Microwave Engineering MCC121, 7.5 hec, 2014

Lecture 12 (11 December)
Microwave measurement techniques

Introduction - Microwave measurement techniques

Klas Yhland

SP Technical Research Institute of Sweden

You are welcome to ask
questions during the presentation

Lecturer background, affiliation

- Klas Yhland
    - M.Sc. Electrical engineering at Lund University of Technology, 1992
    - Microwave design engineer, Ericsson Microwave Systems, 1992 - 1994
    - Ph.D. in Microwave Electronics at Chalmers 1999
    - Head of RF & Microwave Lab. at SP Technical Research Inst. of Sweden, Dec. 1999 to date
    - Adjunct professor (adjungerad professor) at the Thz and Millimetre wave Laboratory, Chalmers 2012
- SP Technical Research Institute of Sweden
    - In total ~1400 employees where ~100 in metrology
- The microwave lab
    - Vector Network Analyzer and power metrology
        - Research on calibration and uncertainty calculation methods
        - Calibration services up to 40 GHz
    - Education in microwave measurement techniques
    - Analysis and design of customer equipment
    - Members of the GHz Centre at Chalmers
        - PhD. student supervision
        - Research on
            - measurement problems from GHz – THz
            - device modeling

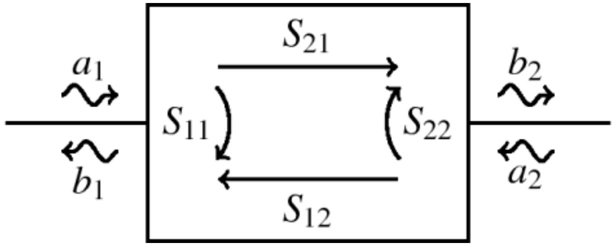
The measurement need

Question: Can you measure the input impedance and gain of this circuit?

$$Z_1 = \frac{v_1}{i_1}$$

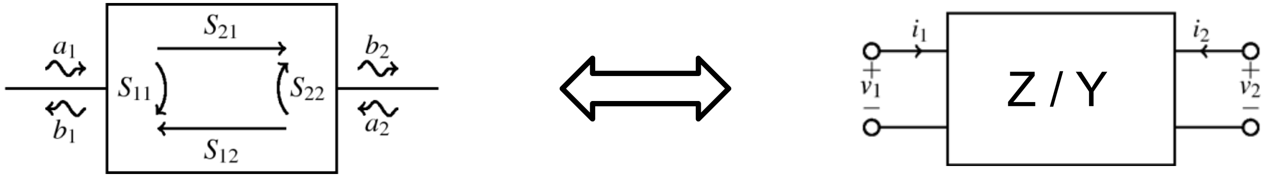
$$Gain = \frac{v_2}{v_1}$$

Answer: Yes, but we will measure S-parameters
Because we measure waves rather than voltages and currents



$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

Conversion to Z or Y-parameters



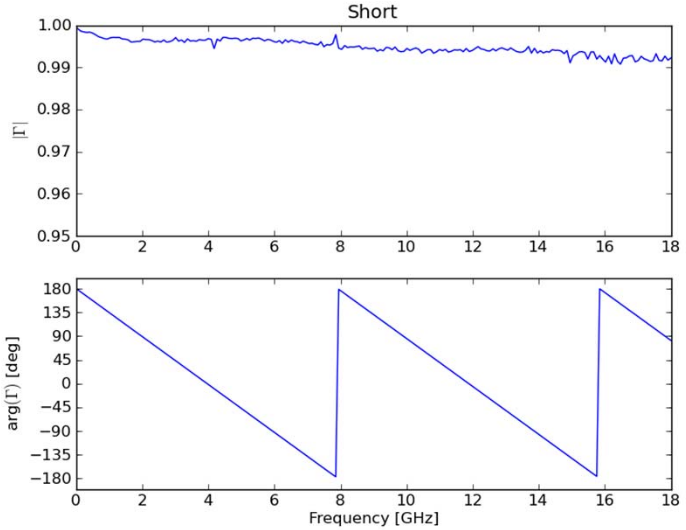
$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \quad \Longleftrightarrow \quad \begin{aligned} \begin{pmatrix} v_1 \\ v_2 \end{pmatrix} &= \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \begin{pmatrix} i_1 \\ i_2 \end{pmatrix} \\ \begin{pmatrix} i_1 \\ i_2 \end{pmatrix} &= \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \end{pmatrix} \end{aligned}$$

S, Z and Y-parameters are complete models of a linear two port
But Z and Y parameters may become singular for some networks

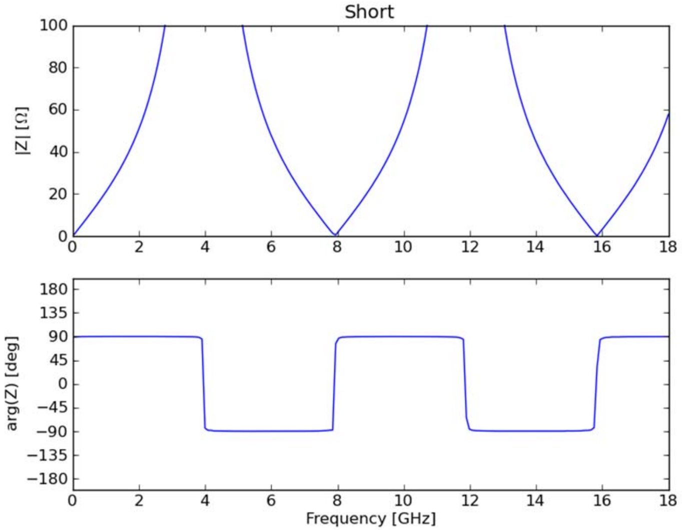
For conversion equations see: J. Stenarson and K. Yhland, "Uncertainty Propagation Through Network Parameter Conversions," IEEE Transactions on Instrumentation and Measurement, vol. 58, no. 4, pp. 1152-1157, April, 2009

S versus Z-parameters for an offset short circuit

S-parameter

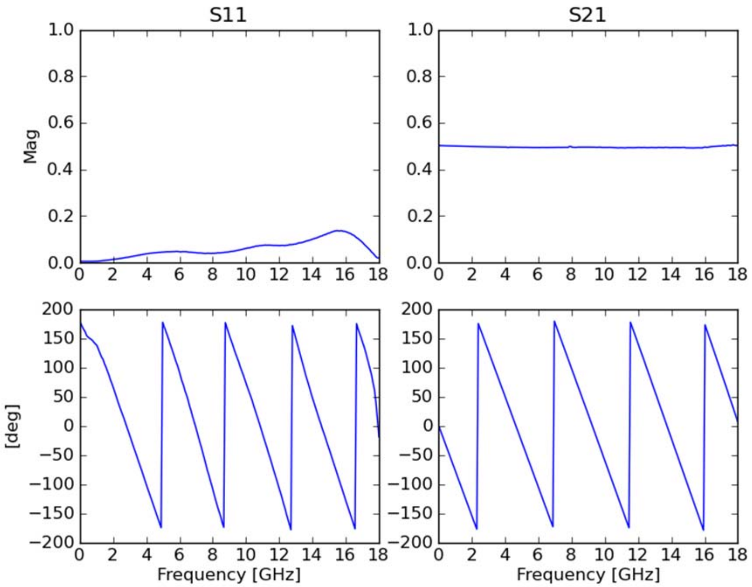


Z-parameter

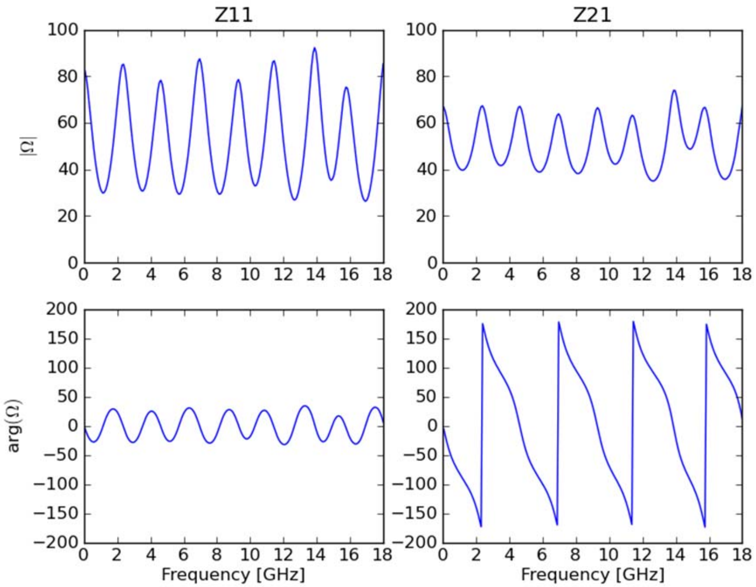


S versus Z-parameters for a 6 dB attenuator

S-parameters

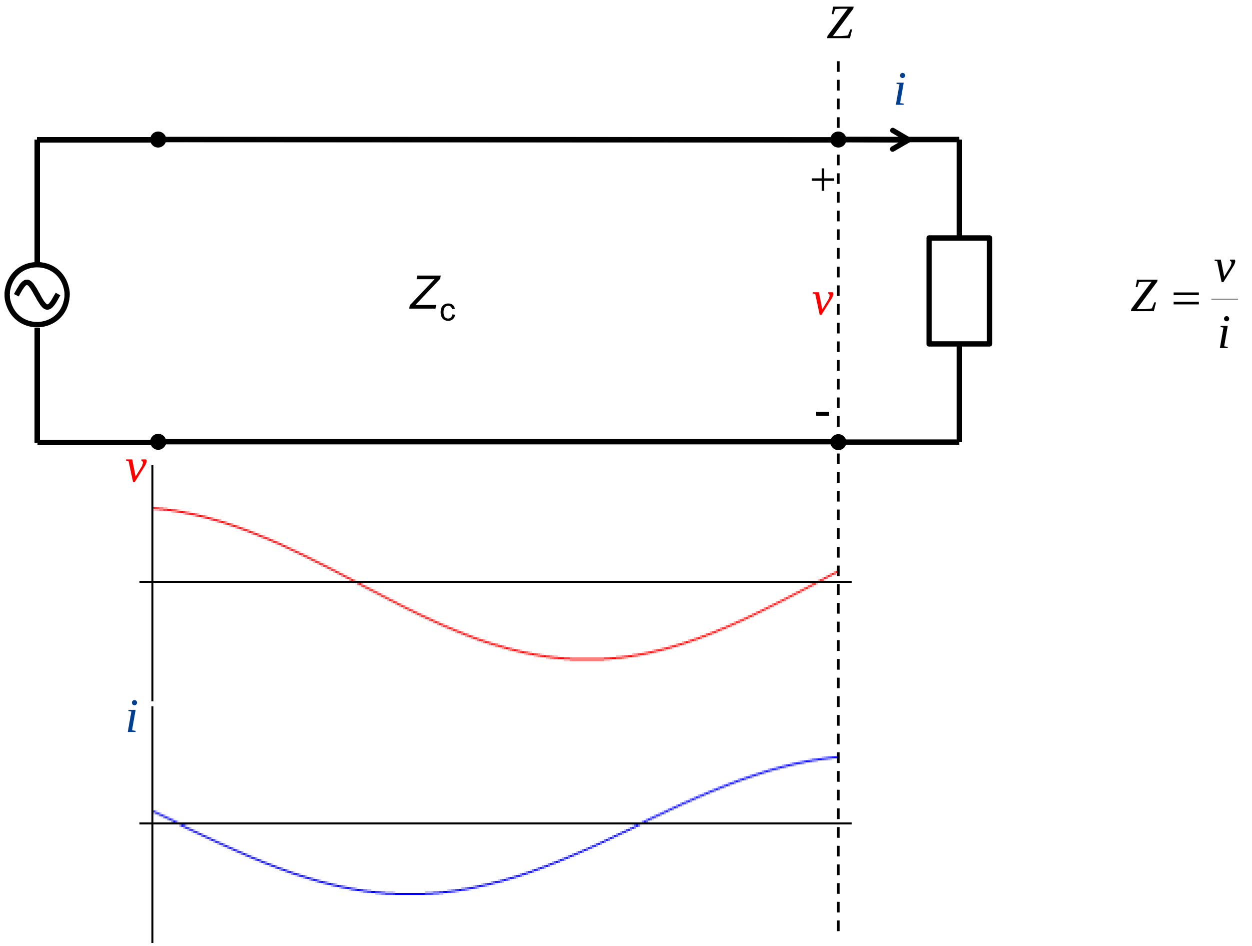


Z-parameters



The disadvantage with *v* and *i* measurements

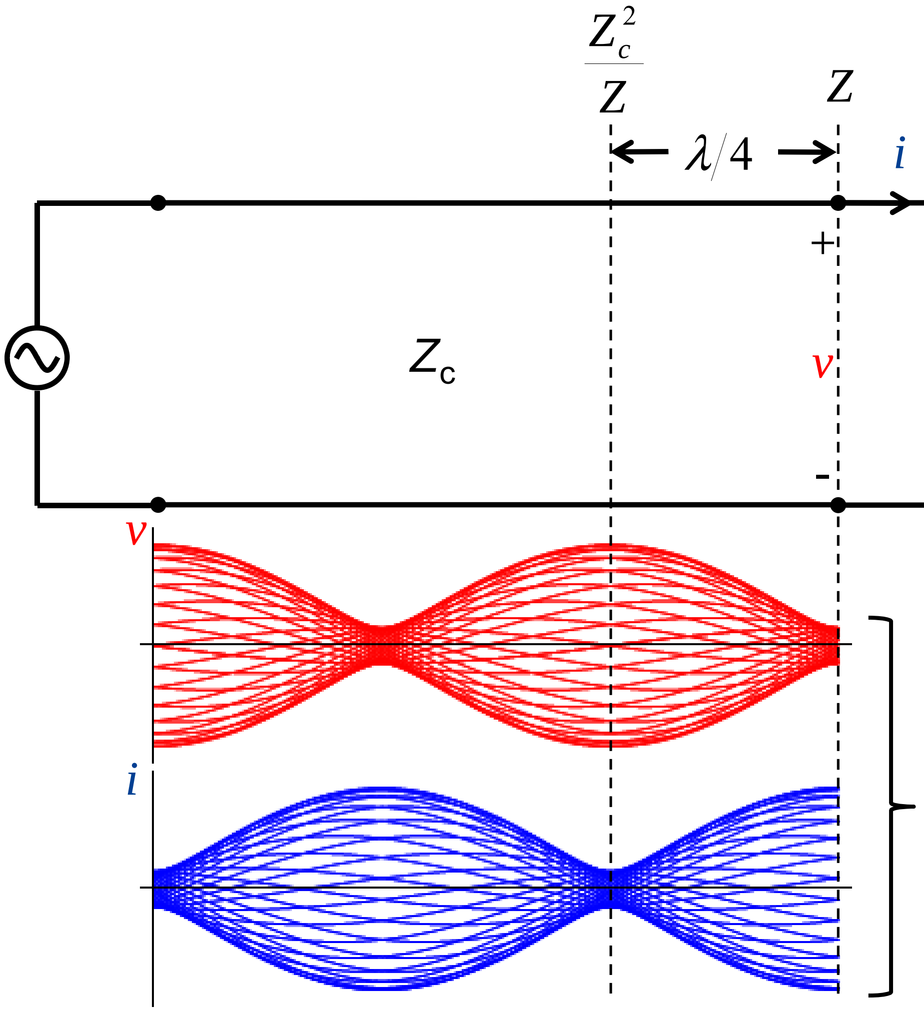
At high frequencies, short wavelengths, we get problems with standing waves



$$Z = \frac{v}{i}$$

The disadvantage of *v* and *i* measurements

At high frequencies we get problems with standing waves

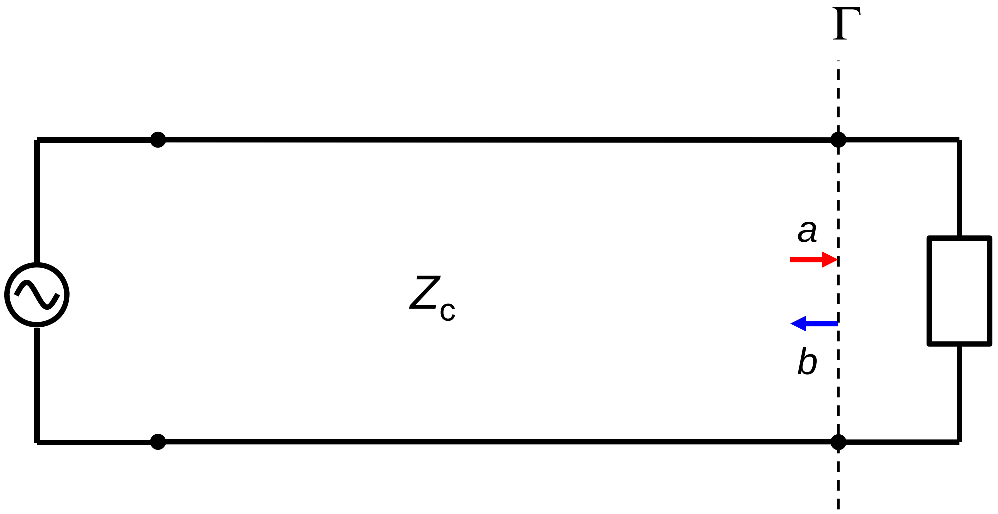


Z is inverted over
a short distance

The advantage of wave measurements

We measure the reflection coefficient Γ

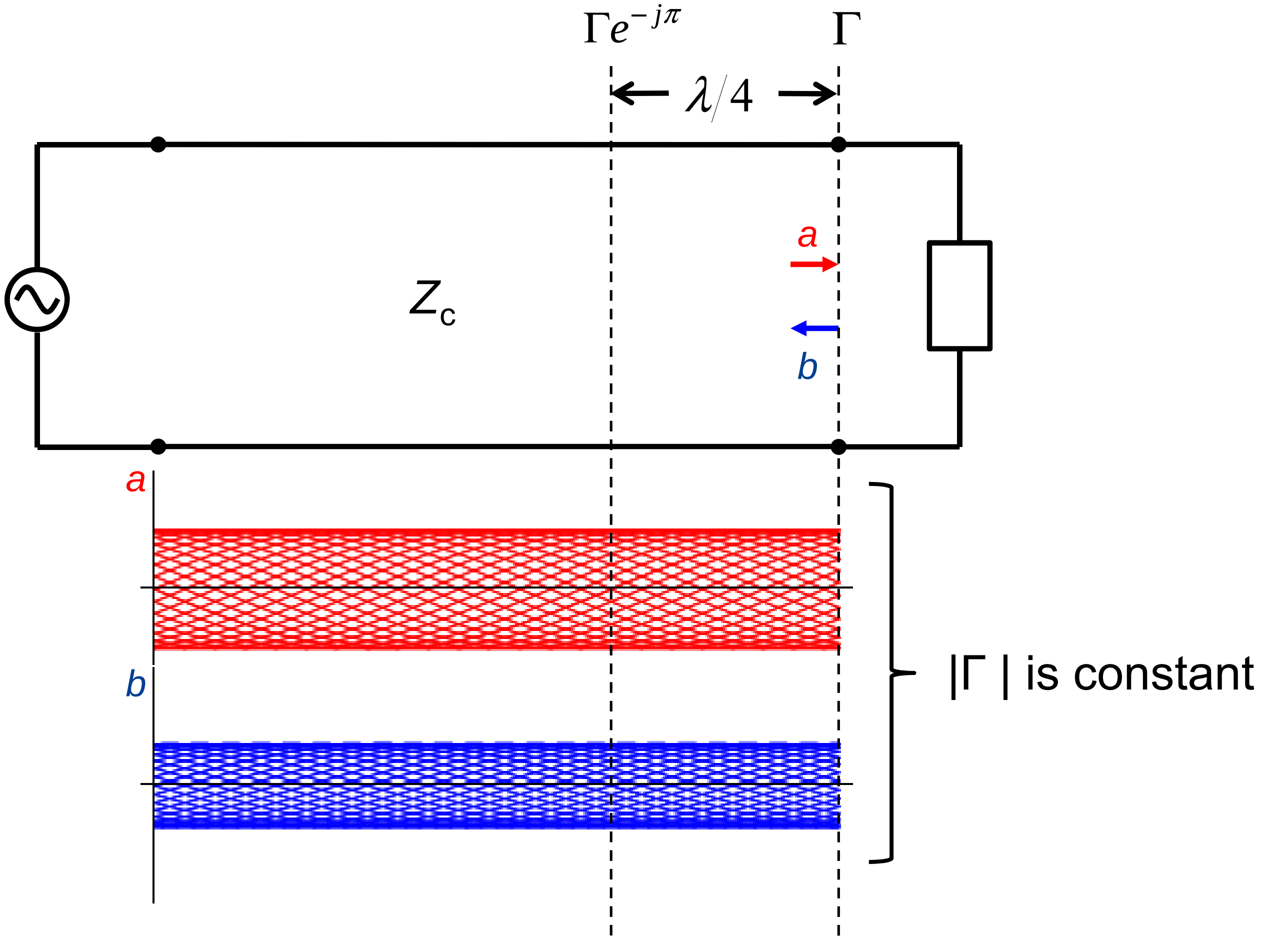
Z_c is the characteristic impedance of the connecting transmission line



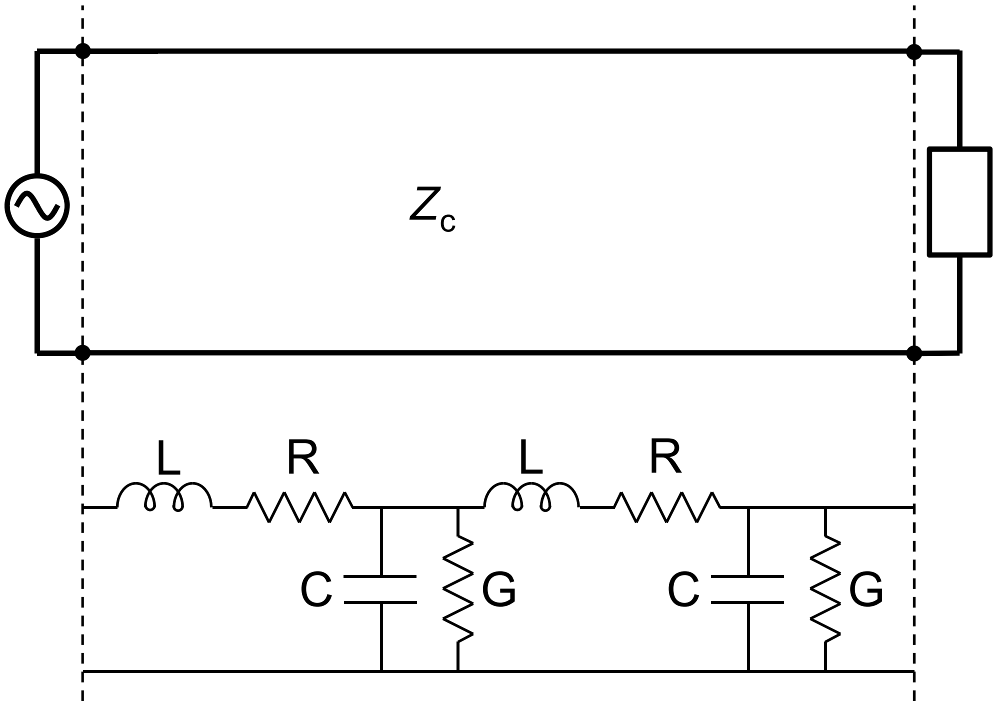
$$\Gamma = \frac{b}{a} = \frac{Z - Z_c}{Z + Z_c}$$

The advantage of wave measurements

Wave ratios only change phase along a lossless transmission line



Characteristic impedance



$$Z_c = \sqrt{\frac{j\omega L + R}{j\omega C + G}} \approx \sqrt{\frac{L}{C}}$$

Usually the system impedance $Z_s = Z_c = 50\ \Omega$

Characteristic impedance – why 50 Ω?

