11th International Summer School on RF MEMS and RF Microsystems
IHP, Frankfurt (Oder) – Germany June 22nd – 26th 2015

Basics of mm-wave Measurements

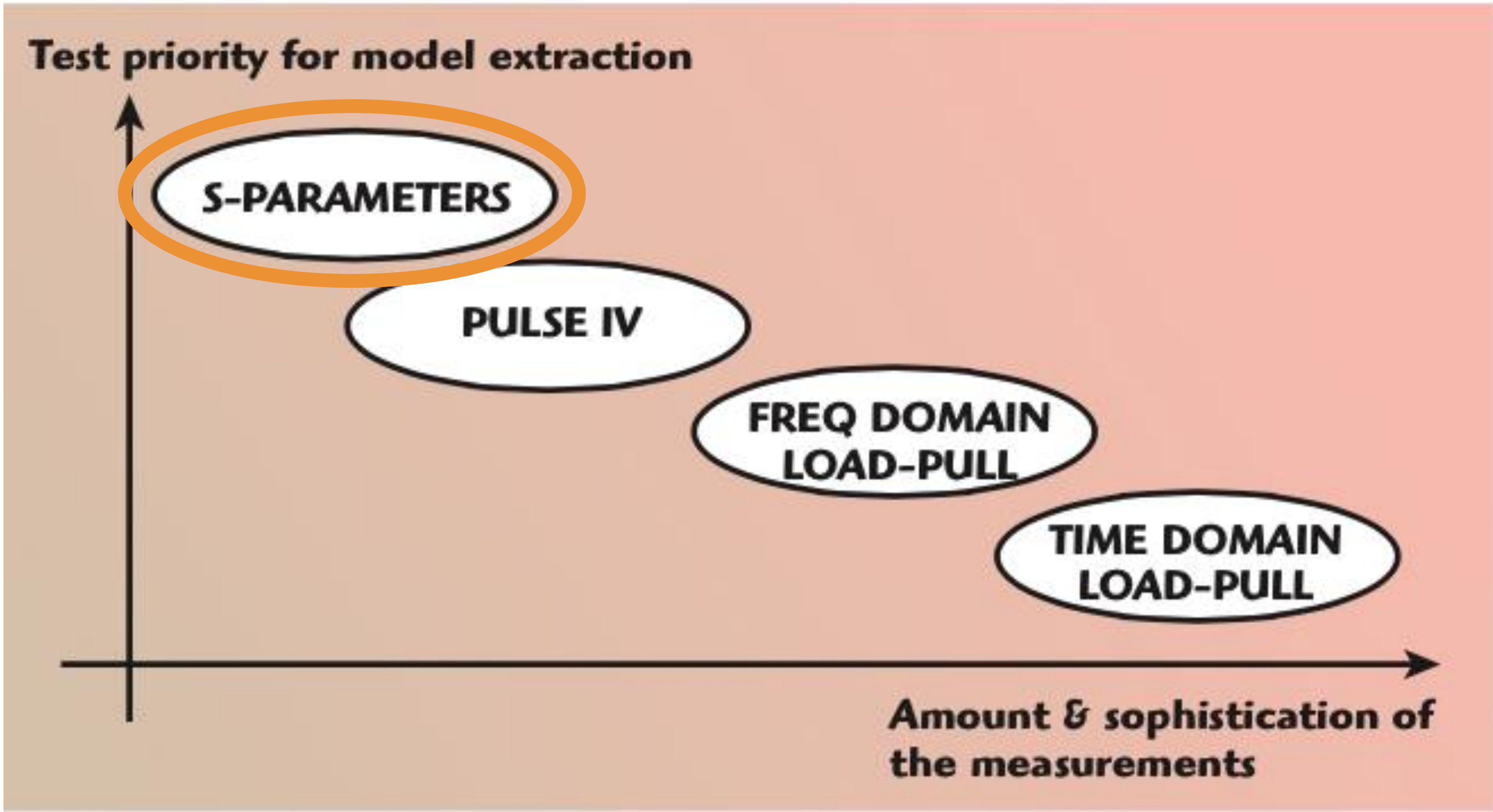
Dr. Andrej Rumiantsev

Director RF Technologies MPI Corporation

Outline

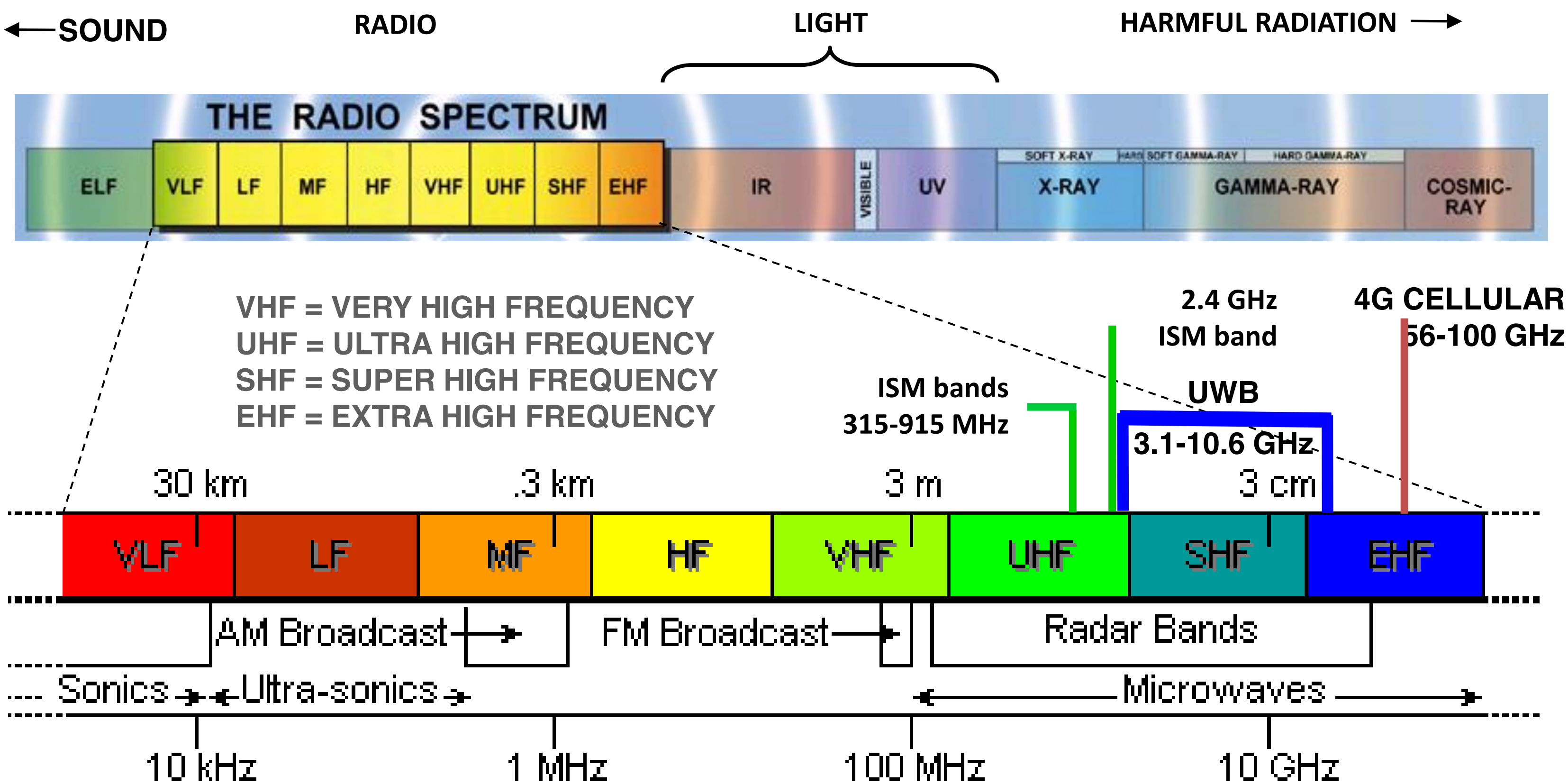
- Introduction
- S-parameters Basics
- Measurement of S-parameters
- VNA Building Blocks
- Instrumentation

Importance of RF-Measurements



T. Gasseling , MW Journal, 03-2012

Where Do RF & Microwaves Start?



10 GHz ~ 3 cm wave length

Source: [JSC.MIL]

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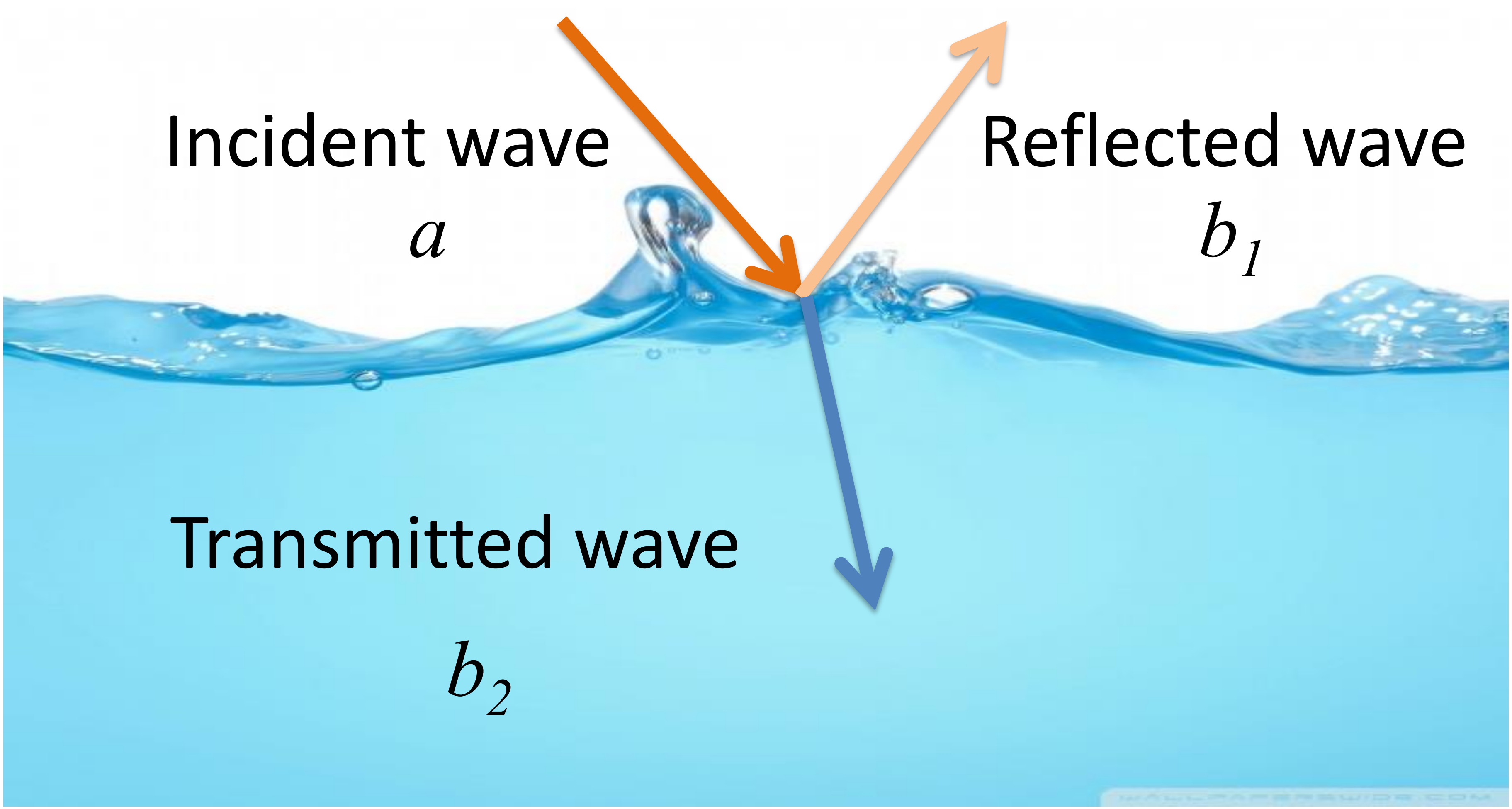
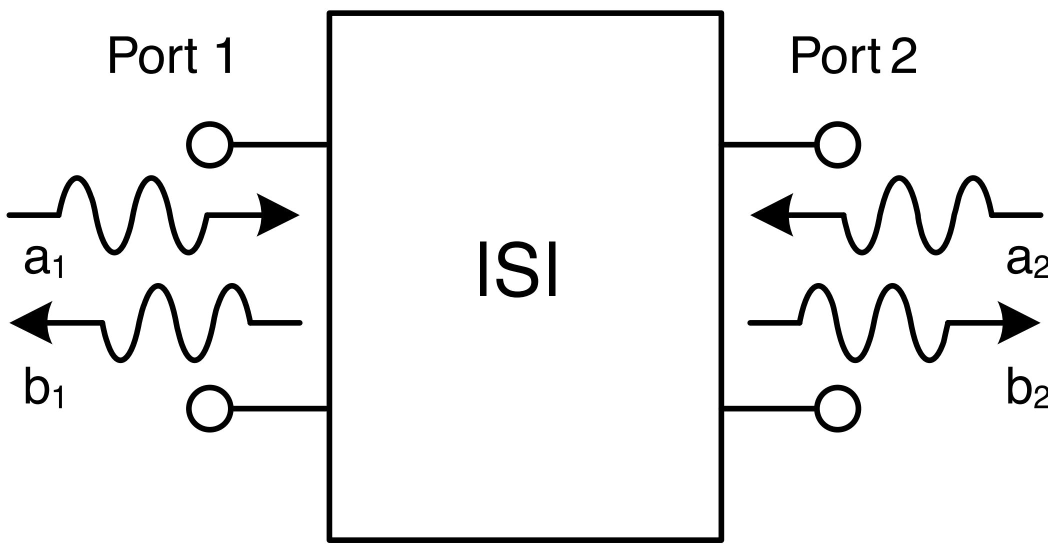
..its all about Waves



… over S-Parameters

- Relationship of:
  - incident (a) and reflected/transmitted (b) waves at device terminals



Why S-Parameters

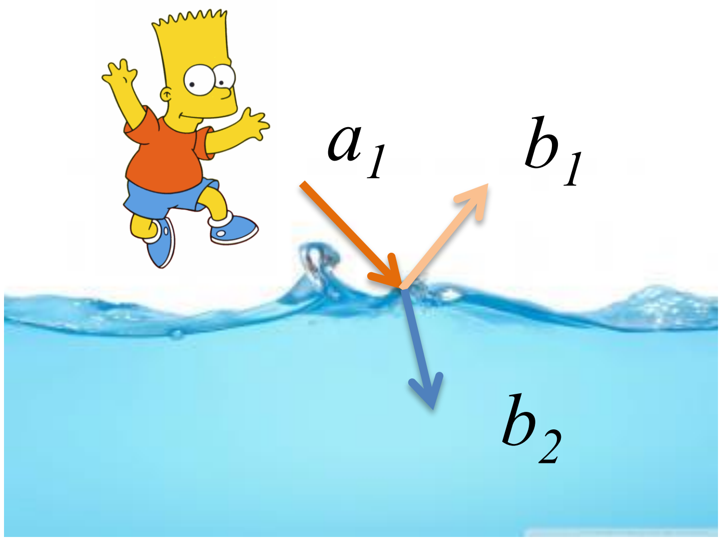
- Wave quantities are easy to measure
- Can be converted to *Z*-, *Y*-, *H*- and other parameters

$$S_{ii} = \frac{b_i}{a_i} = \frac{Z_{DUT} - Z_{REF}}{Z_{DUT} + Z_{REF}}$$

S-Parameter Matrix

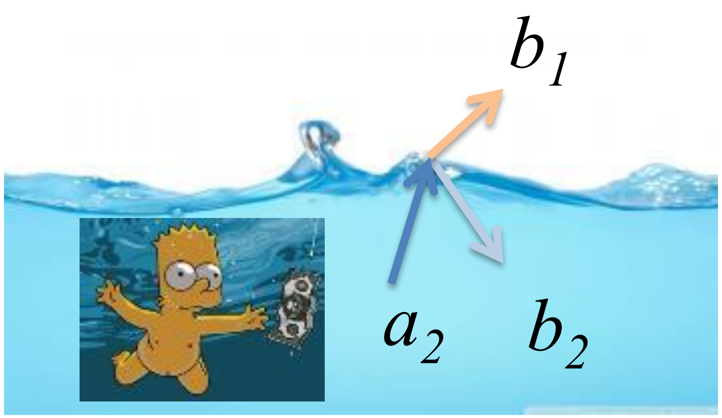
- Forward direction

$S_{11}=b_1/a_1$ $S_{21}=b_2/a_1$



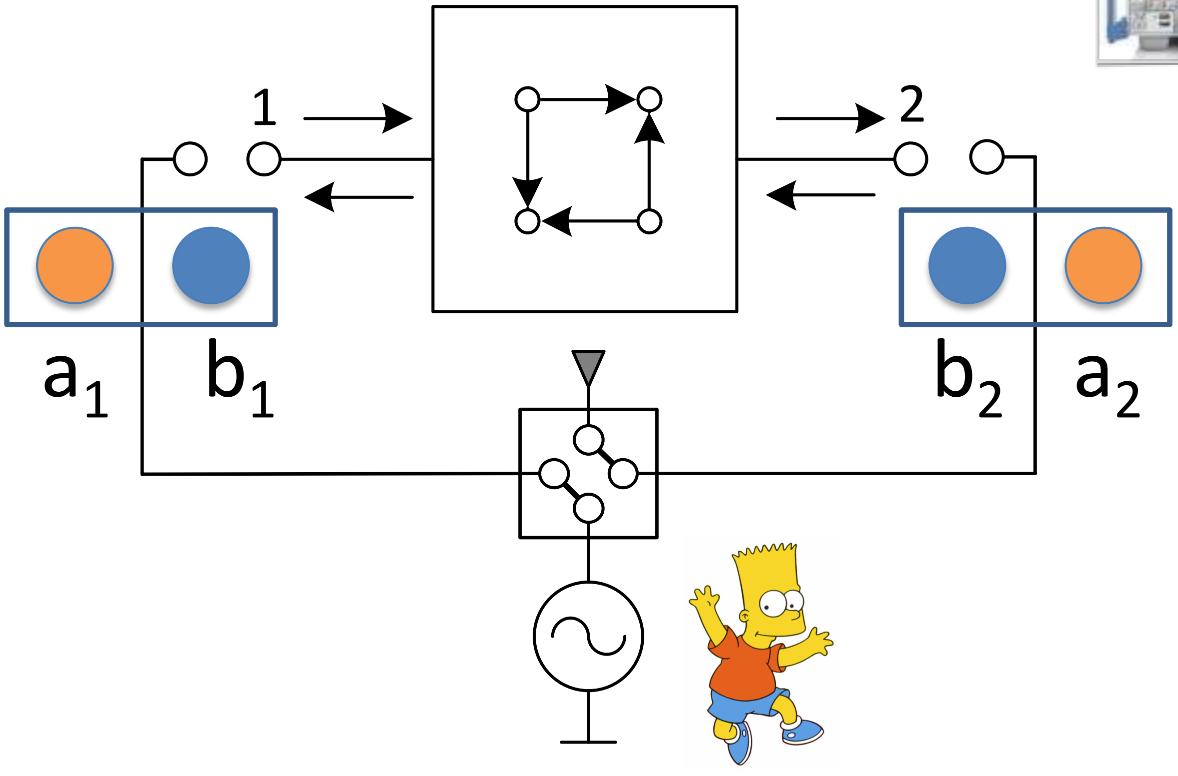
- Reverse direction

$S_{22}=b_2/a_2$ $S_{12}=b_1/a_2$



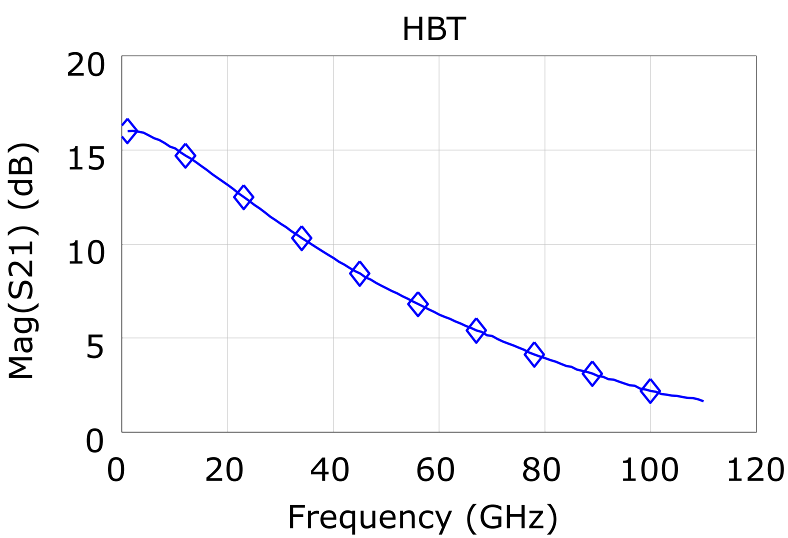
S-Parameters Measured by VNA

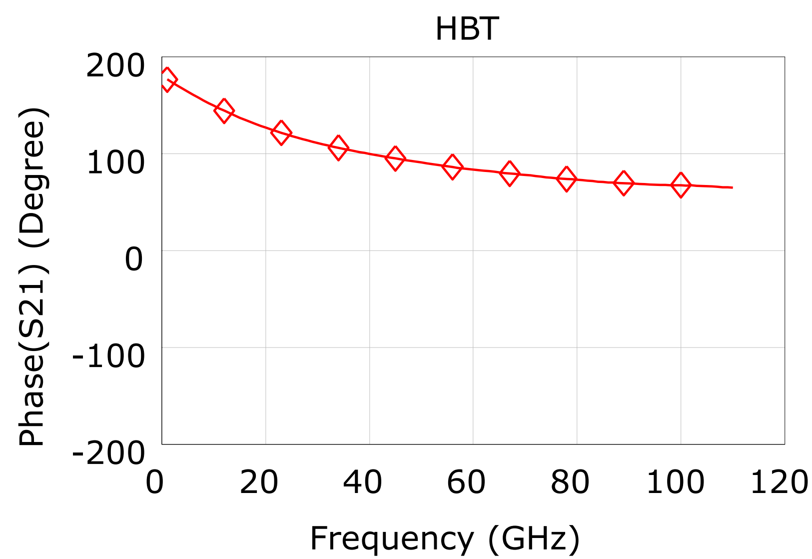
- Vector Network Analyzer (VNA)



