force scanning microscope

Keysight Training Services

Build new skills. Extract more value





- ❑ Enable your teams to achieve the mastery necessary to optimize the use of your Network Analyzers and use them to their fullest potential

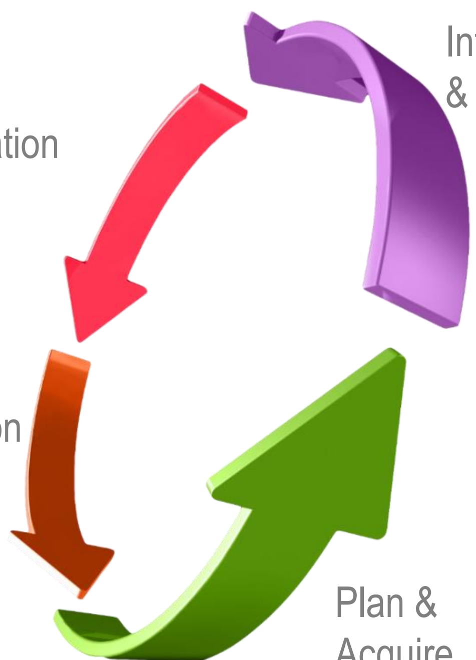
- ❑ Access a comprehensive portfolio of technical training courses

- ❑ Utilize modular materials that focus on developing expertise in specific instruments, technologies or processes

www.keysight.com/find/Training

Keysight Technology Refresh

Minimize capital and operating expenses



Product Purchase Alternatives: Lower cost and flexible financing at Keysight quality
- Keysight Premium Used
- Keysight Instant Buy[1]
- Keysight Store on eBay

Consulting Services: Solve tough problems by leveraging our expertise
- Start-Up Assistance
- Test process analysis consulting

Asset Management: Stay ahead of required maintenance and regulatory audits with automated notifications

Technology Refresh Service: Extend, upgrade or migrate your existing test systems

[1]Available in US, Canada, Germany, UK & France

Thank you !

Backup

Keysight
Vector Network Analyzer Portfolio

Industry Broadest Price/Performance Choices

PNA-X (N524XA), NVNA
Most advanced & flexible Microwave NA

PNA (N522XA)
High-performance Microwave NA

PNA-L (N523XA)
Economy Microwave NA

PNA Family
Reach for unrivaled excellence
300 k to 1.1 THz

mm-wave Solution
Up to 1.1 THz

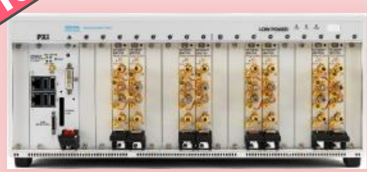
PNA-X Receiver
8530A Antenna Replacement

E5080A
The next-generation ENA

E5071C, E5072A
High-performance RF NA

E5061B, E5063A
NA + ZA in one-box
Low cost RF NA

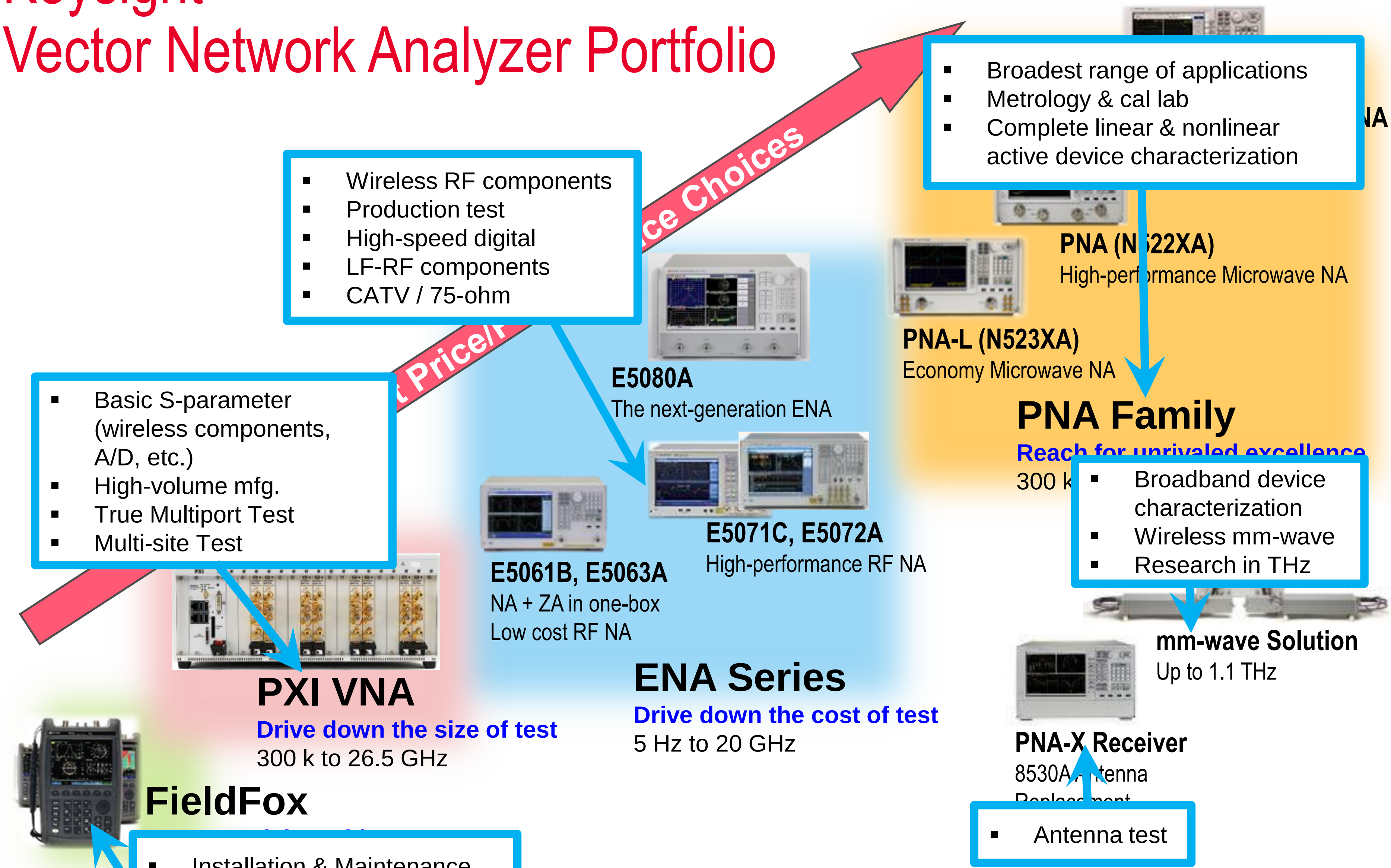
ENA Series
Drive down the cost of test
5 Hz to 20 GHz



