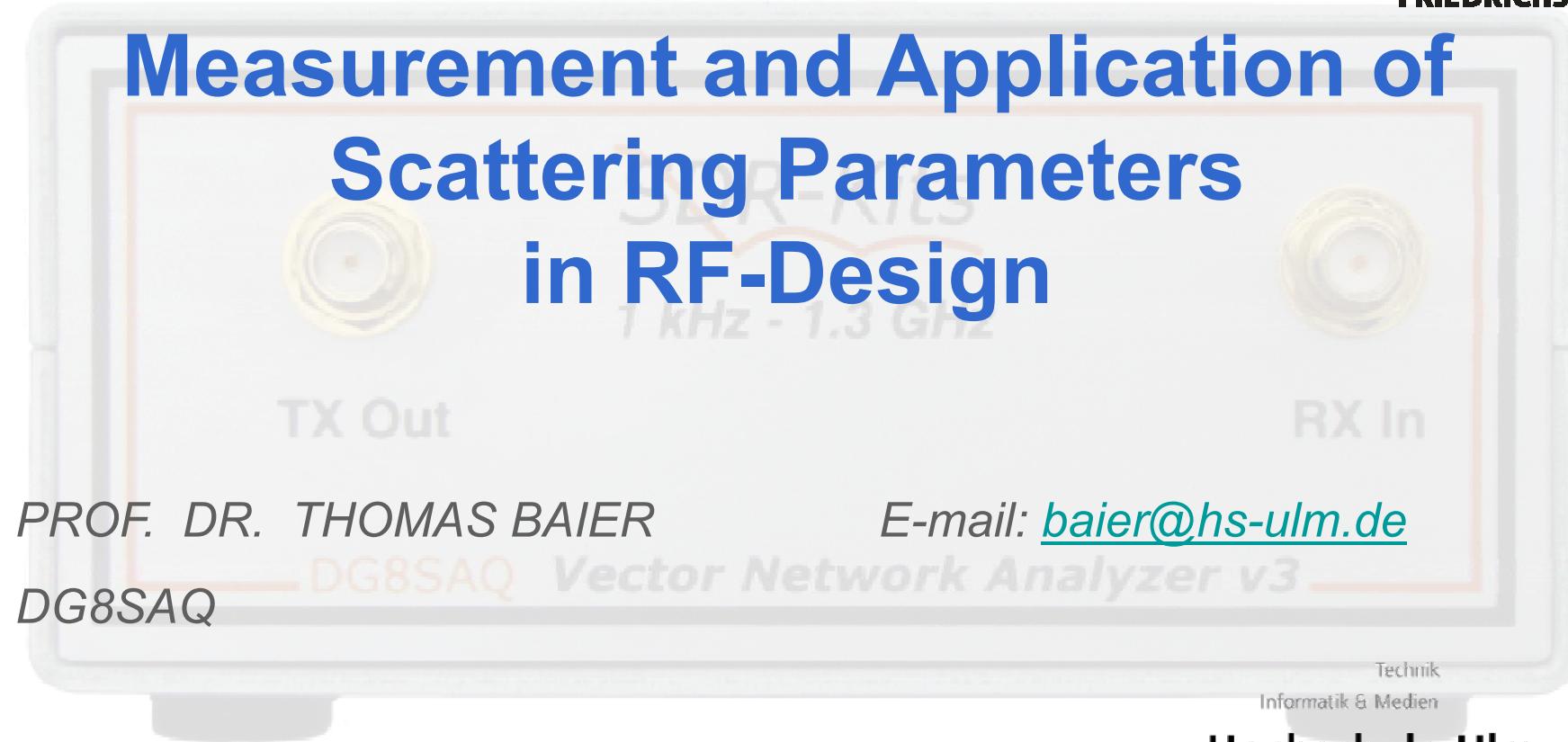


HAM RADIO 2013



Measurement and Application of Scattering Parameters in RF-Design



PROF. DR. THOMAS BAIER

DG8SAQ

E-mail: baier@hs-ulm.de

Hochschule Ulm
Prittitzstrasse 10
89075 Ulm

University of Applied Sciences
Ulm
Germany

Technik
Informatik & Medien

Hochschule Ulm



University of
Applied Sciences

Program

- Scattering (S-) parameters
 - Break
 - Measuring S-parameters with a VNA
 - Applications
- 

Many thanks to:

- Eric Hecker
- Kurt Poulsen

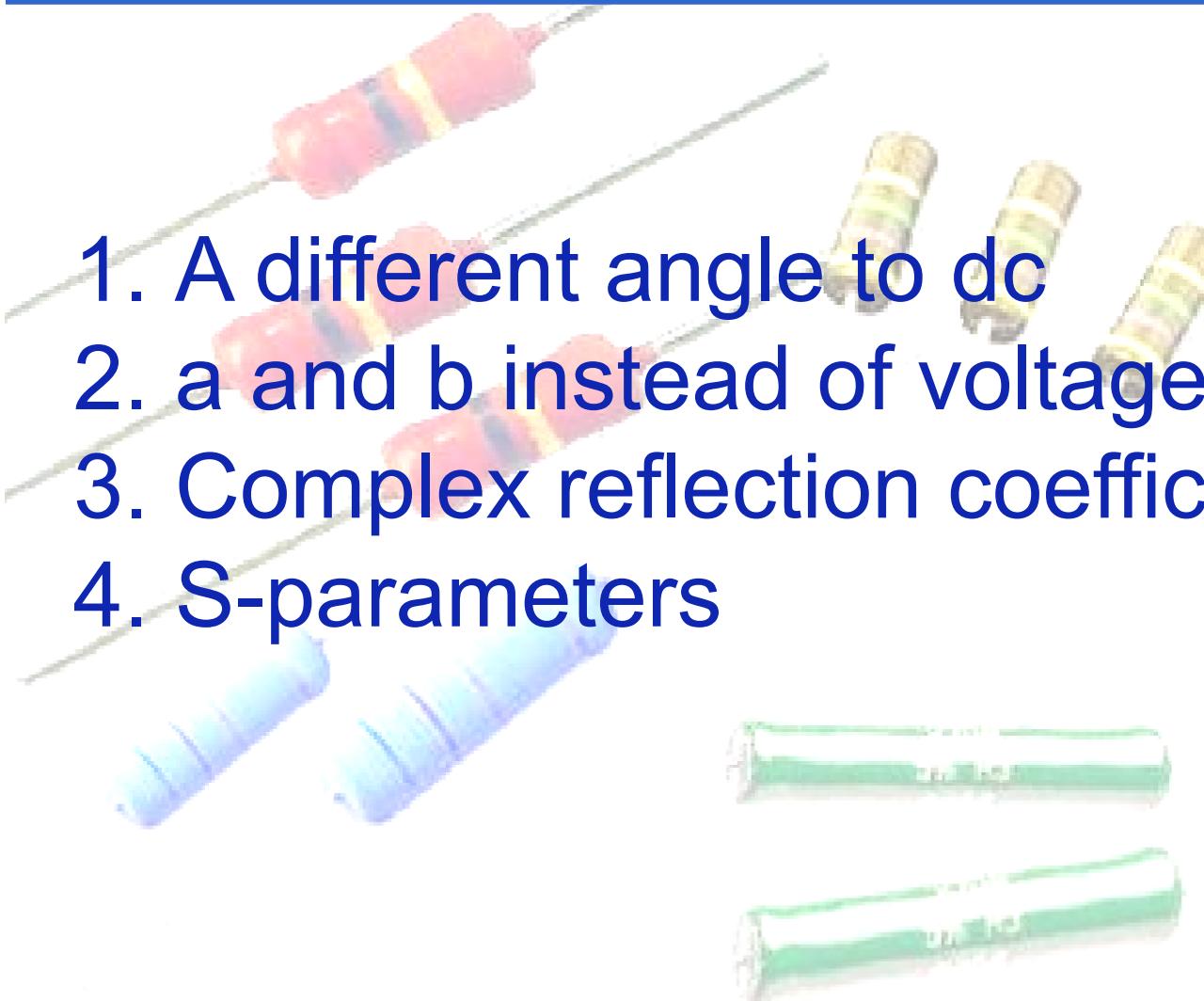
- Gerfried Palme
- Alan Rowe

- Jan Verduyn
- Jim Tonne

Hochschule Ulm



What are Scattering Parameters?