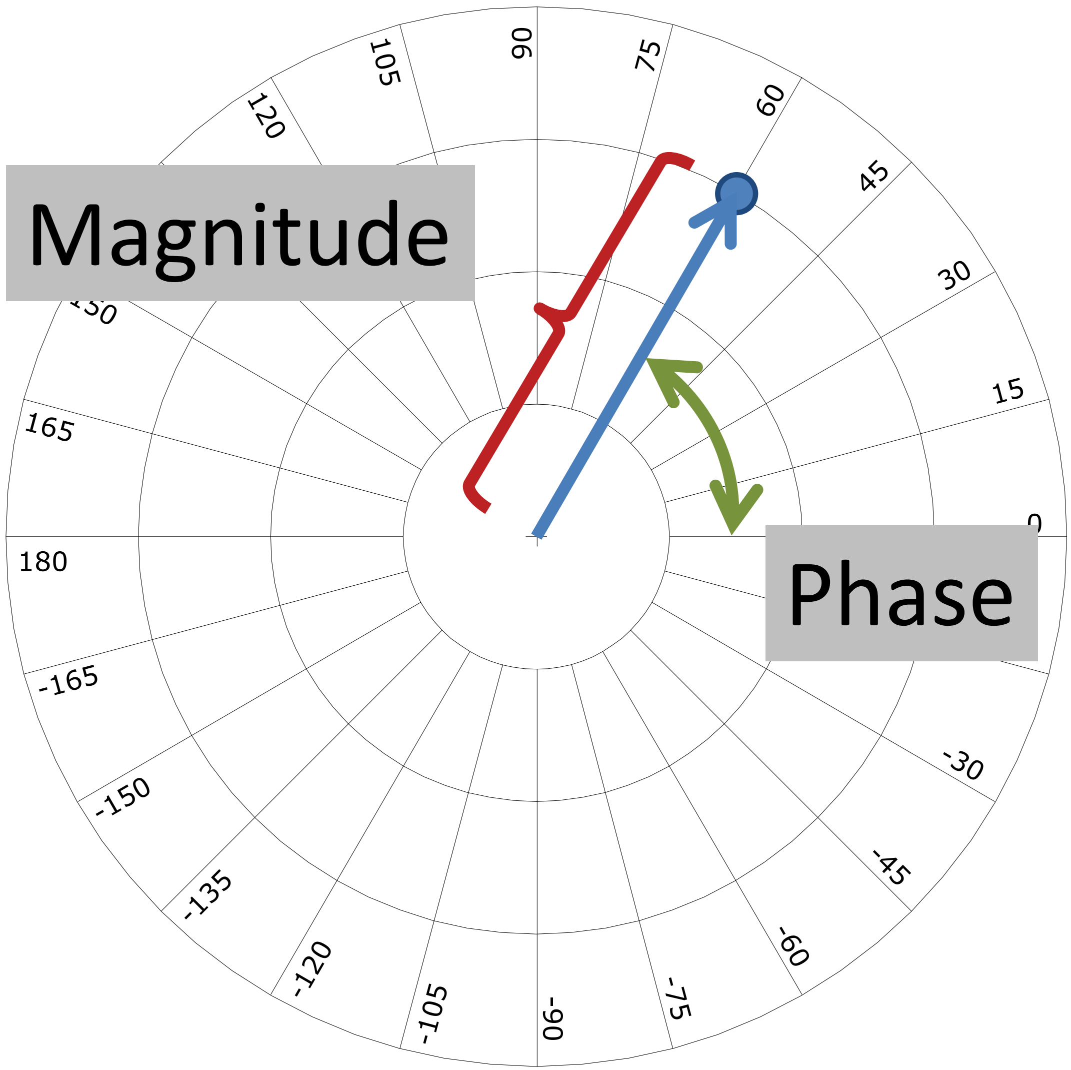
Why "Vector" ?

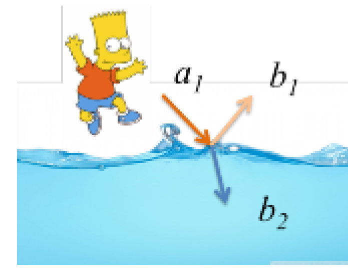
- S-parameters are complex quantities:
  - Magnitude
  - Phase





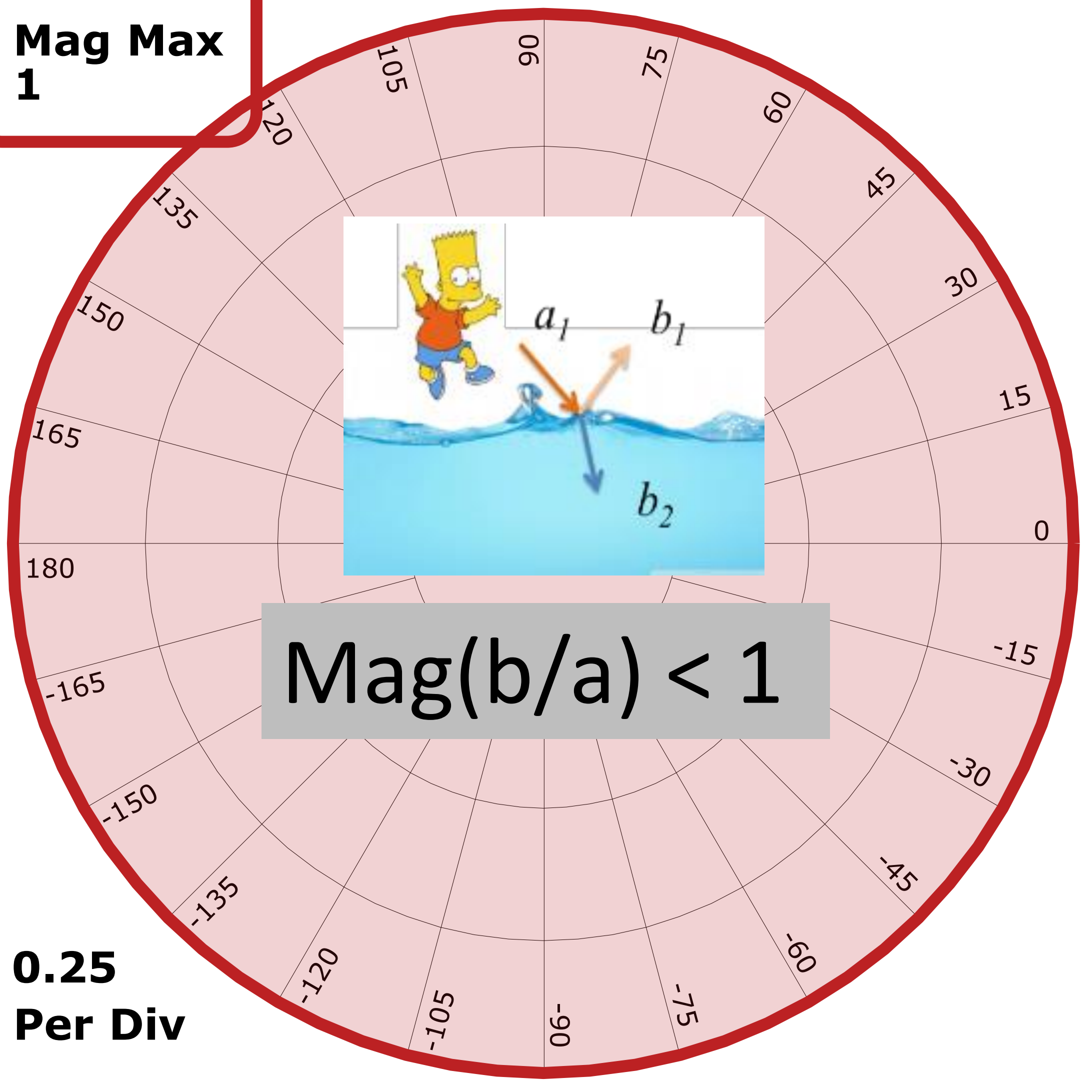
Vector on Polar Plot





Passive Component

Mag Max
1

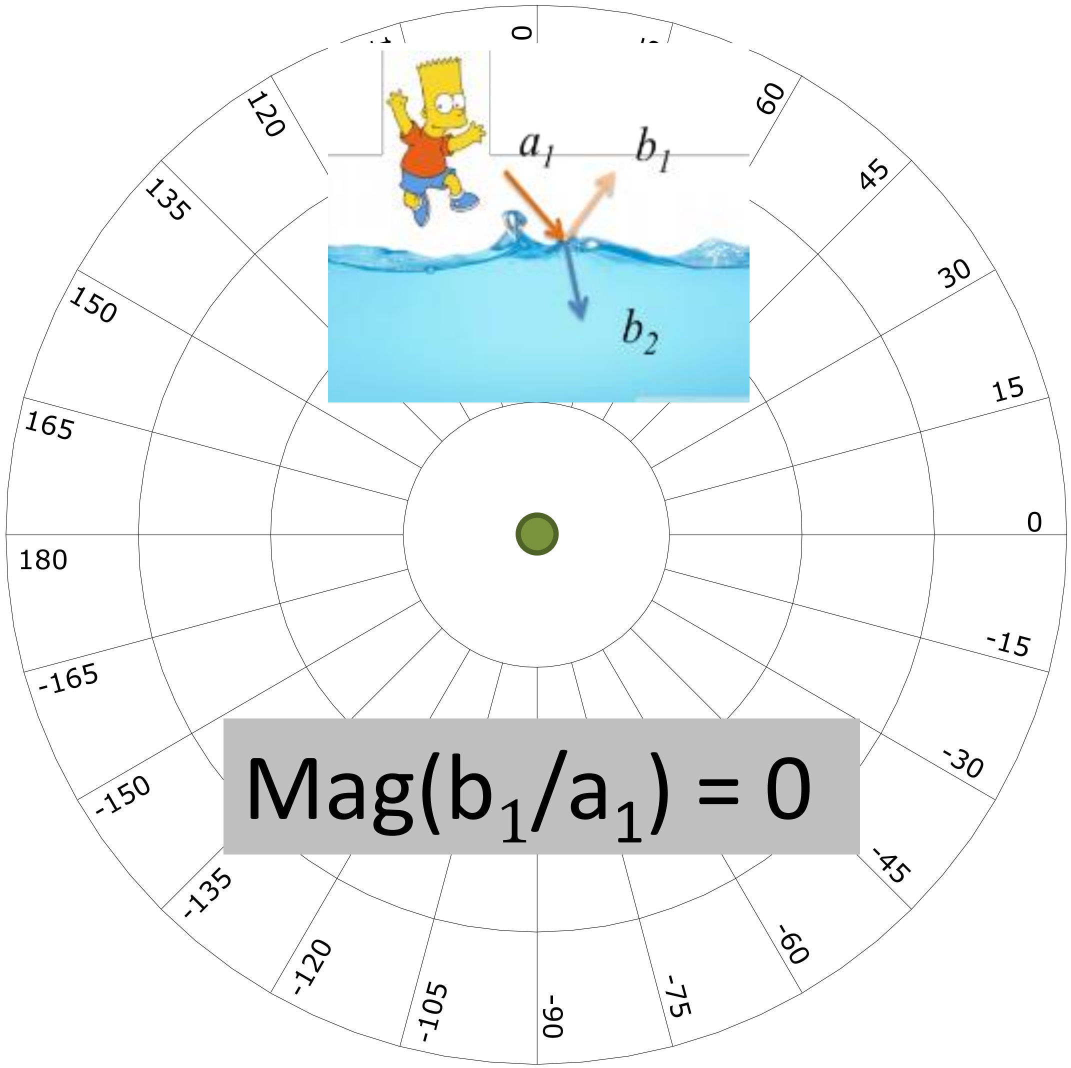


1.0

Mag(b/a) < 1

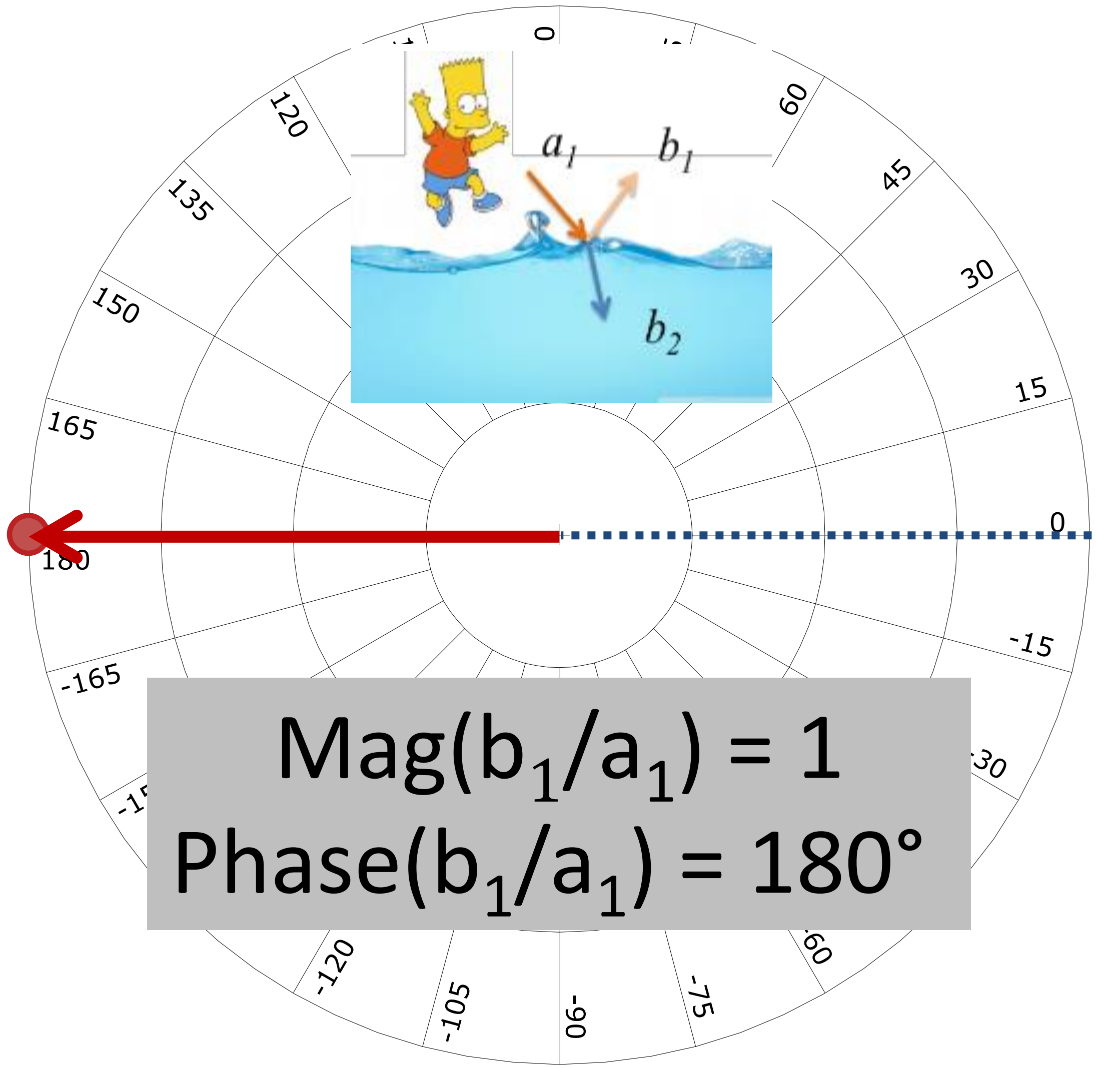
0.25
Per Div

Match (Load)



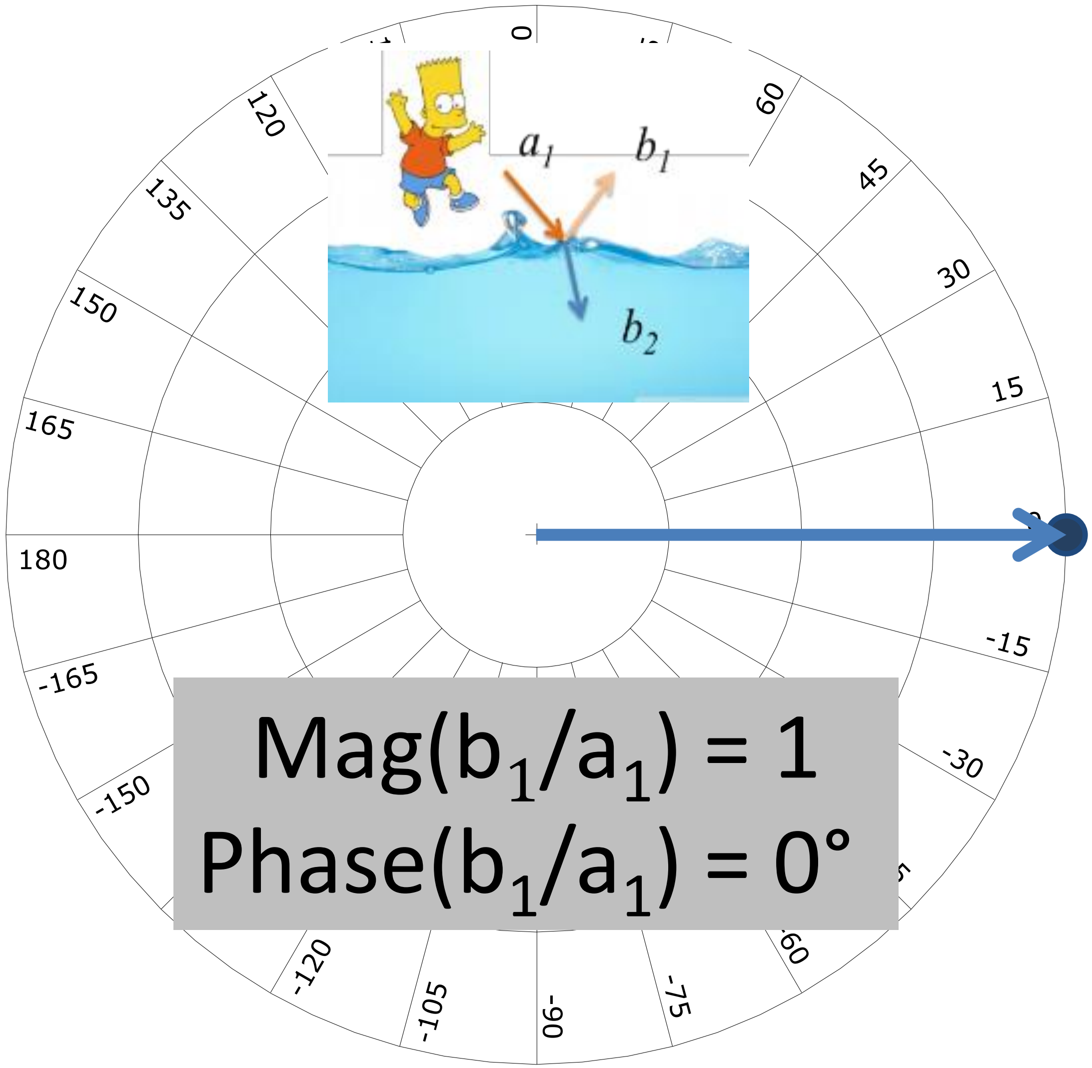
a_1
b_1
b_2
0
15
30
45
60
120
135
150
165
180
-165
-150
-135
-120
-105
-90
-75
-60
-45
-30
-15
$\mathrm{Mag}(b_1/a_1) = 0$