1. Maximum power handling in coaxial at 30 Ω. Set by breakdown in connector air interface.
2. Minimum attenuation in coaxial: 77 Ω for air dielectric, 64 Ω for expanded PTFE and 52 Ω for solid PTFE .

⇒ 50 Ω good compromise for general purpose cables

⇒ 75 Ω common for antenna cables. But why? For dipole antenna matching (77 Ω)?

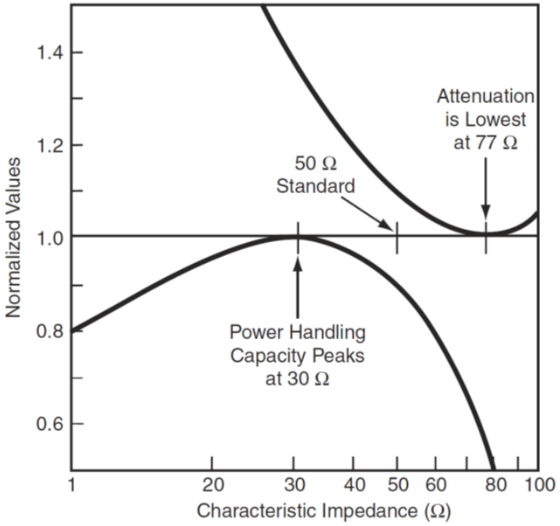
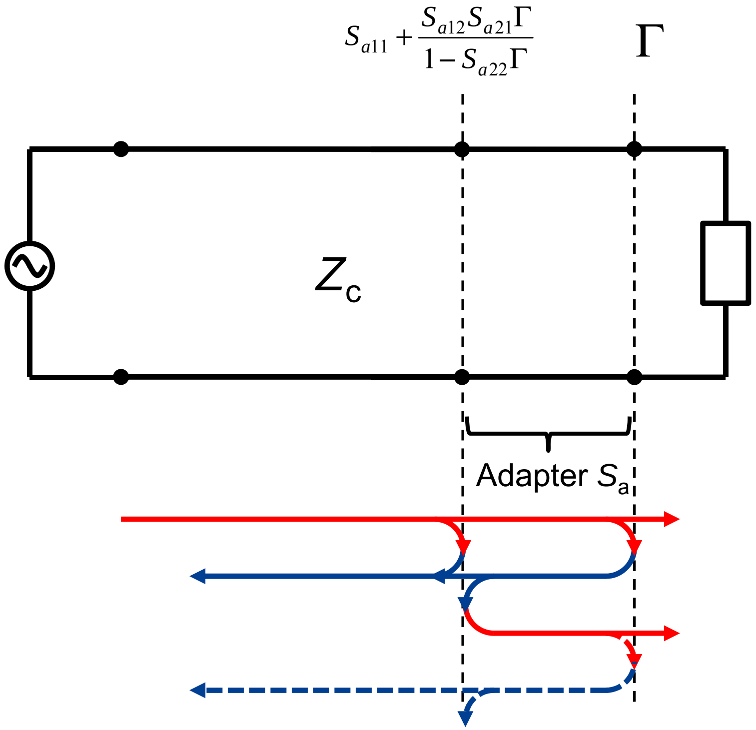


Diagram: Maury Microwave Corporation, Appl. Note 5A-021

On circuit boards it is easy to design transmission lines from 20 Ω to 100 Ω. In circuit design we need both higher and lower impedances than our system impedance.

⇒ 50 Ω good compromise.

Mismatch in adapters and connectors

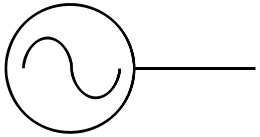


Conclusion:
Measure very close to DUT
or use vector error correction

Common instruments in the microwave lab

- Signal generator

Picture: www.anritsu.com

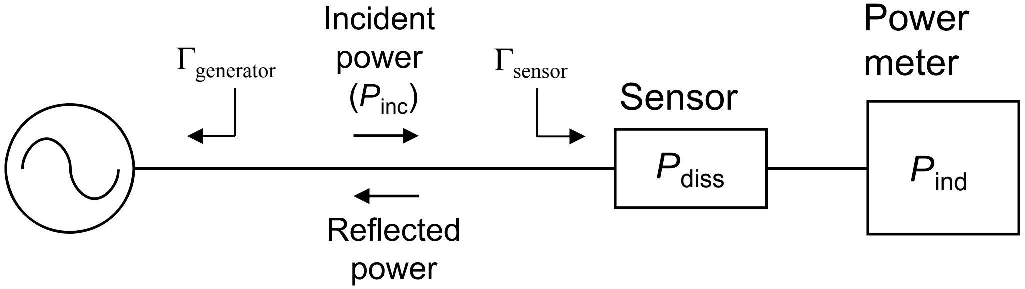


  - Looks simple but demands on
    - pure signal (low harmonics, low spurioses, low phase noise),
    - high output power, low output power
    - advanced modulation schemes

Principle of power sensing

- Power meter

Photo: www.rohde-schwarz.com



$\Gamma_{\text{generator}}$

Incident power (P_{inc})

Γ_{sensor}

Sensor

Power meter

P_{diss}

P_{ind}

Reflected power

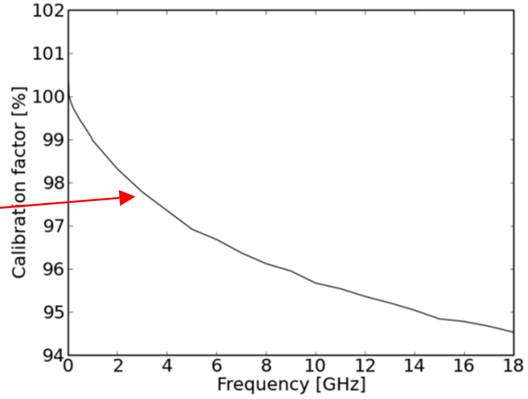
Error correction

$$P_{\text{inc}} = P_{\text{ind}} \frac{\left|1 - \Gamma_{\text{sensor}} \Gamma_{\text{generator}}\right|^2}{K(f)} \approx \frac{P_{\text{ind}}}{K(f)}$$

$$K(f) = K_{\text{reference}} K_{\text{relative}}(f)$$

Pre-calibrated or determined at measurement start

Frequency dependent calibration factor

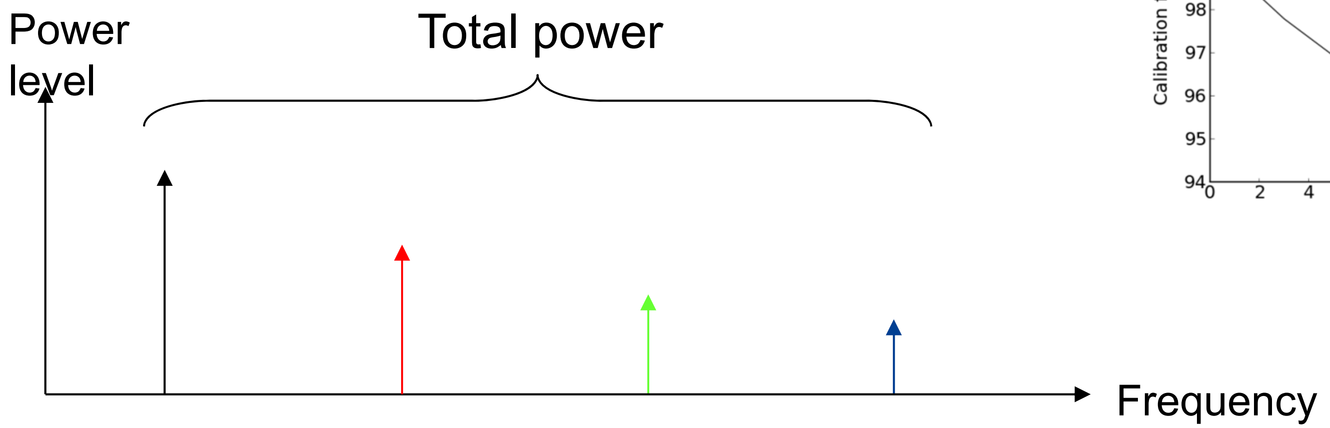


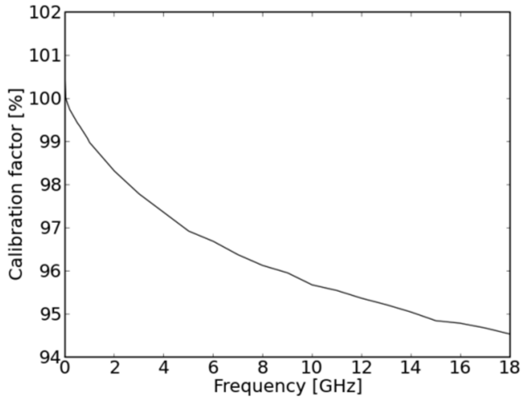
Power meter

Broadband detection & frequency dependent error correction

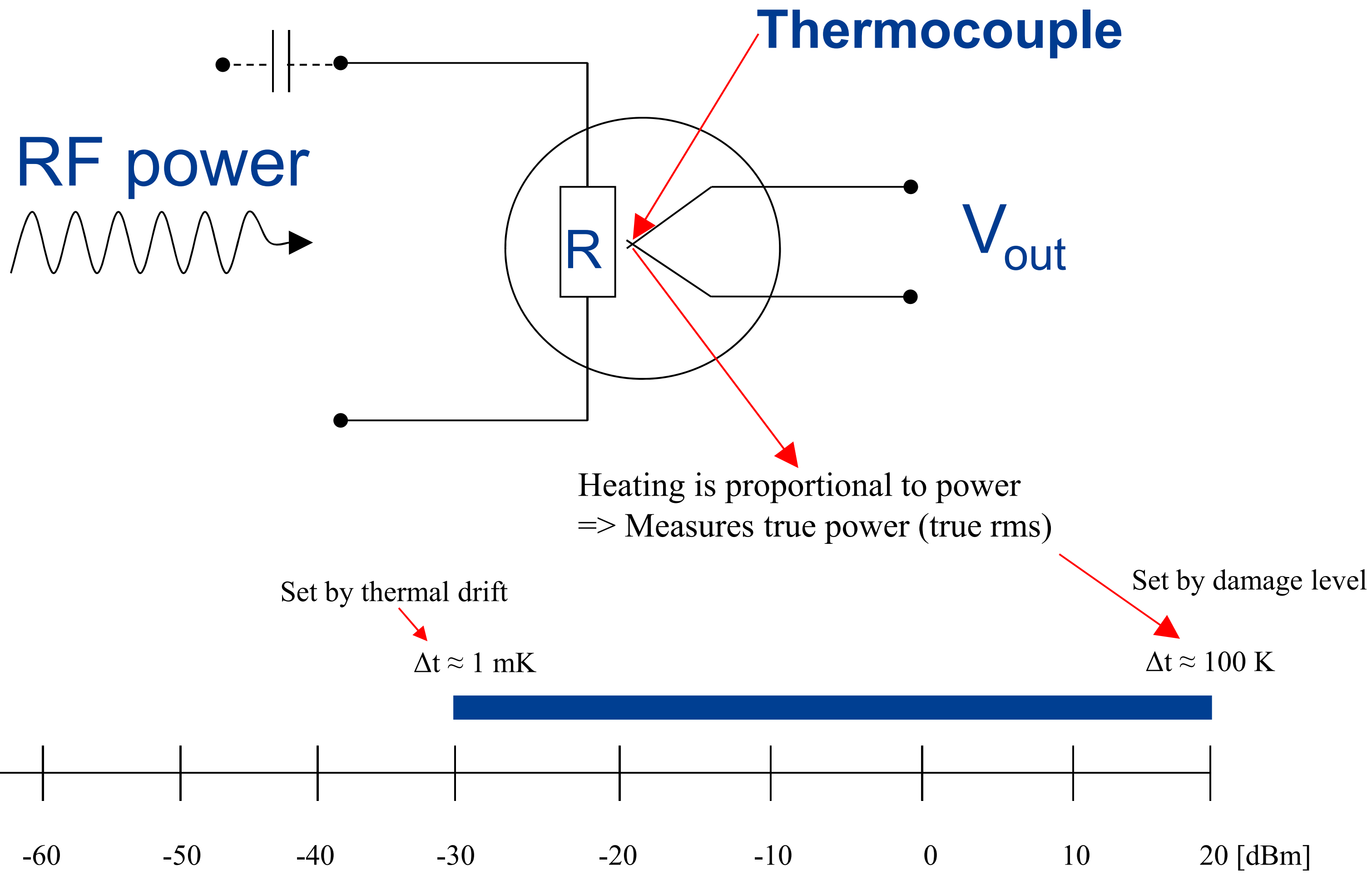
=> Assumes narrowband signal

=> Multiple signals become difficult to measure





Power meter, thermocouple sensor



Heating is proportional to power
=> Measures true power (true rms)

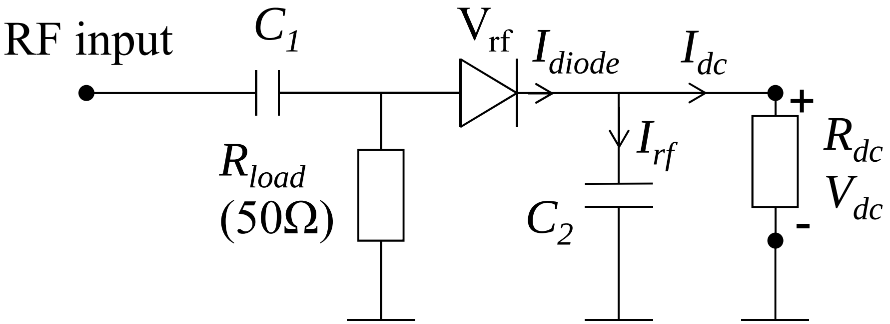
Set by thermal drift

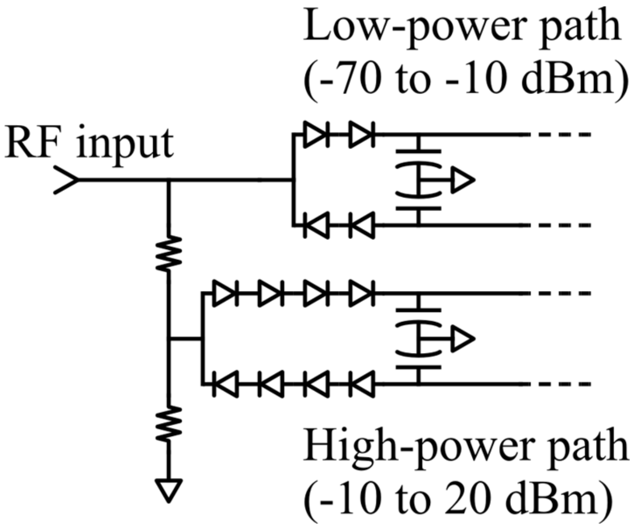
$\Delta t \approx 1$ mK

Set by damage level

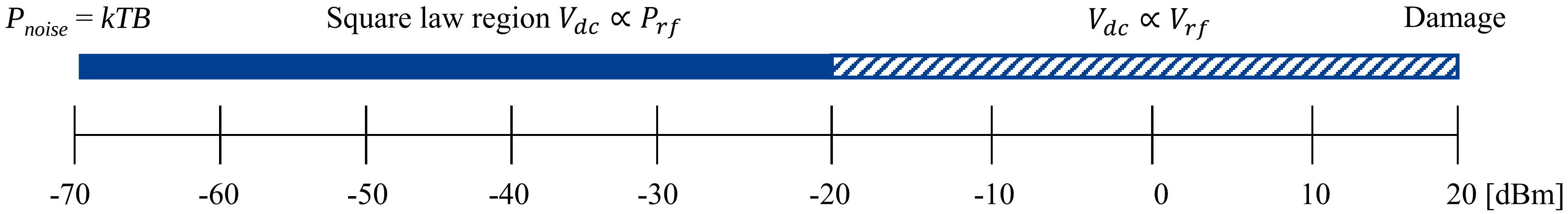
$\Delta t \approx 100$ K

Power meter, diode sensor

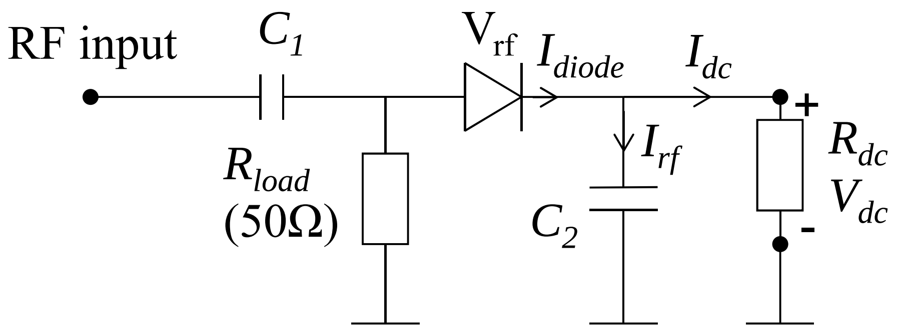


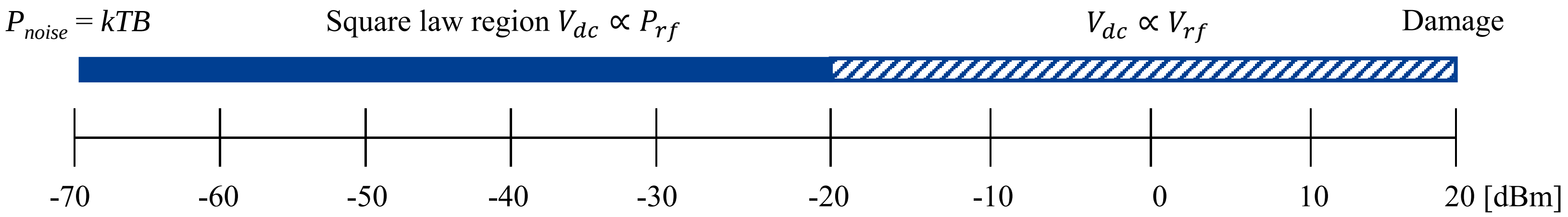


Schematic: www.agilent.com



Power meter, diode sensor – square law region





$$V_{rf} = V\cos\omega t$$

$$I_{diode} = k_1 V_{rf} + k_2 V_{rf}^2 + \cancel{k_3 V_{rf}^3 + \cdots}$$

Valid as long as approximation of taylor series is valid

=>

$$I_{diode} = k_1 V\cos\omega t + k_2 V^2 \cos^2\omega t + \cdots$$

$$I_{diode} = \underbrace{k_1 V\cos\omega t}_{I_{rf}} + \underbrace{\frac{k_2 V^2}{2}}_{I_{dc}} + \underbrace{\frac{k_2 V^2 \cos 2\omega t}{2}}_{I_{rf}} + \cdots$$

$$\boxed{V_{dc} = \frac{k_2 V^2}{2} R_{dc} \propto P_{rf}}$$

Power meter

Comparison

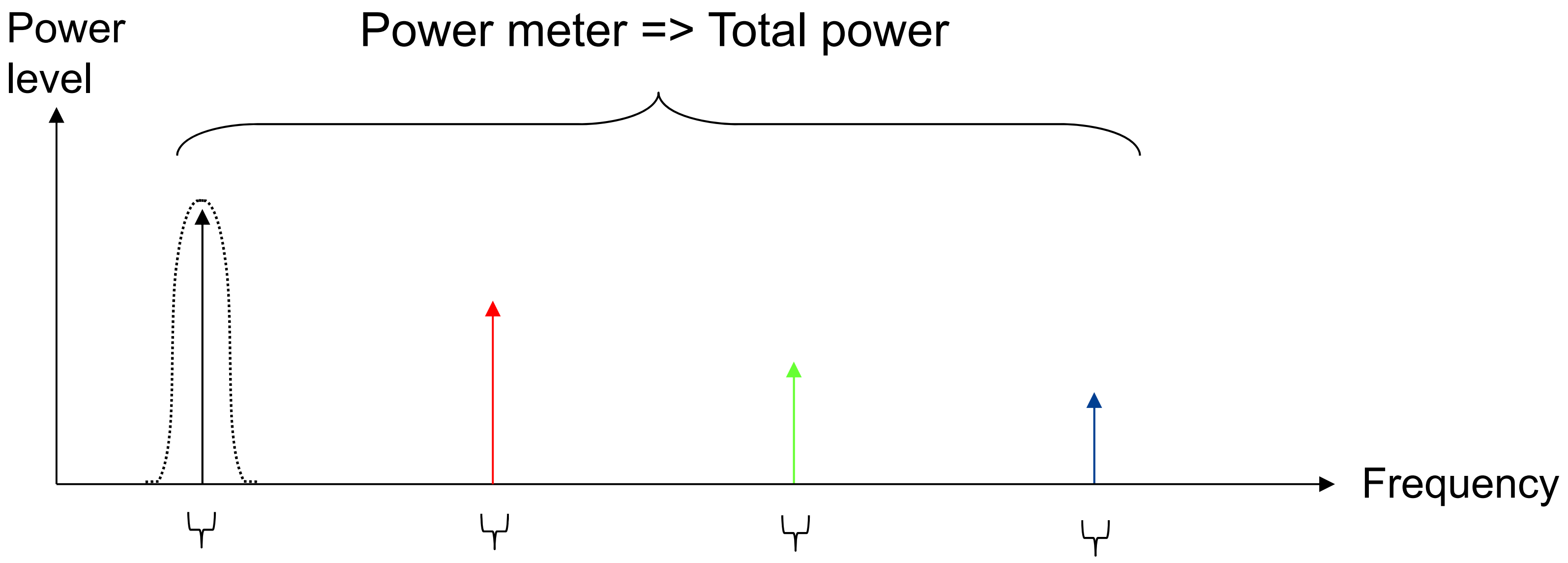
	Advantages	Disadvantages
Diode sensor	• High sensitivity • Fast, can measure envelope and peak power	• Match is worse compared to thermocouple • DC blocked • Worse linearity • Frequency dependent linearity • Sensitive to modulation
Thermocouple	• Can measure DC (eg. R&S) • Good match • Measures true RMS • Linear • Frequency independent linearity	• Lower sensitivity • More sensitive to variations in ambient temperature