- 
1. A different angle to dc
 2. a and b instead of voltage and current
 3. Complex reflection coefficient
 4. S-parameters



Who is afraid of S-parameters!

$$\begin{array}{c} U = R \cdot I \\ b = S \cdot a \\ \text{Response} \quad \text{System} \quad \text{Excitation} \end{array}$$

HAM RADIO 2013



Ohm

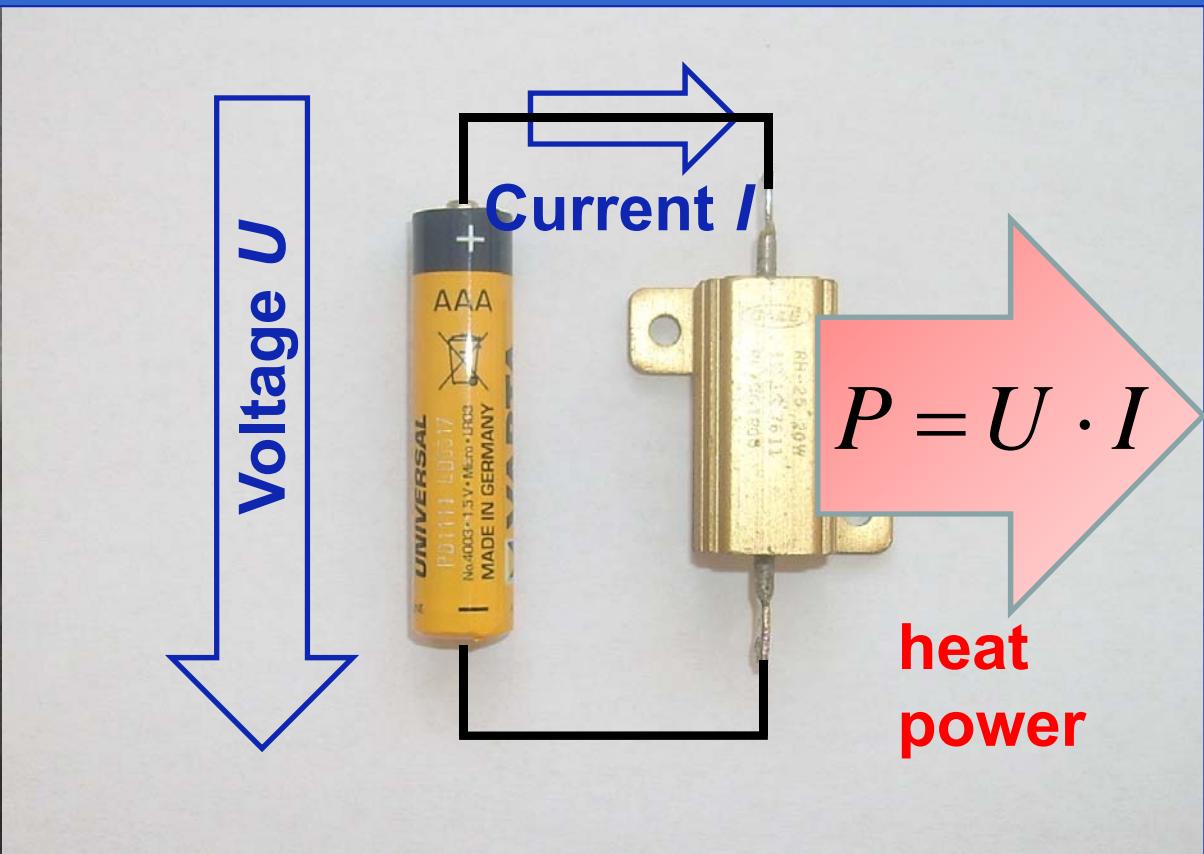
S-Par.

equivalent
description

Hochschule Ulm



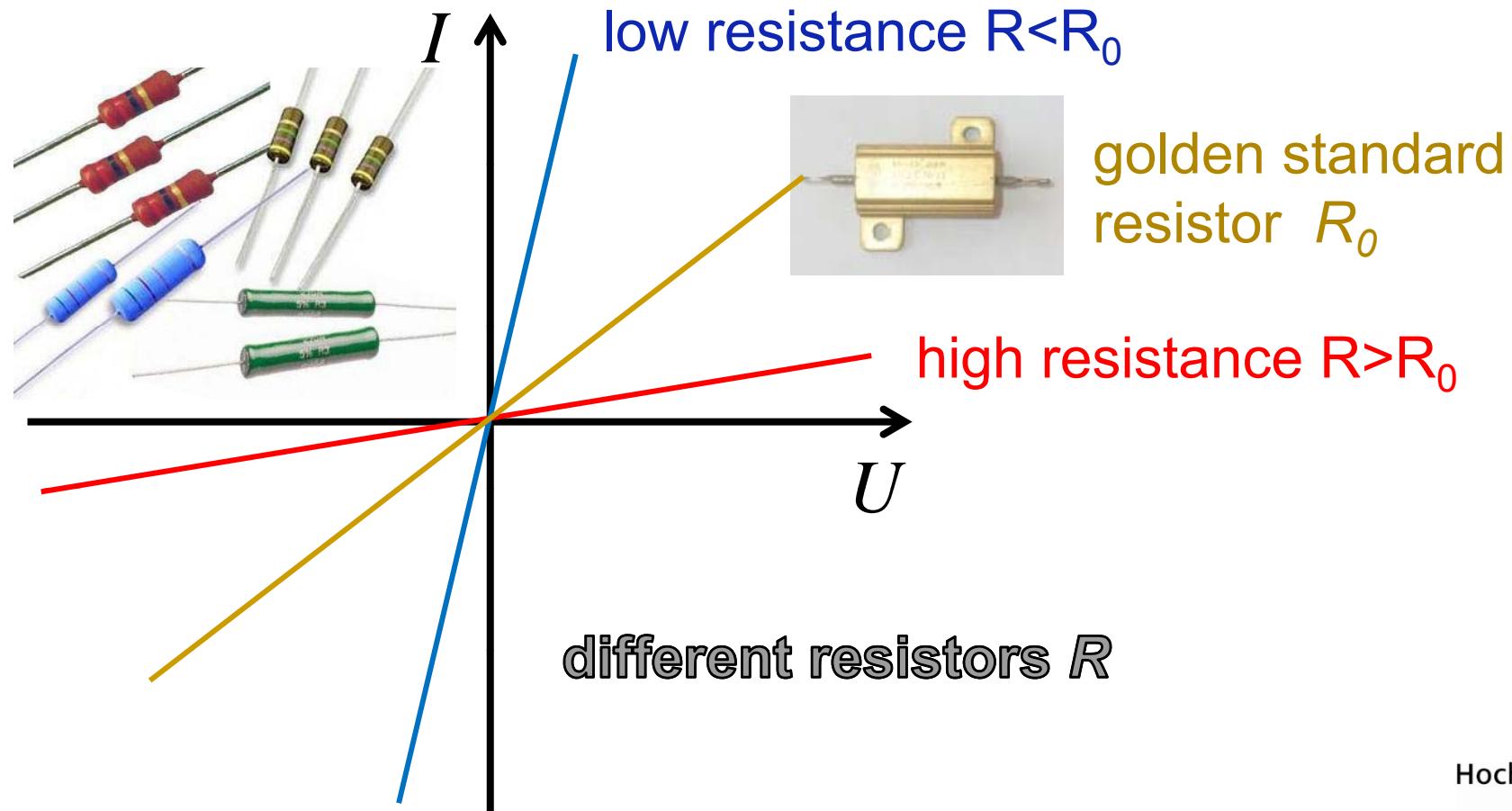
A different angle to dc Ohms' Law (1)



**Georg Simon Ohm
(1789-1854)**

$$U = R \cdot I$$

Ohms' Law (2)



Normalizing Resistor R to Reference Resistor R_0

We scale arbitrary resistors in multiples of our reference resistance R_0 :

Resistor R



$$r = \frac{R}{R_0}$$

normalized r

Resistor R_0



$$r_0 = \frac{R_0}{R_0} = 1$$

normalized 1

Hochschule Ulm



New Units for Voltage and Current: Normalization of U und I via R_0

Focus on power P dissipated in R_0 :

$$\sqrt{P} = \sqrt{U \cdot I} = \sqrt{\frac{U^2}{R_0}} = \frac{U}{\sqrt{R_0}} \equiv u$$

$$= \sqrt{I^2 \cdot R_0} = I \cdot \sqrt{R_0} \equiv i$$

Hochschule Ulm



New Units for Voltage and Current:

$I \rightarrow i$

$U \rightarrow u$

Focus on power P dissipated in R_0 :

$$i \equiv I \cdot \sqrt{R_0} = \sqrt{P} = \frac{U}{\sqrt{R_0}} \equiv u$$

u and i are still voltage and current, but units have changed.

u and i have identical units, namely $\sqrt{\text{Watt}}$



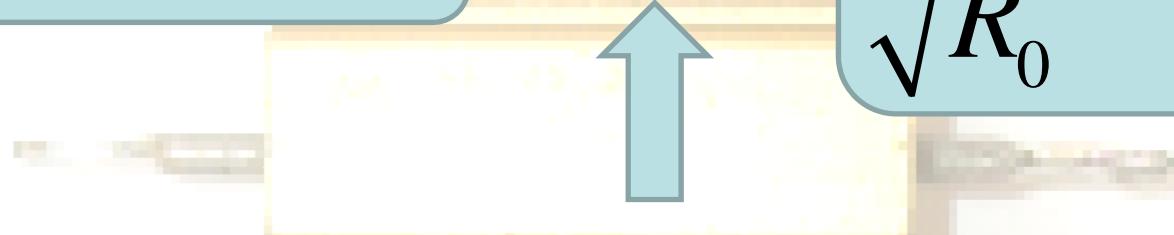
New Units for Voltage and Current:

$$I \rightarrow i$$

$$U \rightarrow u$$

Focus on power P dissipated in R_0 :

$$i \equiv I \cdot \sqrt{R_0} = \sqrt{P} = \frac{U}{\sqrt{R_0}} \equiv u$$



Here special case $u = i = \sqrt{P}$

Reason: $R = R_0$
i.e. $U = R_0 \cdot I$

Now arbitrary Resistor R instead of R_0

Ohm's Law still applies:

$$u = r \cdot i$$

because:

$$\frac{u}{i} = \frac{\frac{U}{\sqrt{R_0}}}{I \cdot \sqrt{R_0}} = \frac{U}{I \cdot R_0} = \frac{R}{R_0} \equiv r$$

Normalized
resistance!