Short



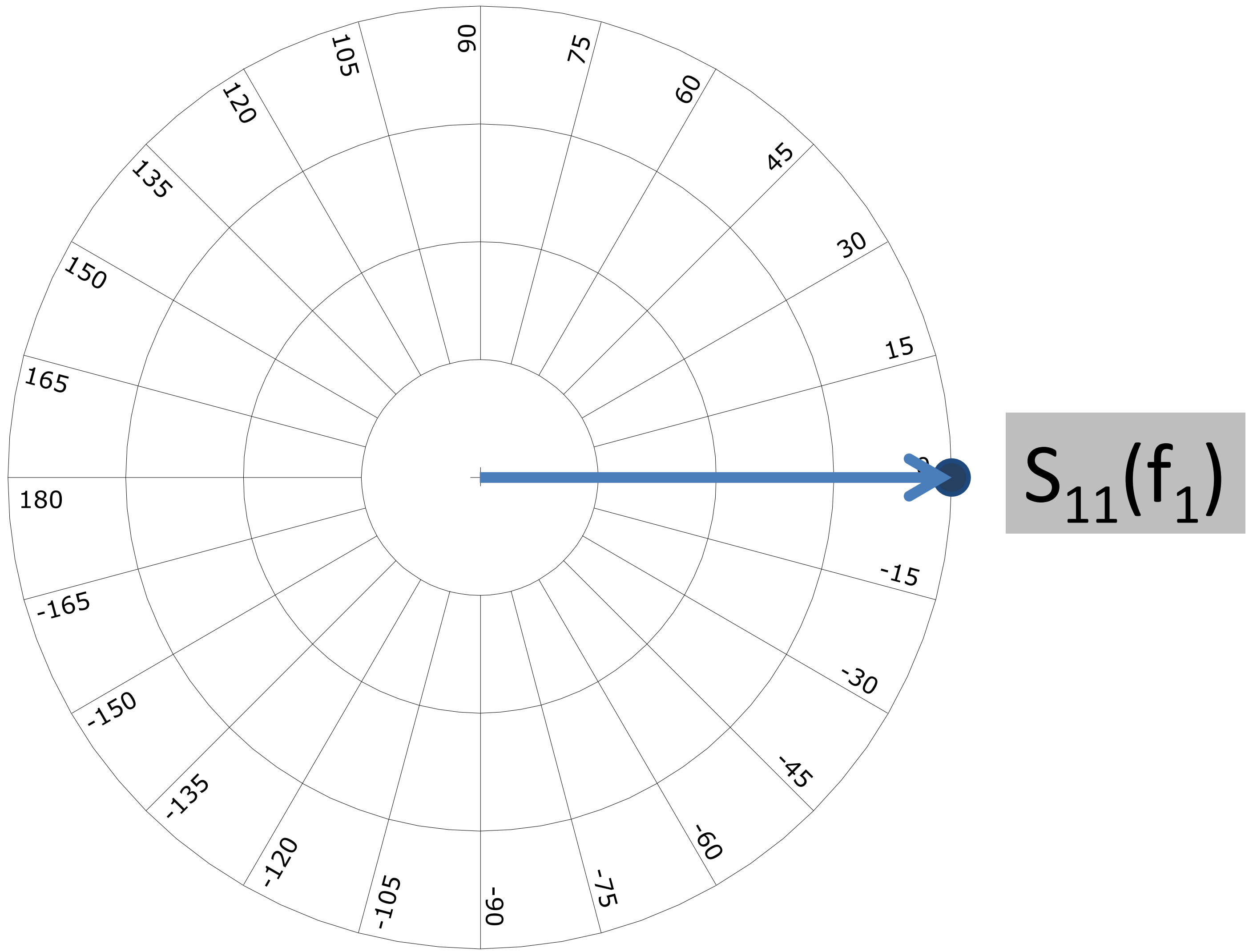
$$\mathrm{Mag}(b_1/a_1) = 1$$
$$\mathrm{Phase}(b_1/a_1) = 180°$$

Open

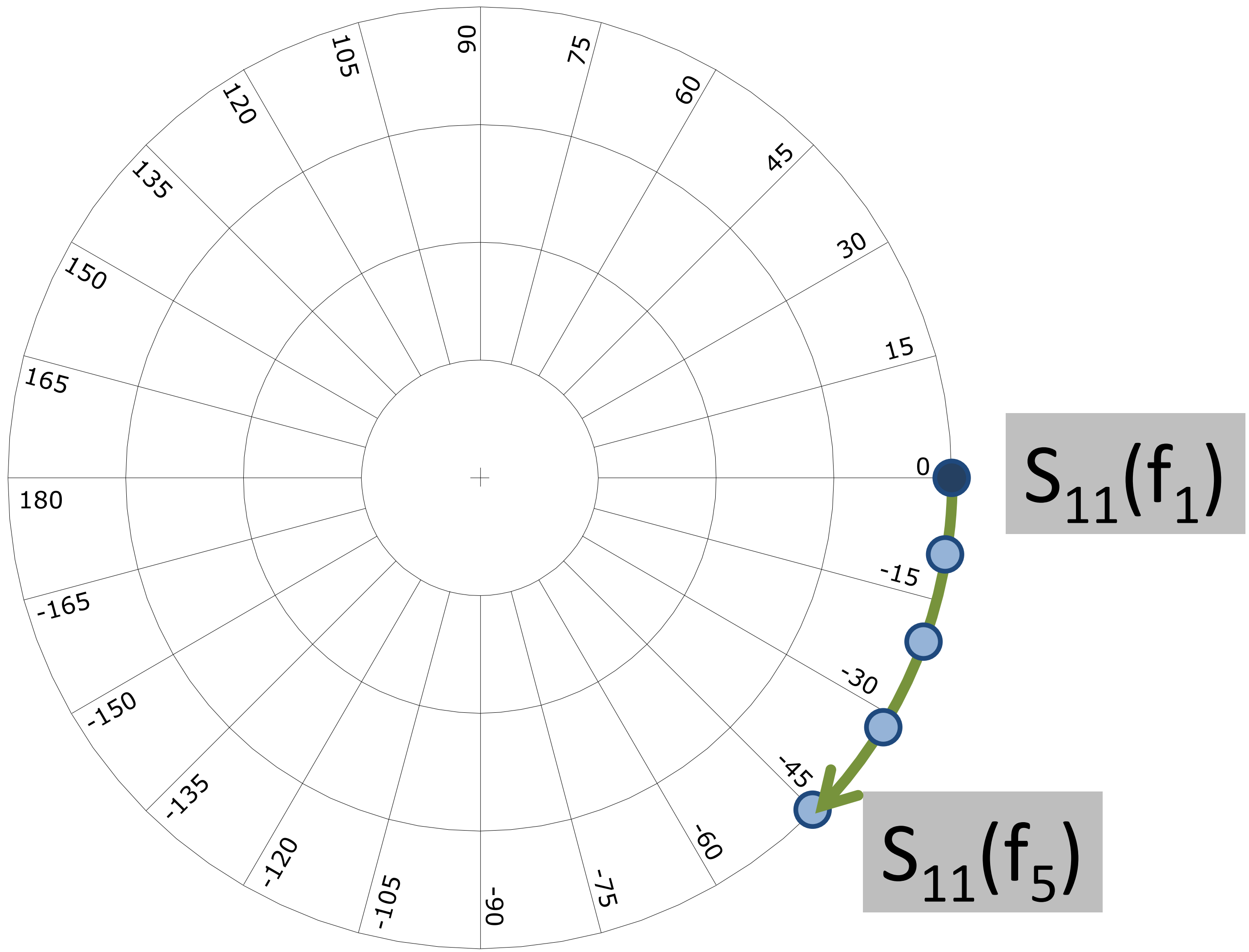


$$\mathrm{Mag}(b_1/a_1) = 1$$
$$\mathrm{Phase}(b_1/a_1) = 0°$$

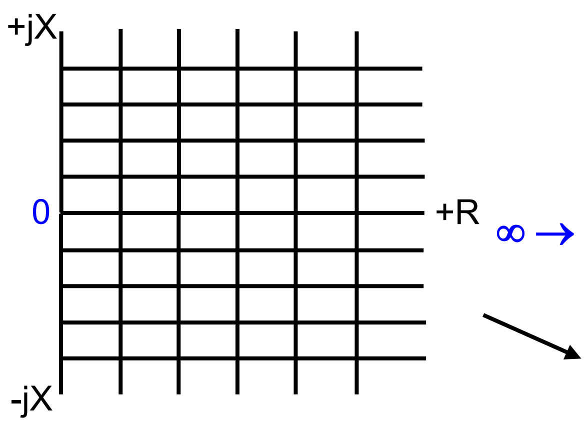
Data over Frequency



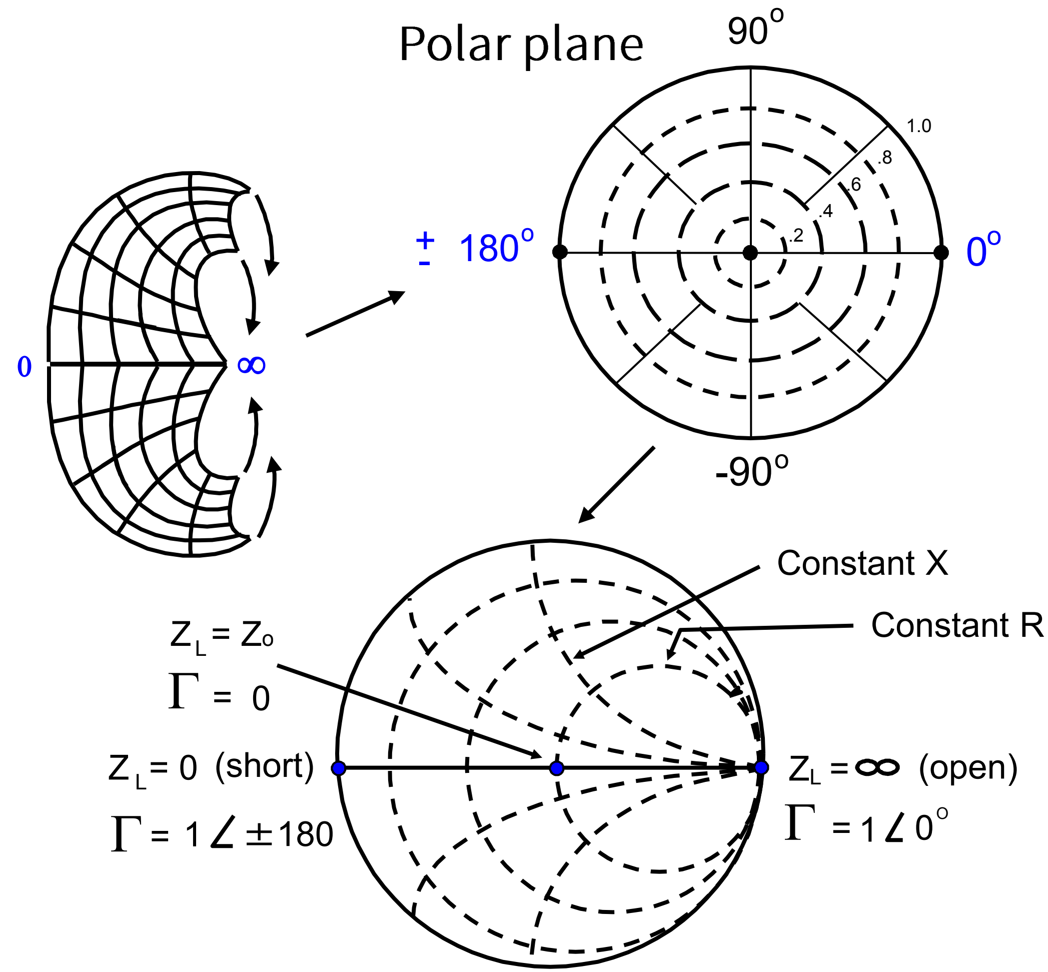
Data over Frequency



Smith Chart



Rectilinear impedance plane

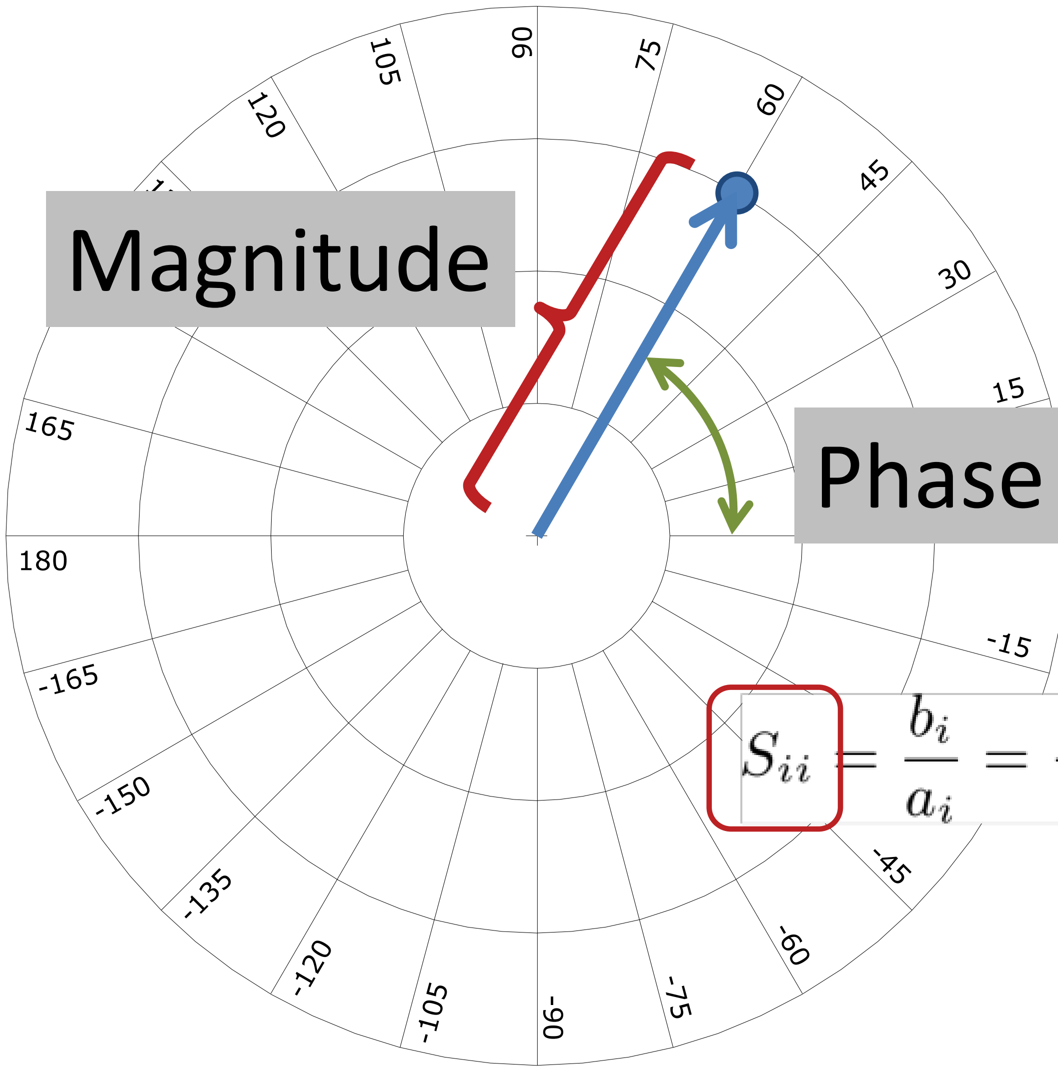


Smith chart

Smith Chart maps rectilinear impedance plane onto polar plane

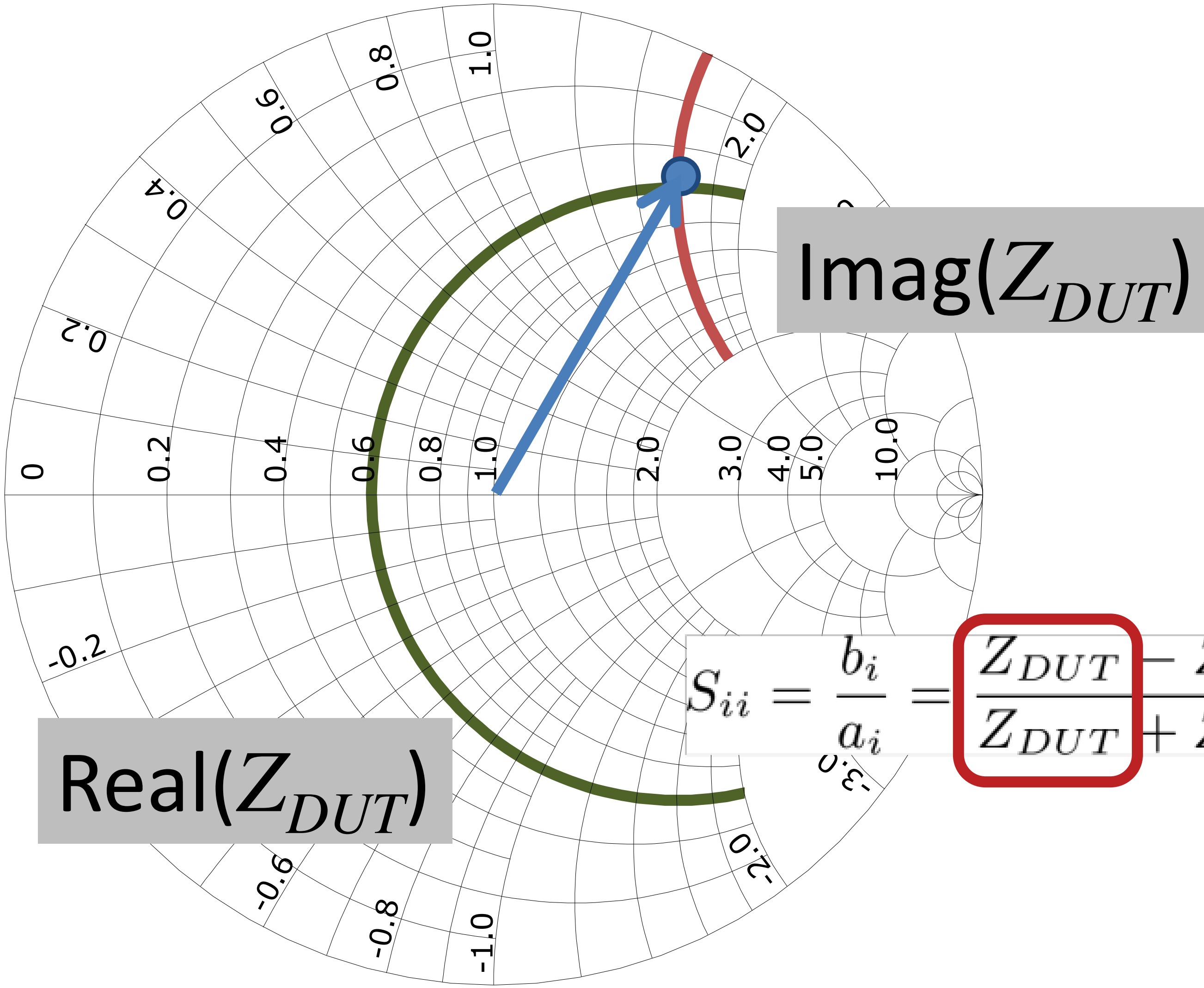
Picture source: D. Ballo Keysight

Polar Chart vs. Smith Chart



$$\boxed{S_{ii}} = \frac{b_i}{a_i} = \frac{Z_{DUT} - Z_{REF}}{Z_{DUT} + Z_{REF}}$$