Power meter

References

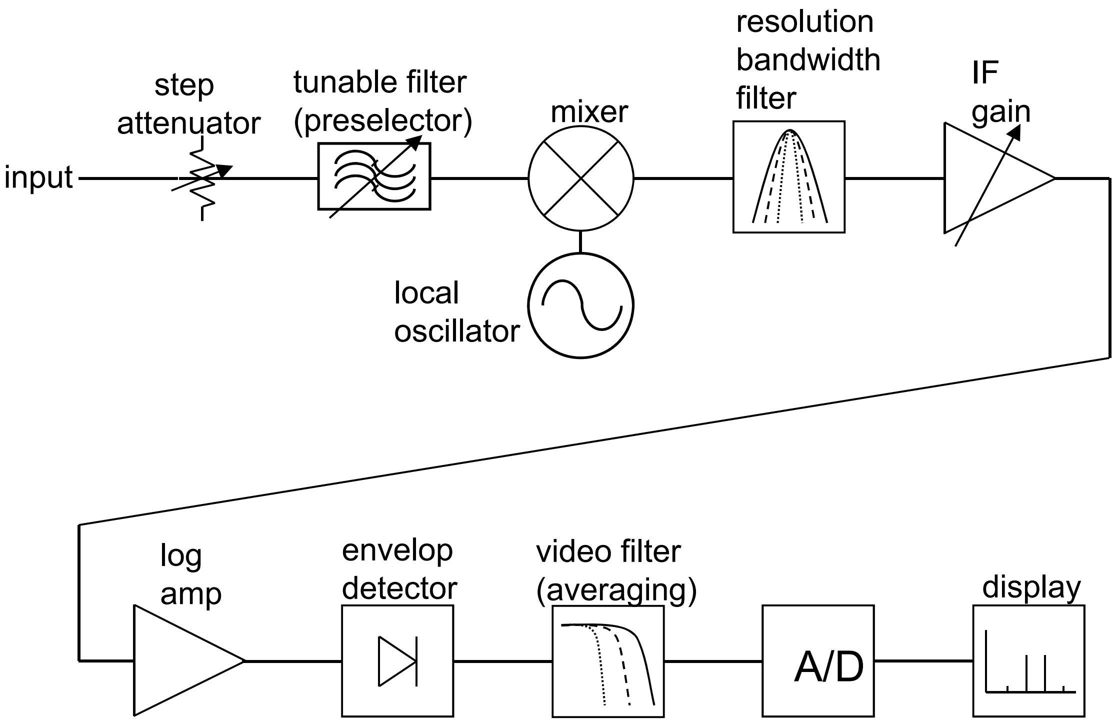
1. "Fundamentals of RF and Microwave Power Measurements," Agilent Technologies AN 1449-1, 2003.
2. "4 Steps for Making Better Power Measurements," Agilent Technologies AN 64-4D, 2006.
3. "Choosing the Right Power Meter and Sensor," Agilent Technologies Product Note 5968-7150, 2000.

Common instruments in the microwave lab

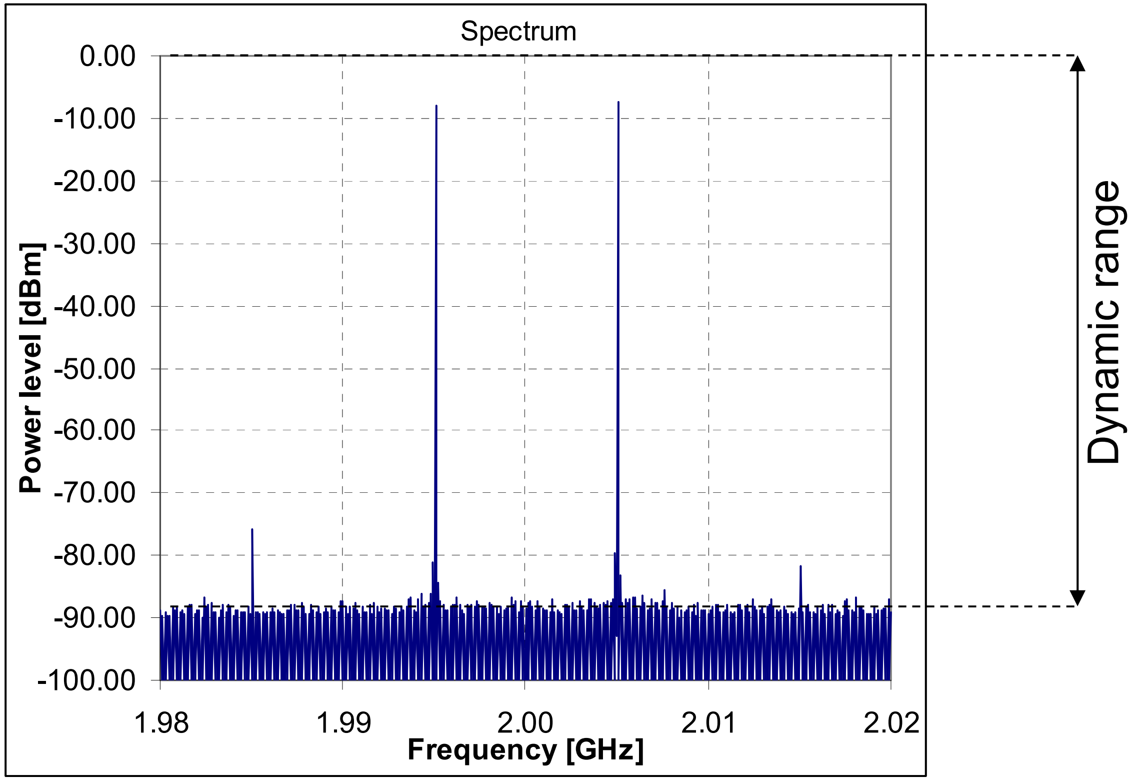


Spectrum analyser => Individual frequency components

Spectrum analyzer



Spectrum analyzer



The spectrum analyser measures four signals: -76, -8, -8 and -82 dBm
A power meter would measure -5 dBm

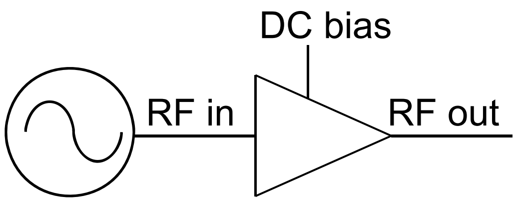
The dynamic range has two limits

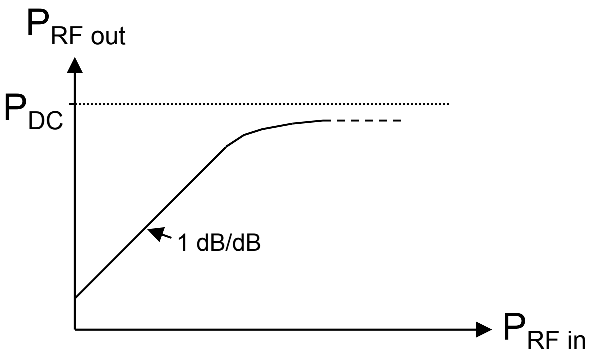
- Upper limit: Nonlinearities
  - Causing compression, harmonics, intermodulation
  - Attenuator dependent

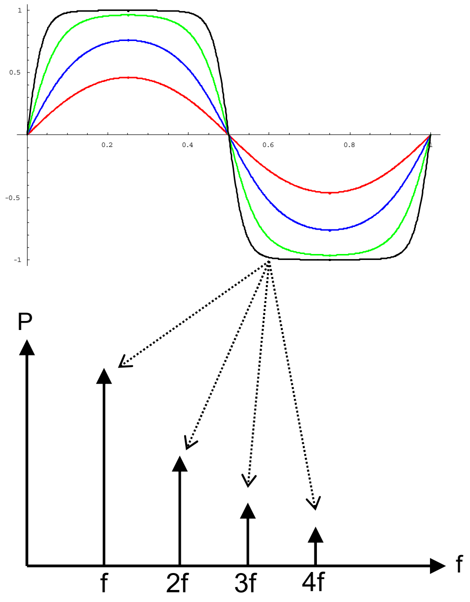
- Lower limit: Noise
  - Attenuator dependent
  - Resolution bandwidth dependent

Nonlinearities, cause and impact

- Cause
  - Saturation, e.g. in an amplifier $P_{RF\ out} < P_{DC} + P_{RF\ in}$

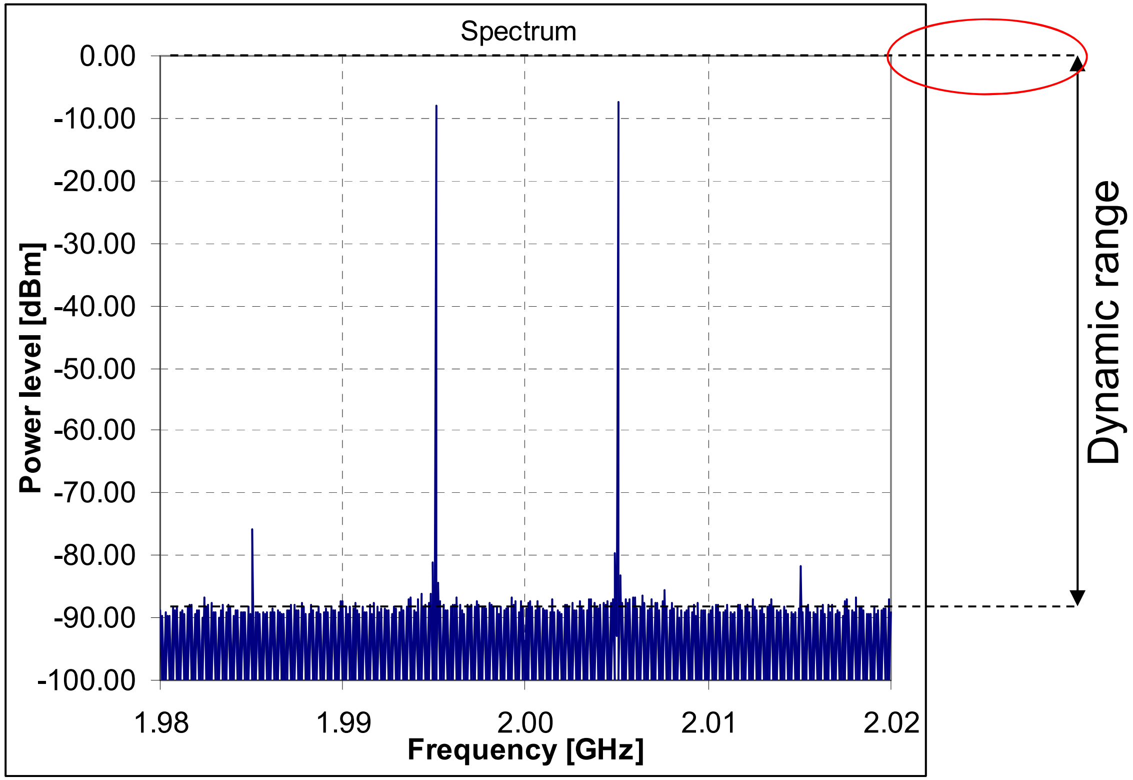






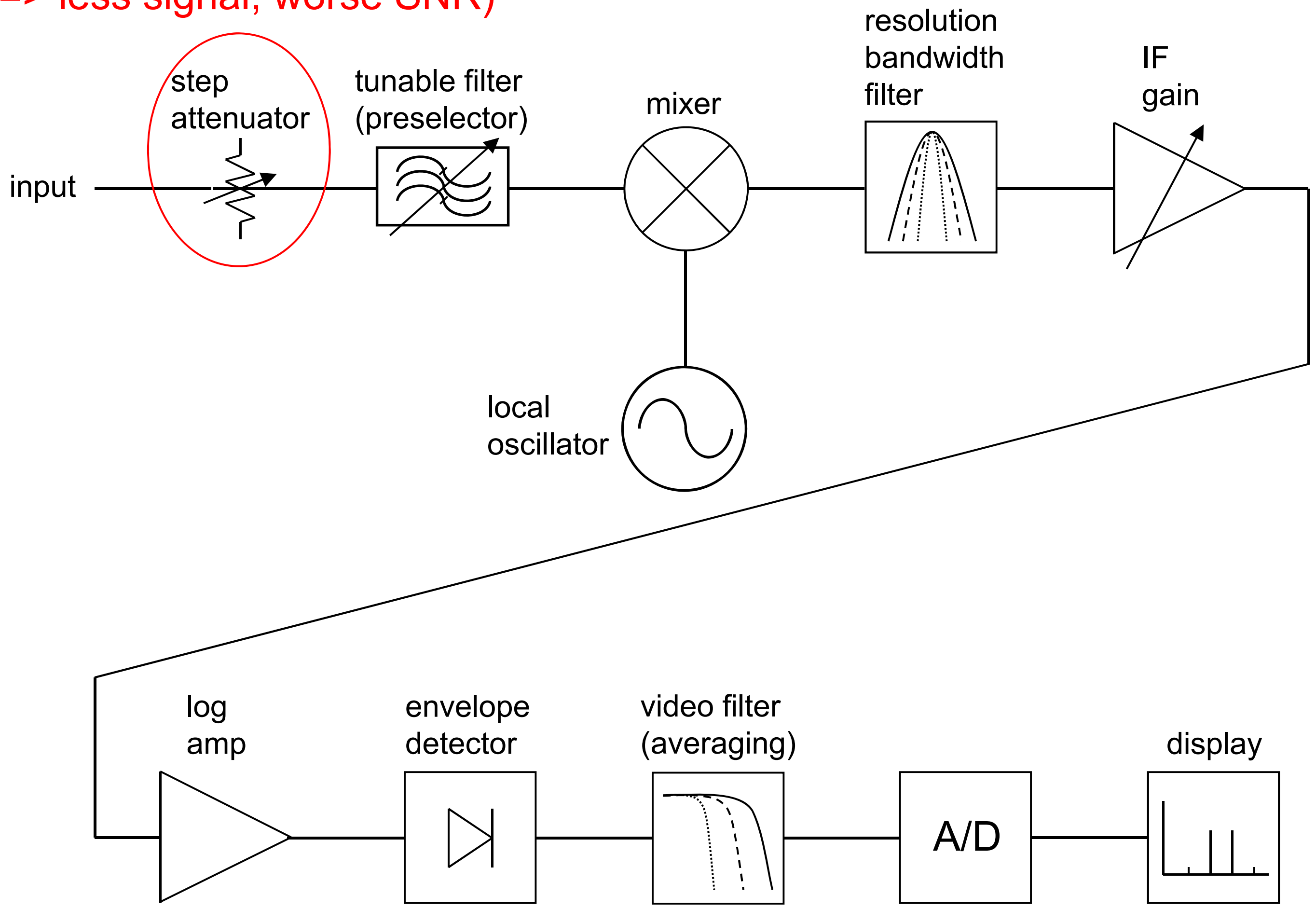
- Impact
  - Compression
  - One input tone => harmonics 2f, 3f, 4f, …
  - Several input tones => intermodulation (IM) $2f_1$, $2f_2$, $3f_1$, $3f_2$, $f_1 \pm f_2$, $f_1 \pm 2f_2$, $2f_1 \pm f_2$, …

Spectrum analyzer



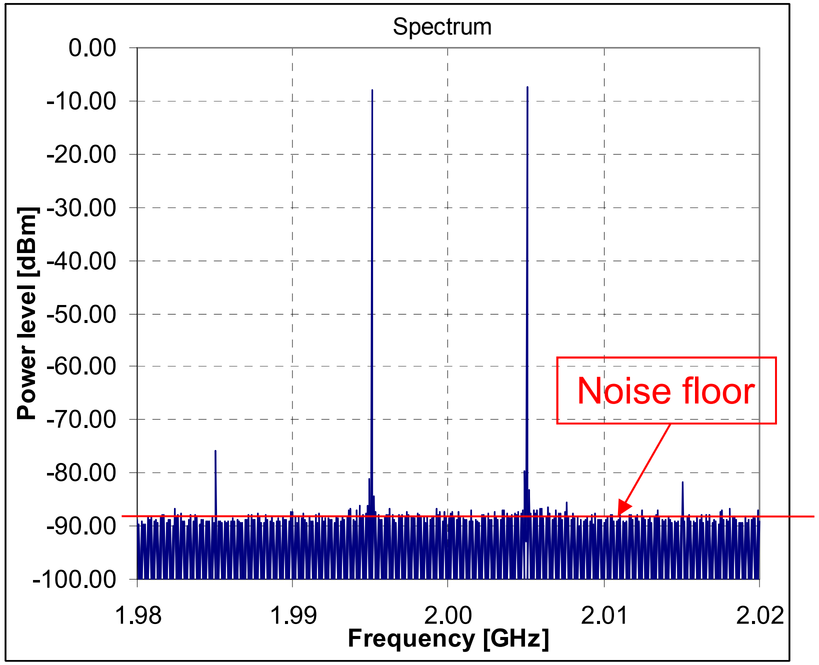
Nonlinearities, countermeasure

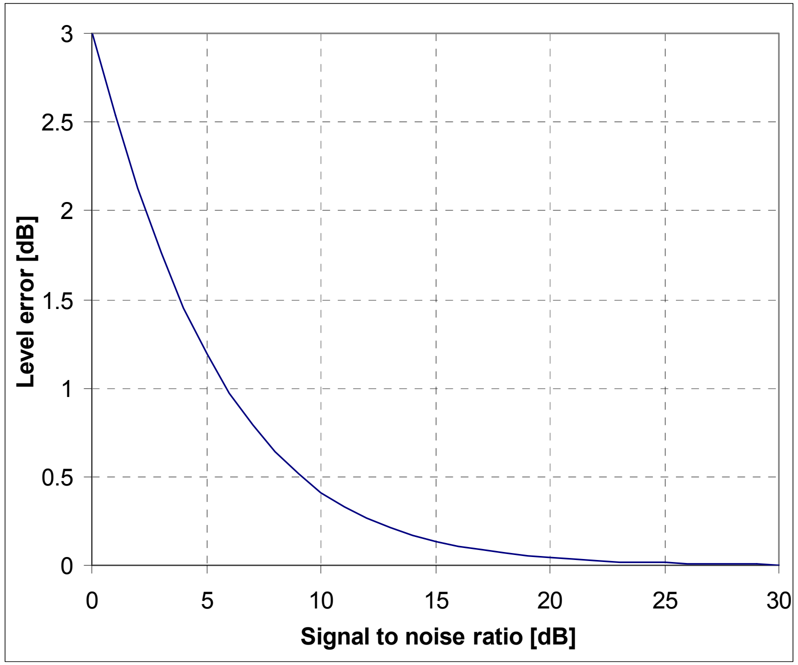
Increase the step attenuator
(=> less signal, worse SNR)