Hochschule Ulm



Dissipated Power in arbitrary Resistor

$$P = u \cdot i$$

still applies

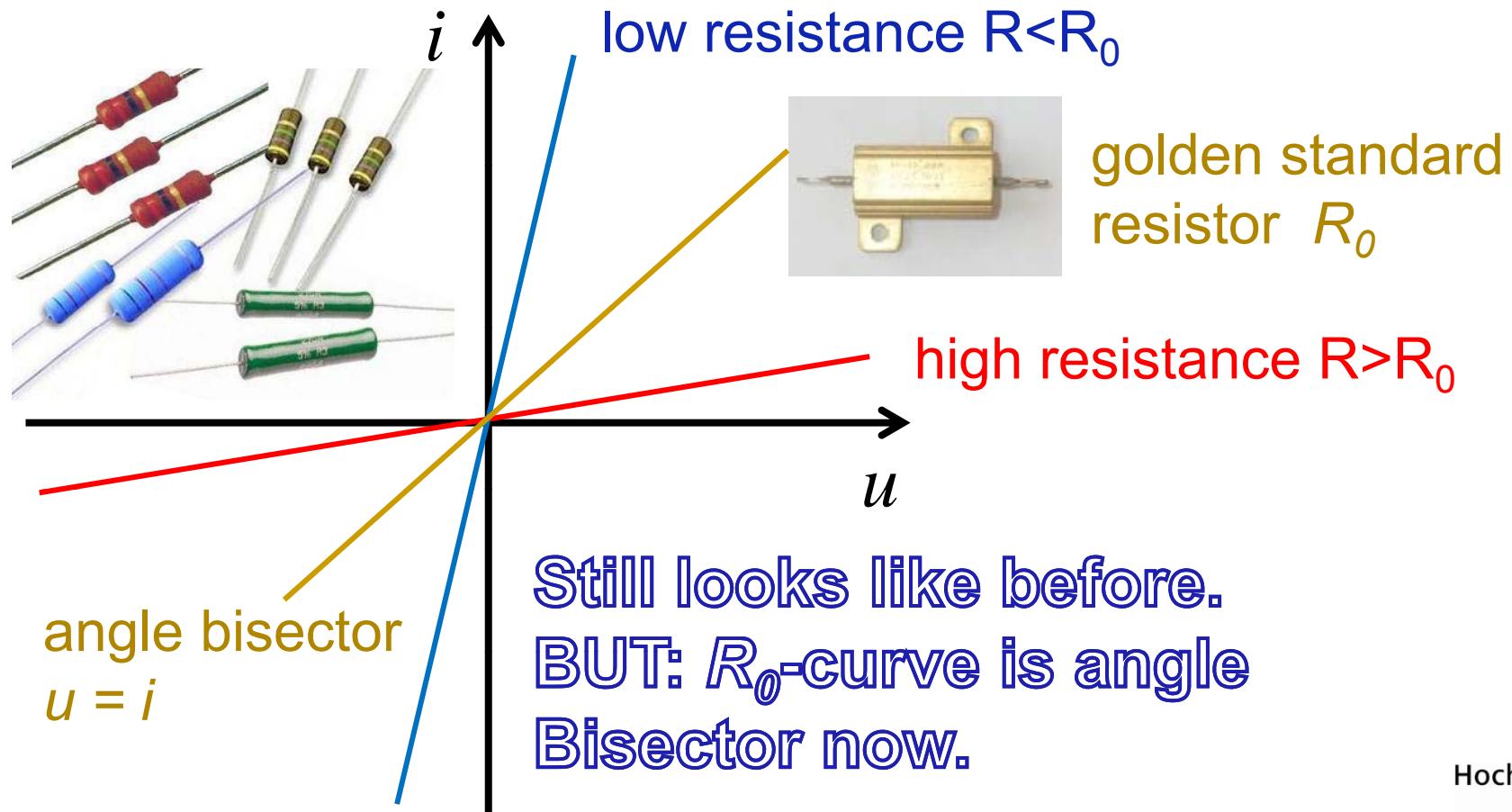
because:

$$u \cdot i = \frac{U}{\sqrt{R_0}} \cdot I \cdot \sqrt{R_0} = U \cdot I = P$$

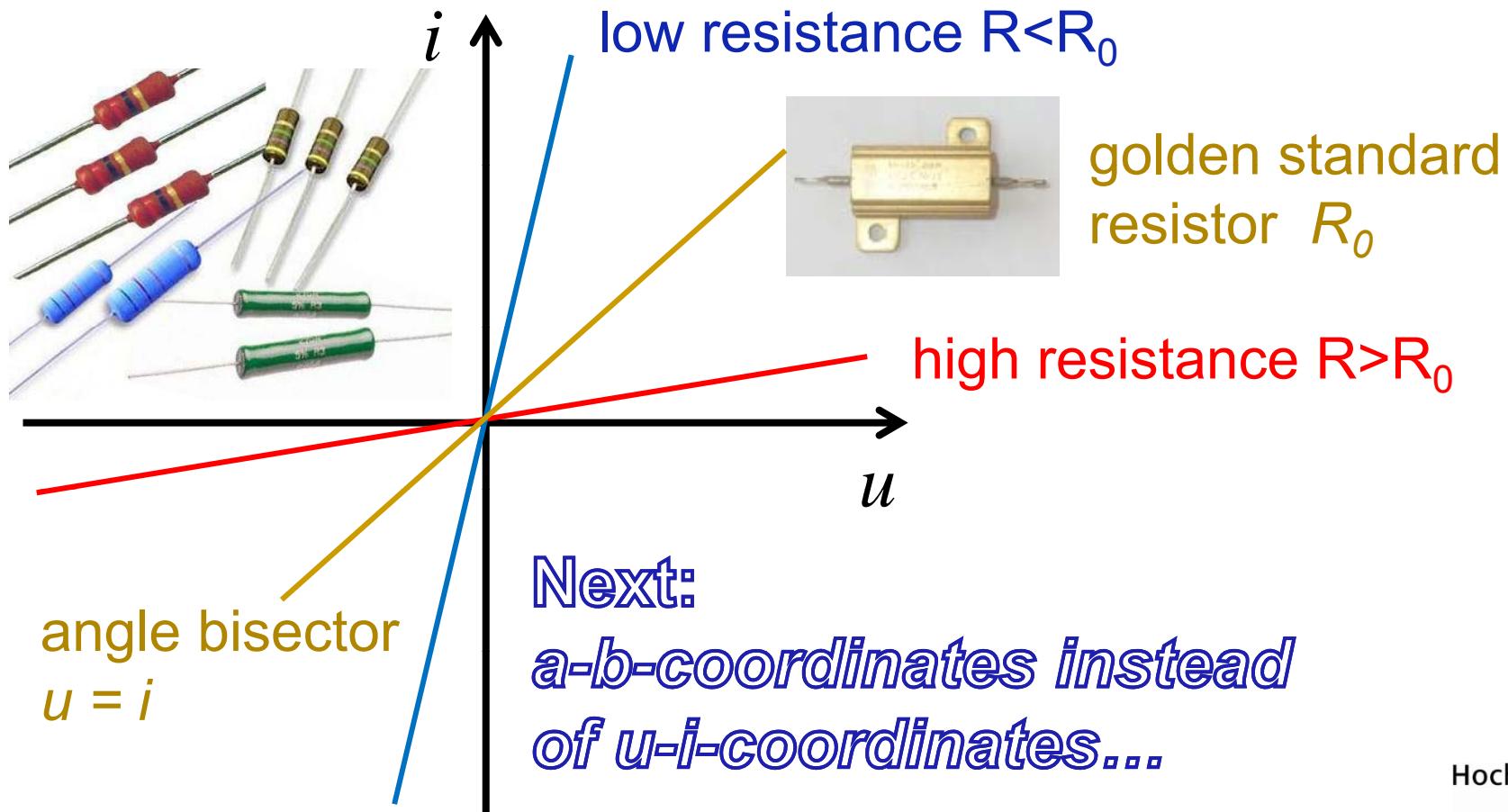
~~$\sqrt{R_0}$~~ reduce!