PXI VNA
Drive down the size of test
300 k to 26.5 GHz

FieldFox
Carry precision with you
30 k to 26.5 GHz

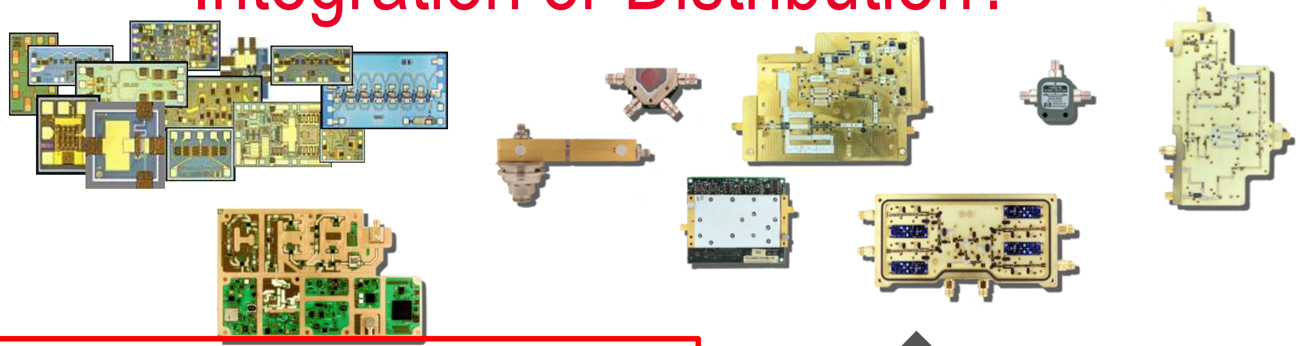
Keysight
Vector Network Analyzer Portfolio



TECHNOLOGIES

KEYSIGHT HOTSPOTS
Where Technologies and Experts Meet

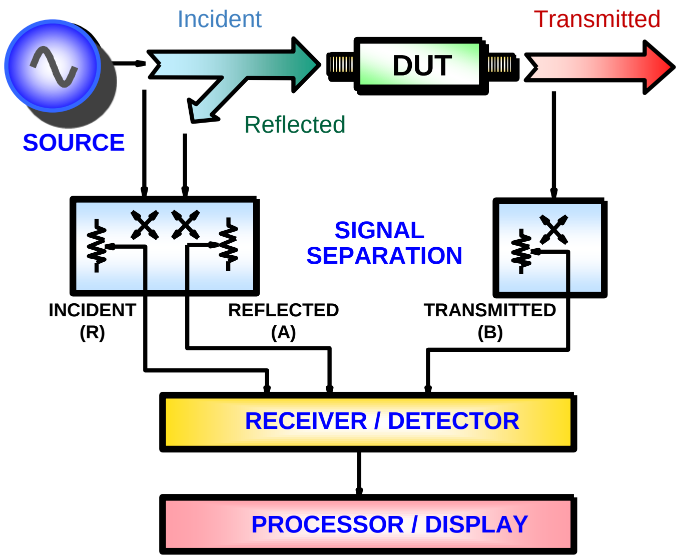
Integration or Distribution?