Polar Chart vs. Smith Chart



$$S_{ii} = \frac{b_i}{a_i} = \frac{\boxed{Z_{DUT}} - Z_{REF}}{\boxed{Z_{DUT}} + Z_{REF}}$$

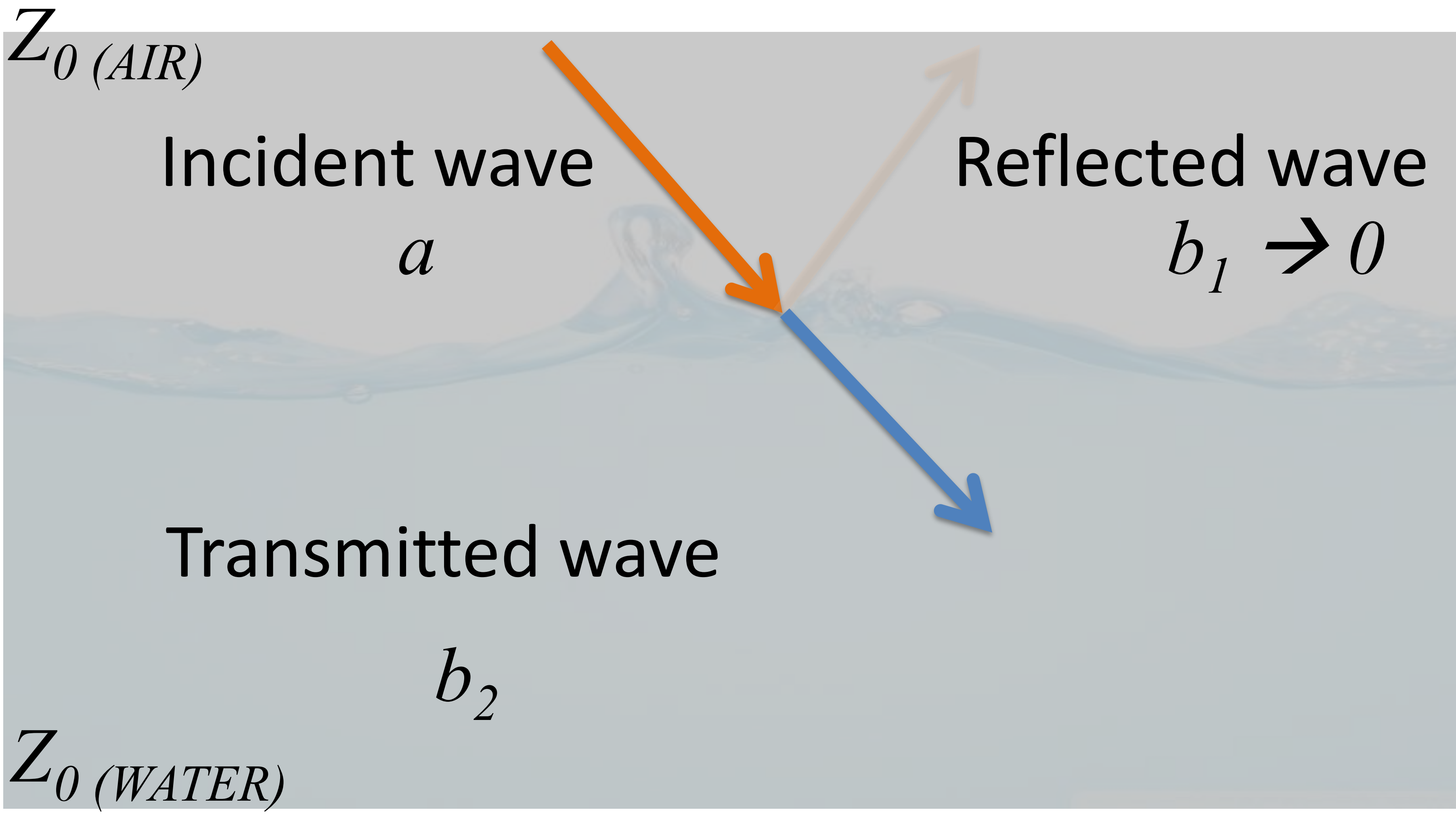
Matching of two Media = Transparency

$Z_{0\ (AIR)}$

$Z_{0\ (WATER)}$

Matching of two Media = Transparency

Matching of two Media = Transparency



Matching Conditions

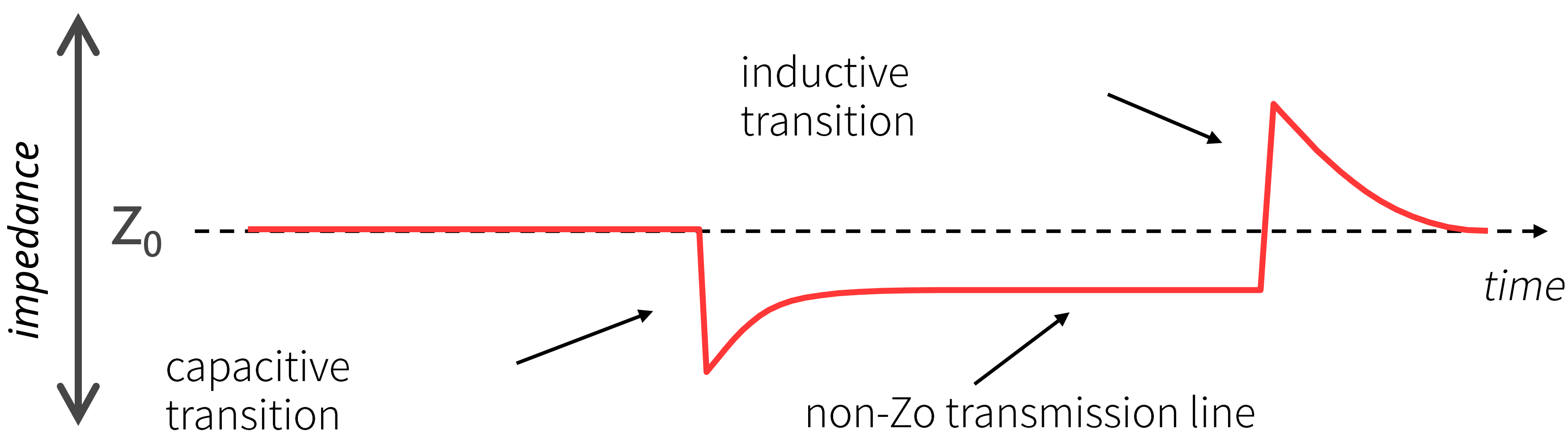
$$S_{ii} = \frac{b_i}{a_i} = \frac{Z_{DUT} - Z_{REF}}{Z_{DUT} + Z_{REF}}$$

$b_1 \rightarrow 0$ $\quad Z_{DUT} = Z_{REF}$ $\quad S_{ii} \rightarrow 0$

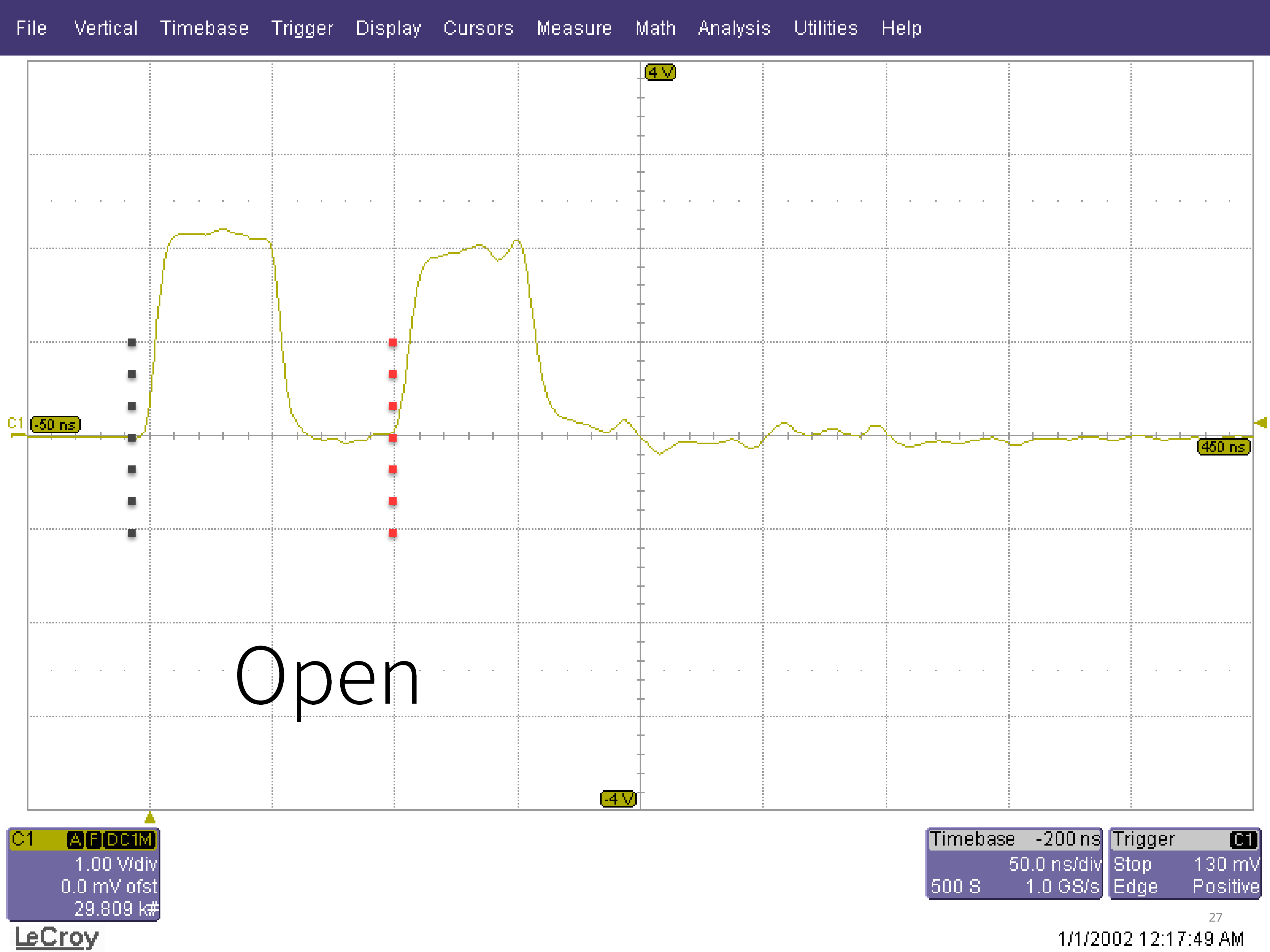
$$\boxed{Z_{REF} = 50\ \Omega}$$

Time-Domain Reflectometry (TDR)

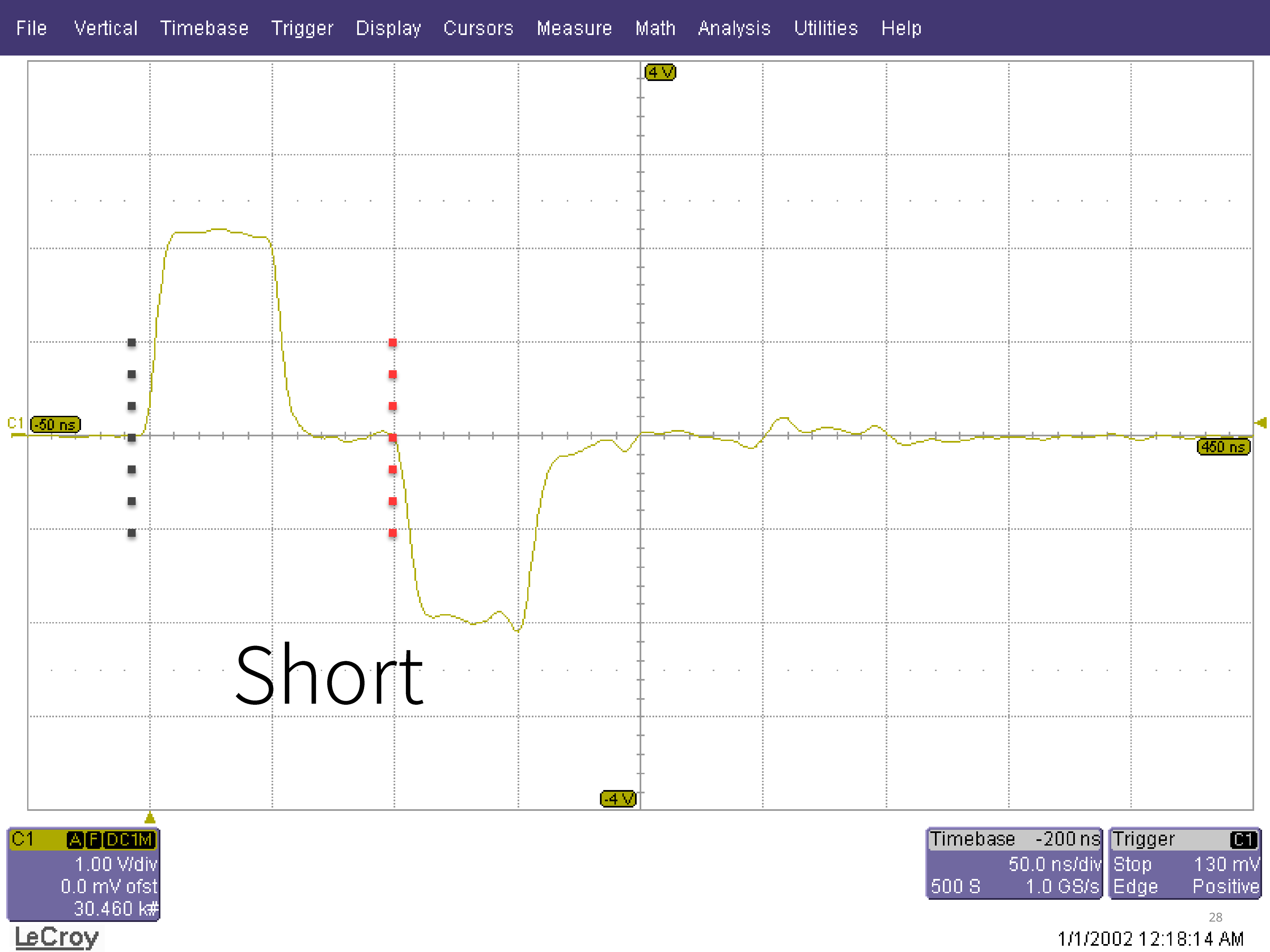
- Analyze impedance versus time
- Distinguish between inductive and capacitive transitions

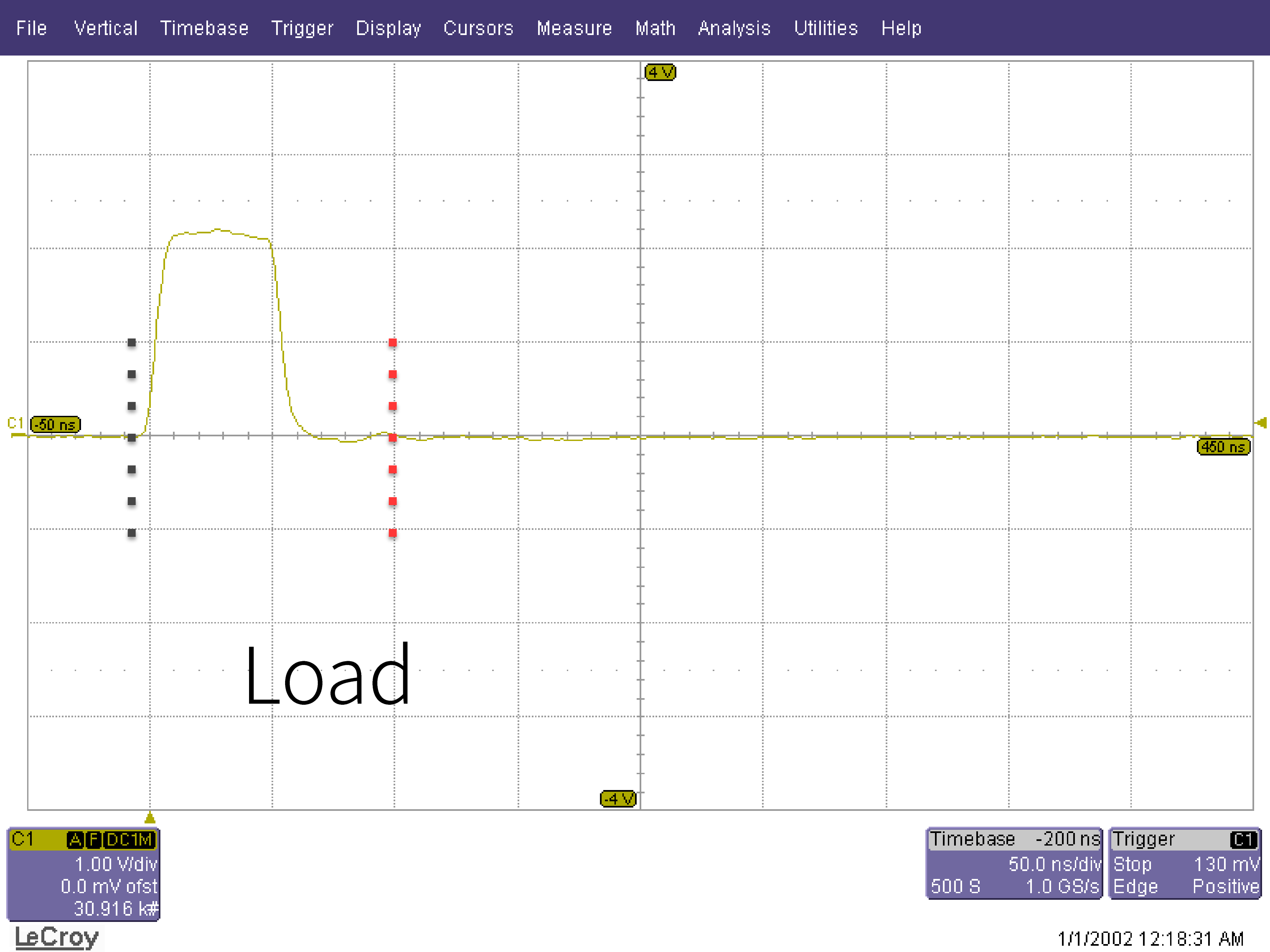


Picture source: D. Ballo Keysight


File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help
4 V
C1
-50 ns
450 ns
-4 V
C1 A F DC1M
1.00 V/div
0.0 mV ofst
29.809 k#
LeCroy
Timebase -200 ns
50.0 ns/div
500 S 1.0 GS/s
Trigger C1
Stop 130 mV
Edge Positive
1/1/2002 12:17:49 AM

Open


File
Vertical
Timebase
Trigger
Display
Cursors
Measure
Math
Analysis
Utilities
Help
4 V
C1
-50 ns
450 ns
Short
-4 V
C1 A F DC1M
1.00 V/div
0.0 mV ofst
30.460 k#
LeCroy
Timebase -200 ns
50.0 ns/div
500 S 1.0 GS/s
Trigger C1
Stop 130 mV
Edge Positive
1/1/2002 12:18:14 AM


File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help
4 V
C1
-50 ns
450 ns
-4 V
Load
C1 A F DC1M
1.00 V/div
0.0 mV ofst
30.916 k#
Timebase -200 ns
50.0 ns/div
500 S 1.0 GS/s
Trigger C1
Stop 130 mV
Edge Positive
LeCroy
1/1/2002 12:18:31 AM