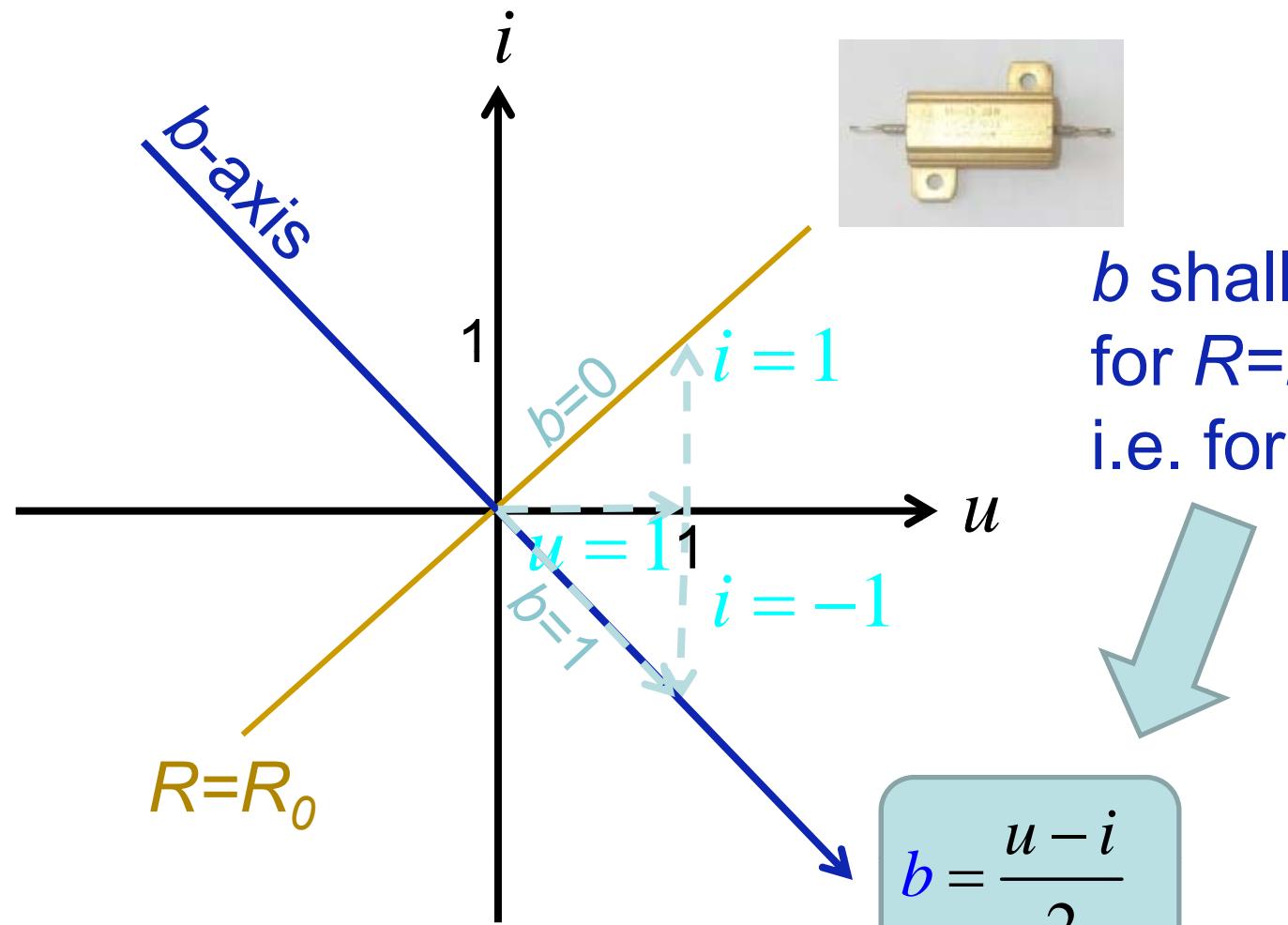
Ohm's Law with new Voltage and Current Units



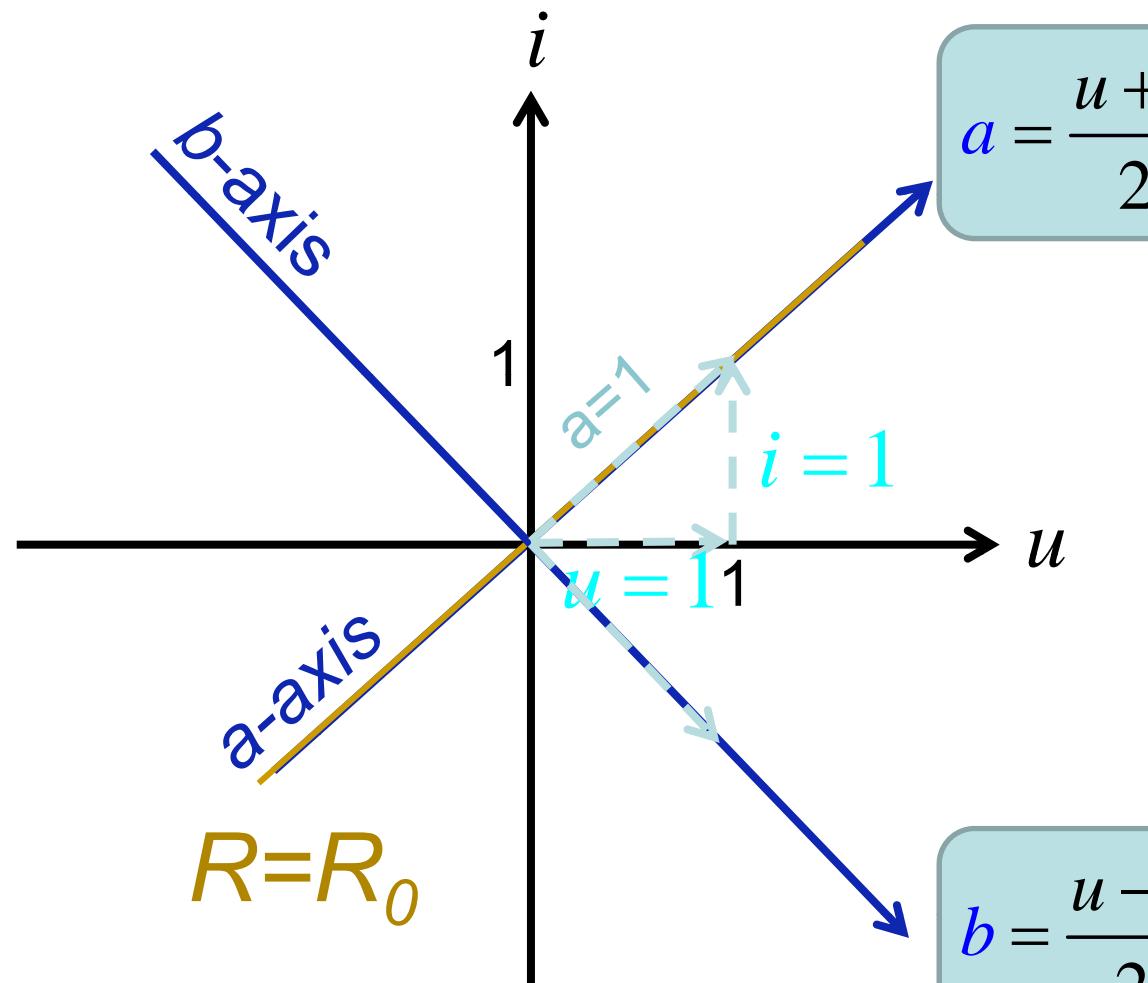
Now we get down to business: A different angle to dc...



From Voltage and Current... ...to b ...