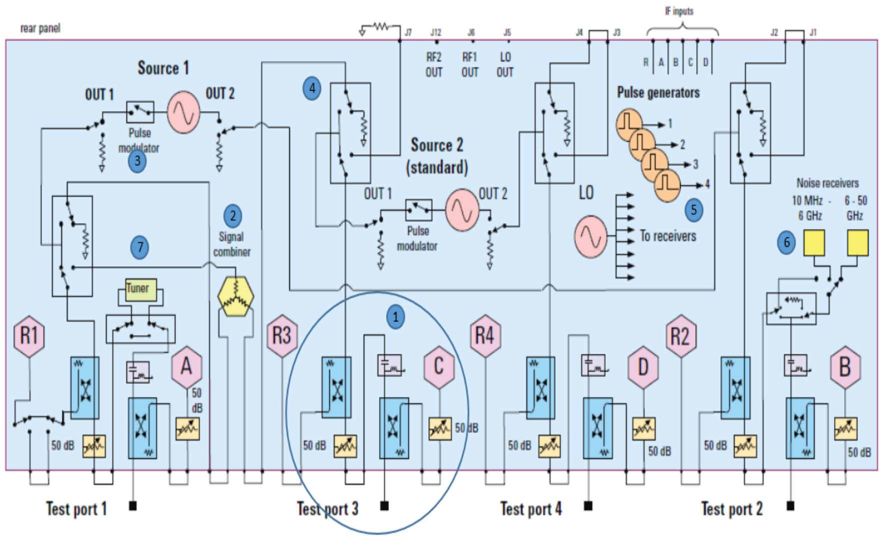


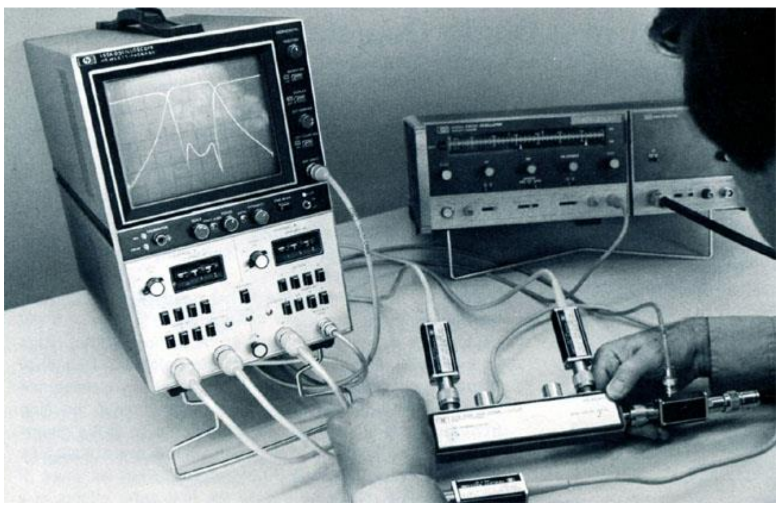
Integration

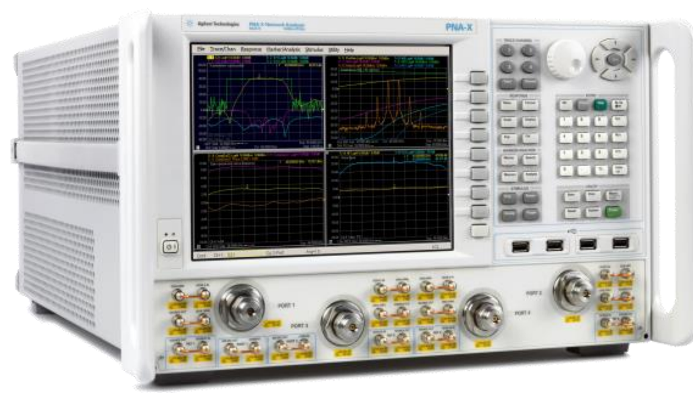
Distribution

Network Analyzer Block Diagram: Yesterday and Today

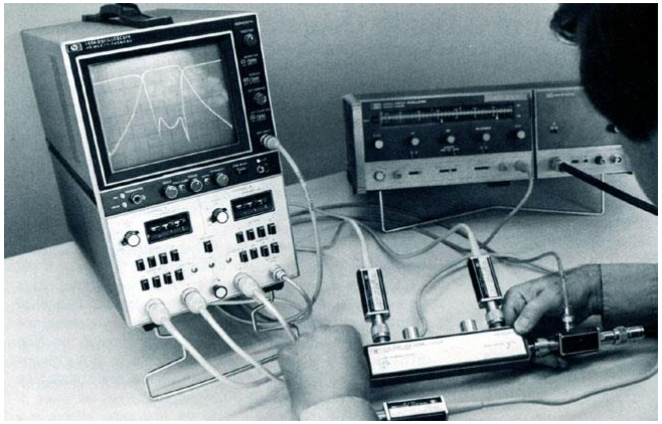






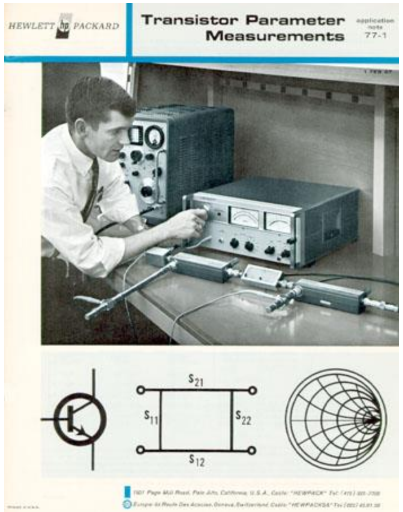


Network Analyzer Block Diagram: Yesterday and Today



Measurements:

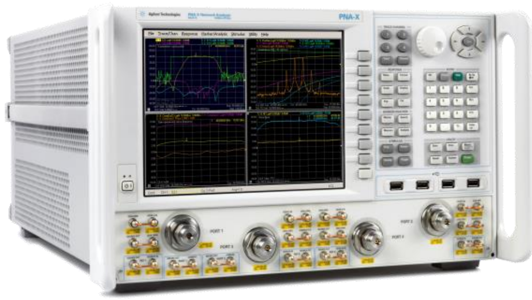
- ✓ **CW S-parameters**

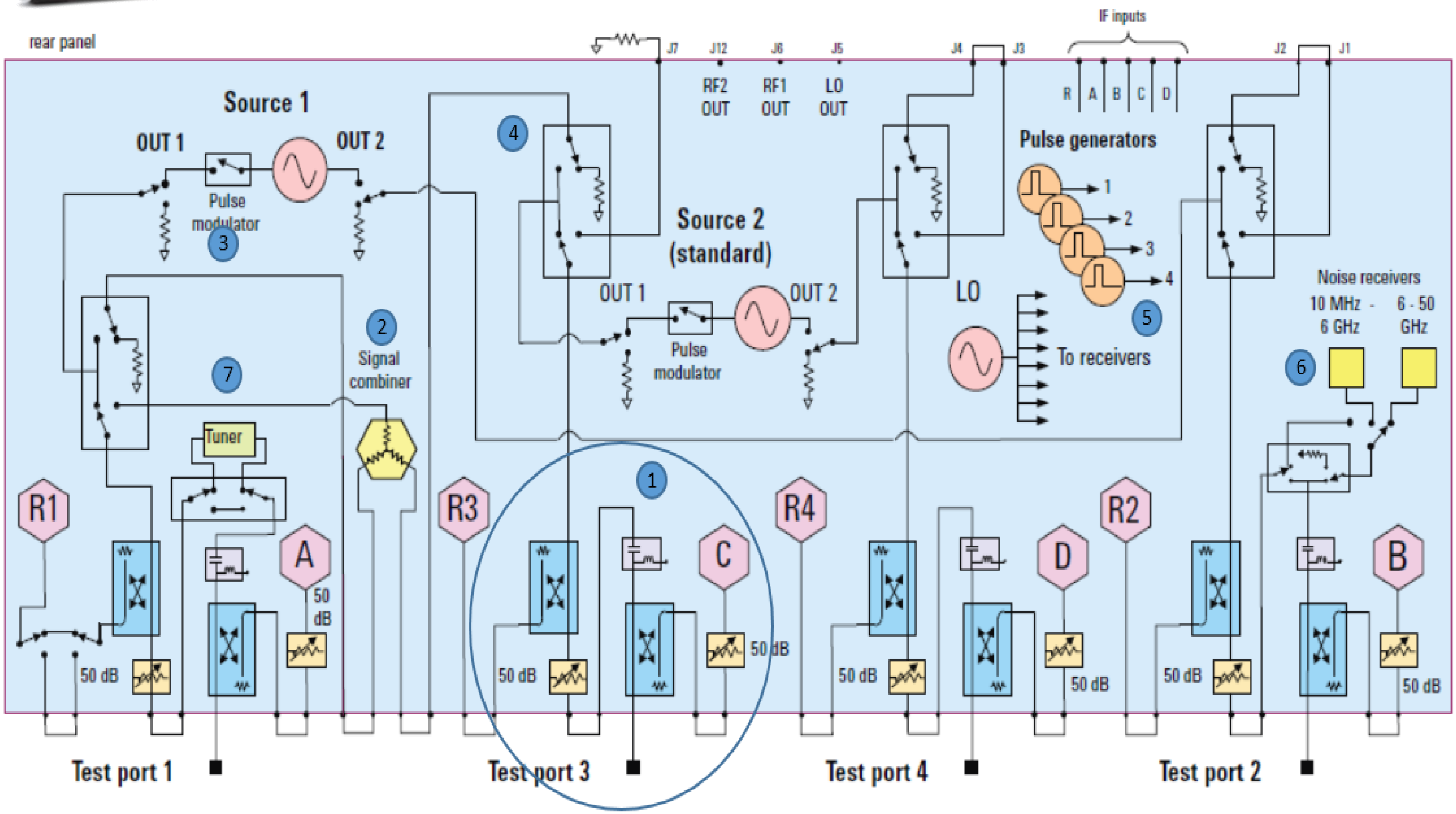


Measurements:

- ✓ **CW S-parameters**
- ✓ **Pulsed S-parameters**
- ✓ **Gain compression**
- ✓ **AM-to-PM conversion**
- ✓ **Harmonics**
- ✓ **Intermodulation distortion**
- ✓ **Noise Figure**
- ✓ **Hot-S-parameters**
- ✓ **Phase versus drive**
- ✓ **True-mode differential stimulus**
- ✓ **Spectrum Analysis**

PNA- X Block Diagram





KEYSIGHT TECHNOLOGIES

KEYSIGHT HOTSPOTS
Where Technologies and Experts Meet

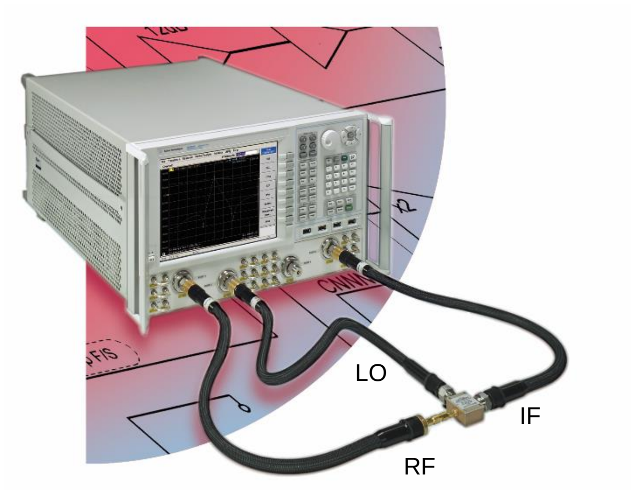
PNA-X: Single Connection, Multiple Measurements

Easily switch between measurements:

- CW S-parameters
- Pulsed S-parameters
- Gain compression
- AM-to-PM conversion
- Harmonics
- Intermodulation distortion
- Hot-S-parameters
- Phase versus drive
- True-mode differential stimulus
- Conversion loss/gain
- Noise Figure
- NVNA

PNA Spectrum Analyzer Option (090)