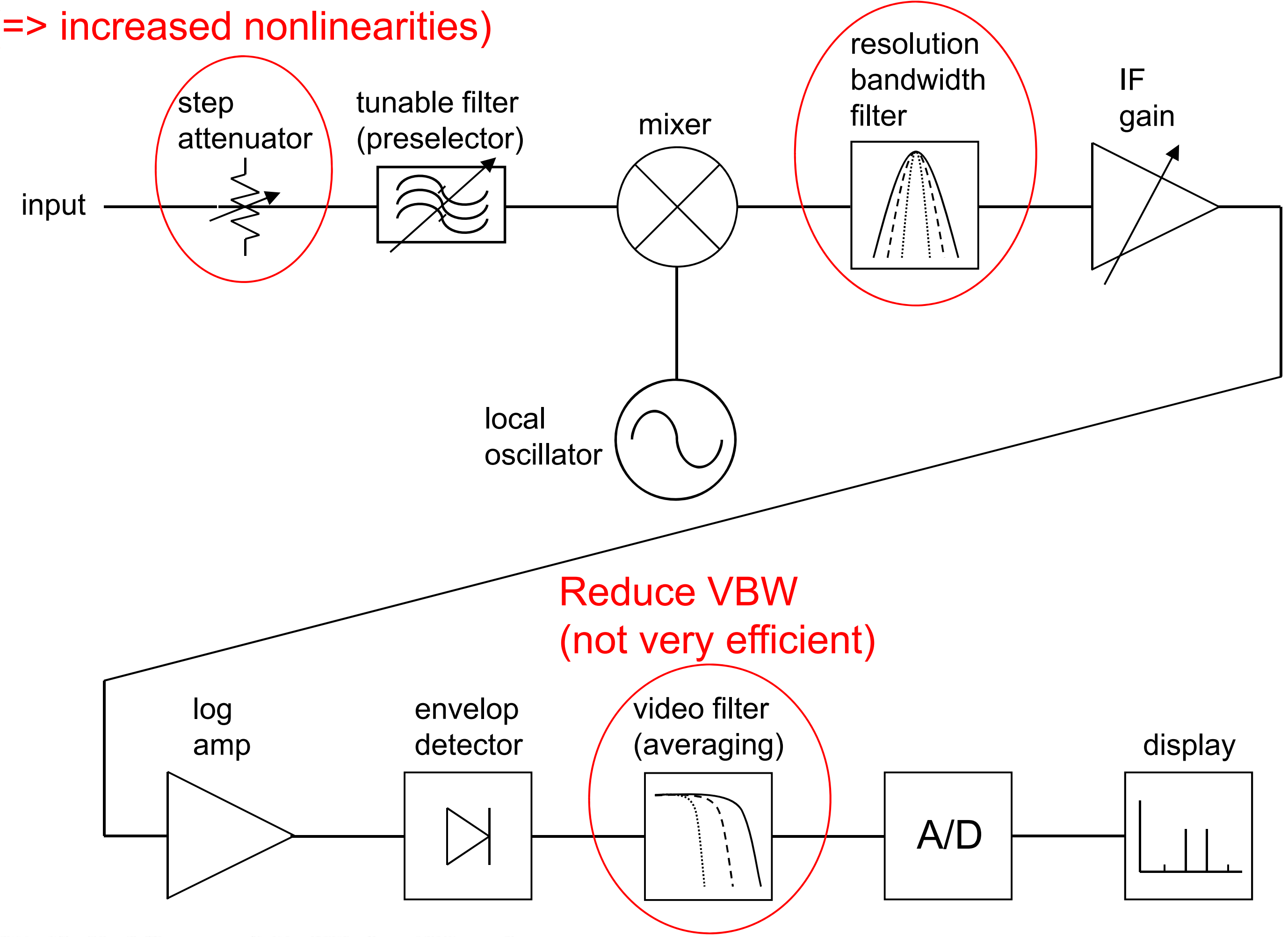
Noise, impact

Signals close to the noise floor will be overestimated.
(If they can be distinguished from the noise)





Noise, countermeasure



Decrease the step attenuator
(=> increased nonlinearities)

Reduce RBW
(=> slower, must keep
RBW >> signal bandwith)

Reduce VBW
(not very efficient)

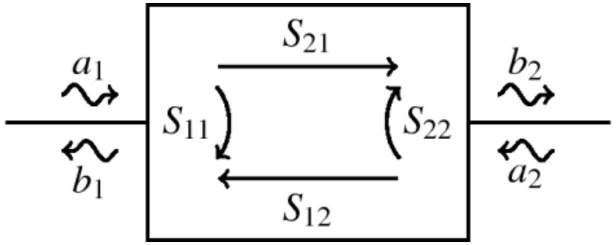
Spectrum analyzer

- References

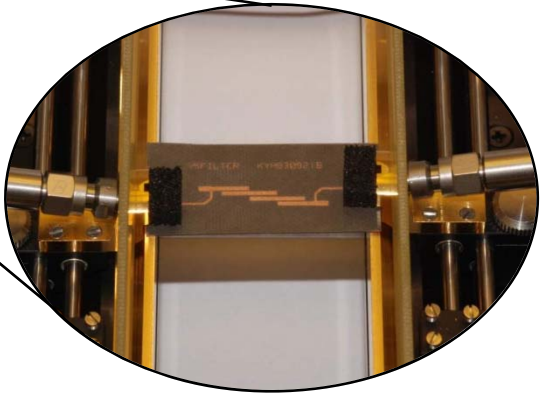
1. C. Rauscher, "Fundamentals of Spectrum Analysis" Rhode & Schwarz, 2002.
2. Agilent, "Application Note AN-150, Spectrum Analysis Basics," Agilent Technologies 2004
3. Agilent, "Application Note 1286-1, 8 Hints for Better Spectrum Analysis," Agilent Technologies 2005
4. Agilent, "Application Note 1391, 8 Hints for Better Millimeter-Wave Spectrum Measurements," Agilent Technologies 2001

Common instruments in the microwave lab

- Network analyzer



$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$



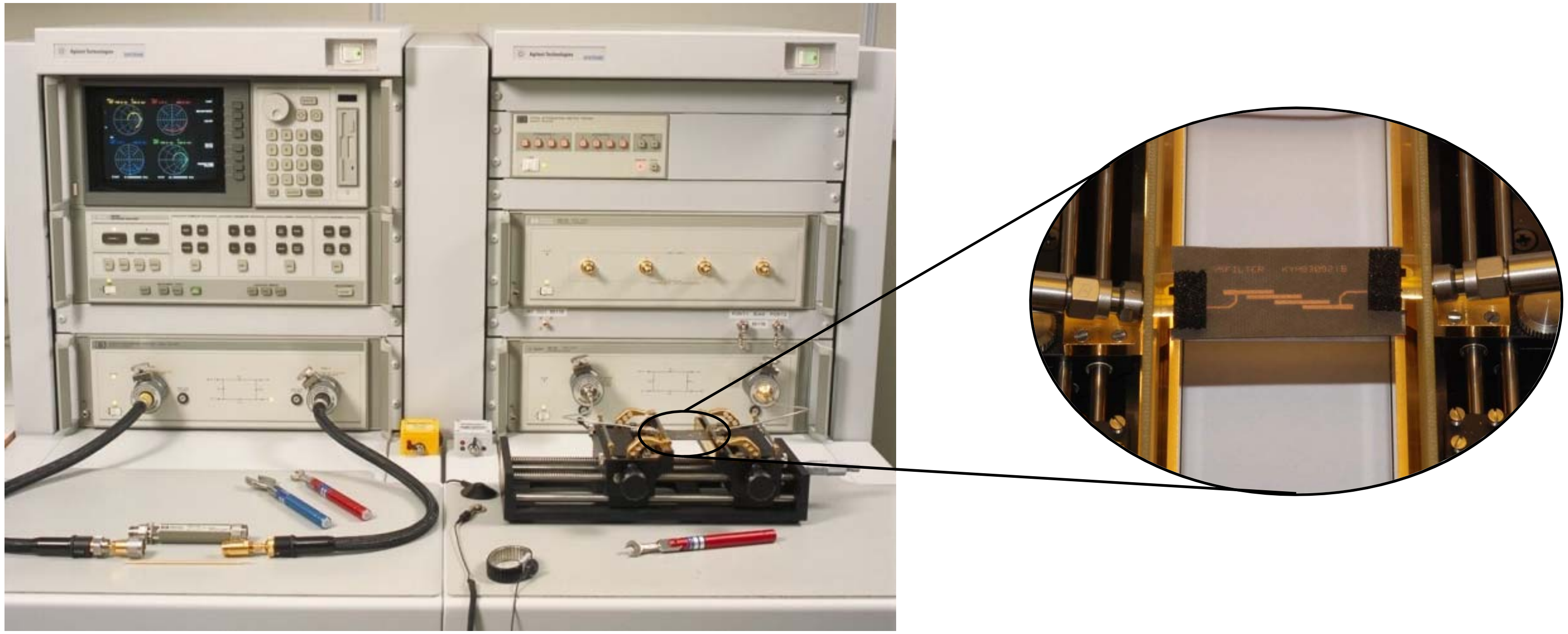
Network analyzer

- References

1. M. Hiebel, Fundamentals of Vector Network Analysis: Rhode & Schwarz, 2007.
2. B. Schiek, "Developments in Automatic-Network Analyzer Calibration Methods," in Review of Radio Science 1993-1996, W. R. Stone, Ed., 1996, pp. 115-155.
3. Agilent, "Applying error correction to network analyzer measurement," Agilent Technologies AN 1287-3, 2002.
4. Agilent, "Understanding the fundamental principles of VNAs," AN1287-1, 1997.
5. Agilent, "Network analyzer Measurements: Filter and amplifier examples," AN1287-4, 1997.

Vector Network Analyzer (VNA) Measurements

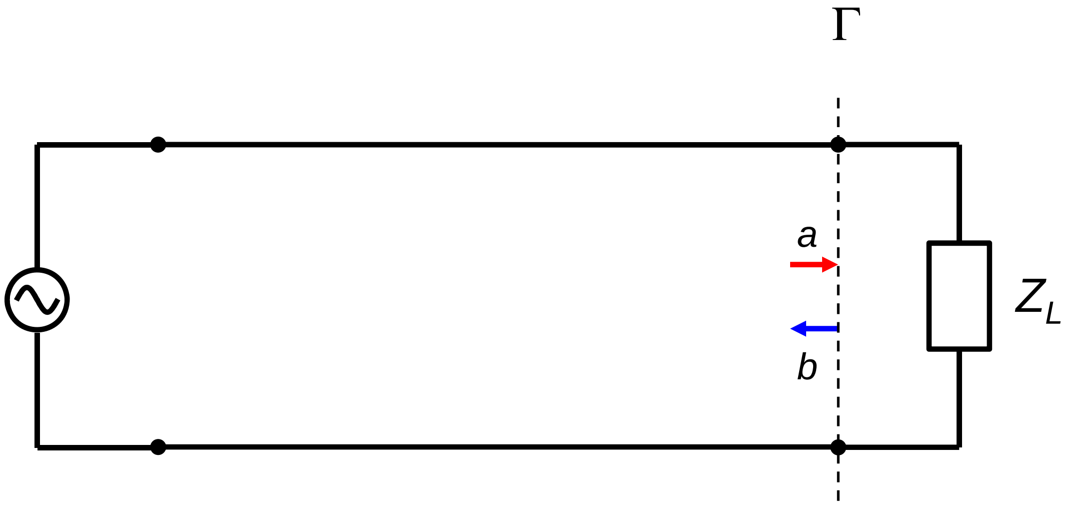
Klas Yhland and Jörgen Stenarson



Contents

- One-port measurements
    - SOL calibration algorithm
- Two-port measurements
    - SOLR calibration algorithm
    - TRL/LRL/LRM calibration algorithm
    - SOLT calibration algorithm
- Connecting your DUT
- Verifying your calibration
- Errors in the calibration
- Further reading

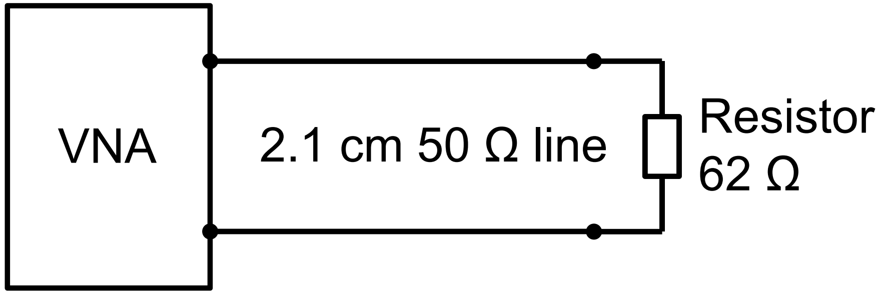
The measurement need



$$\Gamma = \frac{b}{a} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

What does a measurement look like?

- Uncorrected data



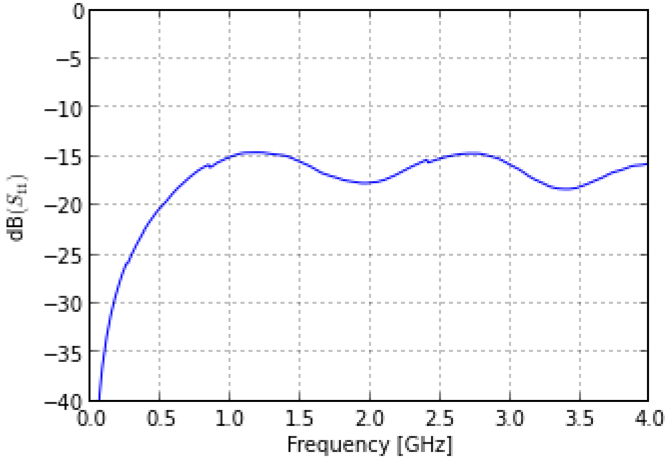
VNA

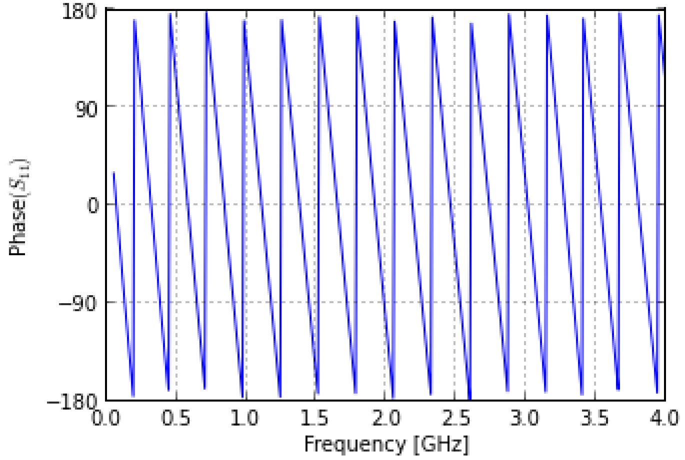
2.1 cm 50 Ω line

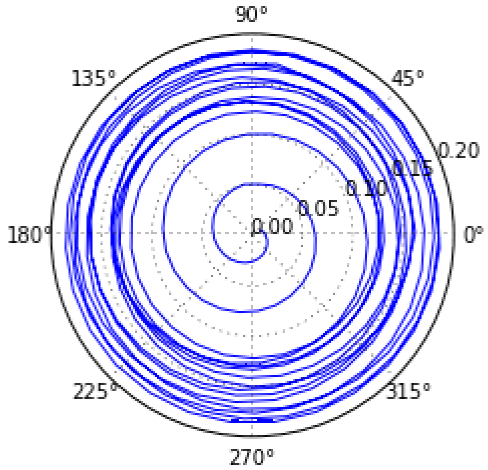
Resistor
62 Ω

62 Ω => |Γ| ≈ 0.11
RL ≈ -19 dB

2.1 cm = λ/4 @ ~3.6 GHz

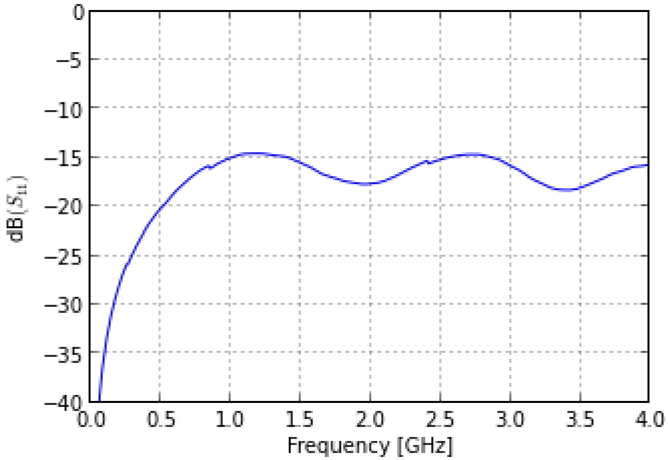


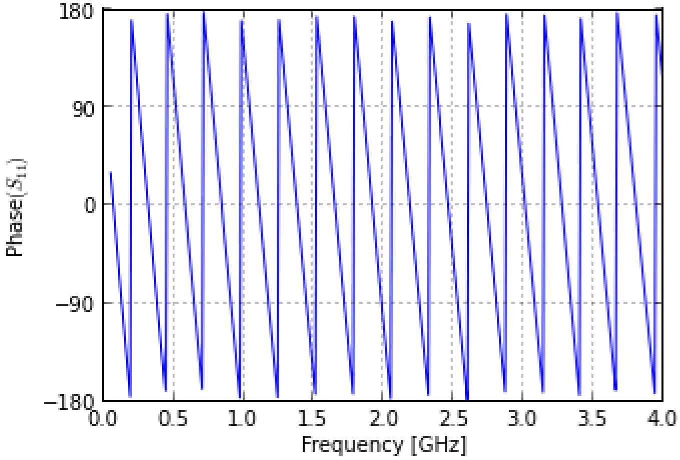


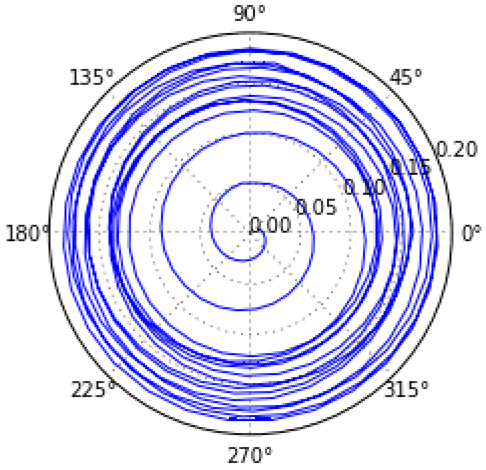


Measurement does not agree!

One-port network analyzer

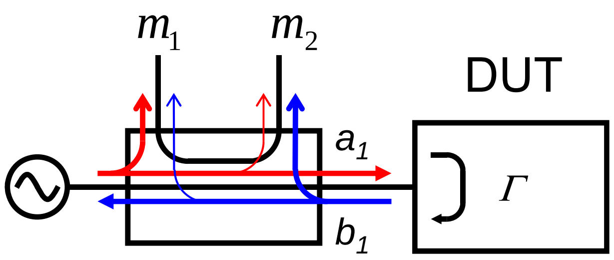






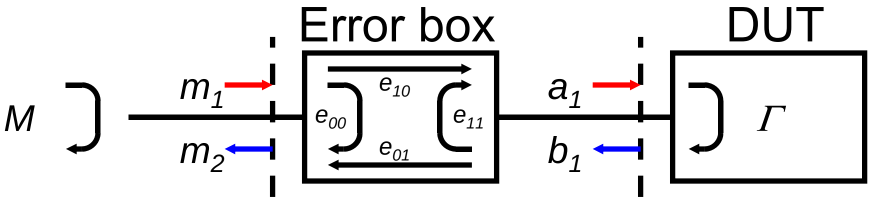
One-port network analyzer

Simple block diagram



$$\begin{pmatrix} m_1 \\ m_2 \end{pmatrix} = \begin{pmatrix} C_f & I_r \\ I_f & C_r \end{pmatrix} \begin{pmatrix} a_1 \\ b_1 \end{pmatrix}$$

Error model



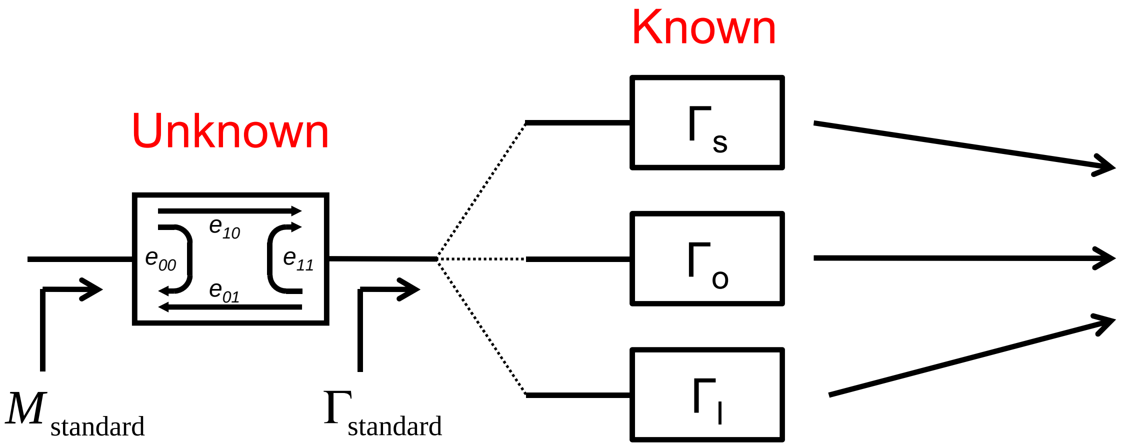
$$\begin{pmatrix} m_2 \\ a_1 \end{pmatrix} = \overbrace{\begin{pmatrix} e_{00} & e_{01} \\ e_{10} & e_{11} \end{pmatrix}}^{\text{S-parameters}} \begin{pmatrix} m_1 \\ b_1 \end{pmatrix}$$

$$M = \frac{m_2}{m_1} = e_{00} + \frac{e_{01} e_{10} \Gamma}{1 - e_{11} \Gamma}$$

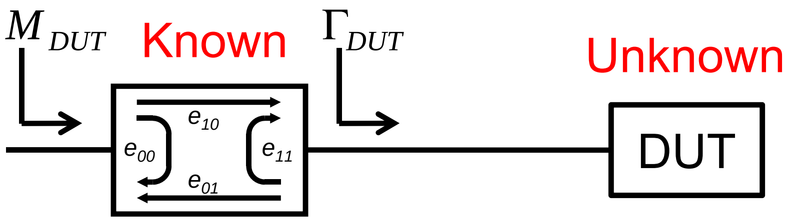
One-port calibration and measurement

- Three known standards are required to calibrate the one-port VNA
- Usually Short, Open, and Load

$$M = e_{00} + \frac{e_{01}e_{10}\Gamma}{1-e_{11}\Gamma}$$



$$\begin{pmatrix}1 & \Gamma_s M_s & -\Gamma_s \\ 1 & \Gamma_o M_o & -\Gamma_o \\ 1 & \Gamma_l M_l & -\Gamma_l\end{pmatrix}\begin{pmatrix}e_{00} \\ e_{11} \\ \det\mathbf{e}\end{pmatrix}=\begin{pmatrix}M_s \\ M_o \\ M_l\end{pmatrix}$$