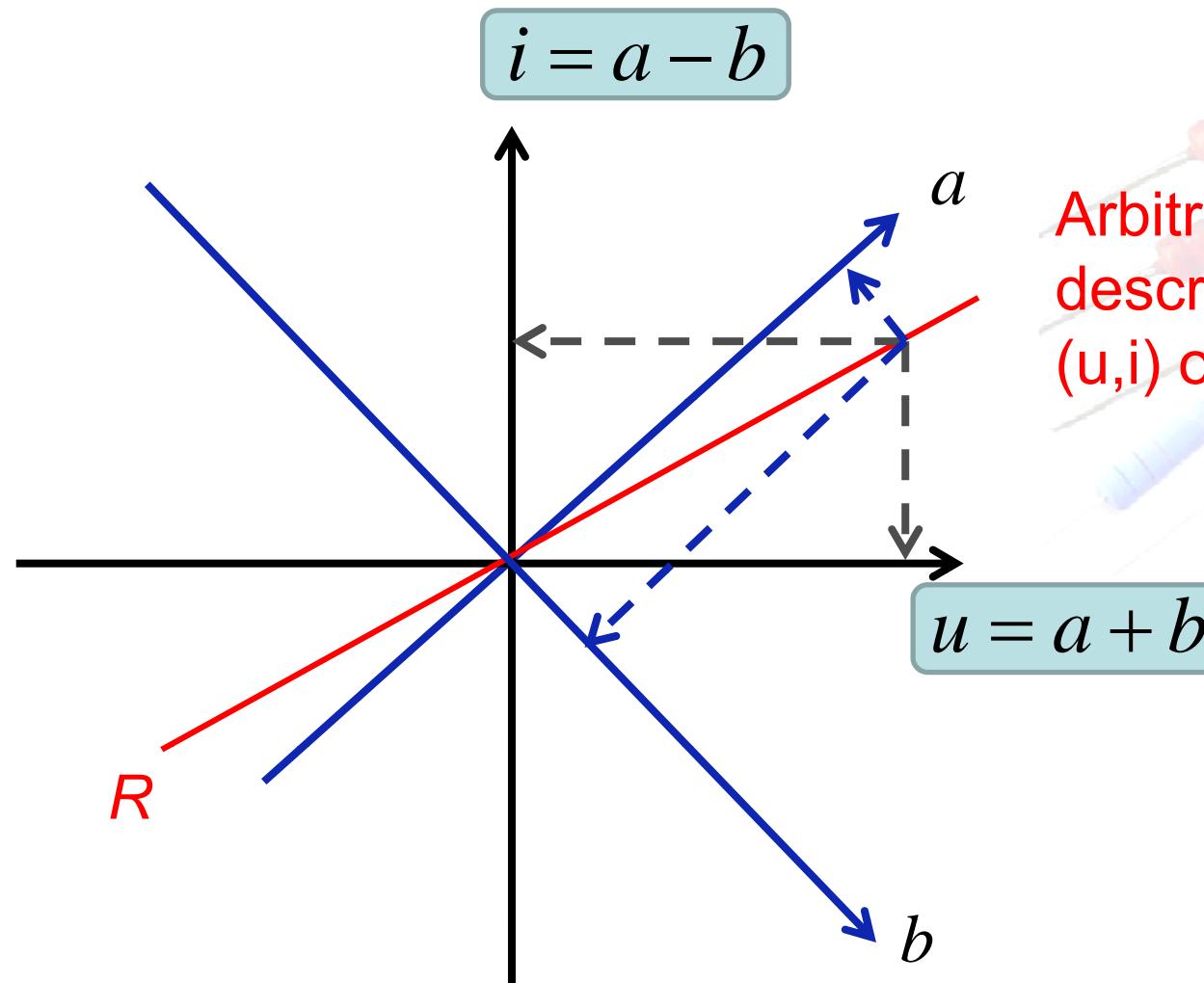


From Voltage and Current... ...to b ...and a !

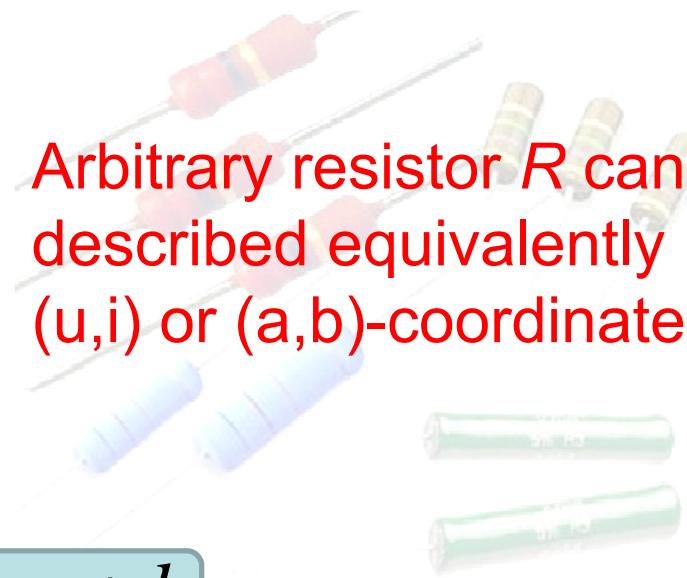


a-axis shall be
perpendicular
to b -axis

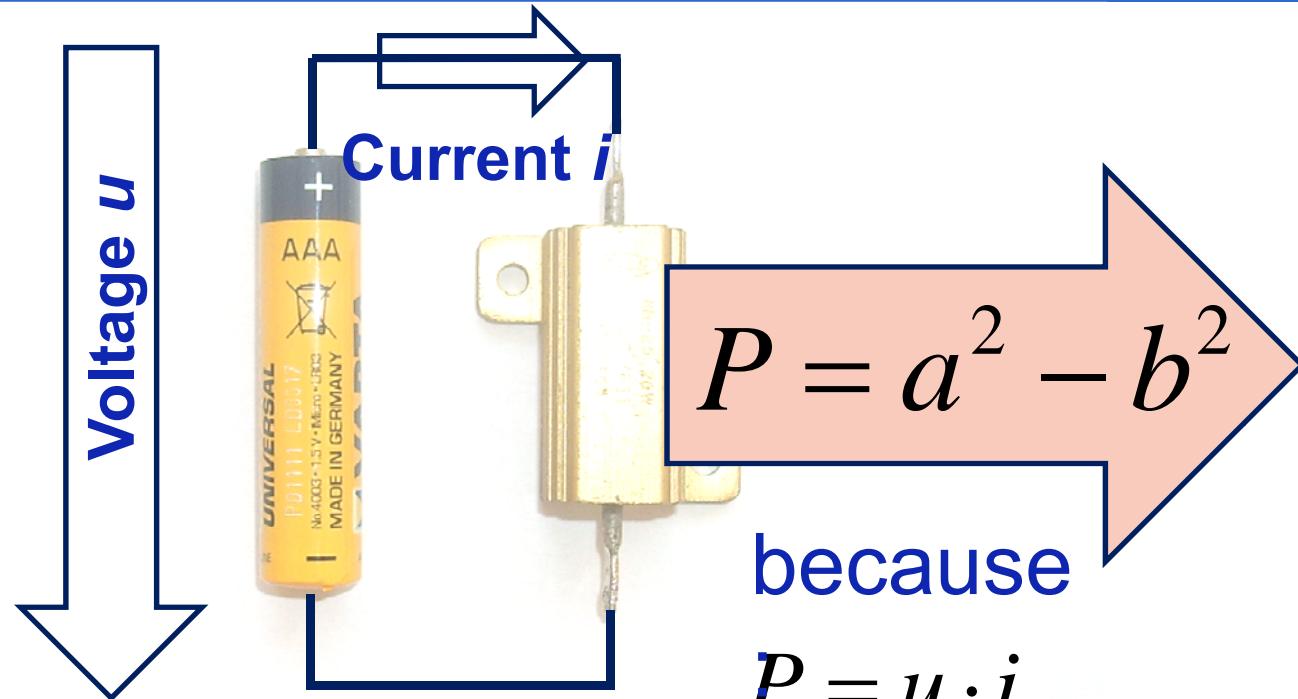
This works the other way round, too:
Voltage and Current from a and b



Arbitrary resistor R can be described equivalently in (u,i) or (a,b) -coordinates.



A different angle to dc: Dissipated power in resistor R



$$\begin{aligned} \text{if } R &= R_0 \Rightarrow b = 0 & &= (a + b) \cdot (a - b) \\ & \Rightarrow P = a^2 & &= a^2 - b^2 \end{aligned}$$

Conclusion: a and b
instead of current and voltage



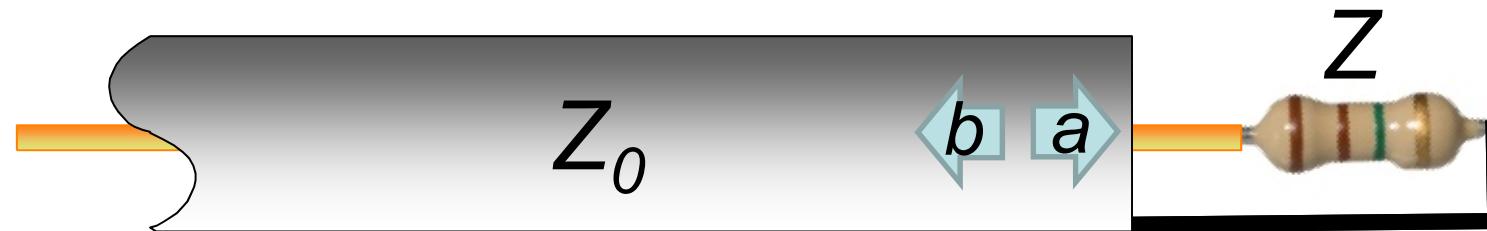
$$P = a^2 - b^2$$

Power $P \leq a^2$
If $b=0$, i.e. $R=R_0$ then $P = a^2$

a and b contain identical information as u and i:

$$\begin{aligned} u &= a + b & u + i &= 2a \\ i &= a - b & \Leftrightarrow & \\ && u - i &= 2b \end{aligned}$$

The Golden RF Reference Resistance: Characteristic Line Impedance Z_0



*Most power dissipated in Z
for $b = 0$, i.e. $Z = Z_0$, i.e. for
matched line termination!*

$$P = |a|^2 - |b|^2$$

$$\left\{ \begin{array}{ll} \text{and} & b = 0 \\ \text{if} & Z = Z_0 \end{array} \right.$$

a = wave incident to Z
 b = wave reflected from Z

Now we apply ac!
Complex Reflection Coefficient $S = b/a$



a, b = complex numbers, contain amplitude and phase information, because we apply ac.

$$S = \frac{b}{a} = \frac{u - i}{u + i} = \frac{\frac{u}{i} - 1}{\frac{u}{i} + 1} = \frac{z - 1}{z + 1}$$