A multi-channel SA with internal swept-signal generators

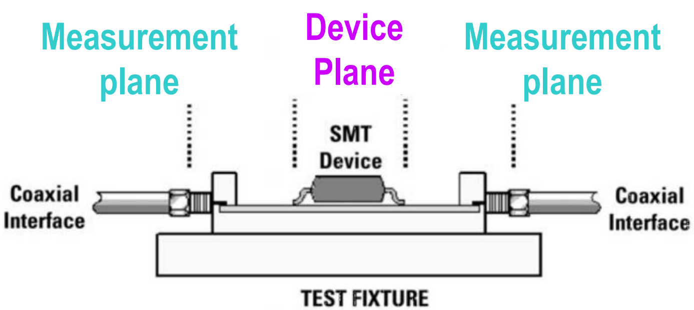


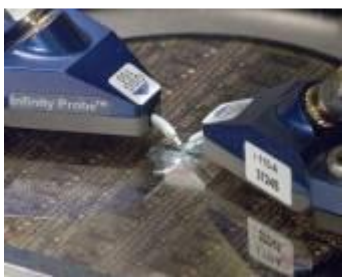
- RF input
- RF reflection
- RF feed-through
- RF harmonics
- LO reflection
- LO feed-though
- LO harmonics
- IF output
- High-/sub-order mixing spurs

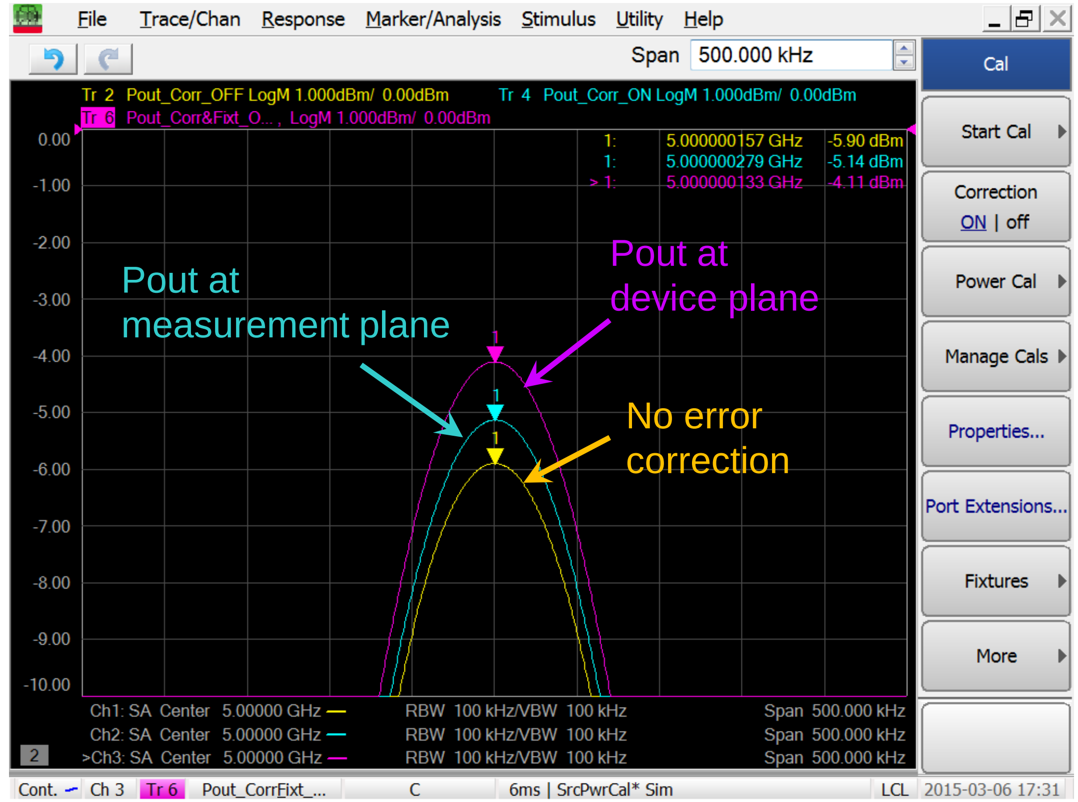
With a single set of connections, the spurious content emanating from all ports is readily apparent during operation with fixed or swept stimuli.

PNA Spectrum Analyzer Option (090)