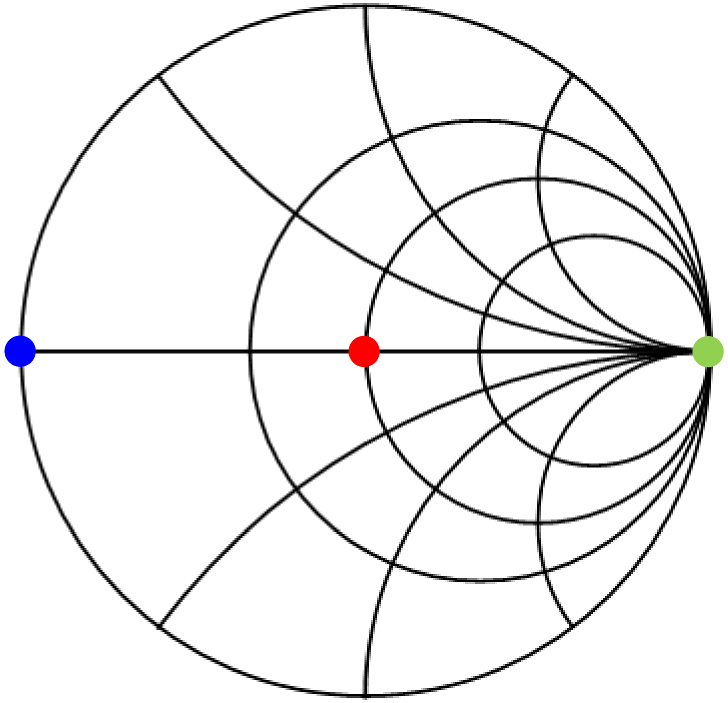
$$\Gamma = \frac{e_{00}-M}{\det\mathbf{e}-Me_{11}}$$

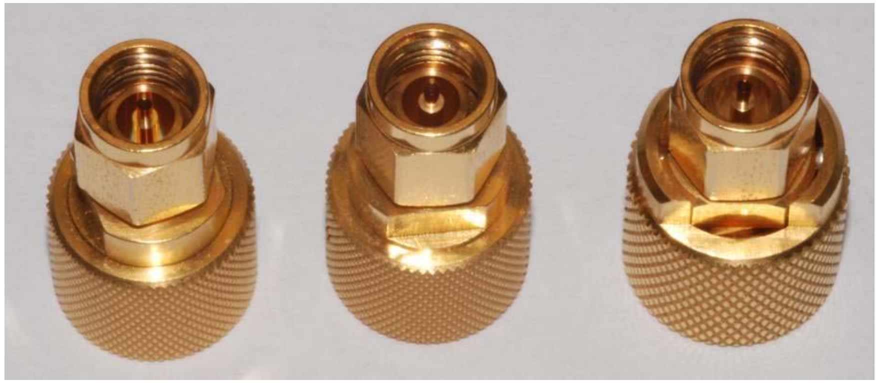
One-port VNA calibration – Short-Open-Load

- Three known standards (SOL) ⇒ determine three unknown error terms

- Short
- Open
- Load

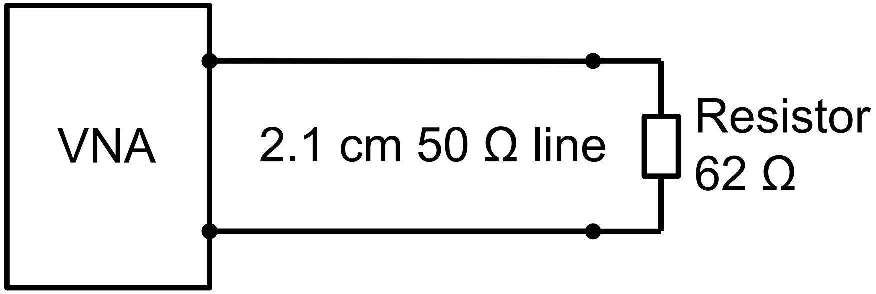
- Traditionally model based
- In modern VNAs also table based





What does a measurement look like?

- Corrected data



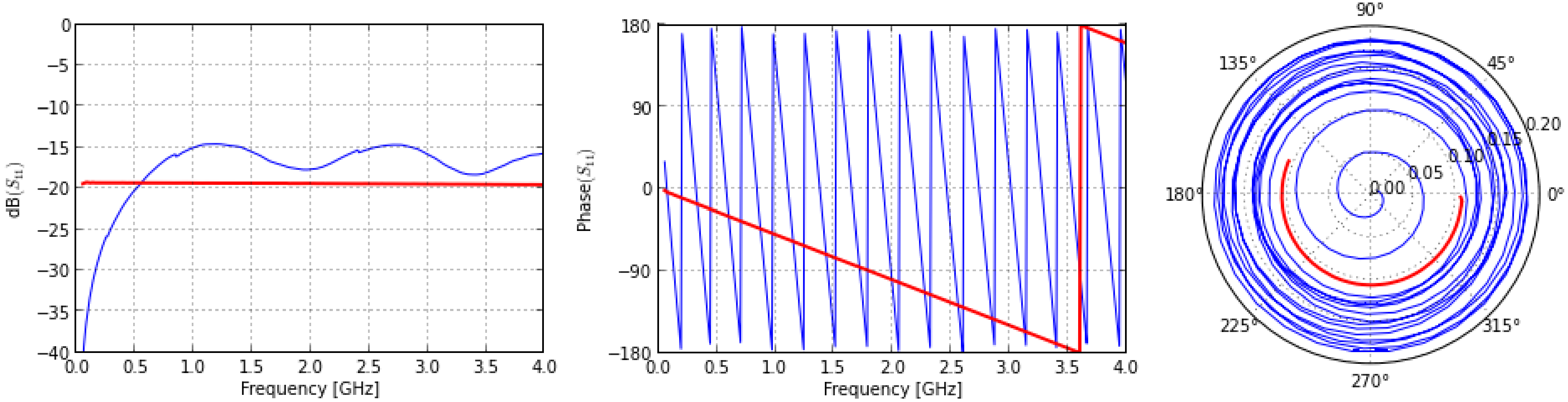
VNA

2.1 cm 50 Ω line

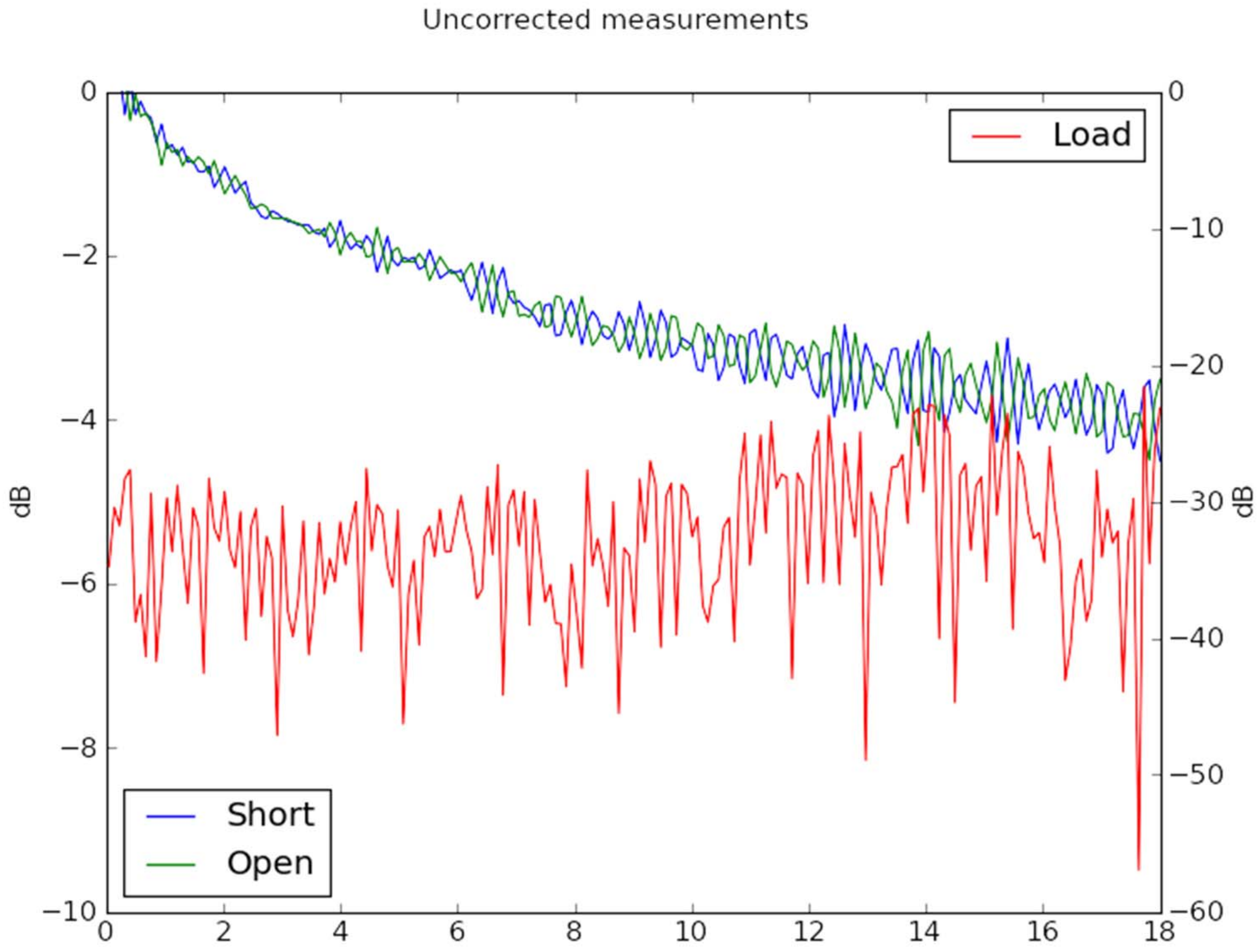
Resistor
62 Ω

62 Ω => |Γ| ≈ 0.11
RL ≈ -19 dB

2.1 cm ≈ λ/4 @ 3.6 GHz



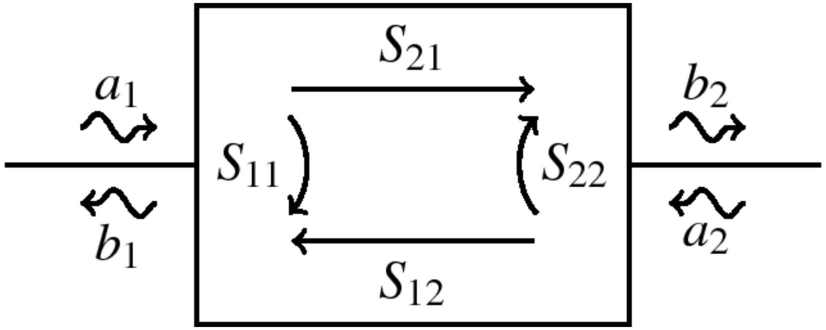
While doing calibration look at uncorrected measurements. What should we expect?



Corrected measurements

Contents

S-parameters



$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

- Transfer functions for incident and reflected waves at the ports
- Complex as a function of frequency
- Defined in relation to the system impedance

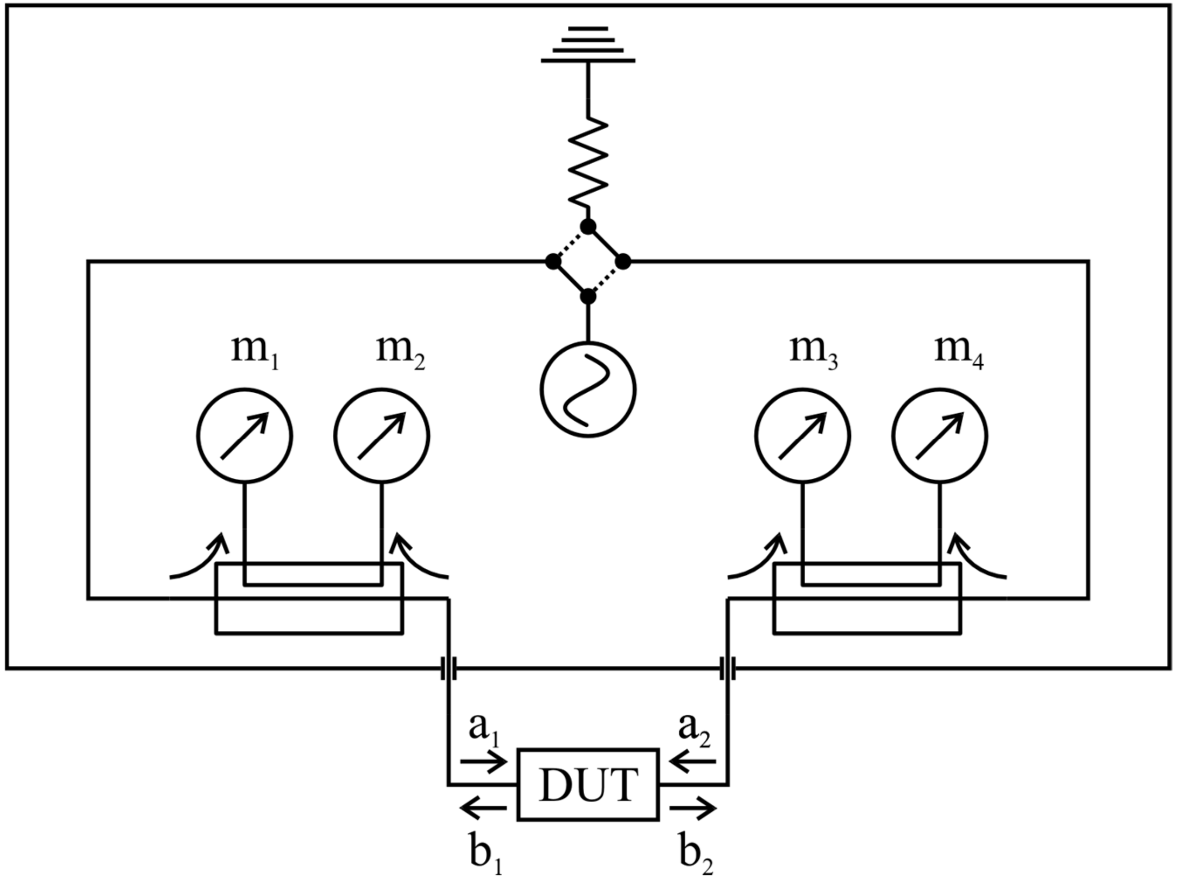
Four-sampler VNA block-diagram

$$m_1 \approx a_1$$

$$m_2 \approx b_1$$

$$m_3 \approx b_2$$

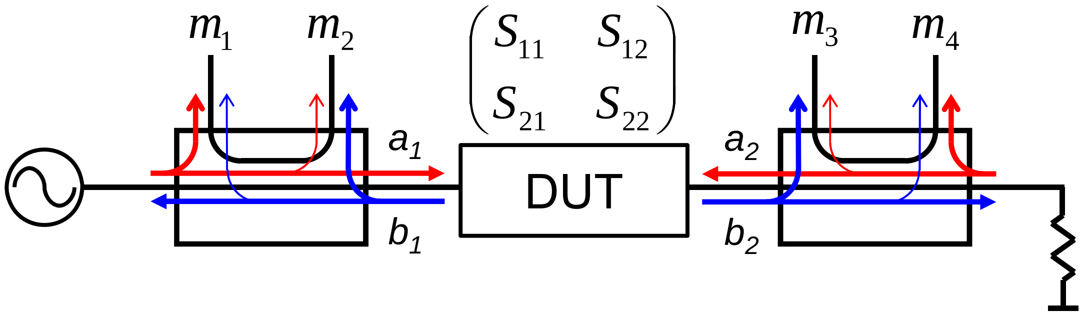
$$m_4 \approx a_2$$

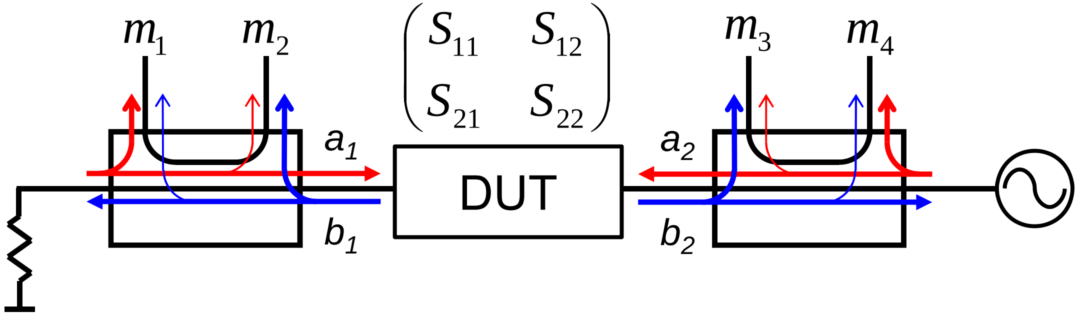


Ideal VNA

- Linear
- Noise less
- Perfect port match
- Perfect directivity
- Perfect switch isolation

Two-port measurements





Two-port measurements

Forward

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

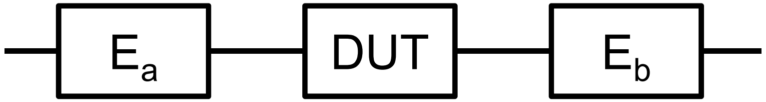
Reverse

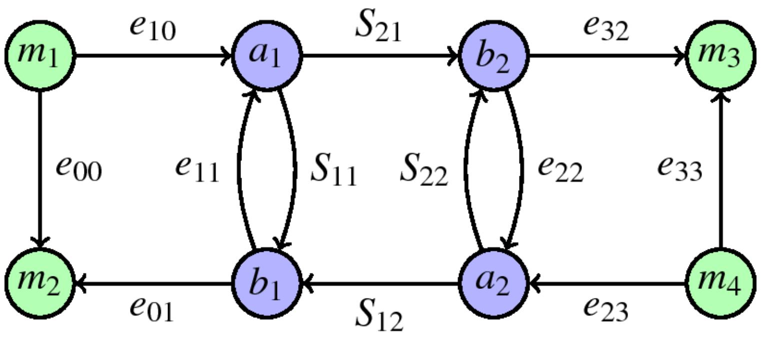
$$\begin{pmatrix} b_1' \\ b_2' \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1' \\ a_2' \end{pmatrix}$$

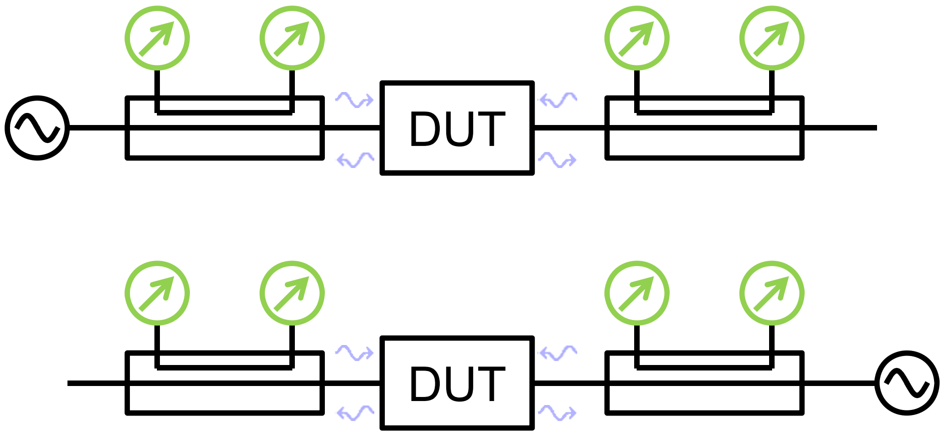
$$\begin{pmatrix} b_1 & b_1' \\ b_2 & b_2' \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 & a_1' \\ a_2 & a_2' \end{pmatrix}$$

$$\begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} = \begin{pmatrix} b_1 & b_1' \\ b_2 & b_2' \end{pmatrix} \begin{pmatrix} a_1 & a_1' \\ a_2 & a_2' \end{pmatrix}^{-1}$$

Eight (Seven) term error model



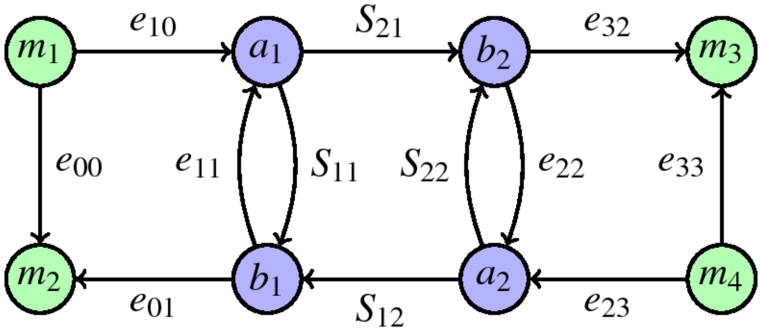




Four receivers
Two-port theory
Advanced calibration methods

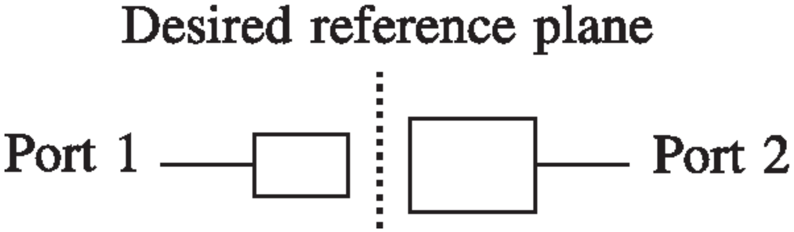
Unknown Thru (SOLR)

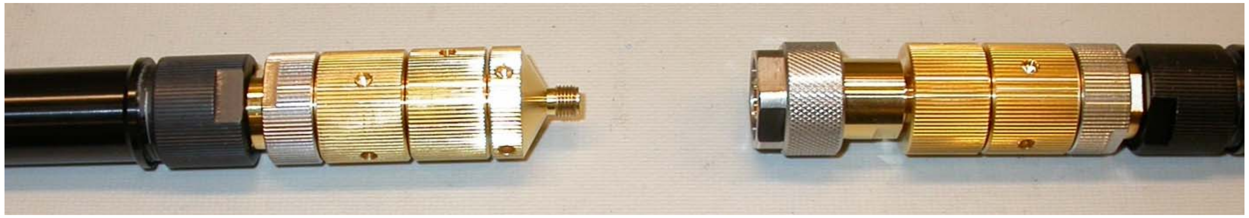
- Eight-term error model
- Same one-port calibrations as in SOL
- Only reciprocity is required of the Thru standard
- Load standard determines system impedance
- Not practical for on-wafer calibration