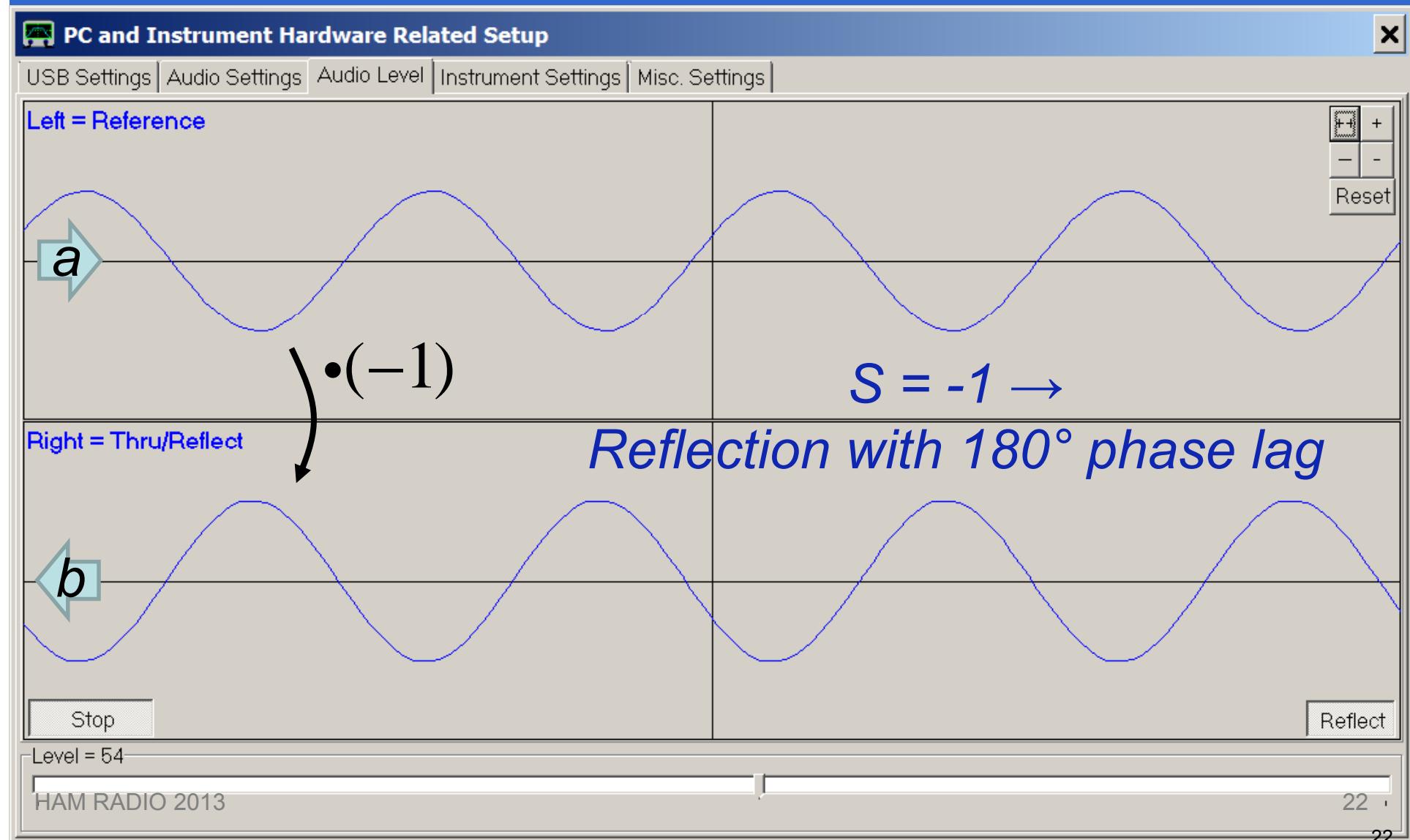
$$\text{with } z = \frac{Z}{Z_0}$$

Hochschule Ulm

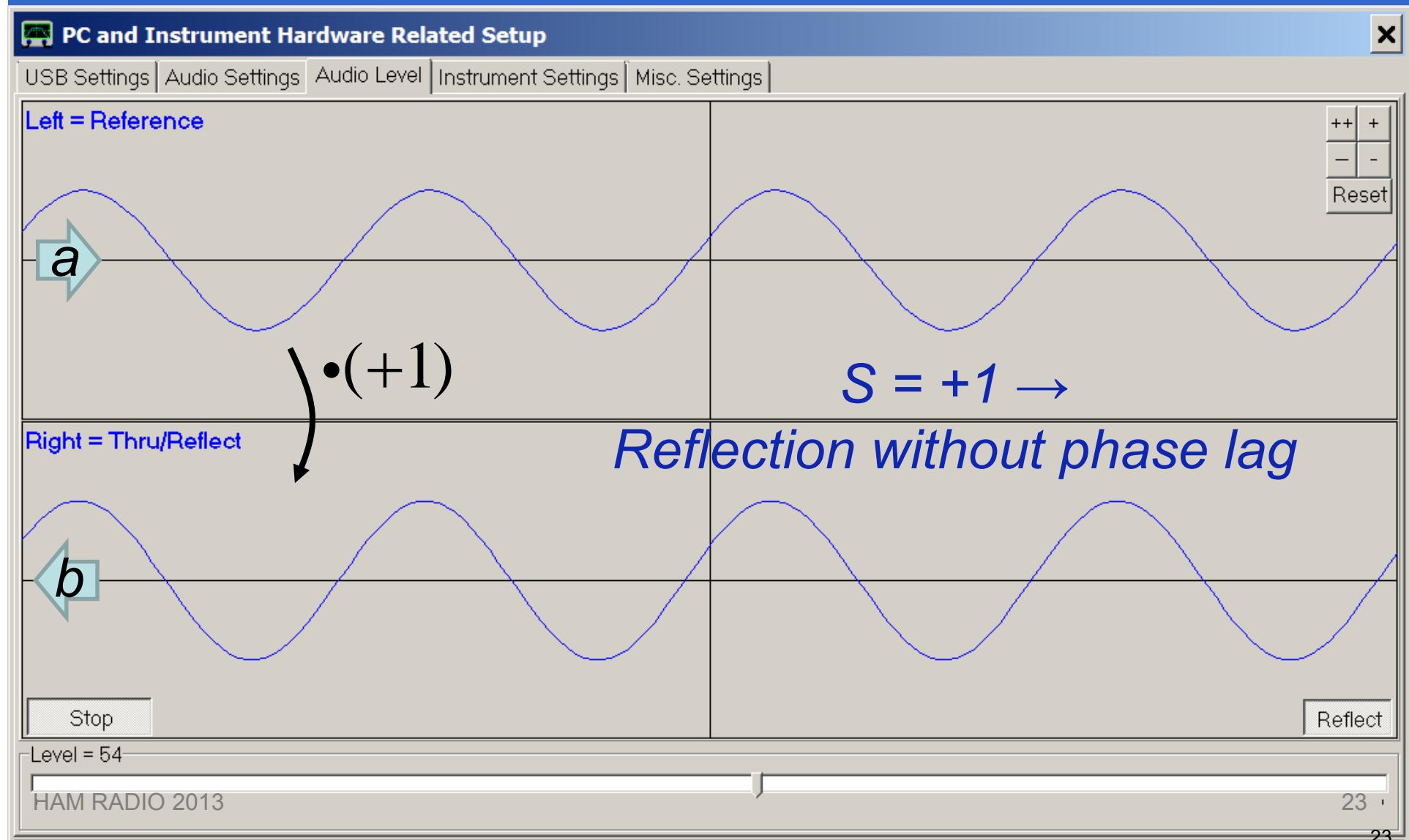


e.g. Short: $z = 0 \rightarrow S = -1$

We can see a and b using the VNWA
E.g. Short Circuit $S=-1$

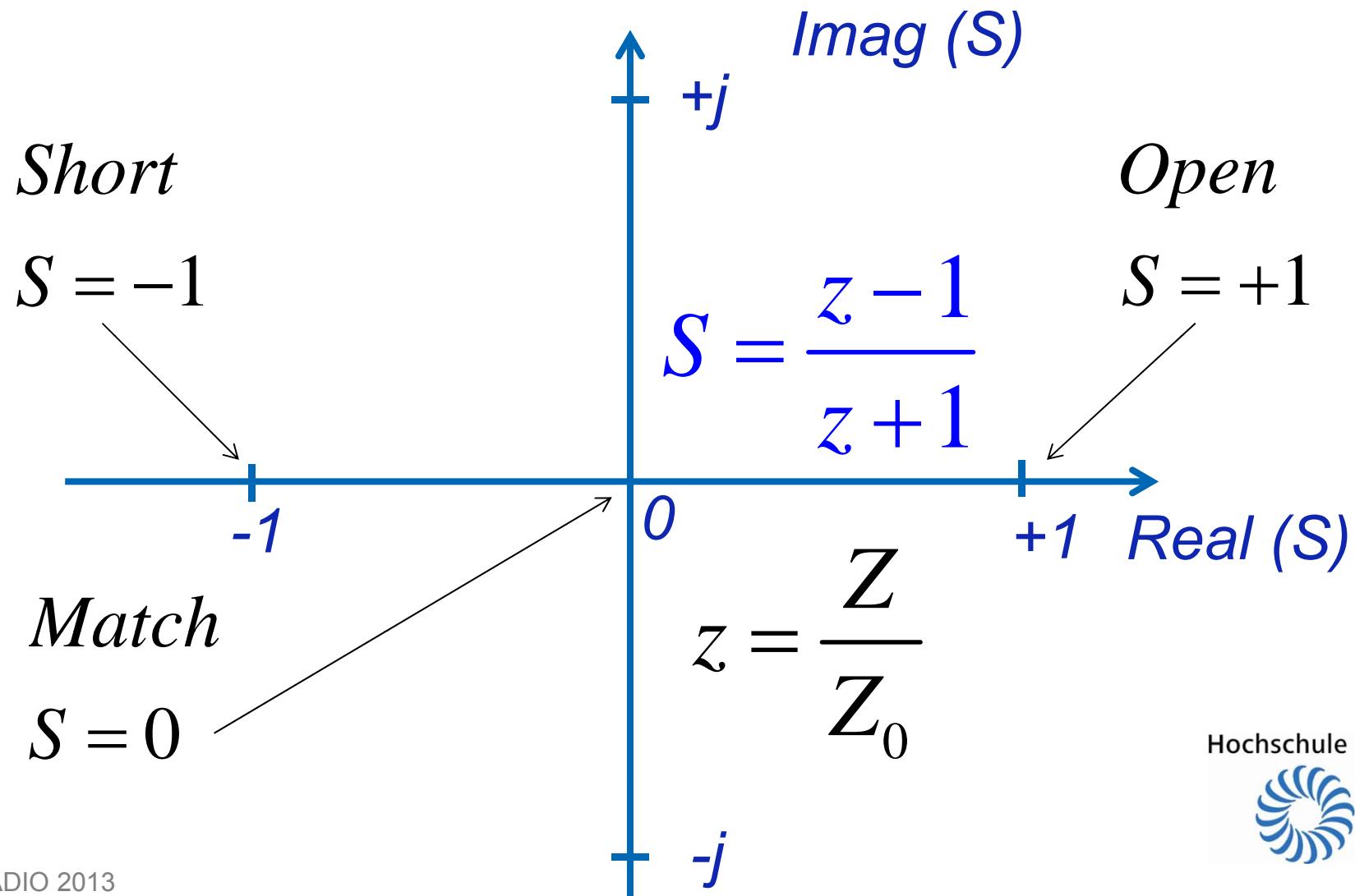