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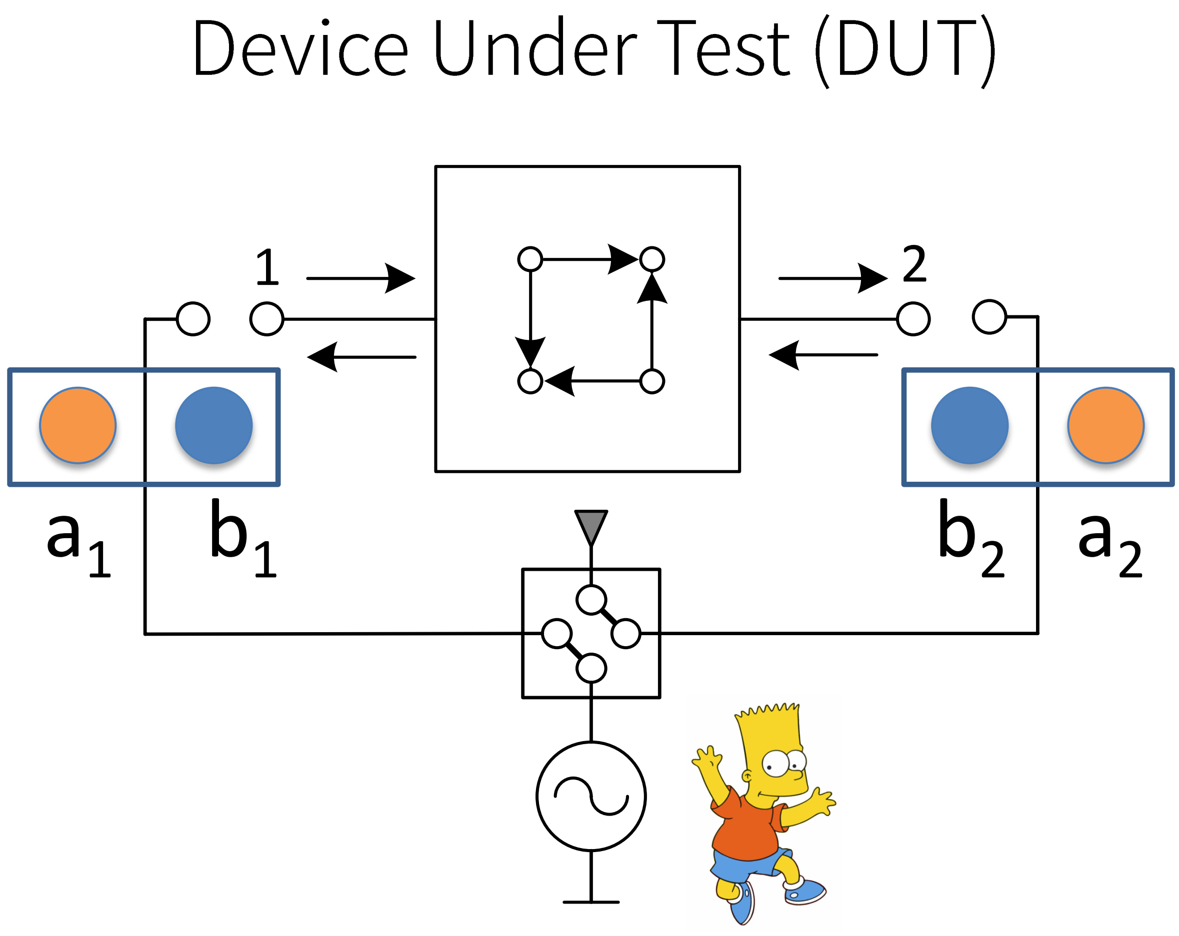
Vector Network Analyzer



At the early days…

- Dr. Rohde and Dr. Schwarz first commercial product for RF measurement: 1933
- Z-g Graph from Rohde & Schwarz, early 50s

End of 60s···70s···80s···

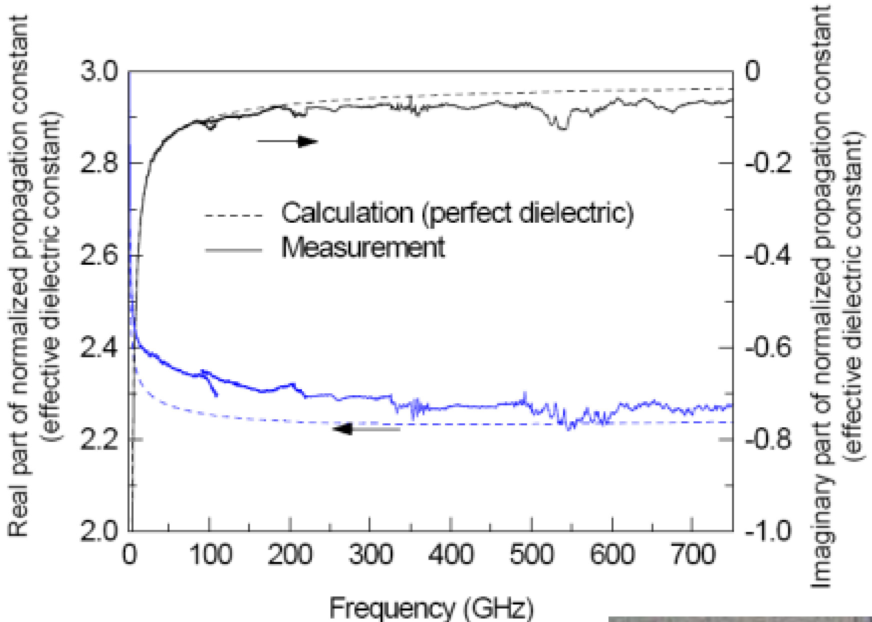
HP 8410

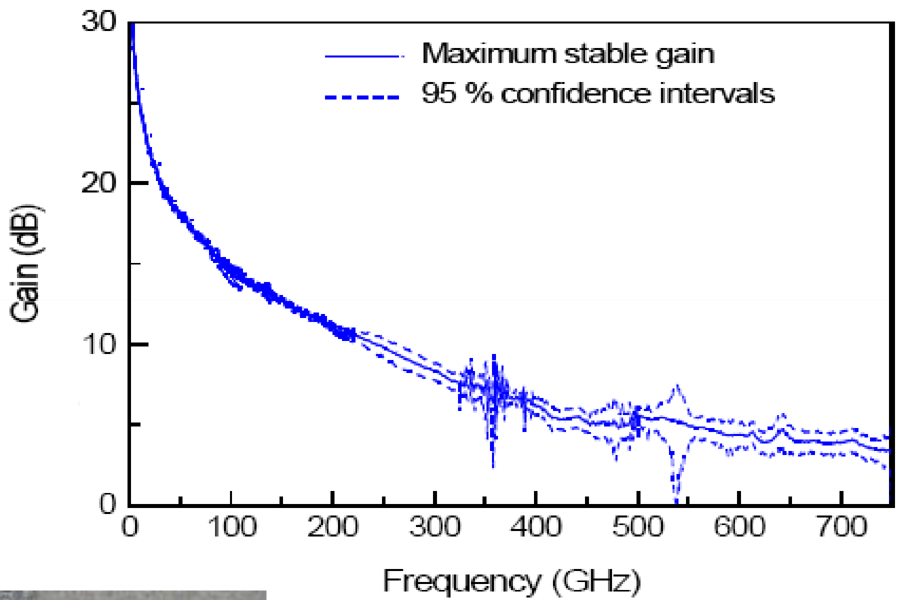
Wiltron 310

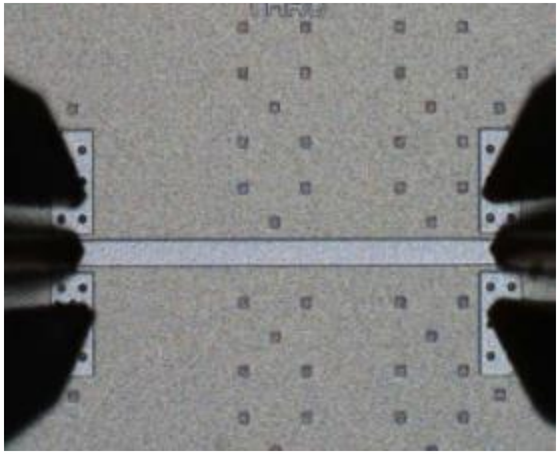
R&S

HP8410 Still Alive!

Today: On-Wafer Measurement







Williams, IMS-2014

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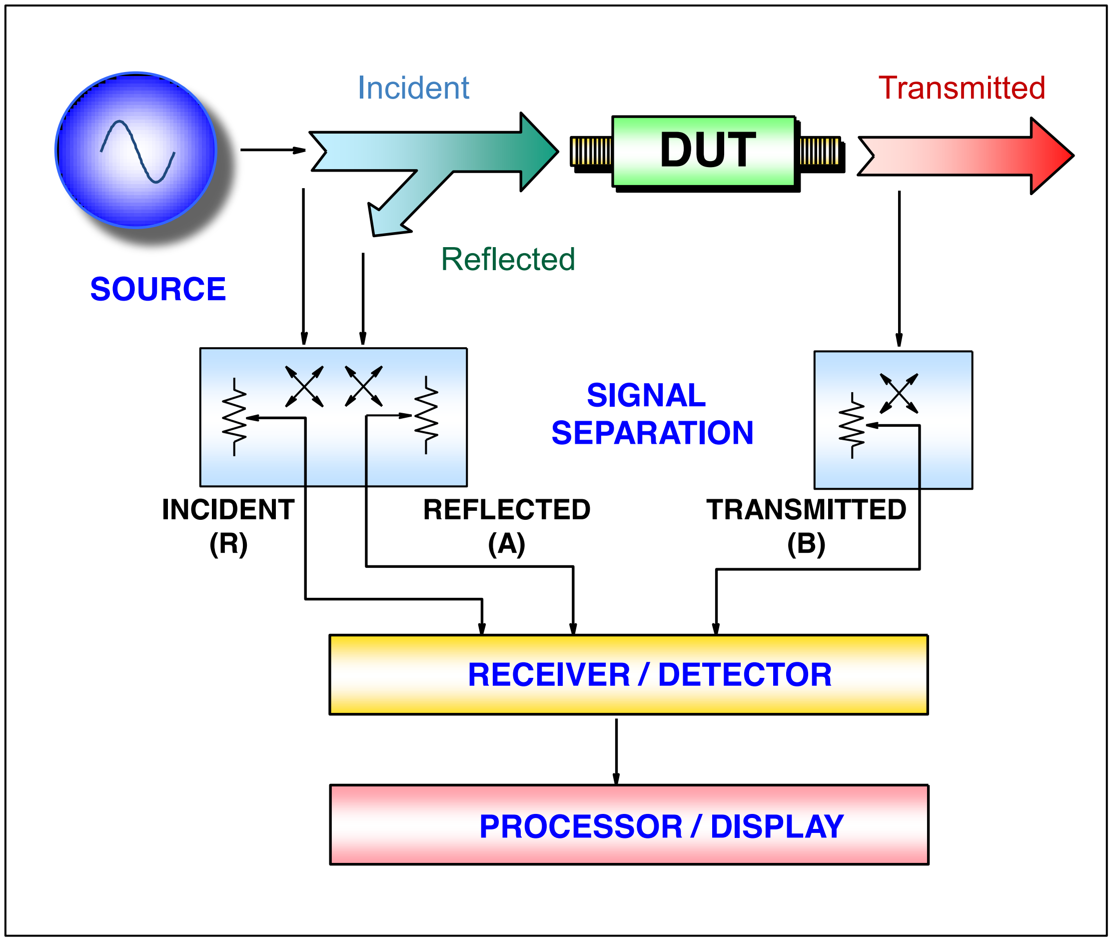
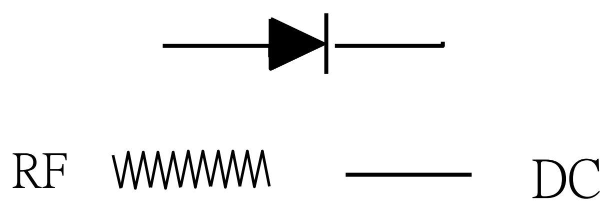
VNA Building Blocks



Picture source: D. Ballo Keysight

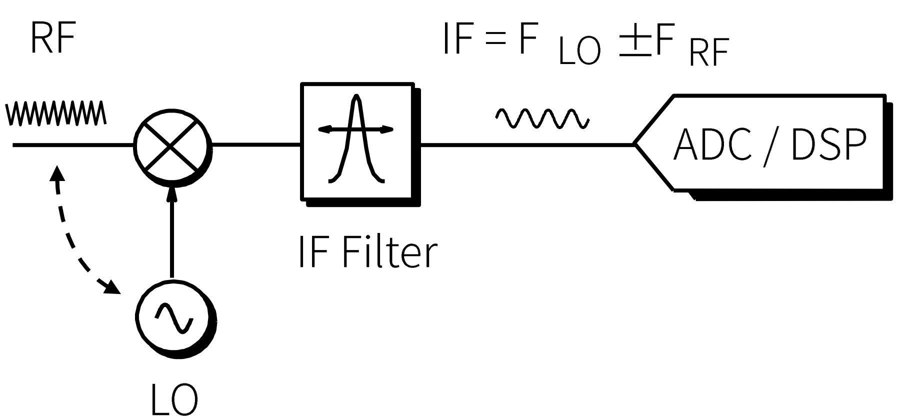
Receiver / Detectors

Diode



Scalar
(no phase information)

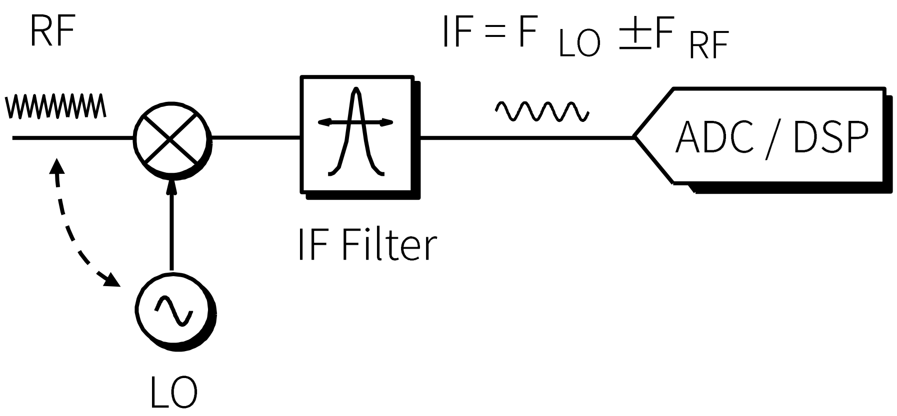
Tuned Receiver

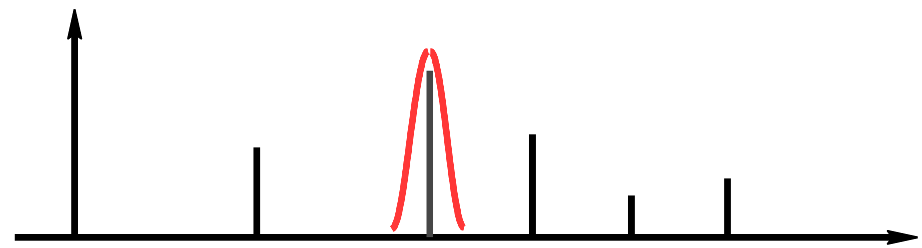


Vector
(magnitude and phase)

Picture source: D. Ballo Keysight

Narrowband Detection: Heterodyne Receiver

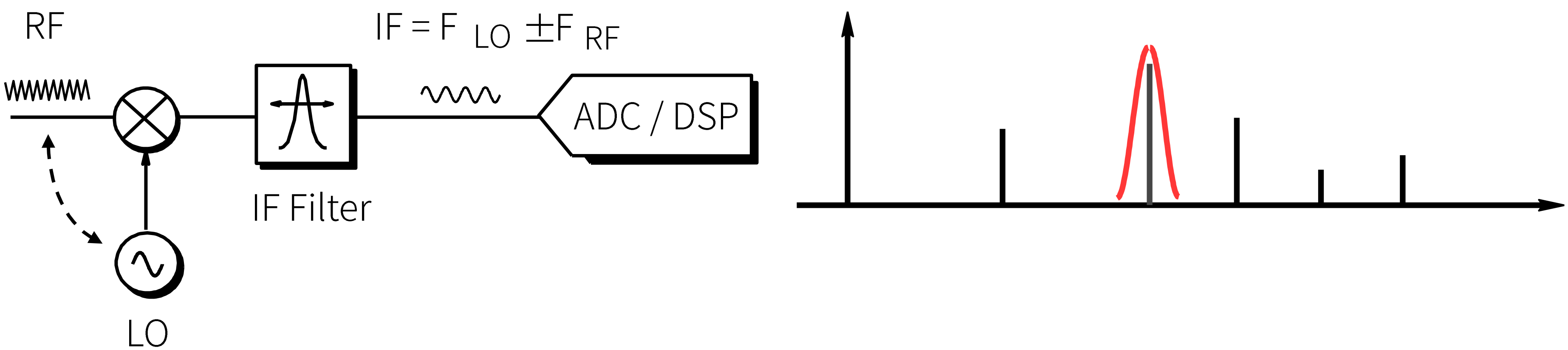




- Best sensitivity / dynamic range
- Provides harmonic / spurious signal rejection

Picture source: D. Ballo Keysight

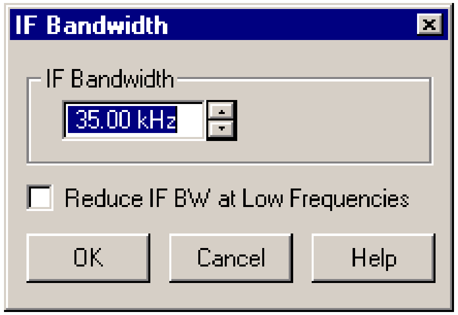
Narrowband Detection: Heterodyne Receiver



Trade off: noise floor and measurement speed

IF Bandwidth and Averaging

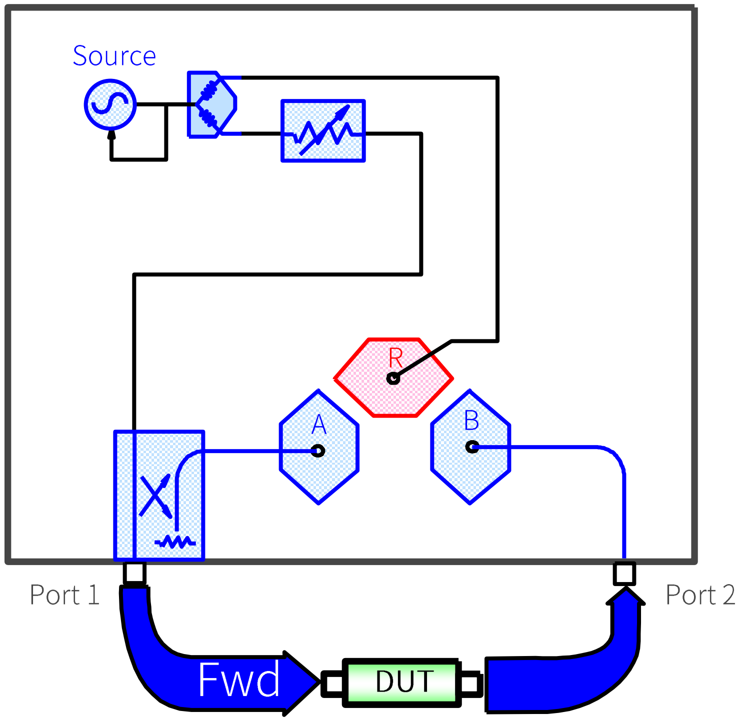
- Improve dynamic range by:
  - – increasing power,
  - – decreasing IF bandwidth, or
  - – Averaging



- Recommended IFBW value 100 Hz
- Averaging : OFF

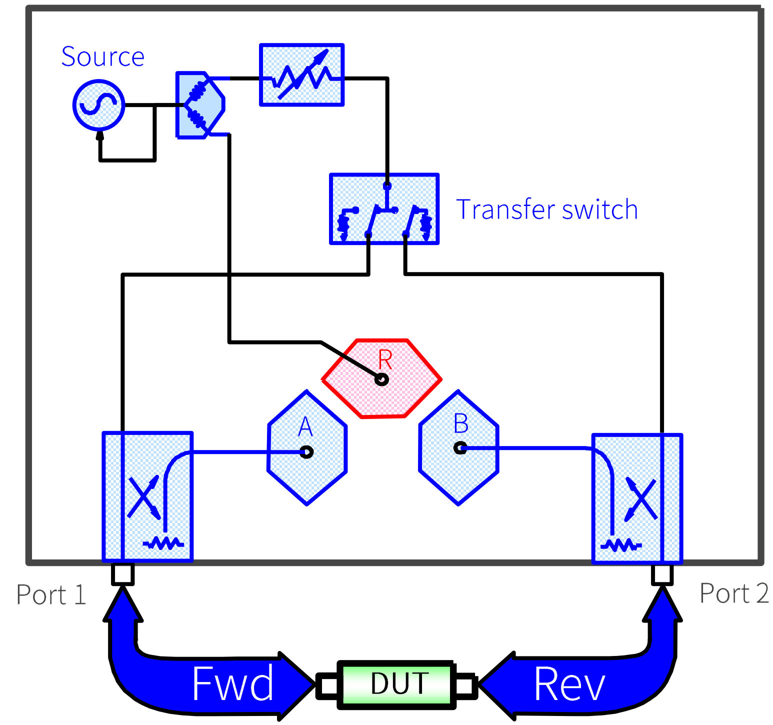
T/R Versus S-Parameter Test Sets

Transmission/Reflection Test Set



RF always comes out port 1
Port 2 is always receiver
Response, one-port cal available