Unlock true performance with in-fixture spectrum analysis



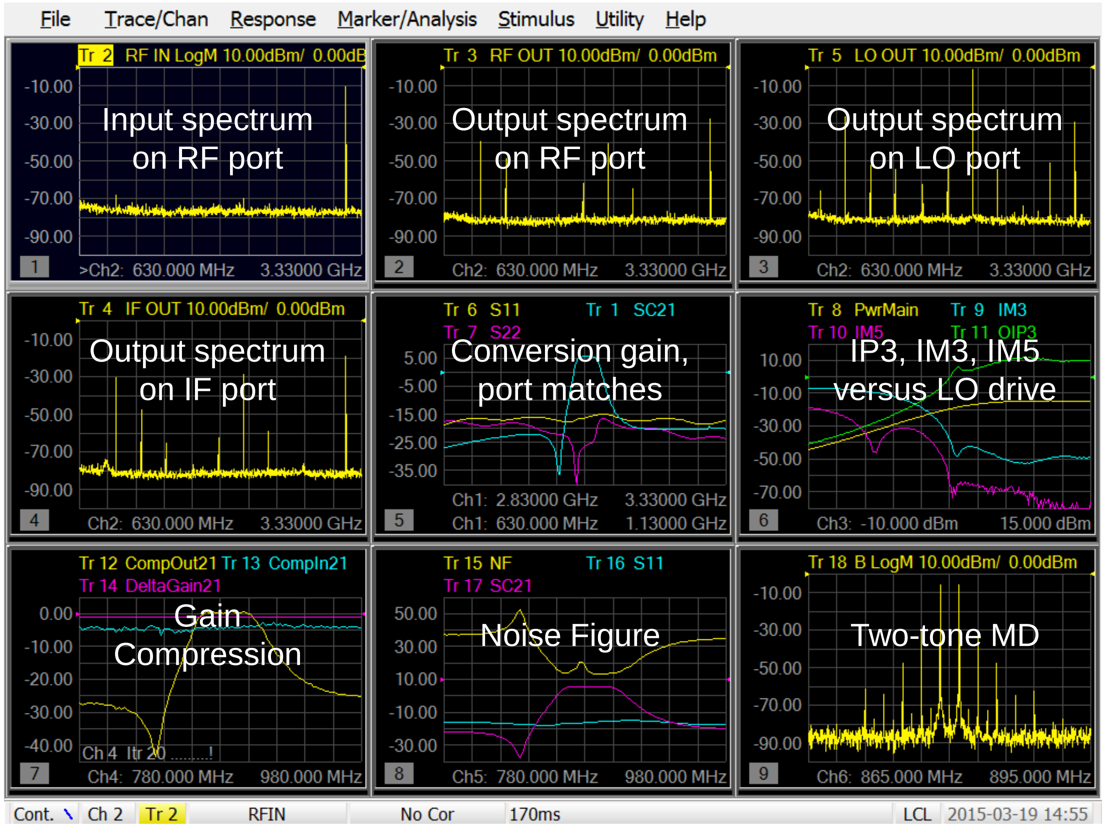


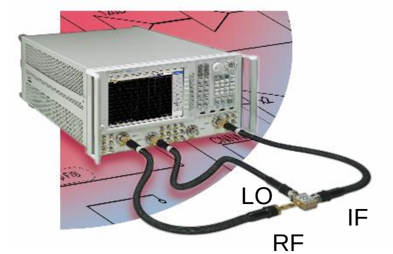


VNA calibration and fixture de-embedding remove cable and fixture effects and correct receiver response errors, providing calibrated in-fixture spectrum analysis.

PNA Spectrum Analyzer Option (090)

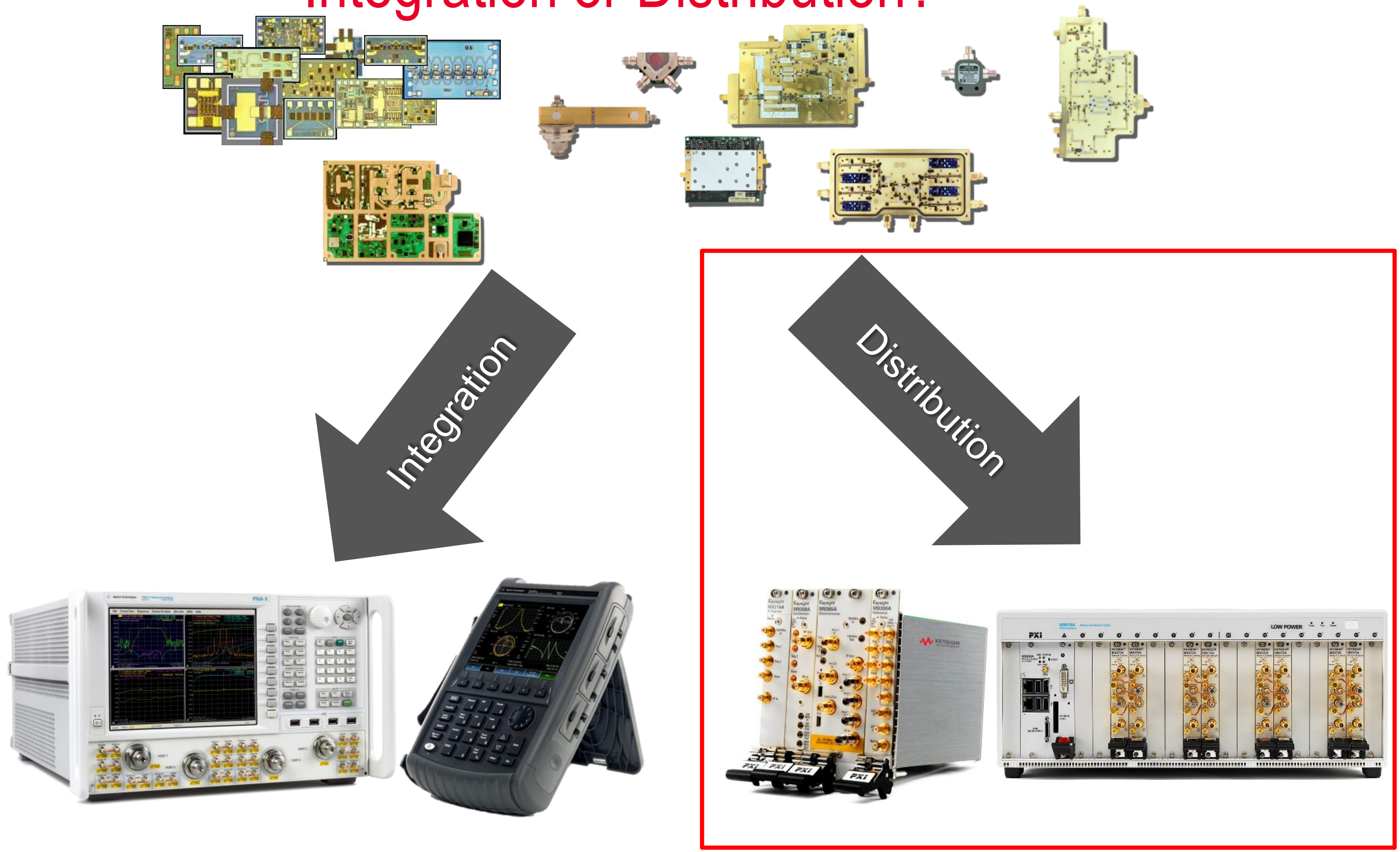
Spectrum analyzer option adds to suite of PNA apps





SA option further enriches the PNA capabilities for component tests with a single set of connections.