We can see a and b using the VNWA
E.g. Open Circuit $S=+1$:

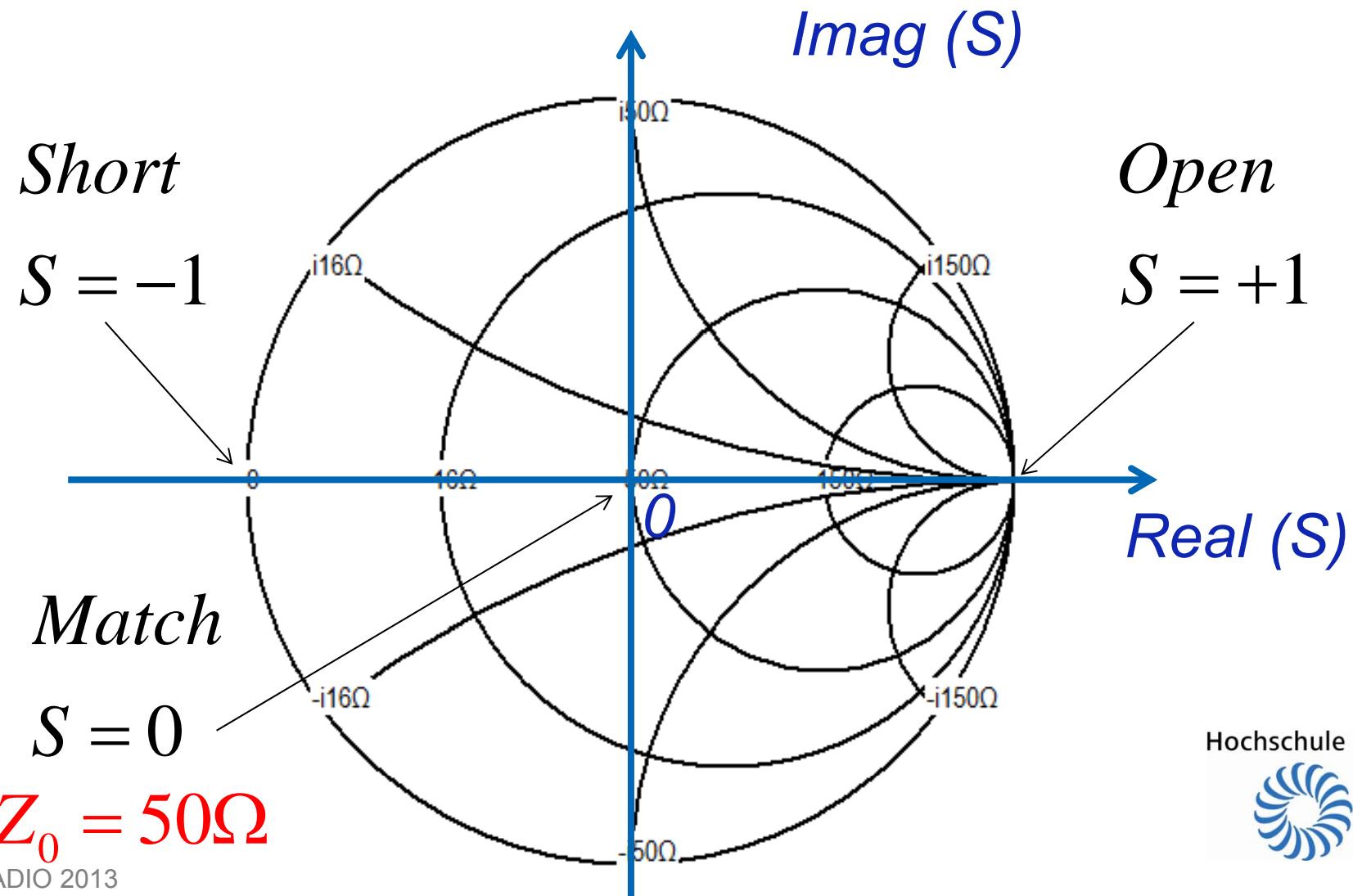


Complex Reflection Coefficient $S = b/a$

...



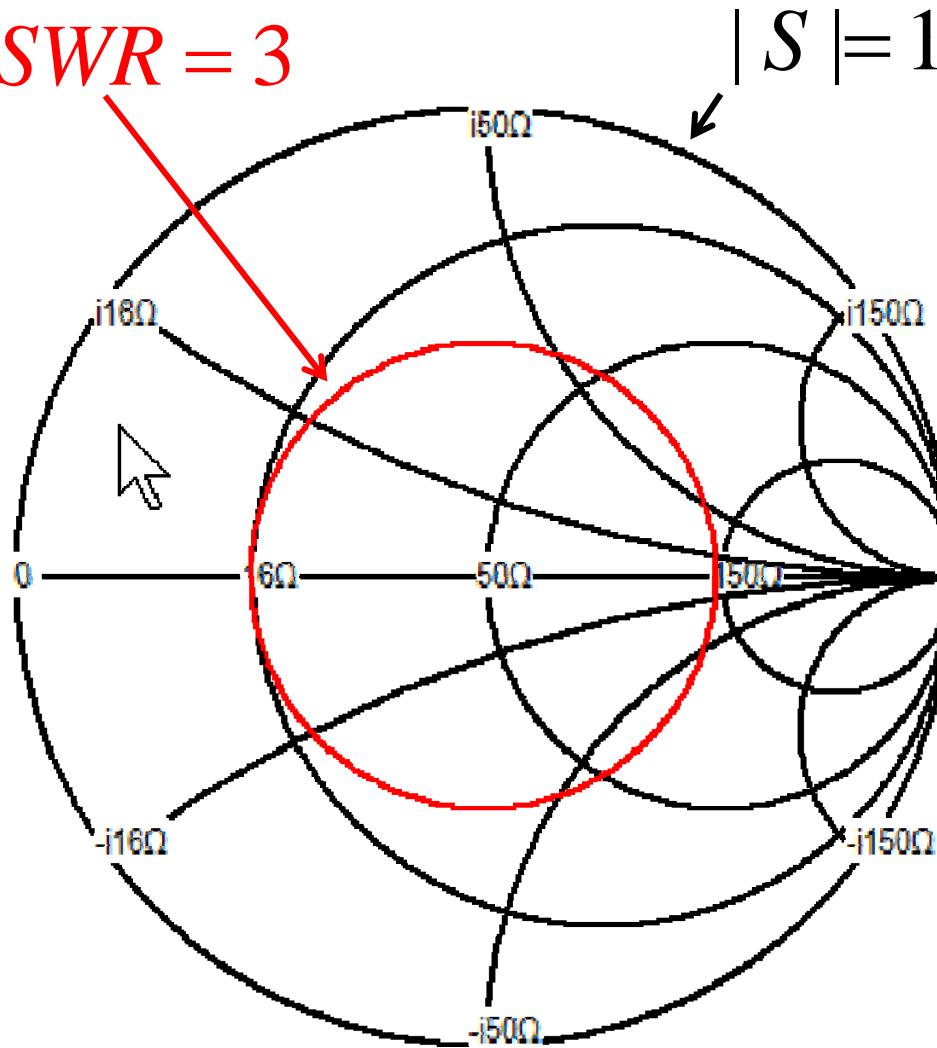
Complex Reflection Coefficient $S = b/a$ and Smith Chart