S-Parameter Test Set

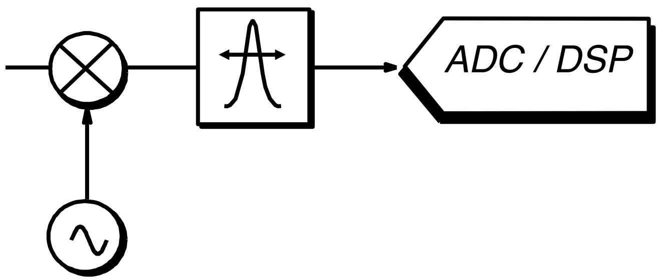


RF comes out port 1 or port 2
Forward and reverse measurements
Two-port calibration possible

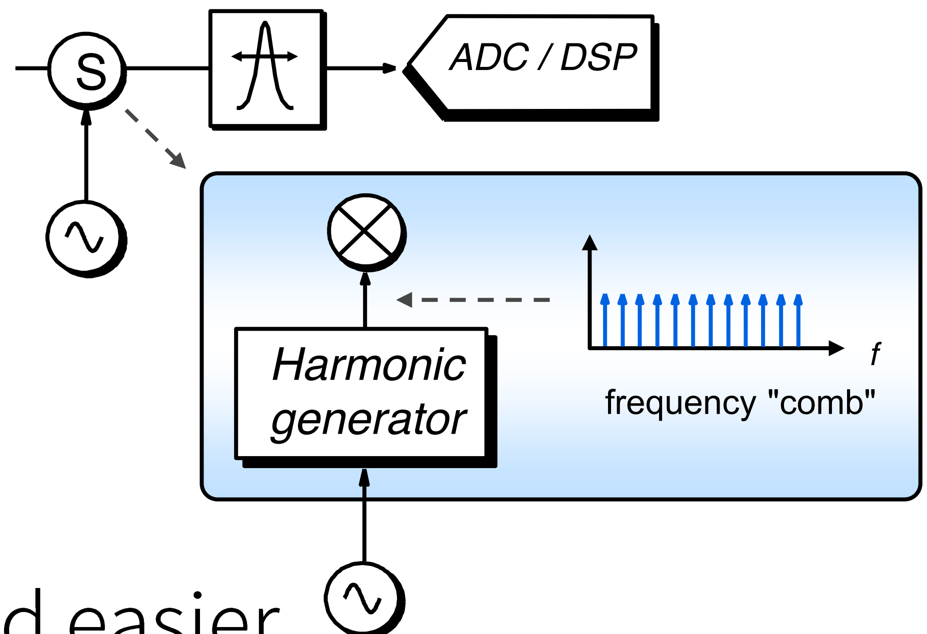
Picture source: D. Ballo Keysight

Front Ends: Mixers Versus Samplers

Mixer-based front end



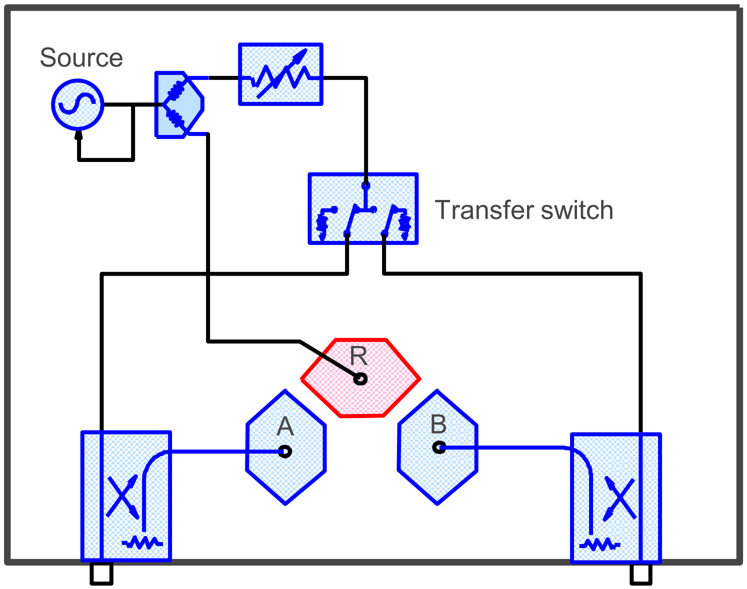
Sampler-based front end

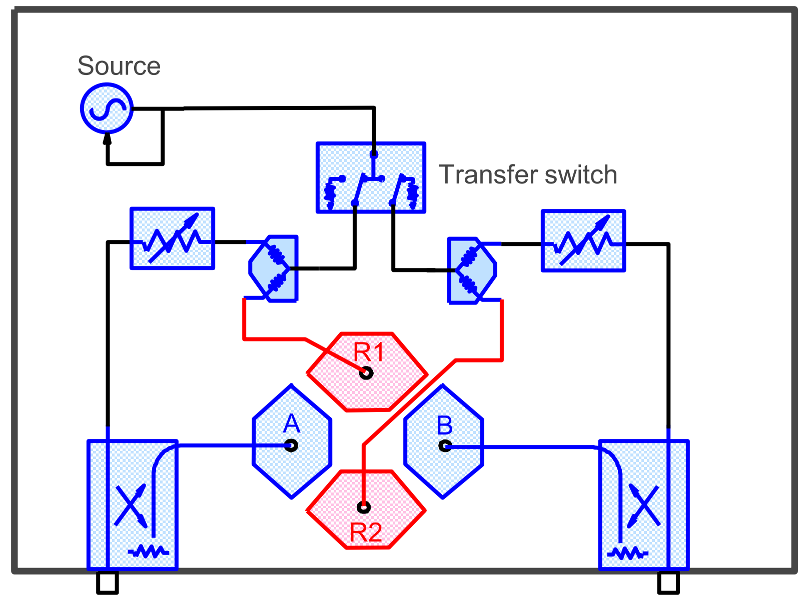


- Samplers: cheaper and easier
- Dynamic range?

Picture source: D. Ballo Keysight

Three vs. Four-Receiver Analyzers





- Reference Channel
  - Economy
  - Up to 20 GHz
- Double-Reflectometer
  - High-end
  - Up to THz

Picture source: D. Ballo Keysight

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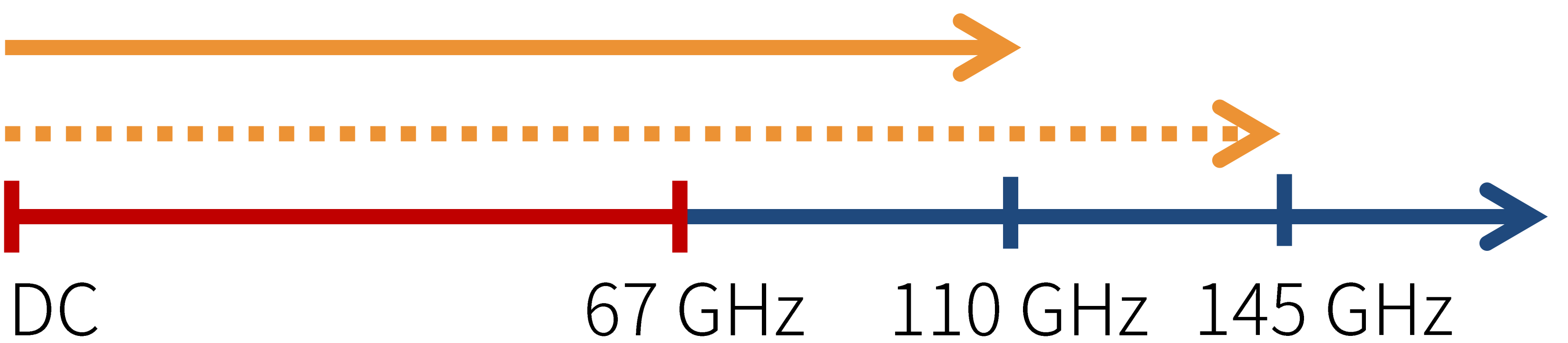
What do we have today?

Instruments

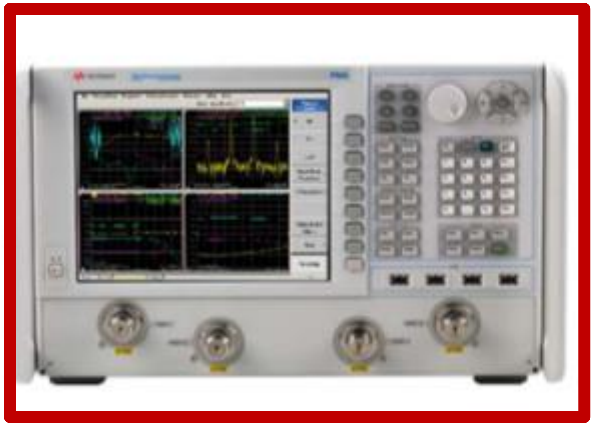
Frequency Extenders

Frequency Range

- Baseband unit
  - From few Hz to 67 GHz
- Frequency extenders
  - From 67 GHz to 1.1 THz
  - Single sweep: from DC to 110 GHz (145 GHz)



Keysight (former Agilent)



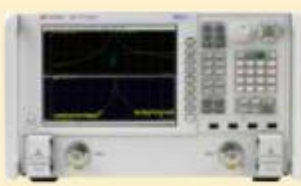
PNA-X

FiledFox

PXI-VNA

ENA

PNA Family

	Model		Typical application	Frequency range
PNA Family *Reach for unrivaled excellence*		**N524xA PNA-X Series** *Most advanced and flexible VNA*	– Replace an entire rack of equipment with one instrument – Complete linear and nonlinear active device characterization	– 10 MHz to 8.5/13.5/26.5/ 43.5/50/67 GHz – Up to 1.1 THz with extenders
		**N522xA PNA Series** *High performance microwave VNA*	– Highest performance passive component analysis – Active components characterization – Metrology and cal lab	– 10 MHz to 13.5/26.5/ 43.5/50/67 GHz – Up to 1.1 THz with extenders
		**N523xA PNA-L Series** *Economy microwave VNA*	– Microwave S-parameter test – Signal integrity – Material measurements	– 300 kHz to 8.5/13.5/20 GHz – 10 MHz to 43.5/50 GHz

ENA Family

	Model		Typical application	Frequency range
ENA *Drive down the cost of test*		**E5072A ENA** *High performance RF VNA with configurable test set*	– RF amplifier test – BTS components – PIM measurements	– 30 kHz to 4.5/8.5 GHz
		**E5071C ENA** *High performance RF VNA*	– RF component test – Multiport module test – Material measurements – Signal integrity	– 9 kHz to 4.5/6.5/8.5 GHz – 300 kHz to 14/20 GHz
		**E5061B ENA** *LF-RF VNA with impedance analysis function* *Low cost RF VNA*	– LF component/circuit test – Component Z evaluation – RF component test – CATV component test	– 5 Hz to 3 GHz – 100 kHz to 1.5/3 GHz
		**E5063A ENA** Low-cost RF VNA for passive component test	– Antenna manufacturing test – RF passive component test – Material measurements – PCB manufacturing test	– 100 kHz to 4.5/8.5/18 GHz

High-end: ZVA

Midrange: ZVB 40GHz

Economy: ZVD 8.5GHz

Portable: ZVL 13.5GHz

Anritsu envision : ensure

VectorStar: ME7838

ShockLine: MS46xxx 40GHz

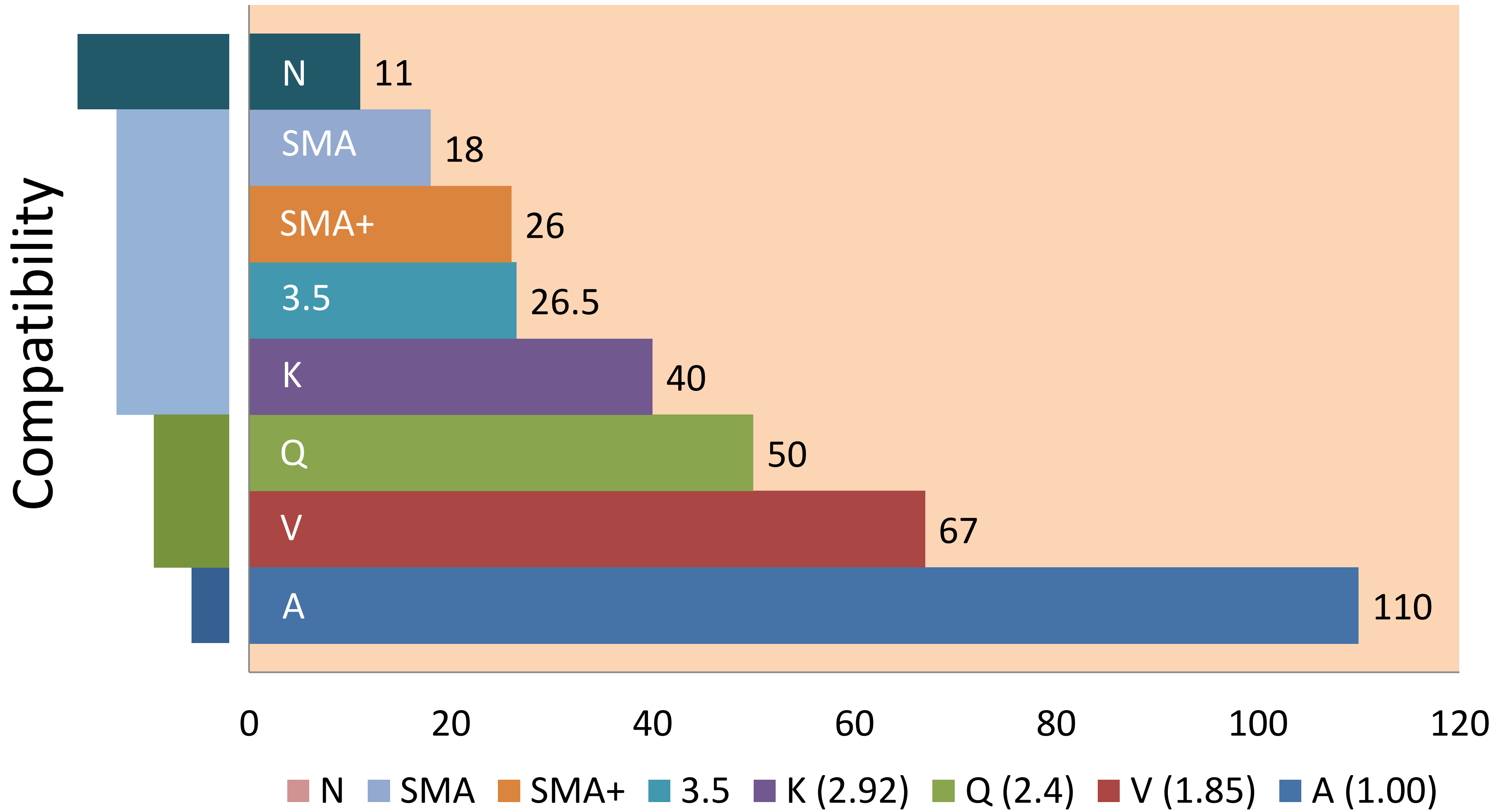
New Players

S5048 4.8GHz

P814 8.0GHz

PXIe-5632. 8.5GHz

Frequency Limits and Compatibility



Cable and Connectors

SMA

K (2.92 mm)

Q (2.4 mm)

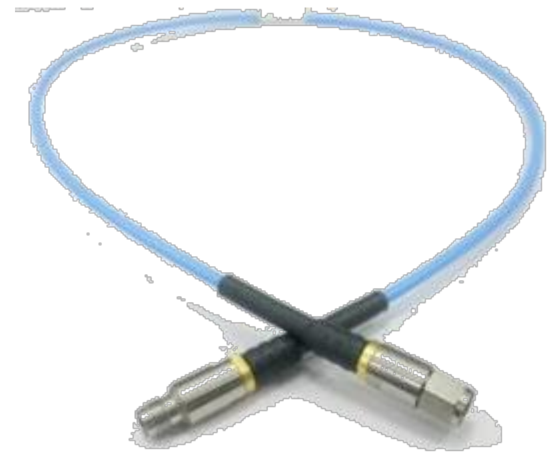
V (1.85 mm)

A (1.00 m)