Non-mating connectors are easily handled by SOLR

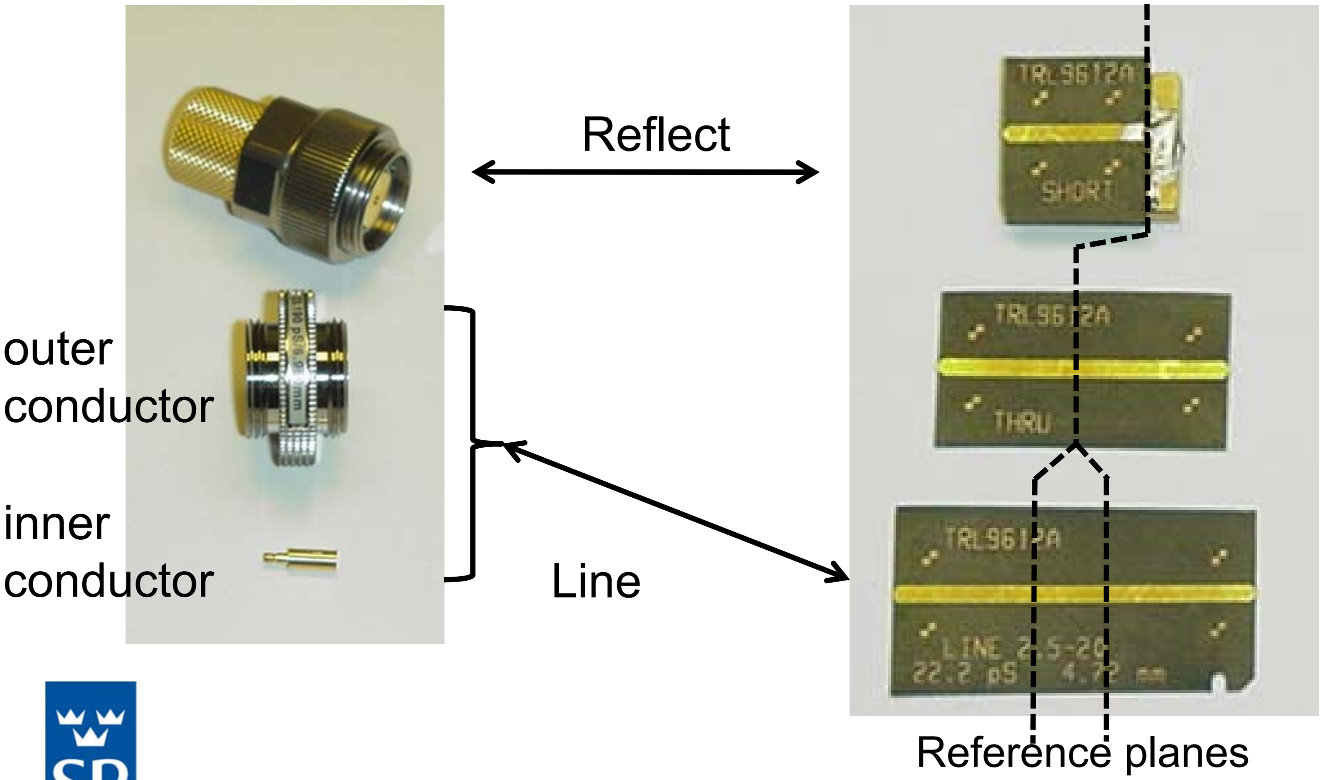
- Male – Male
- Female – Female
- Type-N – 3.5 mm
- Coaxial – planar
- Waveguide – coaxial





Thru Reflect Line (TRL/LRL/LRM)

- Self-calibration technique
- Well matched line or match standard
- Same reflect standard on both ports



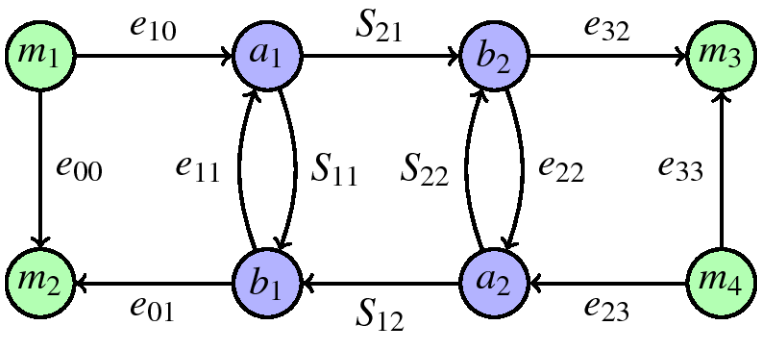
$$S^{\mathrm{Reflect}} = \begin{pmatrix} \Gamma_r & 0 \\ 0 & \Gamma_r \end{pmatrix}$$

$$S^{\mathrm{THRU}} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$S^{\mathrm{LINE}} = \begin{pmatrix} 0 & e^{-\gamma l} \\ e^{-\gamma l} & 0 \end{pmatrix}$$

Thru Reflect Line (TRL/LRL/LRM)

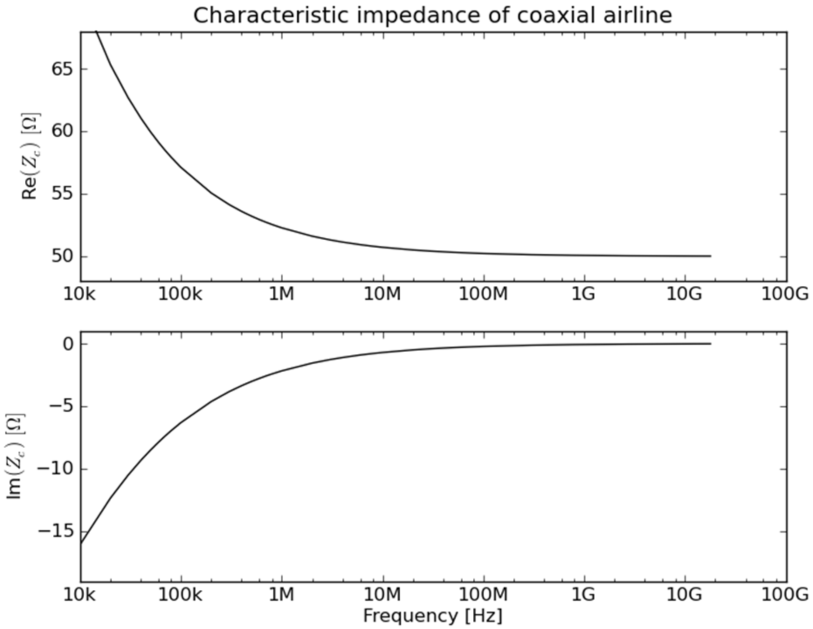
- Eight-term error model
- Good quality transmission line standards/Match standard
  - Line characteristic impedance sets system impedance
  - Electrical length (20°-160°), specify delay (ps)
- Equal reflection standards on each port
  - Approximate reflection within (known ±90°), specify delay and DC reflection
  - Non-equal reflect standards influence the reference plane positions
- Often easier to manufacture than SOL for planar and wave-guide circuits



Use LRM rather than TRL at low frequencies

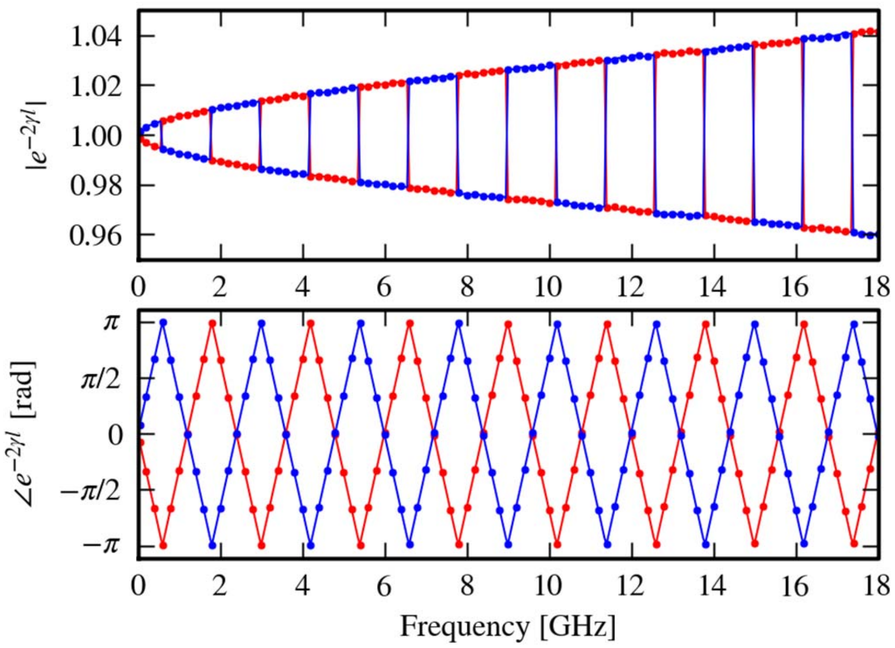
- The line standard becomes very long if it is to work at low frequencies
- When using TRL the system impedance is equal to the characteristic impedance of the Line standard
- The characteristic impedance of most delay lines deviates rapidly from 50 Ω at low frequencies due to skin effect

=> At low frequencies ~200 MHz, it is better to use LRM with a lumped load

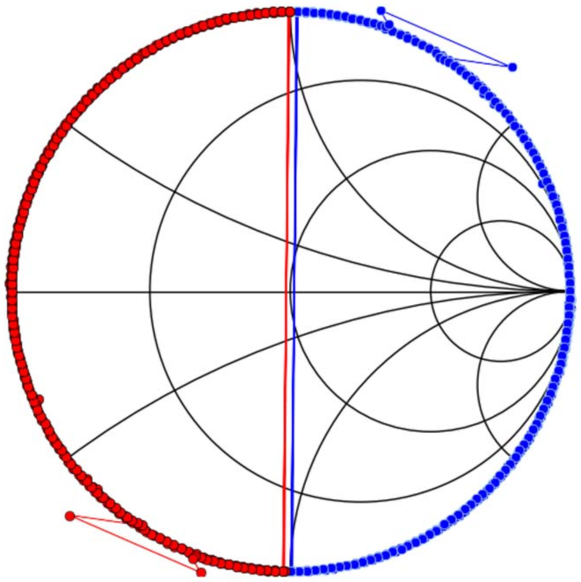


Root choice problem in TRL algorithm

Line

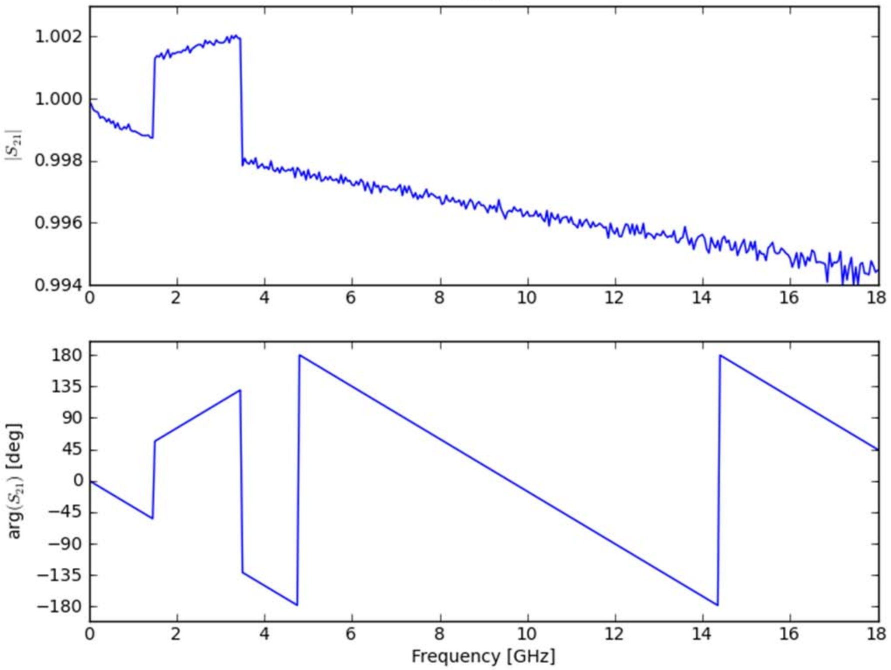


Reflect

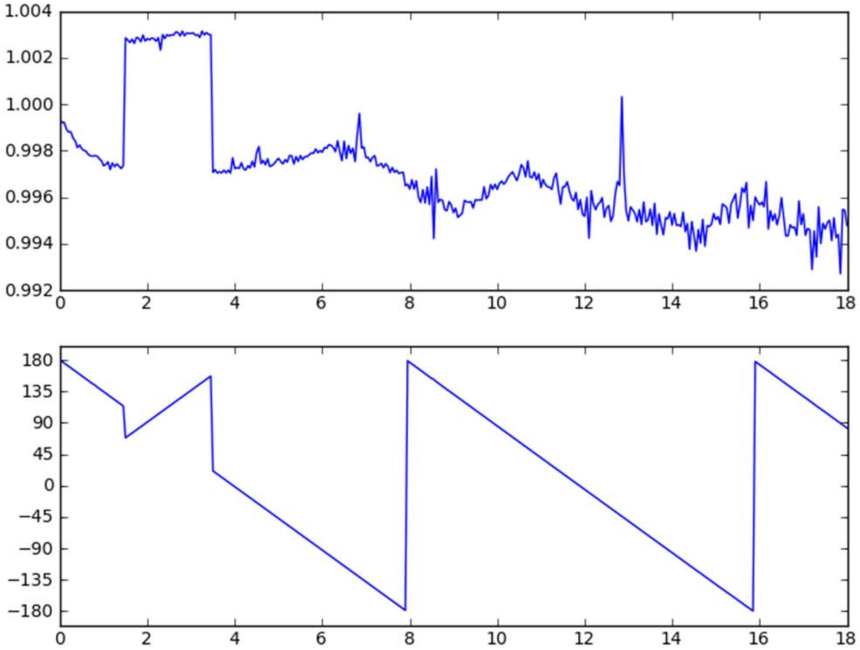


Erroneous root choice for Line standard

Measurement on Line



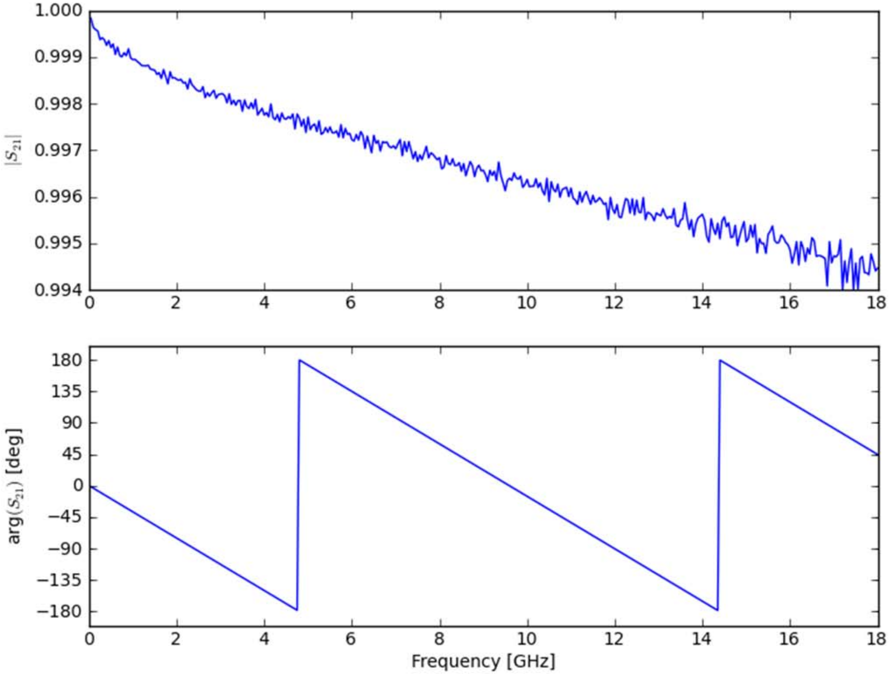
Measurement on Short



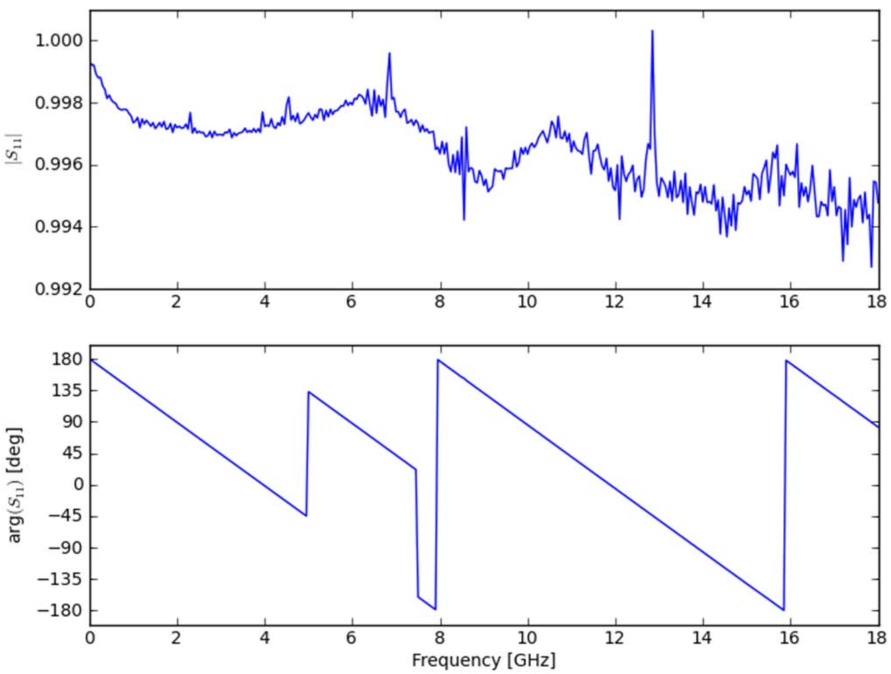
Change the delay specification of the Line standard