Integration or Distribution?



Integration or Distribution?

Vector Network Analyzer, 8510X

PXIe Vector Network Analyzer, M937XA

Dynamic range (for transmission measurements)

	Frequency range (GHz) 0.045–2	2–8	8–20	20–26.5
Maximum power measured at port 2	+2 dBm	+3 dBm	+3 dBm	–1 dBm
Reference power at port 1 (nominal)	–5 dBm	–9 dBm	–14 dBm	–25 dBm
Minimum power measured at port 2	–98 dBm	–98 dBm	–100 dBm	–99 dBm
Receiver dynamic range	100 dB	101 dB	103 dB	98 dB
System dynamic range	93 dB	89 dB	86 dB	74 dB

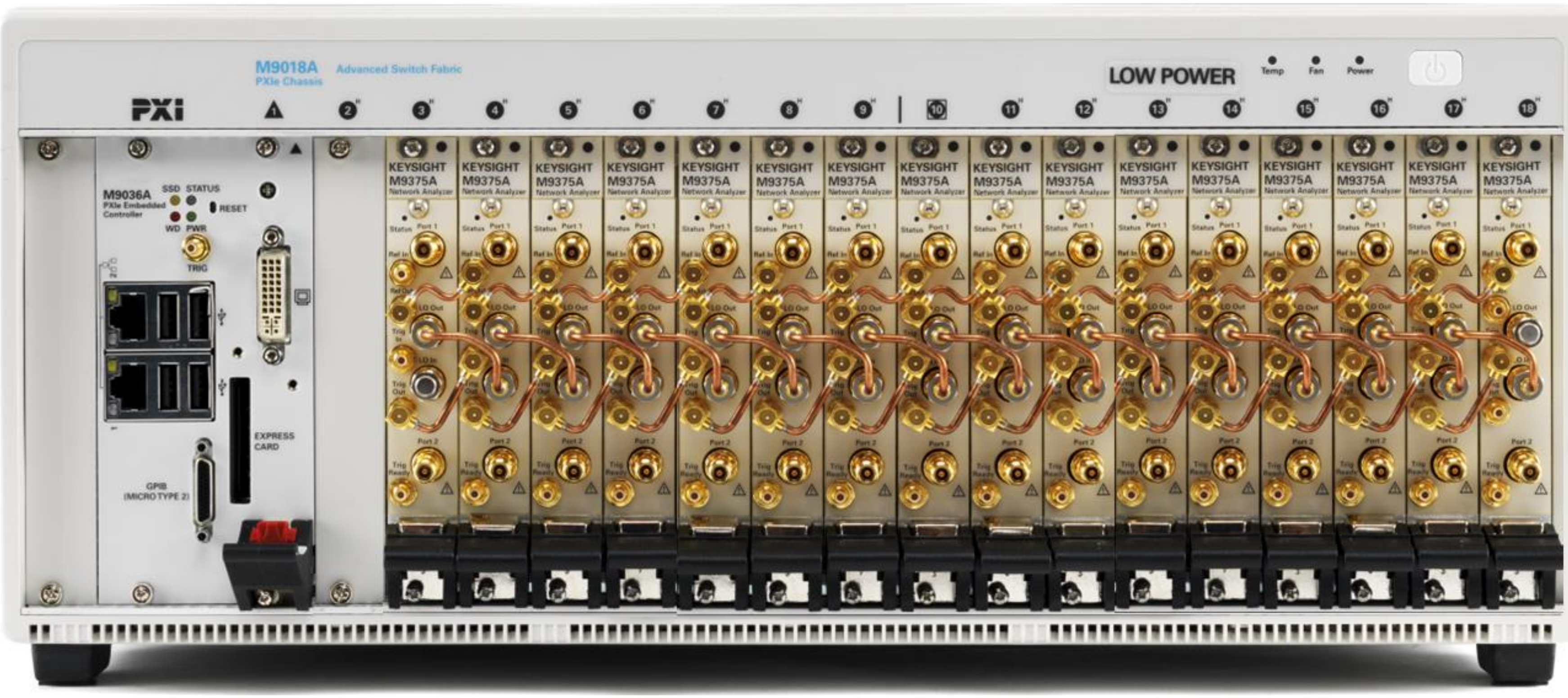
Full two-port network analyzer in just one slot up to 26.5 GHz
Maximum Power : + 10 dBm

Dynamic range: 114 dB (9 GHz), 110 dB (20 GHz)

Trace noise: < 0.003 dB specified, < 0.001 dB typical

Stability: ±0.005 dB/°C at 4 GHz, ±0.020 dB/°C at 26.5 GHz

32-port True Crossbar 26.5 GHz VNA in 4U Chassis



Portable - Pick up FieldFox for its Ergonomics

Vertical portrait orientation makes FieldFox comfortable to hold, and the keypad layout lets you easily operate it with your thumbs

Weighing just 3.0 kg (6.6 lbs) FieldFox is easier to carry than similar analyzers

Bright, low-reflective display and backlit keys enable easy viewing in darkness or direct sunlight

One-button measurements simplify complex setups and ensure quick, accurate results

The intuitive user interface is designed for the work you do every day, enabling measurements in just a few key presses

Large keys are easy to operate, even when wearing gloves

"I really like the packaging, and you've done a lot to simplify the controls and menus."
- DoD technical lead for military contracts

…and Depend on its Durability

Specially designed connector bay protects connectors from damage due to drops or other external impacts