Cables

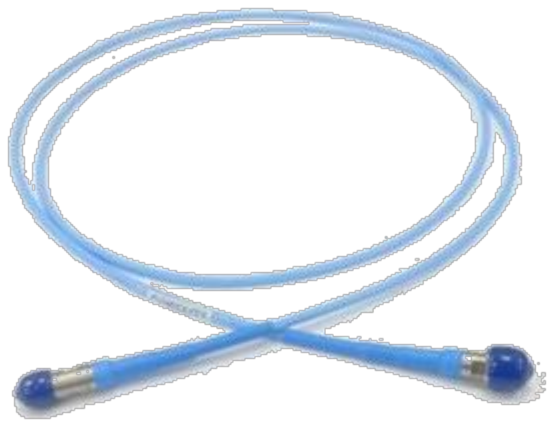
26 GHz

40 GHz



50 GHz

50 GHz

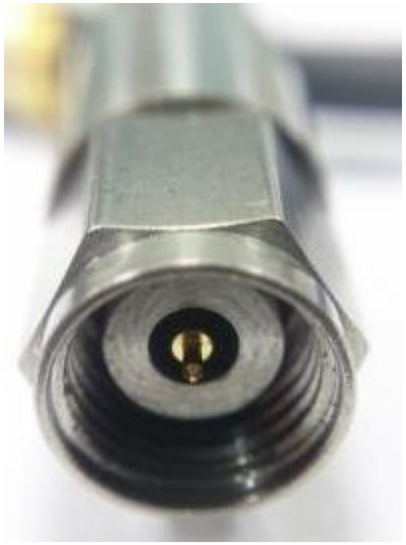


67 GHz

110 GHz

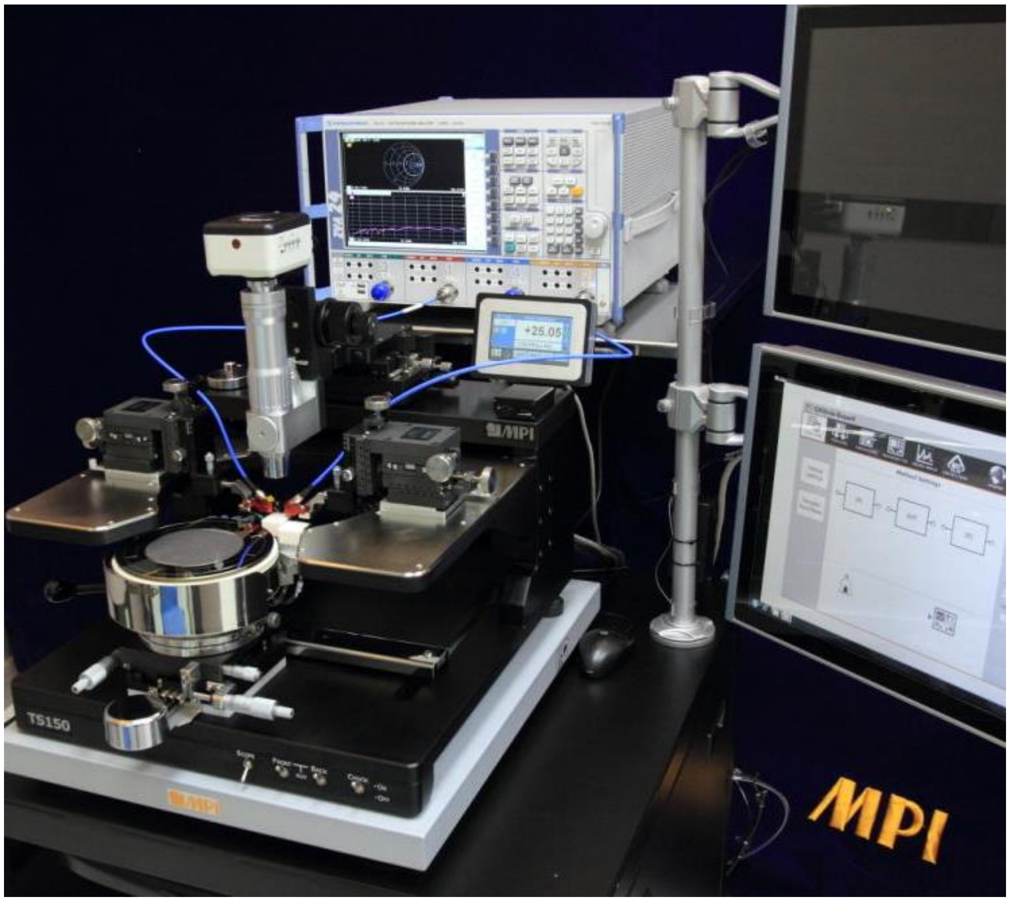
Comparison

Entry-level



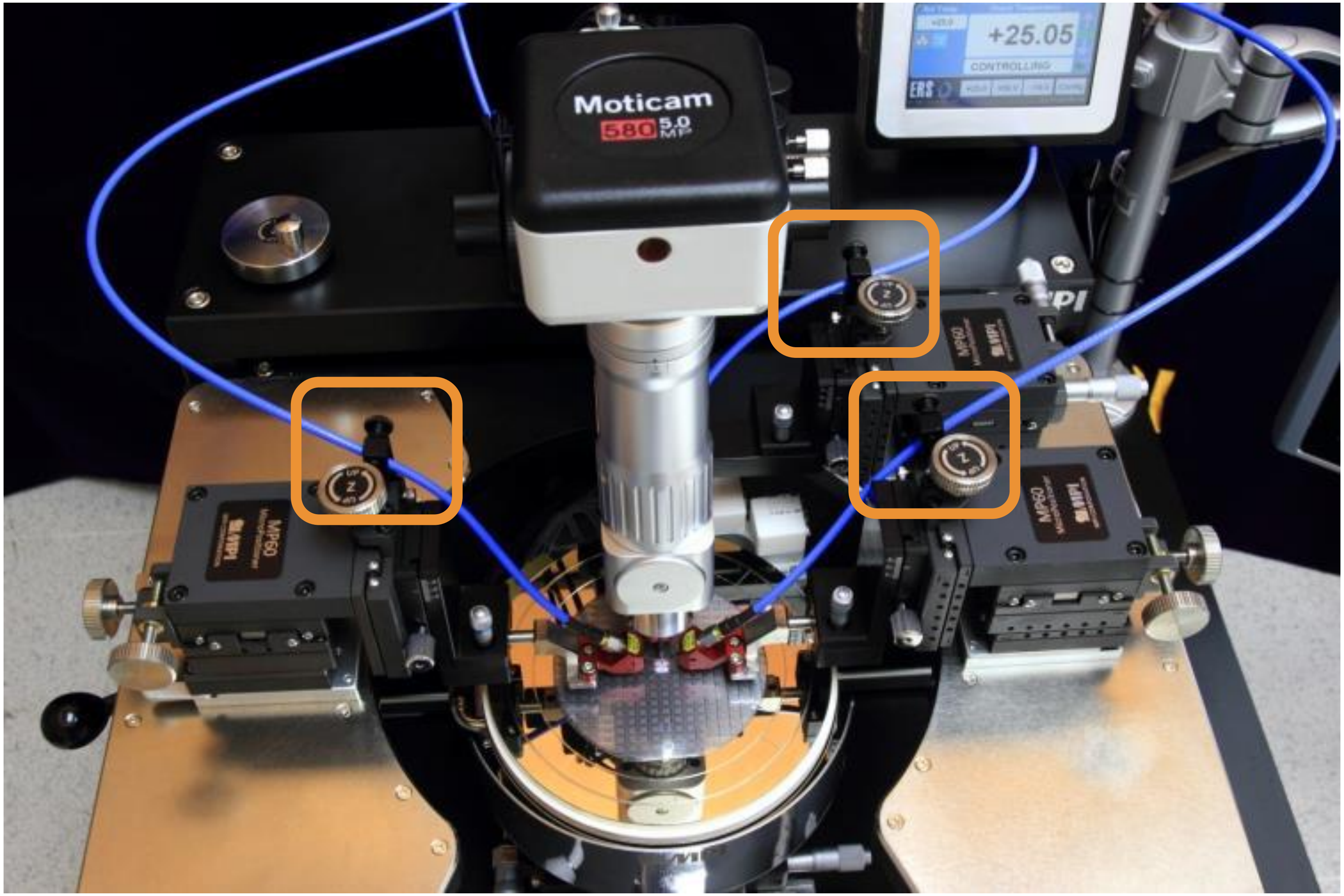
High-end

VNA Integration



- At the back
- Integrated shelf
- Optimized cable length: 80 cm

Cable Management on Positioner

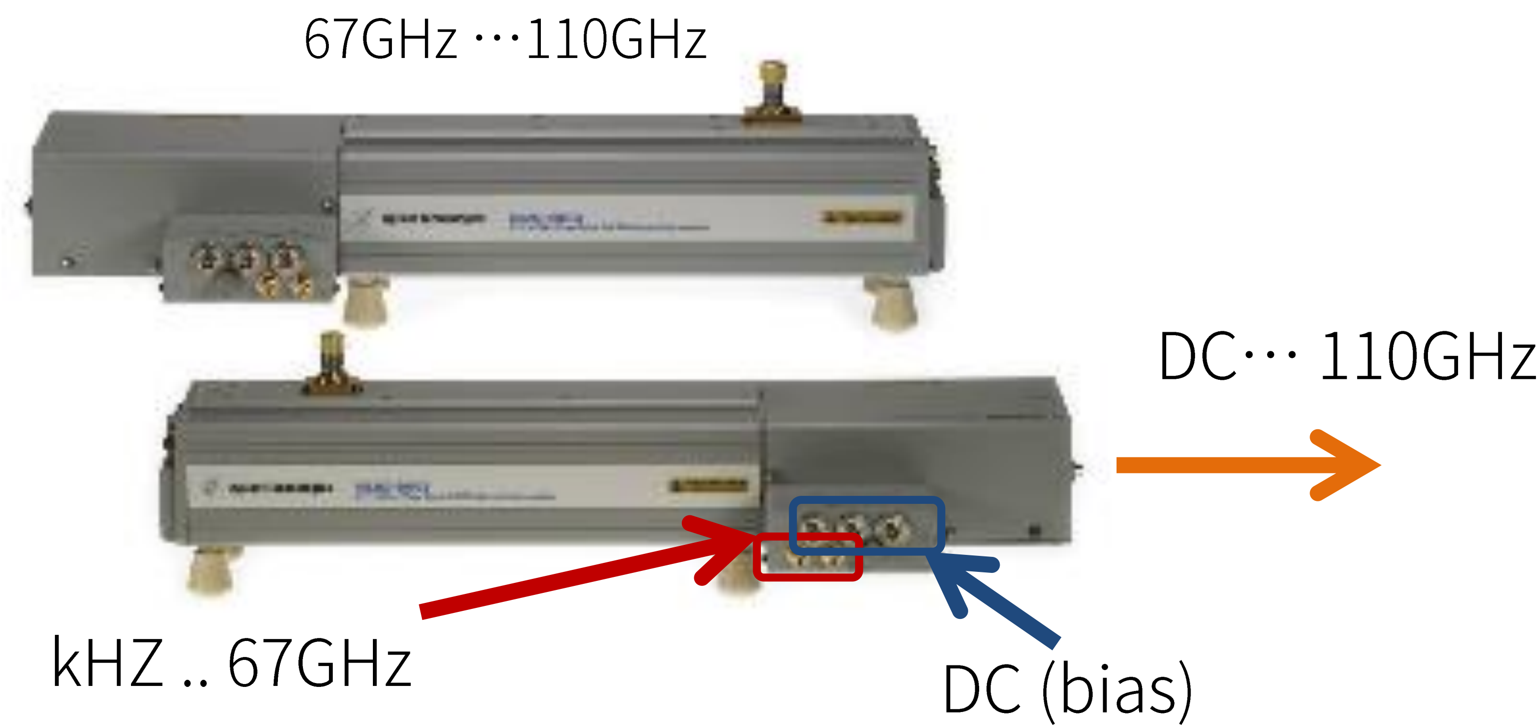


Beyond 67 GHz below 110 GHz

- External mm-wave heads (“extenders”)
  - From 67 GHz to 110 GHz
- Combiners
  - DC (bias source)
  - kHz…67GHz (baseband VNA)
  - 67GHz..110GHz (extenders)

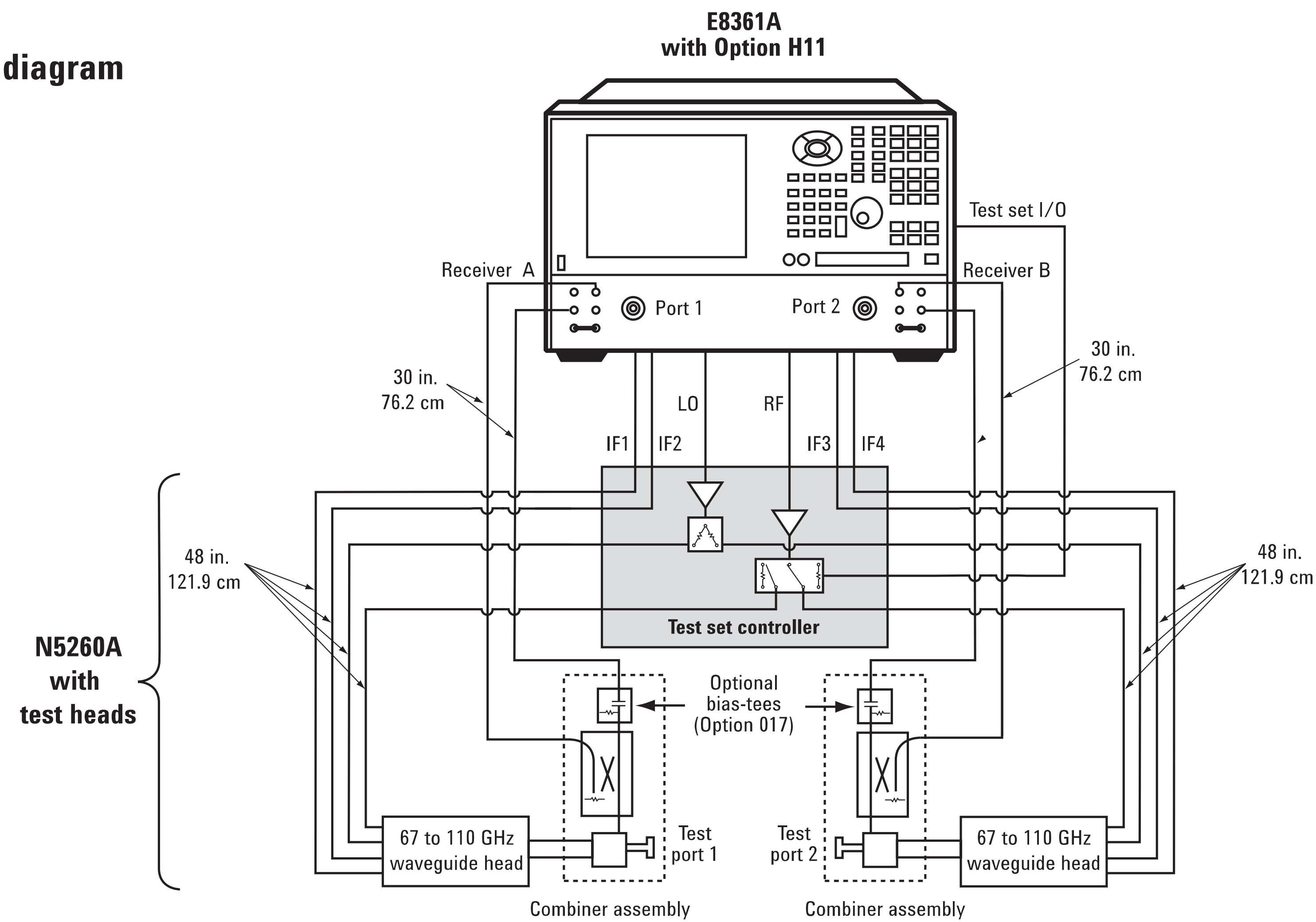
- Broadband S-parameter measurement system

mm-Wave Heads



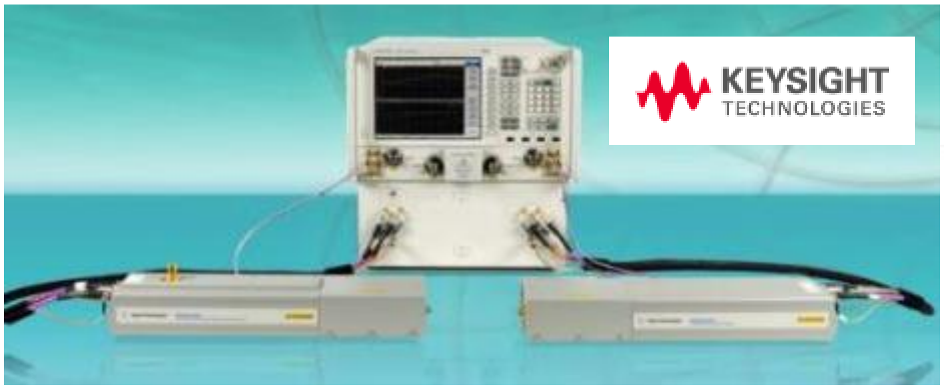
- IV/ S-Parameters measurements
- Device characterization for modeling

N5250A system block diagram



Picture source: Keysight

Broadband Systems



Anritsu envision : ensure

Key Wafer-Level Requirement

- mm-wave heads close to the DUT

Banded Solutions

Band	WR15	WR12[1]	WR10[1]	WR08	WR06	WR05	WR03	WR02.2
Waveguide Interface								
Frequency (GHz)	50-75	60-90	75-110	90-140	110-170	140-220	220-325	325-500