Erroneous root choice for Reflect standard

Measurement on Line



Measurement on Short



Change the offset delay specification of the Reflect standard

Three-sampler VNA block-diagram

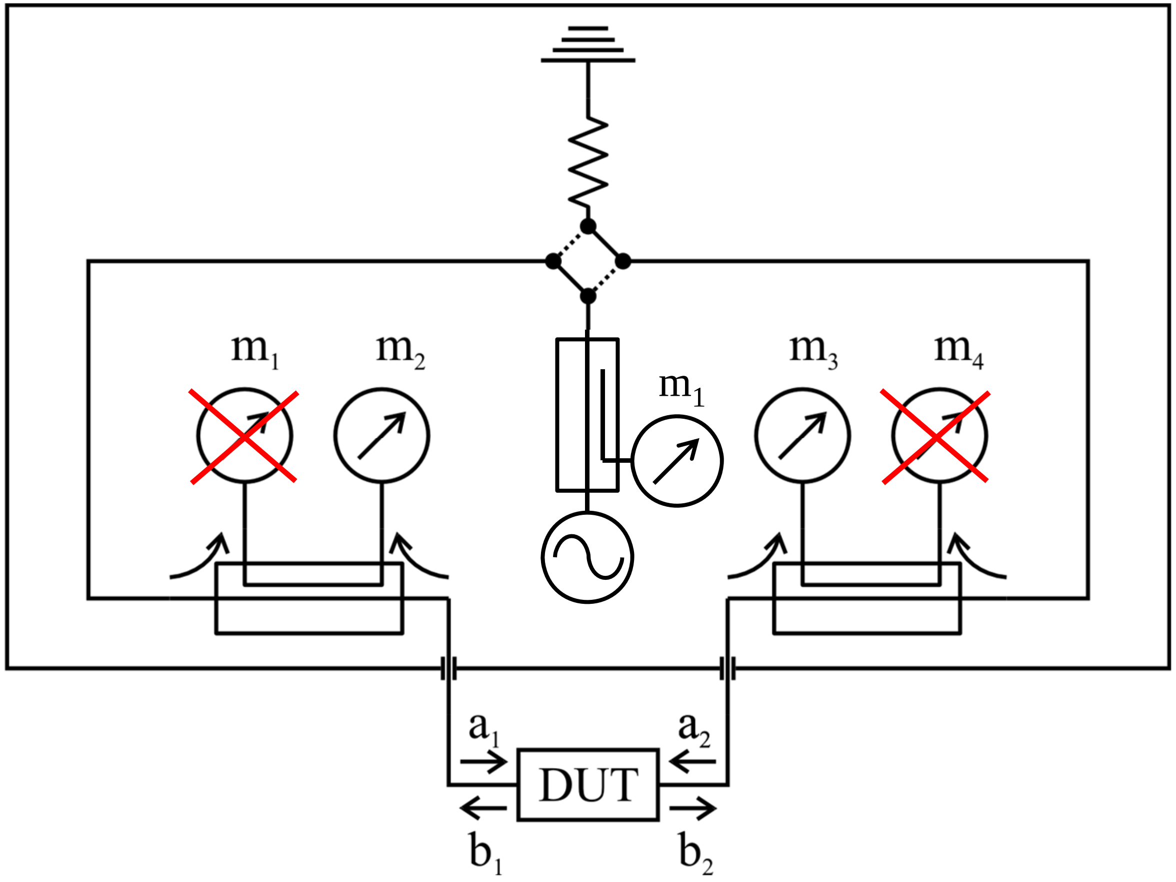
Three receivers: less expensive

$m_1 \approx a_1 \text{ or } a_2$

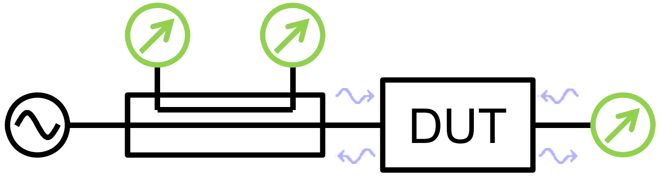
$m_2 \approx b_1$

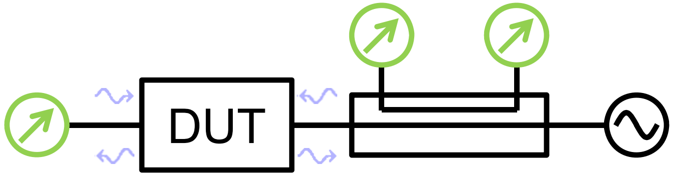
$m_3 \approx b_2$

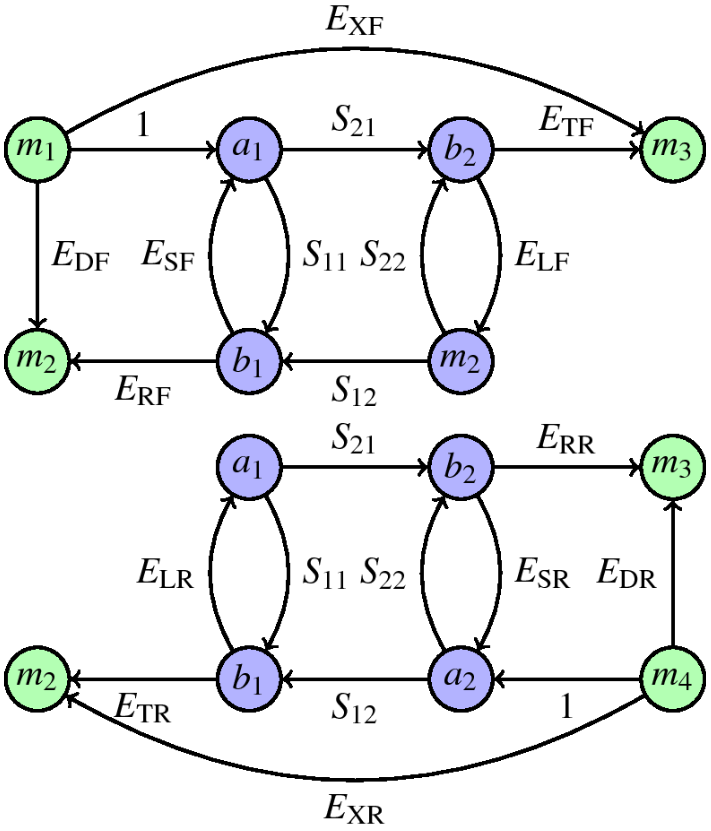
$\cancel{m_4 \approx a_2}$



Three sampler VNA / Twelve term error model



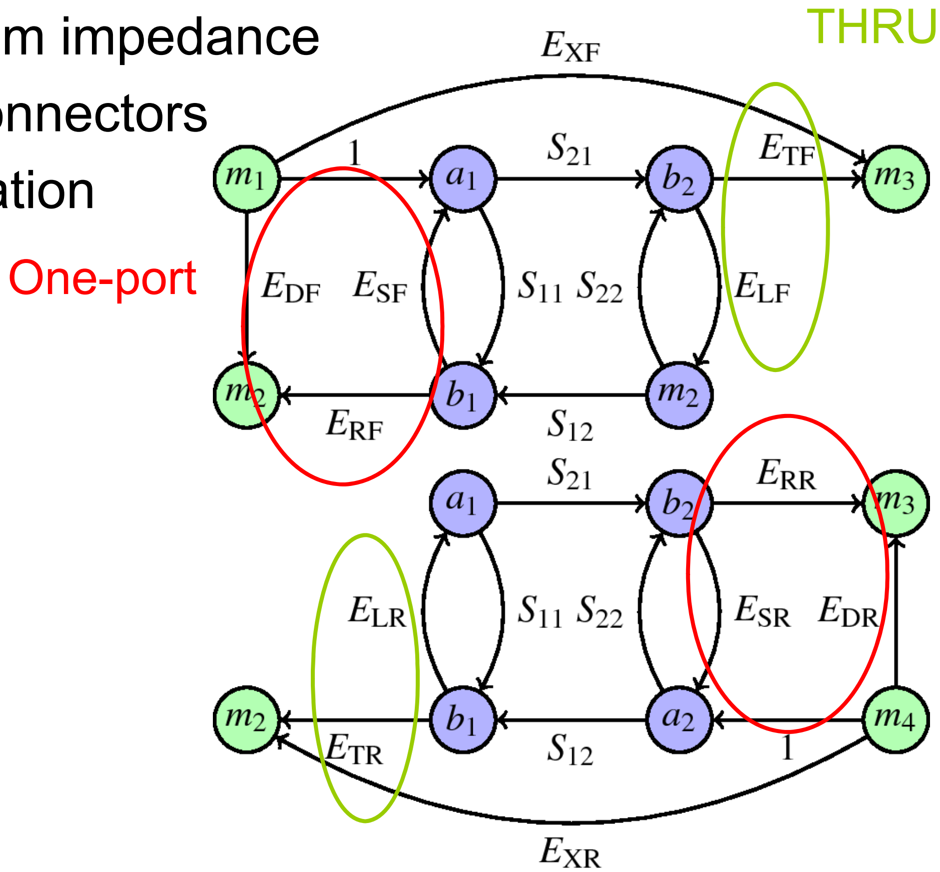




First solved by Stig Rehnmark from Chalmers:
Rehnmark, S.; , "On the Calibration Process of Automatic Network Analyzer Systems (Short Papers),"
Microwave Theory and Techniques, IEEE Transactions on , vol.22, no.4, pp. 457- 458, Apr 1974

Short Open Load Thru (SOLT)

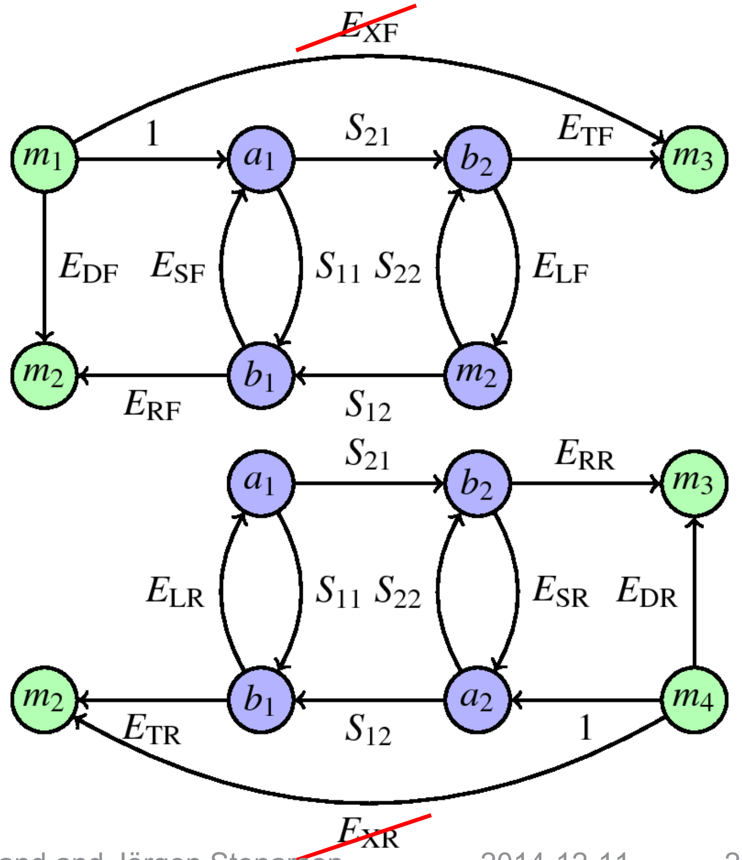
- Twelve term model
- Same one-port calibrations as in SOL
- Needs fully known standards
- Load standard determines system impedance
- Difficult to handle non-mating connectors
- Not practical for on-wafer calibration



The isolation calibration problem

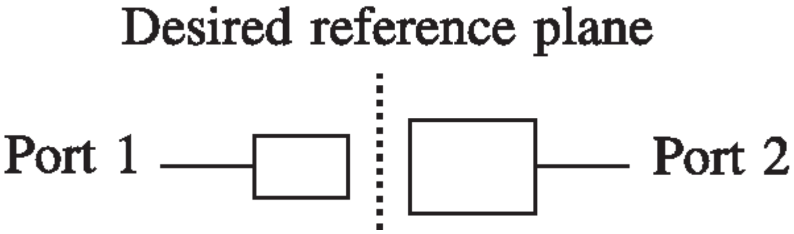
- The isolation term is rarely a good model of the leakage
- The isolation calibration step measures noise on a good VNA
- Need a sixteen term to model isolation properly

Skip the isolation term!!



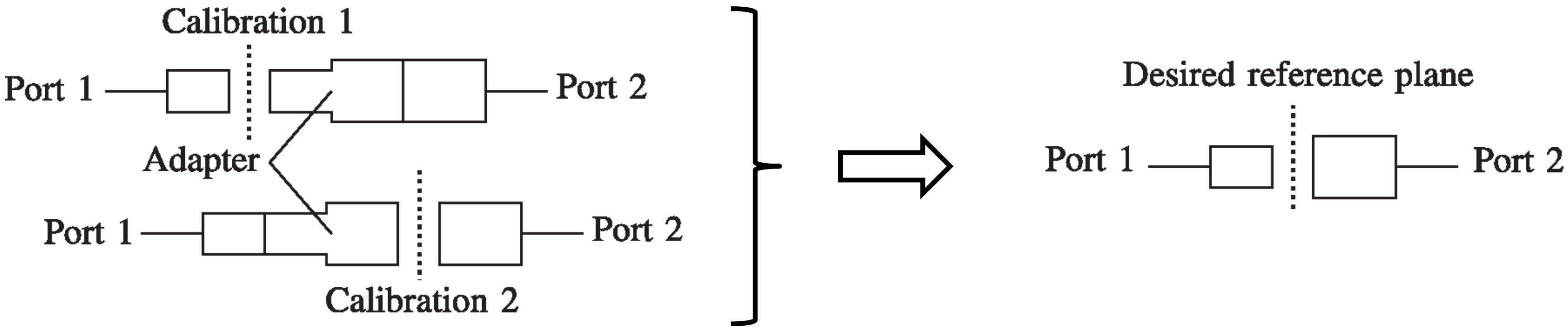
Non-mating connectors are a problem for SOLT

- Male – Male
- Female – Female
- Type-N – 3.5 mm
- Coaxial – planar
- Waveguide – coaxial



Adapter removal

- SOLT requires Thru connection
- Two full two-port calibrations are combined to get the final calset
  - Specify electrical length of adapter within 180°
  - Can be difficult to specify electrical length for waveguides
- Twice the work of a single calibration
- Sensitive to repeatability problems

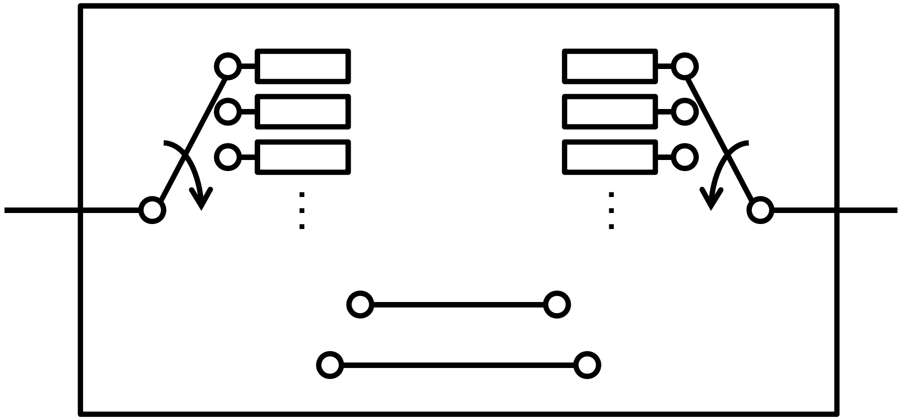


Summarized requirements on calibration standards

	SOLR	SOLT	TRL/LRL/LRM
One-port standards	Full model or measured data needed	Full model or measured data needed	Equal on both ports Phase known within 180°
Thru standard	Reciprocity assumed Known within 180°	Ideal Thru assumed	Transmission difference within 20°-160°
Line standard			
System impedance defined by	Load	Load	Line or Match
Reference planes defined by	Short and Open	Short, Open, and Thru	Reflect and Thru
Handles non-insertable devices	Yes, simple	Yes, tedious	No

Electronic calibration unit

- E-cal is faster, only one connection
- E-cal stores S-parameter table model internally, requires a modern VNA
- E-cal unit is locked to one manufacturer
- Only available in coaxial



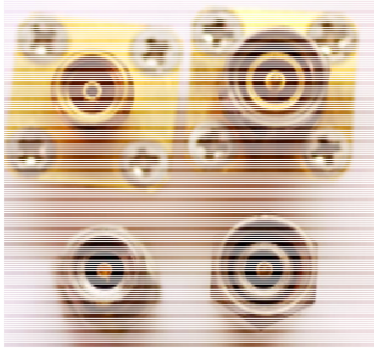
Contents

- One-port measurements
  - SOL calibration algorithm
- Two-port measurements
    - SOLR calibration algorithm
    - TRL/LRL/LRM calibration algorithm
    - SOLT calibration algorithm
- Connecting your DUT
- Verifying your calibration
- Errors in the calibration
- Further reading

Connecting your DUT, Coaxial

Connector types

SMA



3.5mm

2.92mm

2.4mm

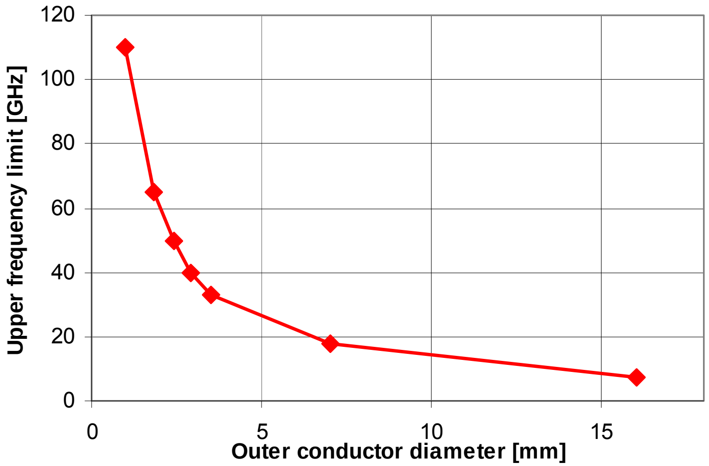
1.85mm

APC7

Type-N

Connecting your DUT, Coaxial

Preferred connectors



7/16	(16 mm)	0 – 7.5 GHz	
Type-N	(7 mm)	0 – 18 GHz	
APC-7	(7 mm)	0 – 18 GHz (do not tighten both nuts)	
SMA		0 – 18 (26.5) GHz (too long male pin)	Compatible
3.5 mm		0 – 26.5 (33) GHz	
2.92 mm (K)		0 – 40 (46) GHz	
2.4 mm		0 – 50 GHz	Compatible
1.85 mm (V)		0 – 65 GHz	
1 mm		0 – 110 GHz	

- Upper frequency limit is usually caused by first waveguide mode

Connecting your DUT, Coaxial

Fingers of slotted 2.4mm female connector

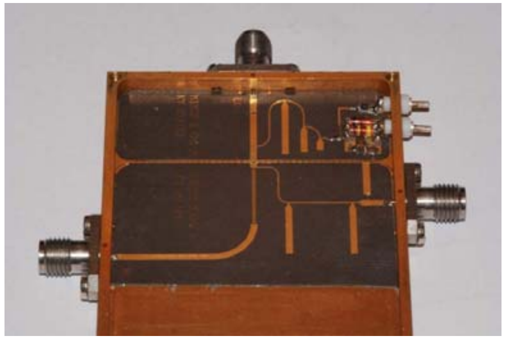
Connecting your DUT, Coaxial
Damaged fingers of slotted 2.92mm female connector

Connecting your DUT, Coaxial

Making connection

- Inspect connectors before mating, do not use damaged connectors
- Align connectors before mating
- Use fingers to pre-tighten the nut
- Only rotate nut – Do NOT rotate connector body
- Use proper torque wrench to do final tightening
- Use spanners to hold body in place while torquing

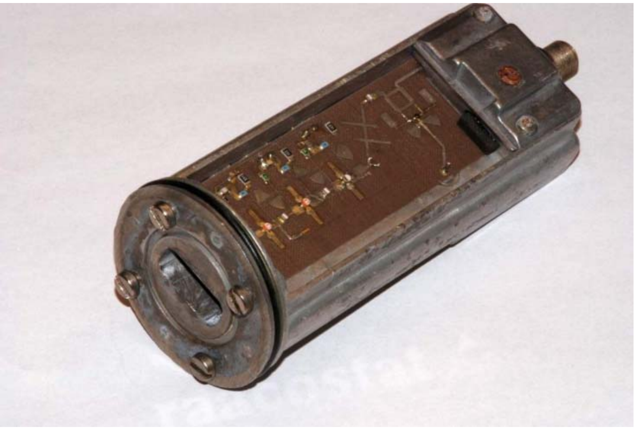
Connecting your DUT, Coaxial

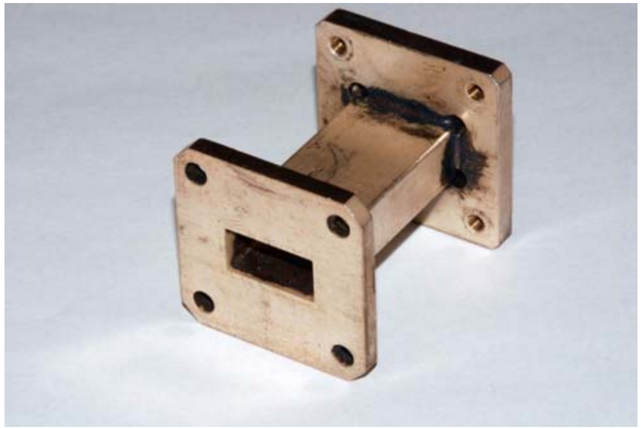


- Preferred calibration kits
  - Electronic calibration units (most convenient)
  - Short-Open-Load (easiest to use of the mechanical kits)
  - Short-Open-Sliding load (more difficult to handle)
  - TRL (most difficult to handle, fragile)
- Hints
  - The reference plane will be at the connector interface and not in the circuit
  - For some VNAs and calibration kits when the dialog says "male short" it refers to a female <u>short</u> connected to a <u>male</u> test port ☺ Check the manual and the cal kit definition in the VNA.
  - Avoid SMA (one-time connectors with a too long male centre pin which easily damages compatible 3.5 mm and 2.92 mm connectors)
  - Avoid BNC, TNC, SMB… (no calibration kits available, reference planes are unclear)

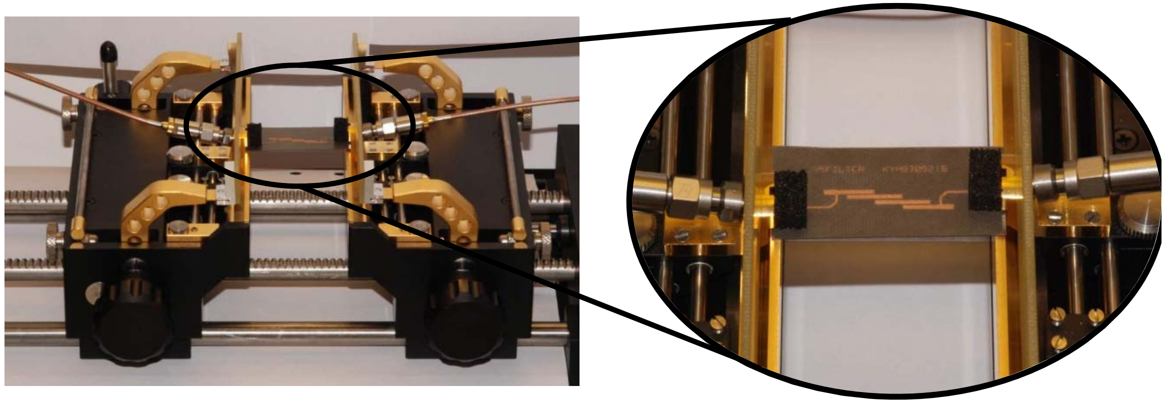
Connecting your DUT, Waveguide

- Preferred waveguides
  - Any standard waveguide (well established up to 110 GHz)
- Preferred calibration kits
  - TRL (many commercially available kits)
- Hints
  - Use all screws in the flange
  - The reference plane will be at the waveguide interface and not in the circuit



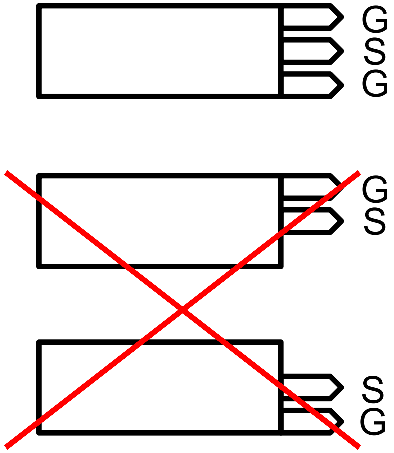


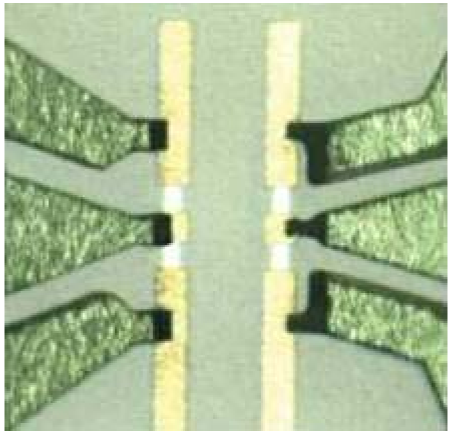
Connecting your DUT, substrate fixture

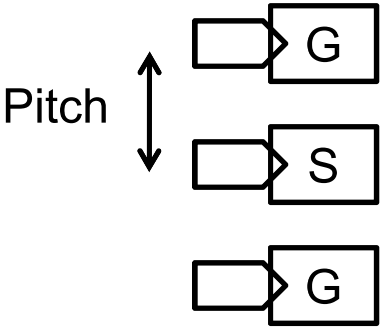


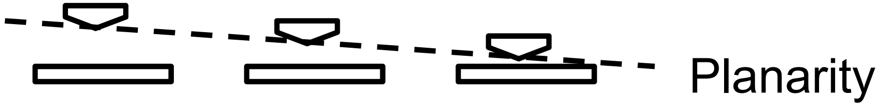
- Fixtures
  - Anritsu/Wiltron
  - Rosenberger
  - Maury
  - Focus
- Preferred calibration kits
  - TRL (easiest to manufacture but has to be made on the same substrate type as the DUT)
- Hints
  - Adapt your circuits to fit the fixture, read the manual.
  - The report [13] contains many valuable hints for the Anritsu 3680 fixture
  - The reference plane will be at the reference plane of your TRL kit
  - Repeatable connections are essential
  - Commercial fixtures may seem expensive but home made ones require much effort before they perform just half as well as commercial ones