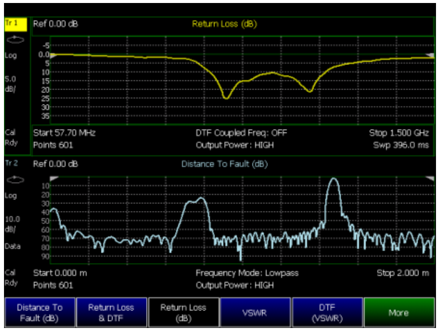
Transfer and archive data through LAN, USB and SD card

Keep going with the easily replaceable Lithium Ion battery

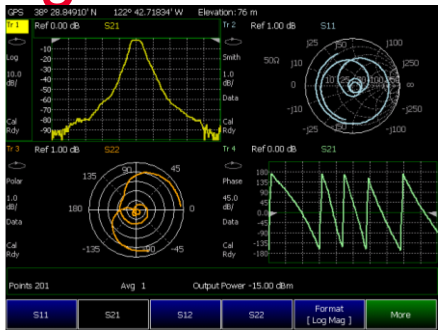
Gasketed doors protect connectors from dust and moisture

Rubber doors protect connectors from dust and moisture

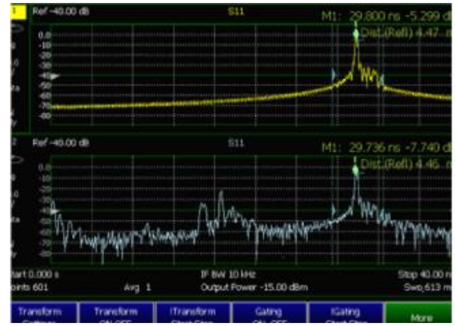
Get a Wide Range of Precise Field Measurements



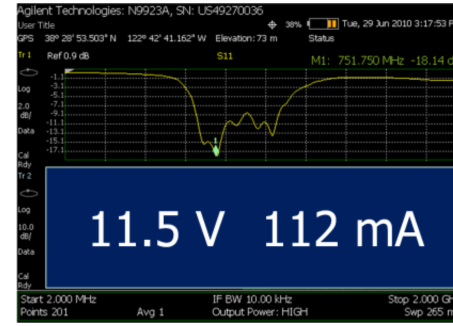
Cable and antenna analysis



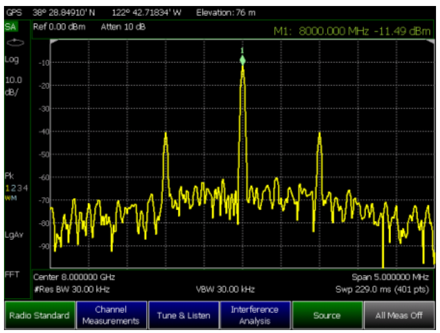
Vector network analysis



Time domain

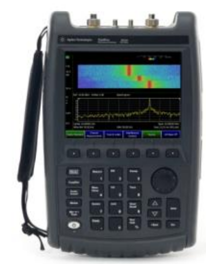


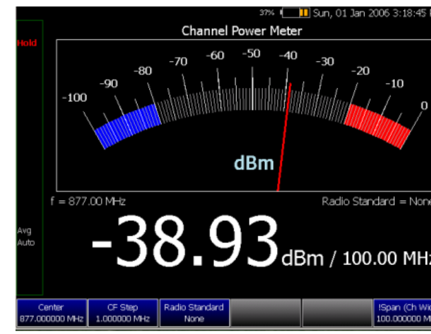
DC source & current monitor



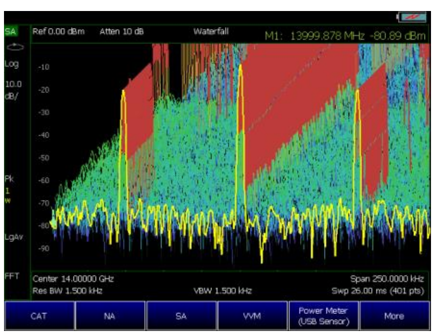
Spectrum analysis

Plus:
- **Built-in GPS**
- **Independent source**
- **Full-band preamplifier**
- **SA frequency counter**

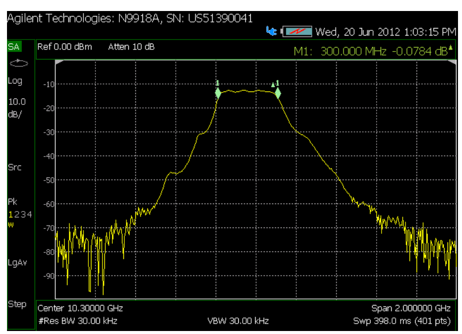




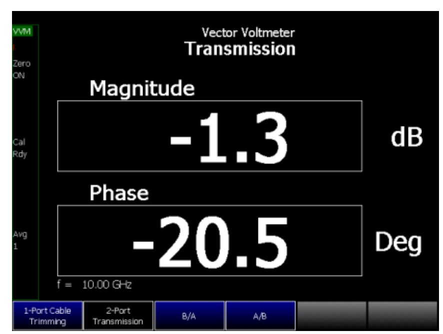
Built-in power meter



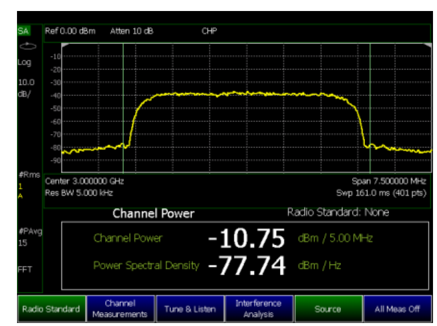
Interference analysis



Full-band tracking generator



Vector voltmeter



Channel power measurement

Find the FieldFox that Meets Your Needs