- Dedicated mm-wave extender per band
- Our interest: from WR-10 and beyond

Banded Solutions: up to 1.1THz

VDI

MPI

Banded Solutions: up to 500GHz

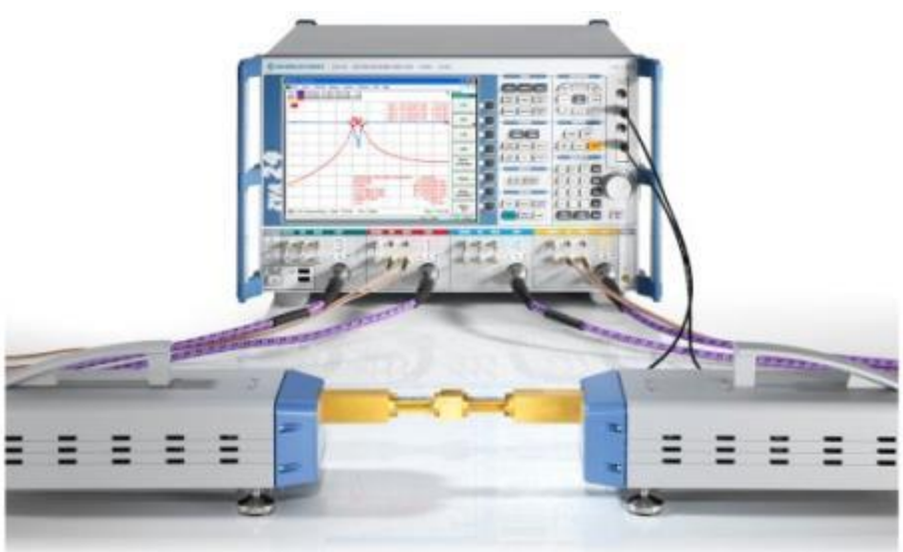
OML

KEYSIGHT TECHNOLOGIES

Anritsu envision : ensure

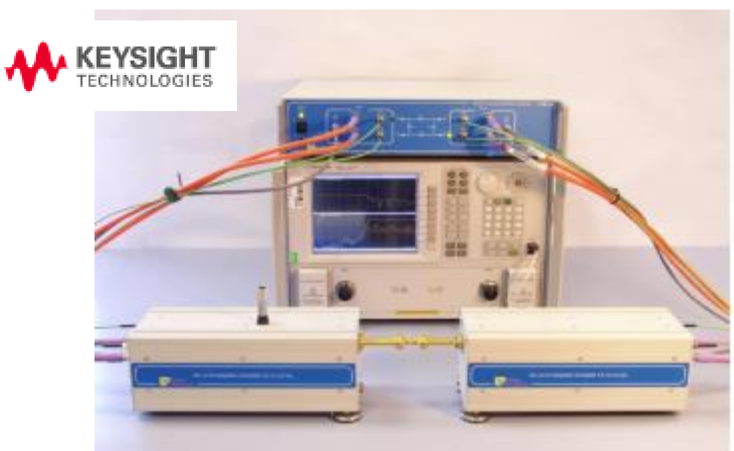
ROHDE&SCHWARZ

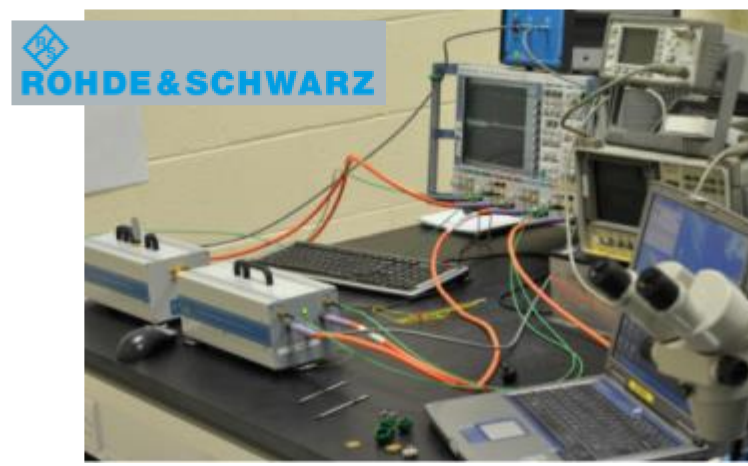
Banded Solutions: up to 500 GHz



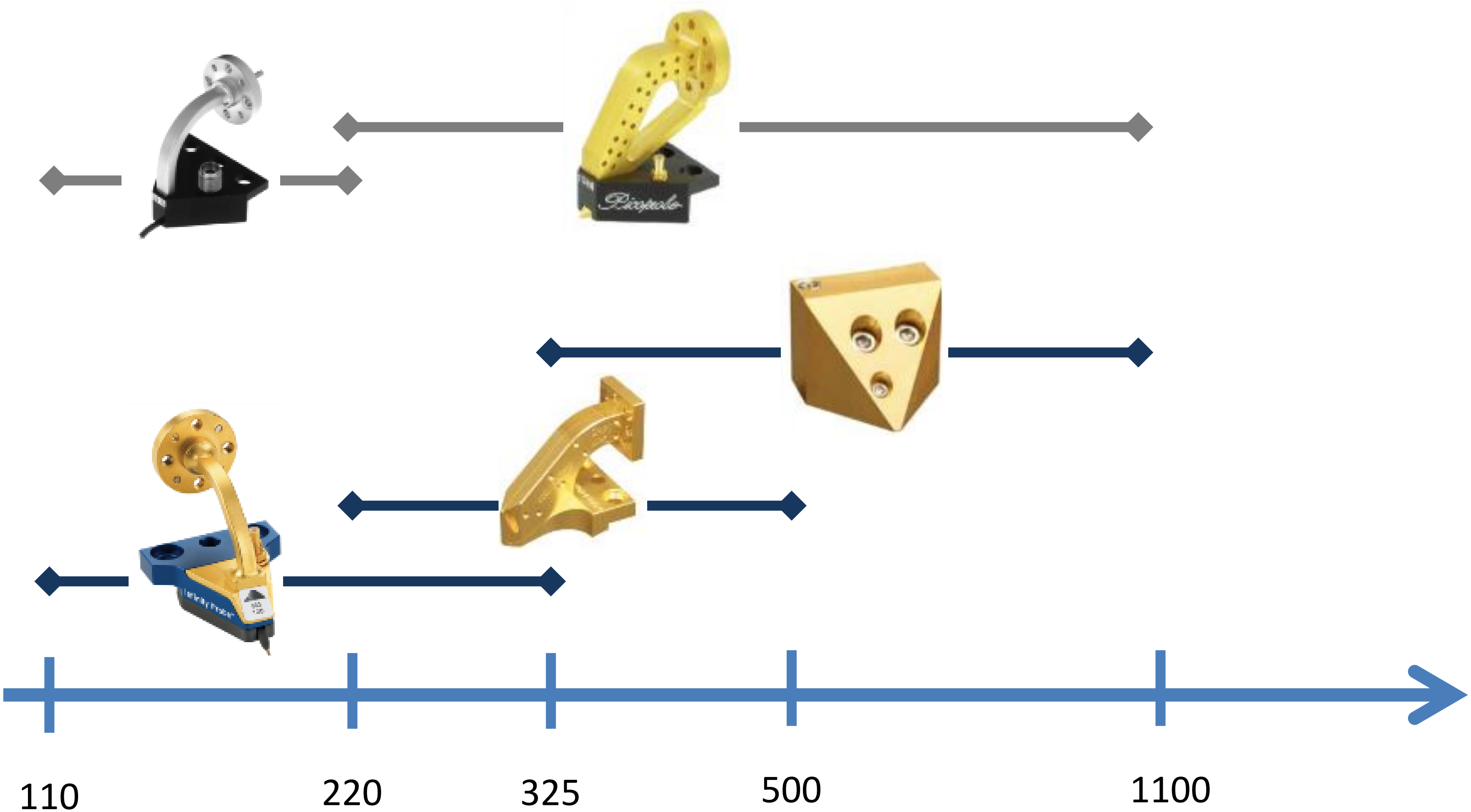
Banded Solutions: up to 325 GHz

Farran Technology
mmWave & Terahertz Solutions, Made Simple

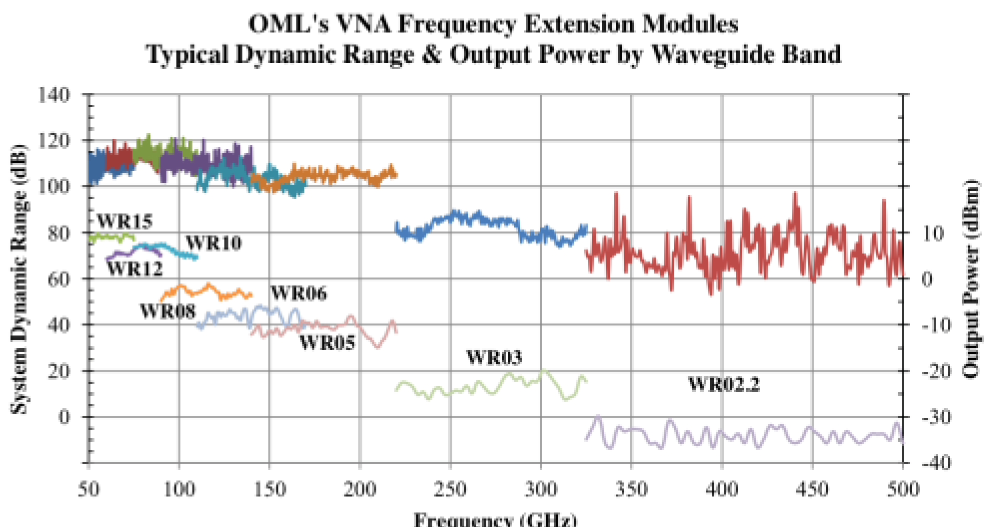




Banded Probes

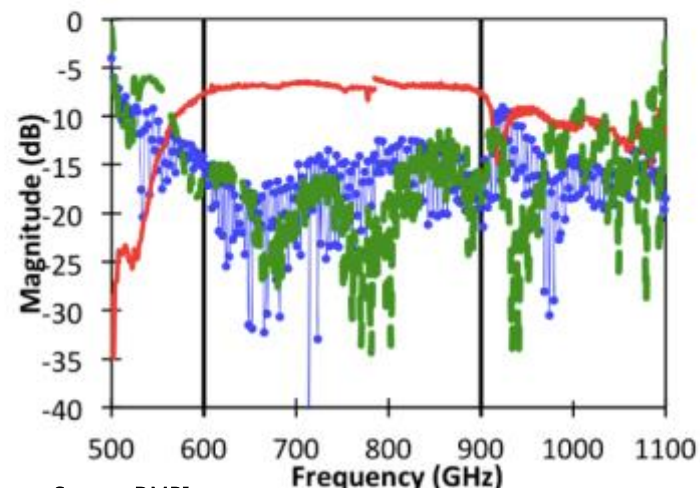


Banded Measurement Challenges



Source: OML

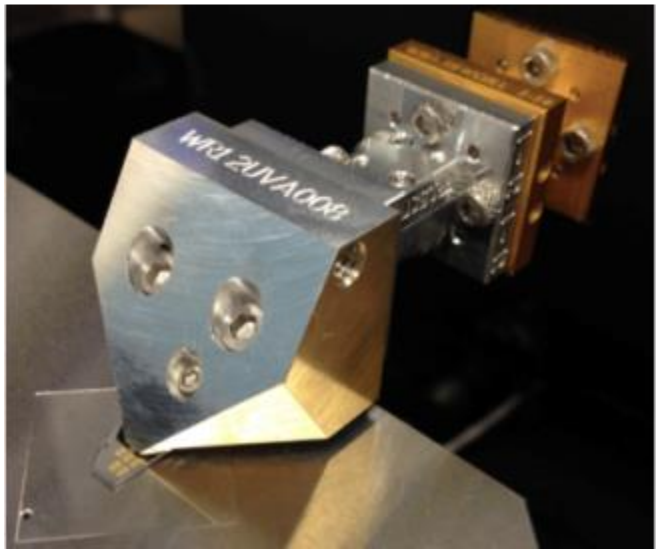
DMPI 1.1 THz Probe

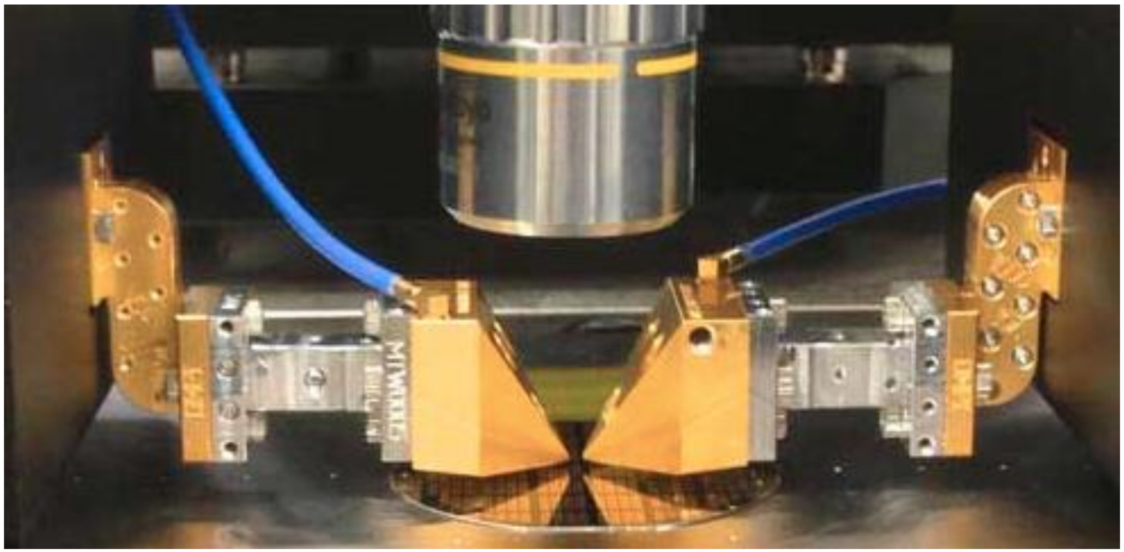


Source: DMPI

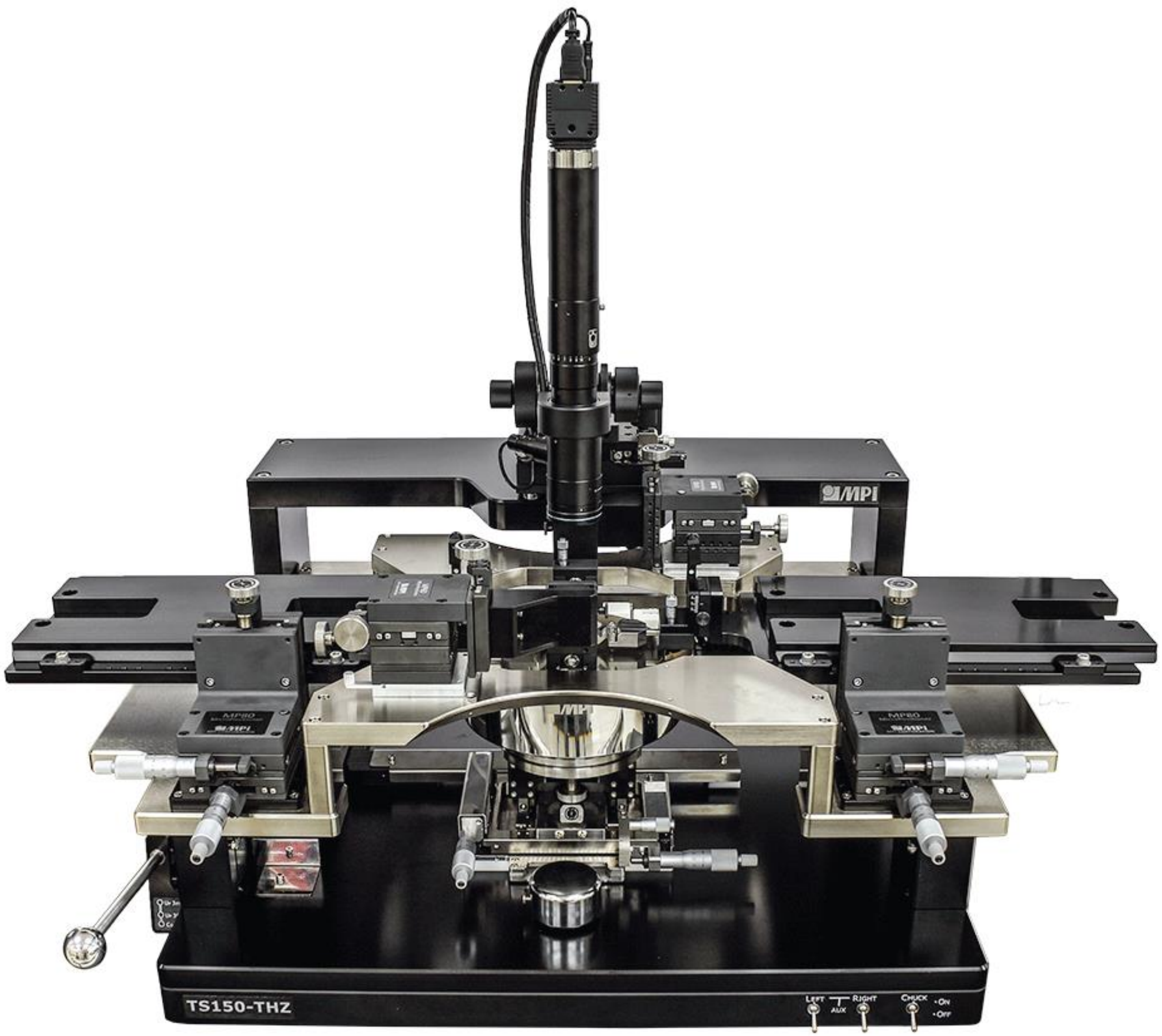
- VNA dynamic range decreases
- Waveguide losses increases
- Probe performance degrades

Probe Integration





Dedicated TS150-THZ System



MPI TS150-THZ | 150 mm Manual Probe System

The first ever, explicit designed probe system for accurate mmW and THz measurements

Microscope Mount and Movement
- Stable bridge for high quality optics
- 90° tilt for easy reconfiguration
- 50 x 50 mm linear XY movement

4-Port Bridge
- Two: in North and South
- Rectangular adjustments for RF positioners
- Designed as standard feature for DC biasing or 4-port RF
- For single DC or RF MicroPositioners

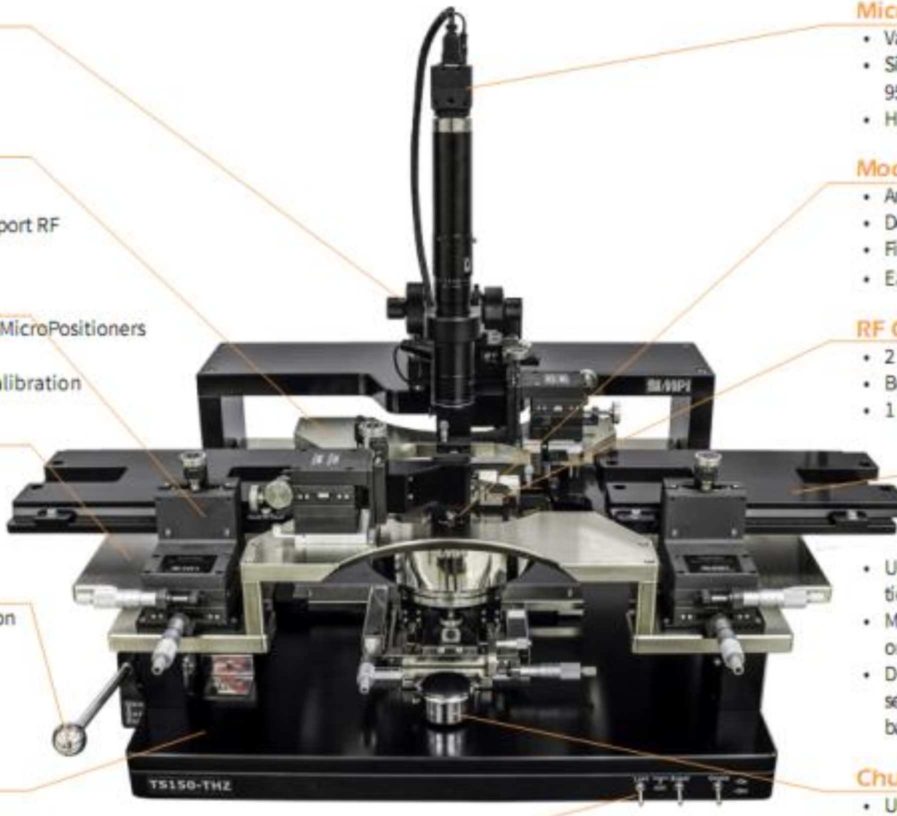
MicroPositioners
- Supports max. two, bold down large area MP80 MicroPositioners
- Unique over-travel control option
- MP80-DX option for accurate multi-line TRL calibration

Probe Platen
- Single large probe platen in rigid design
- 4 probe platen supports for max. stability
- Designed especially to accomodate large positioners for mmW and THz applications

Unique Platen Lift
- Three discrete positions for contact, separation (300 μm) and safety loading 3 mm
- Safety lock function at loading position
- "Automated" contact position with ±1 μm repeatability for consistent contact quality

Small Footprint
- Designed for bench top use
- Comes with vibration absorber base
- Low profile design for maximum usability
- Ideal for mmW, THz and load pull applications

Front Mounted Vacuum Control
- Easy access
- Clearly marked



Available Options
- Various adaptations for different frequency extenders
- Vibration isolation table
- Table with integrated rack for thermal controller, computer and keyboard push tray
  - Dual monitor stand option
  - Instrument shelf option

Microscope and Optics Options
- Various optics options available
- Single tube MPI SZ10, MZ12 with up to 12x zoom and 95 mm working distance
- HDMI cameras with up to 5 MP available

Modular Chucks
- Ambient or hot only chucks
- Dedicated RF or mmW designs
- Field upgradable for reduced cost of ownership
- Easy switch between center and small wafer size control

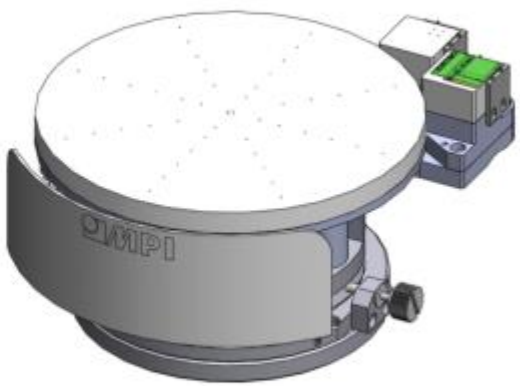
RF Calibration
- 2 auxiliary chucks for calibration substrates
- Built-in ceramic for accurate calibration
- 1 μm flatness for consistent contact quality

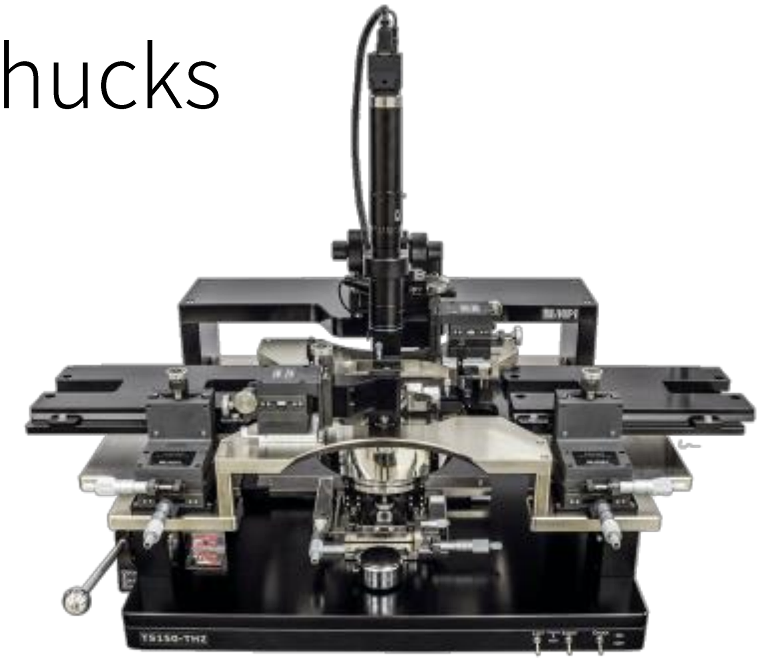
MP80 Integration Modules
- 2 options for waveguide or coax application
- Universal large area platforms for integrating various frequency extenders up to 1.1 THz
- Unique air-spring design for balance weight compensation and max. stability
- Micrometer screws for fine waveguide probe leveling on the platforms
- Dove-tail interface for dedicated adaptations for easy setup and switching between different frequency bands

Chuck XYZ Stage Movement
- Unique puck control air bearing stage for quick one-hand operation
- Large vacuum base for max. stability
- 175 x 225 mm XY fast movement
- 25 x 25 mm micrometer fine XY adjustment
- 10 mm fine Z chuck adjustment
- ±5° Theta fine adjustment
- Extra wide Y-range for easy loading

Designed for unsurpassed stability

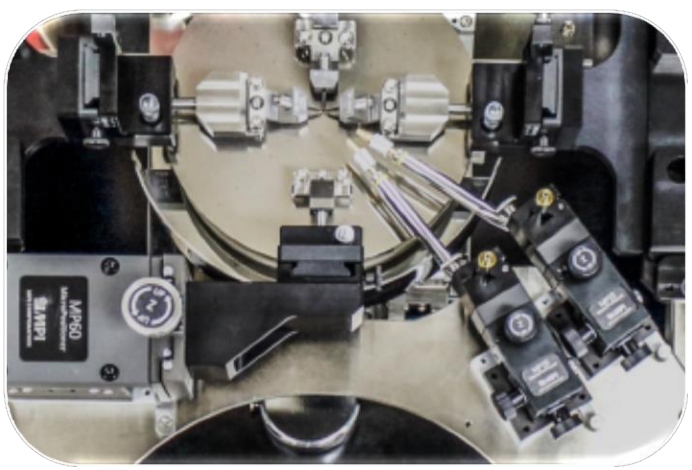
- Large area stainless steel probe platen
- Probe platen at lowest possible position
- No chuck elevation
- Ceramic chuck and AUX chucks

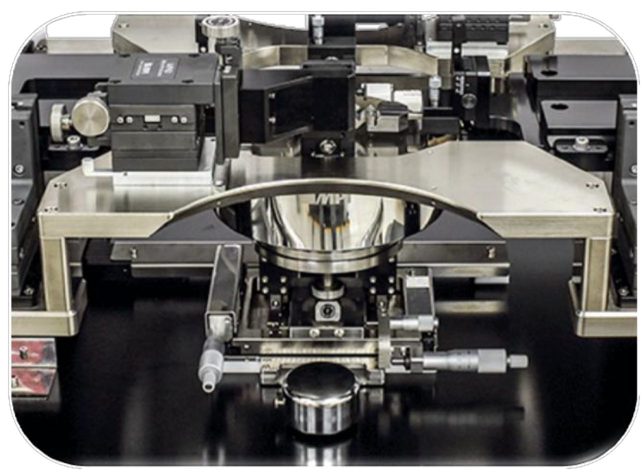




Dedicated Design for THz Application

- Support R&S and all other extenders:
  - up to 1.1THz
- 4-Port as part of the base system
- Fine Z chuck





THANK YOU FOR YOUR ATTENTION

For more information, please visit:
www.mpi-corporation.com