Connecting your DUT, on-wafer probe




GSG probes connected to standards

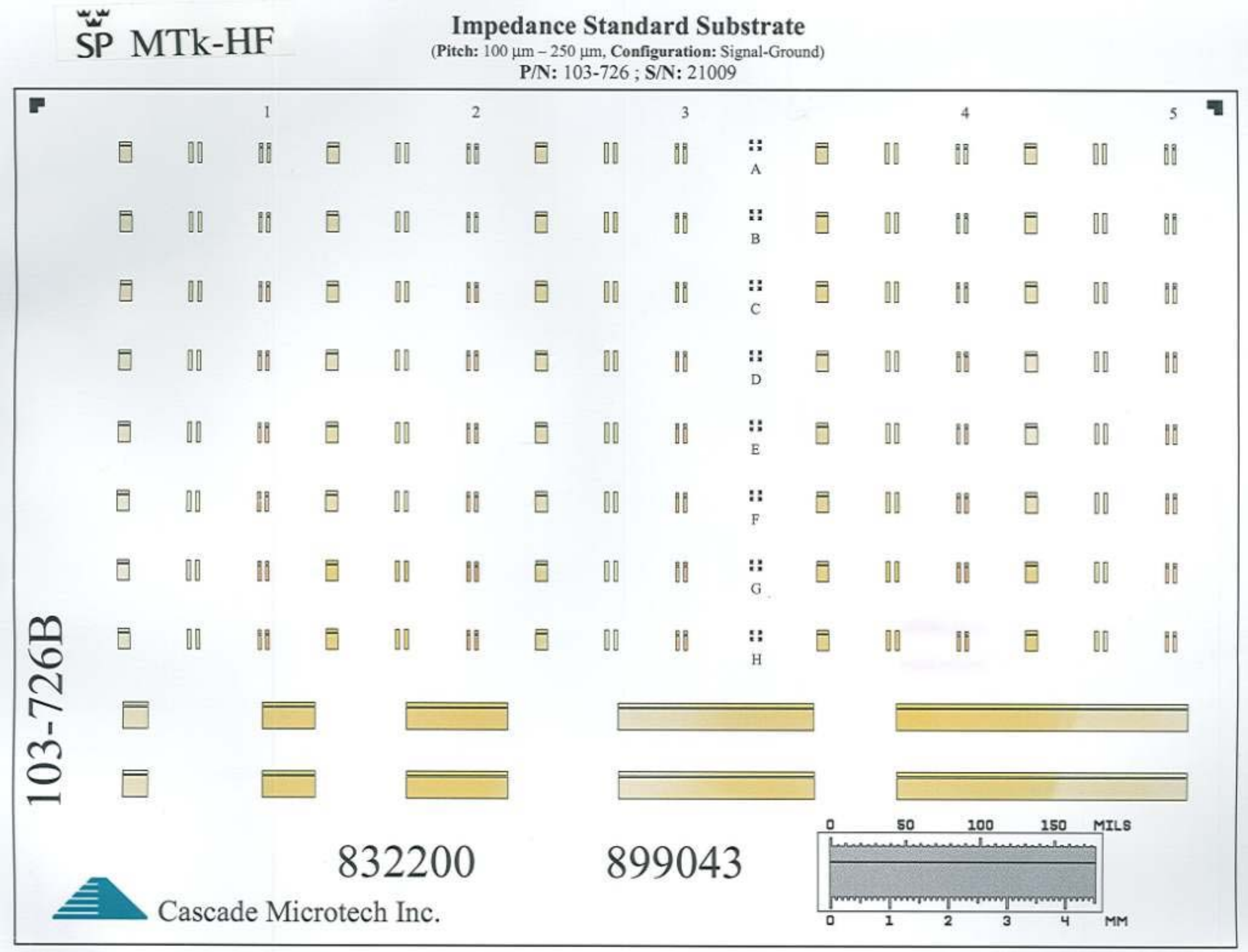




Connecting your DUT, on-wafer probe

- Preferred probes
  - GSG probes with appropriate pitch
- Preferred calibration kits
  - TRL kit on the same wafer as the DUT
  - LRM alumina standard substrate from probe manufacturer. (DUT and calibration kit substrates have to be equal. Match relies on laser trimmed load)
- Hints
  - Using a standard substrate the reference plane will be at the probe tips
  - Always use the same approach to set down the probes to get consistent results
  - Always look in the microscope when moving the probes, there is no standard way to turn the probe manipulators to lift the probes
  - Avoid needle probes (good for low frequency measurements)
  - Avoid GS probes (Ground-Signal) (good for lower microwave region)

Impedance standard substrate



Contents

- One-port measurements
  - SOL calibration algorithm
- Two-port measurements
    - SOLR calibration algorithm
    - TRL/LRL/LRM calibration algorithm
    - SOLT calibration algorithm
- Connecting your DUT
- Verifying your calibration
- Errors in the calibration
- Further reading

Verifying your calibration

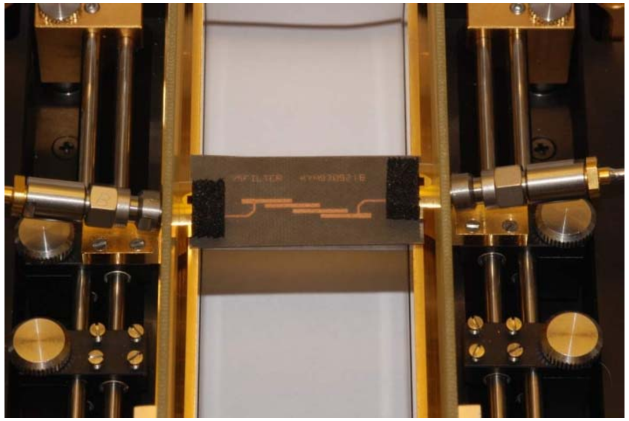
- Re-measure calibration standards. Reconnect devices!
- Measure a known device
- Measure a simple computable device
  (high/low impedance line)
- Measure long line standards
  - low S_{11} & S_{22}
  - S_{12} & S_{21} should be equal and have low ripple

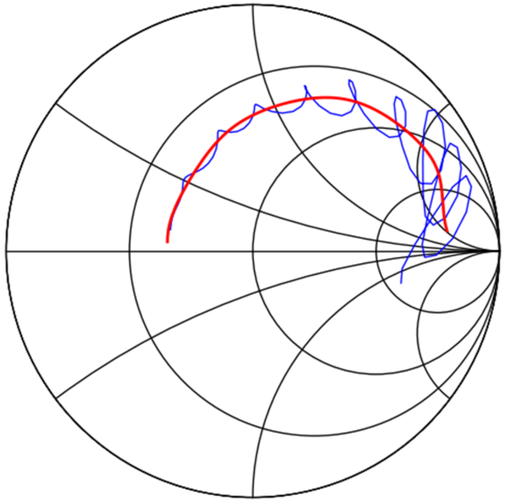
Contents

- One-port measurements
  - SOL calibration algorithm
- Two-port measurements
  - SOLR calibration algorithm
  - TRL/LRL/LRM calibration algorithm
  - SOLT calibration algorithm
- Connecting your DUT
- Verifying your calibration
- Errors in the calibration
- Further reading

Connection repeatability

- Use prescribed tools to do connections
  - Torque wrenches for coaxial connectors
  - All screws for waveguide flanges
- In fixtures
  - To succeed in the removal of the coax – microstrip transition we need very good repeatability





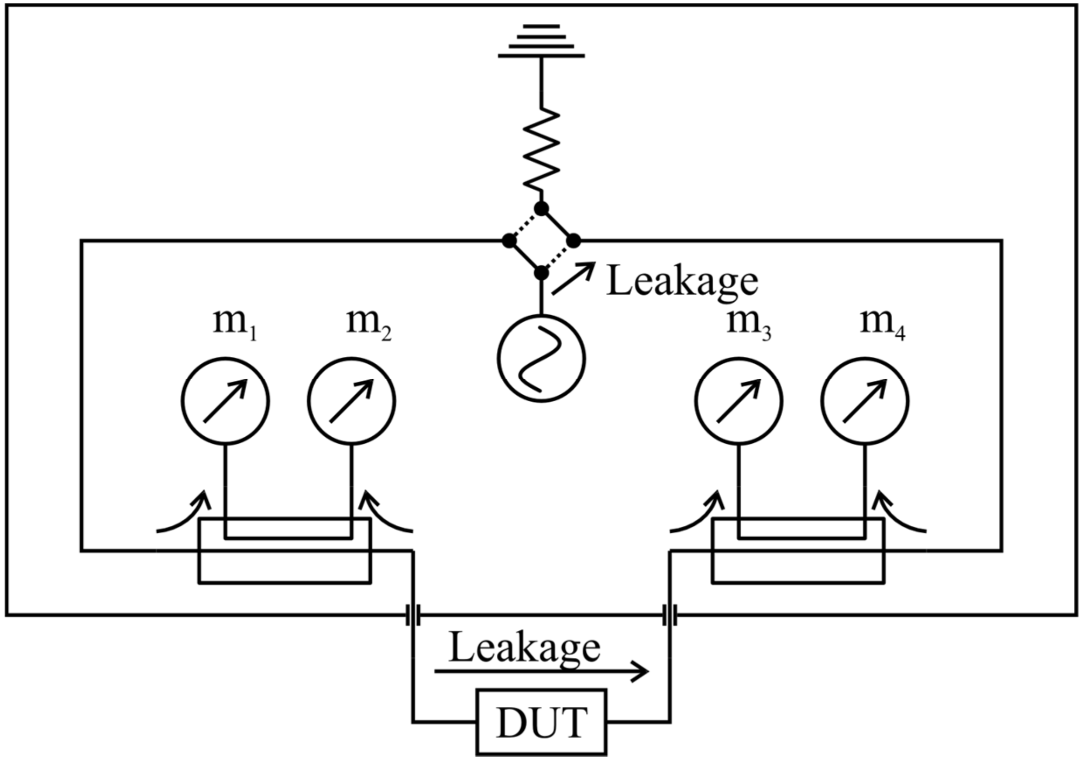
1-21 GHz, Measurement of a resistor
Red – Good transition repeatability
Blue – Bad transition repeatability

Cable flex

- Many flexible cables have poor phase and amplitude stability
- Even expensive VNA testport cables can be damaged and show poor phase and amplitude stability
- When measurements are erratic and change a lot when you touch the setup, bad cables or loose connections may be the cause

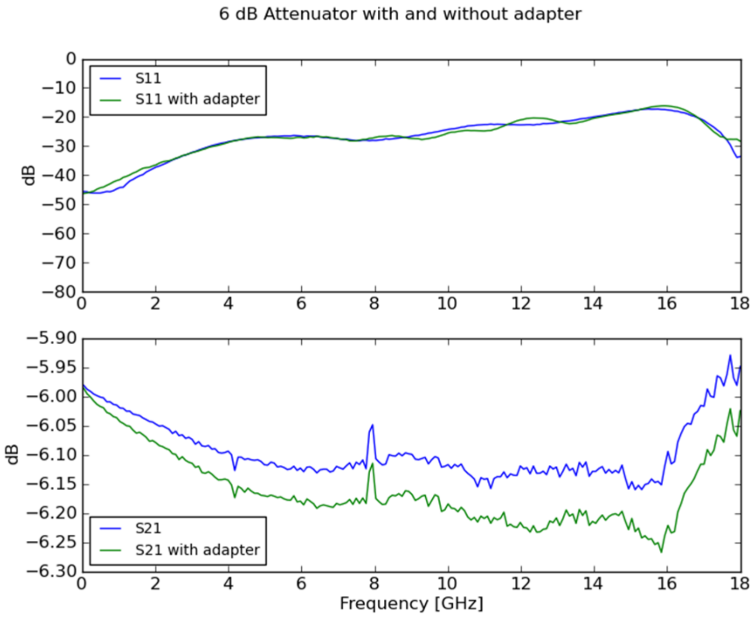
Isolation

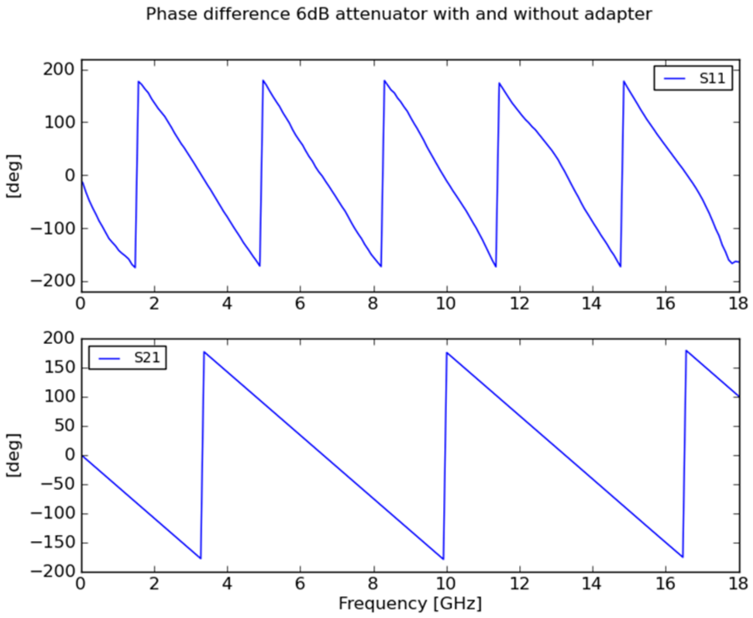
- Internal switch can leak signal to the opposite port
- Leakage between the test ports
  - No problem for coaxial
  - Problems for open structures, e.g. MMICs or microstrip substrates



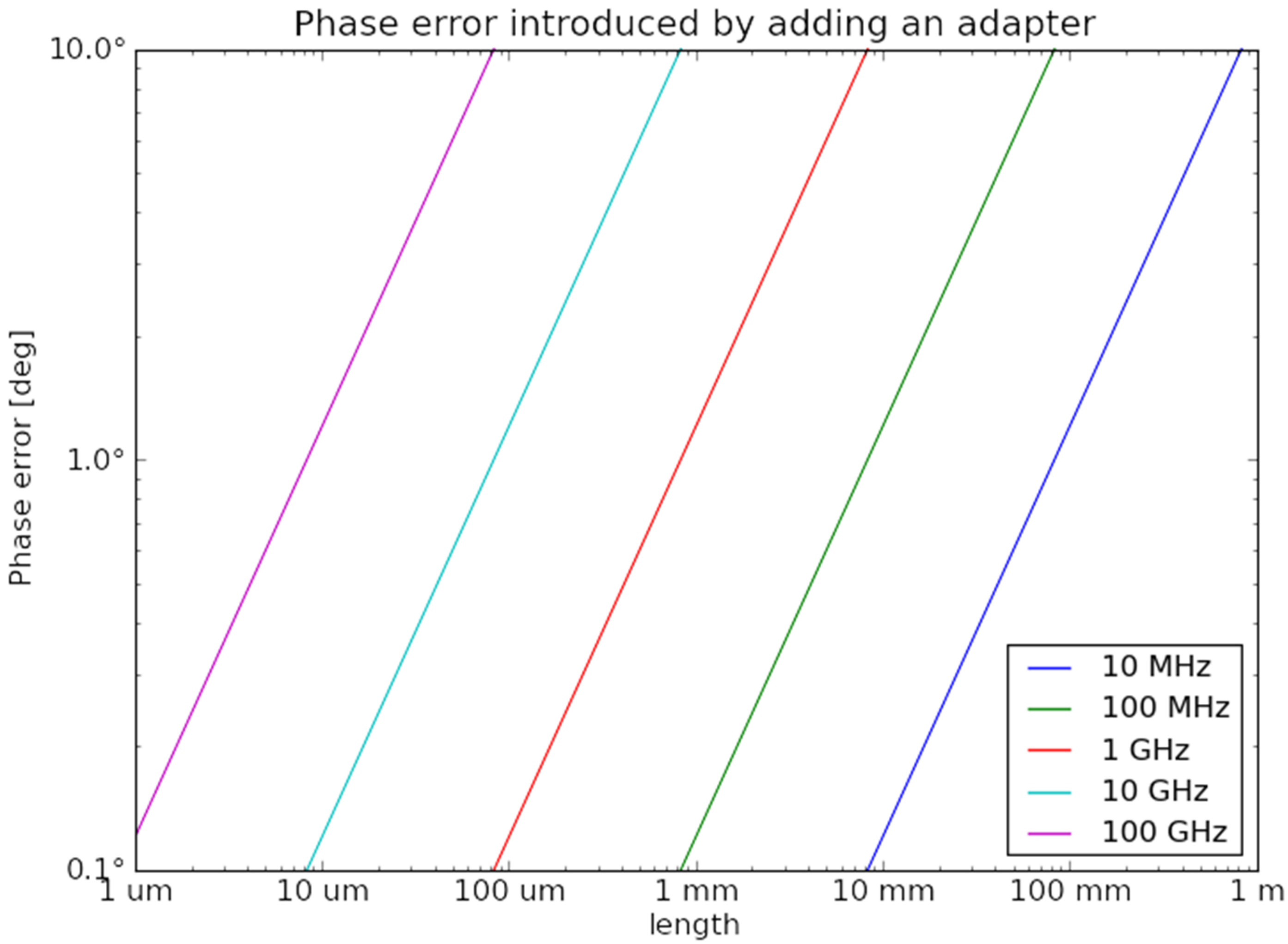
Using adapters after calibration, measurement on a 6 dB attenuator

- Phase errors
- Mismatch errors
- Amplitude errors





Adapter phase error graph



Dynamic range

- Mostly a problem for transmission measurements
  - Noise floor and isolation limits the maximum attenuation that can be measured
  - Non-linearities/compression limits the maximum gain (remember that both the VNA and the DUT can be non-linear)
- Rarely a problem for reflection
  - Directivity is the main limitation which limits the requirements for high dynamic range for reflection measurements

Contents

- One-port measurements
  - SOL calibration algorithm
- Two-port measurements
    - SOLR calibration algorithm
    - TRL/LRL/LRM calibration algorithm
    - SOLT calibration algorithm
- Connecting your DUT
- Errors and verification of the calibration
- Further reading

Further reading (1)

VNA calibration basics

[1] M. Hiebel, Fundamentals of Vector Network Analysis: Rhode & Schwarz, 2007.

[2] B. Schiek, "Developments in Automatic-Network Analyzer Calibration Methods," in Review of Radio Science 1993-1996, W. R. Stone, Ed., 1996, pp. 115-155.

[3] Agilent, "Applying error correction to network analyzer measurement," Agilent Technologies AN 1287-3, 2002.

[4] Agilent, "Understanding the fundamental principles of VNAs," AN1287-1, 1997.

[5] Agilent, "Network analyzer Measurements: Filter and amplifier examples," AN1287-4, 1997.

Advanced VNA calibration

[6] Agilent, "Specifying calibration standards for the agilent 8150 network analyzer," Agilent Technologies AN 8510-5B, 2006.

[7] Agilent, "Calibration - Measuring Noninsertable Devices," Agilent Technologies AN 8510-13 2000.

Postprocessing

[8] Agilent, "Time Domain Analysis Using a Network Analyzer," Agilent Technologies AN1287-12, 2007.

[9] J. Stenarson and K. Yhland, "Uncertainty Propagation Through Network Parameter Conversions," IEEE Transactions on Instrumentation and Measurement, vol. 58, no. 4, pp. 1152-1157, April 2009.

Further reading (2)

Connectors

[10] Agilent, "Coaxial Systems: Principles of Microwave Connector care," Agilent Technologies AN 326, 1988.

[11] Agilent, "Connector Care Quick Reference Card," Agilent Technologies 2006.

Fixtures

[12] Agilent, "TRL for non-coaxial measurements," Agilent Technologies AN8510-8A, 2001.

[13] K. Yhland, "Measuring in-fixture S-parameters, Mixer Conversion Efficiency and Mixer Intermodulation" Paper F in K. Yhland, "Resistive FET mixers,“ Ph D Thesis, Chalmers University of Technology, 1999.

Further reading (3)

S-parameter definitions

[14] R. Collin, Foundations for microwave engineering, McGraw Hill series in electrical engineering: McGraw-Hill, 1992.

[15] R. A. Speciale, "Derivation of the generalized scattering parameter renormalization transformation," in IEEE Internat. Symp. on Circuits and Systems, Houston, Tx, 1980, pp. 166-169.

[16] R. B. Marks and D. F. Williams, "A General Waveguide Circuit Theory," Journal of Research of the National Institute of Standards and Technology, vol. 97, no. 5, pp. 533-561, 1992.

[17] K. Kurokawa, "Power Waves and the Scattering Matrix," IEEE Transactions on Microwave Theory and Techniques, vol. 13, no. 2, pp. 194-202, Mar. 1965.

[18] D. A. Frickey, "Conversion Between S, Z, Y, h, ABCD, and T parameters which are valid for complex source and load impedances," IEEE Transactions on Microwave Theory and Techniques, vol. 42, no. 2, pp. 205-211, 1994.

[19] D. F. Frickey, "Reply to comments on 'Conversion Between S, Z, Y, h, ABCD, and T parameters which are valid for complex source and load impedances'," IEEE Transactions on Microwave Theory and Techniques, vol. 43, no. 4, p. 915, 1995.

The End

Thank you for your attention