Complex Reflection Coefficient $S = b/a$ and Voltage Standing Wave Ratio VSWR

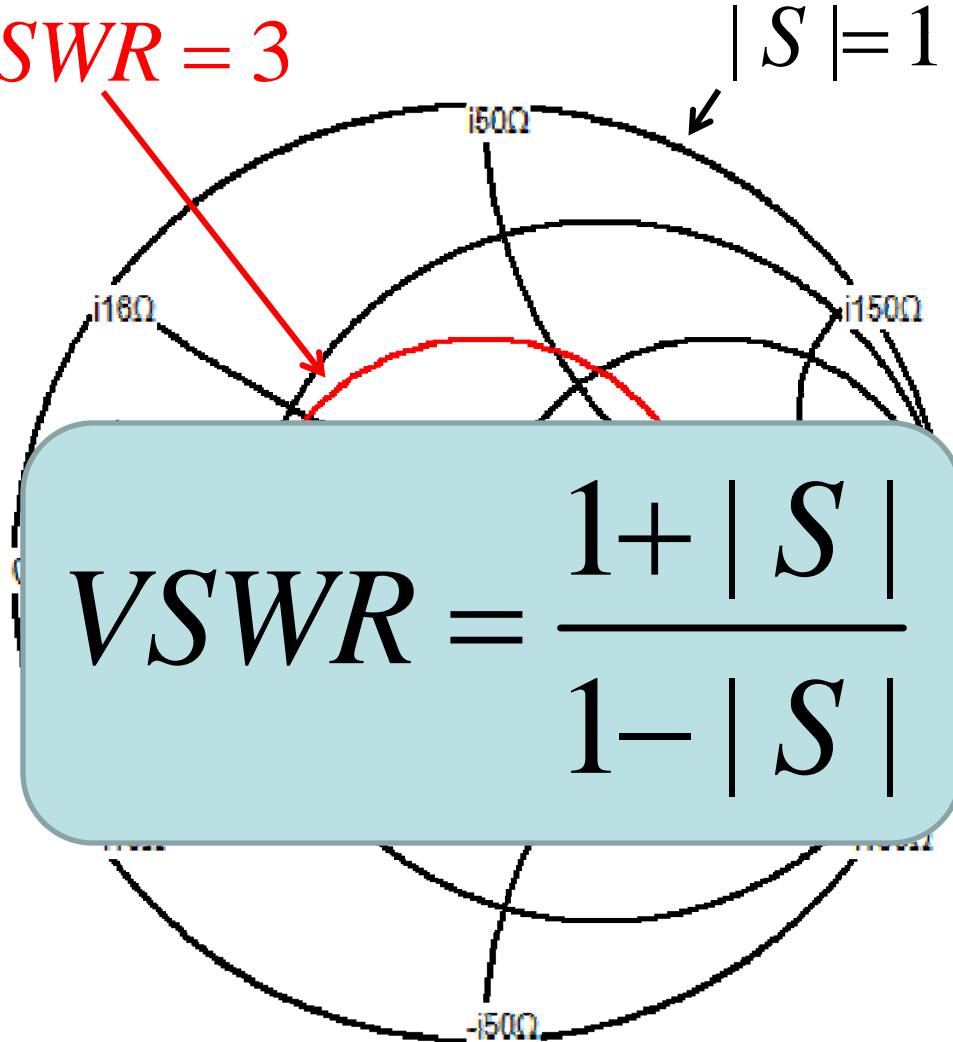
$|S| = 0,5 \quad VSWR = 3$ $|S| = 1 \quad VSWR = \infty$

$0,5 \cdot 0,5 = 25\%$
reflected power



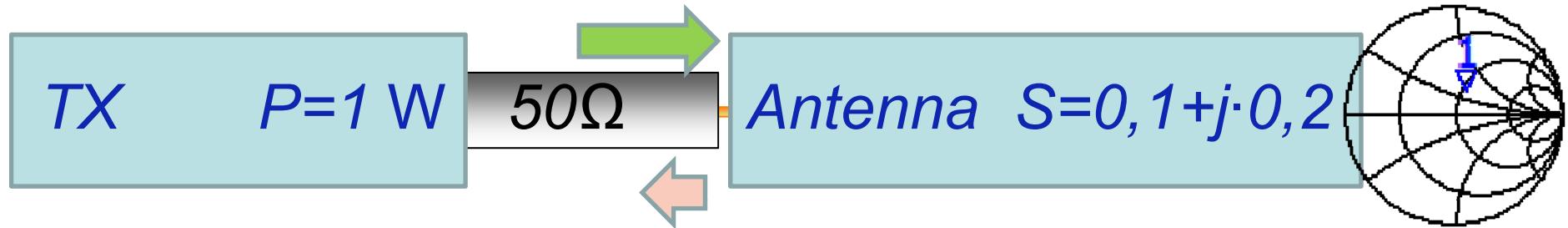
Complex Reflection Coefficient $S = b/a$ and Voltage Standing Wave Ratio VSWR

$|S| = 0,5 \quad VSWR = 3$ $|S| = 1 \quad VSWR = \infty$



Complex Reflection Coefficient $S = b/a$

Calculus Example: Reflected Power



$$a = \sqrt{1 \text{ W}} = 1\sqrt{\text{W}}$$

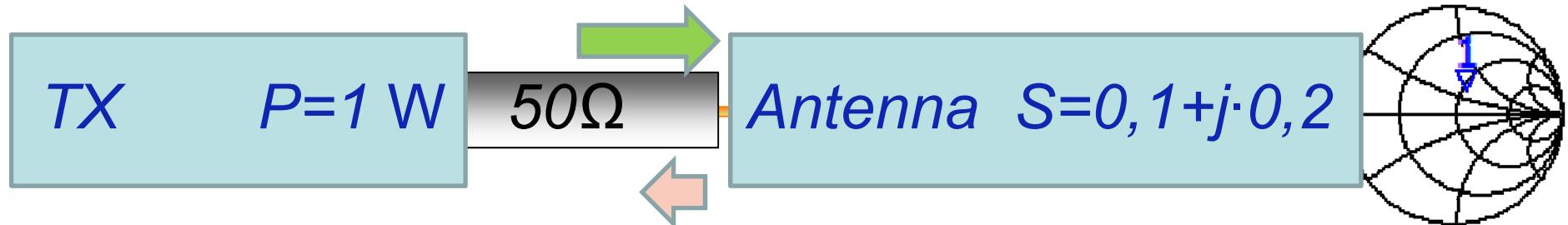
$$b = S \cdot a = (0,1 + j0,2) \cdot \sqrt{1 \text{ W}} = 0,1\sqrt{\text{W}} + j0,2\sqrt{\text{W}}$$

Reflected Power:

$$P_r = |b|^2 = 0,1^2 + 0,2^2 \text{ W} = 0,05 \text{ W}$$

Complex Reflection Coefficient $S = b/a$

Calculus Example: VSWR



$$a = 1\sqrt{\text{W}}$$

$$b = 0,1\sqrt{\text{W}} + j0,2\sqrt{\text{W}}$$

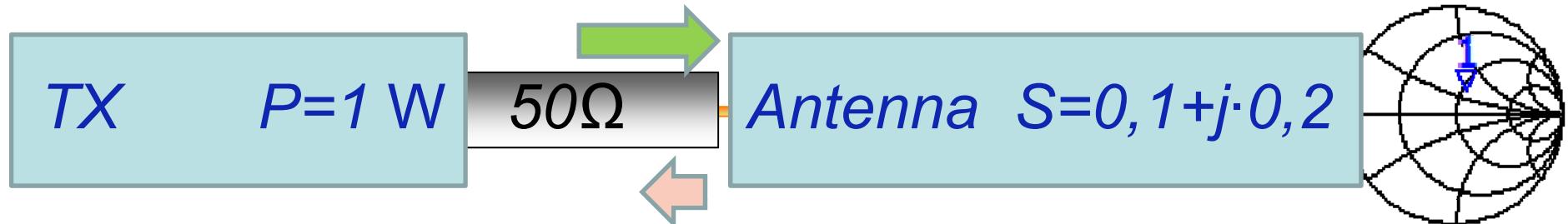
VSWR:

$$|S| = \sqrt{0,1^2 + 0,2^2} \approx 0,22$$

$$VSWR = \frac{1+|S|}{1-|S|} \approx \frac{1+0,22}{1-0,22} \approx 1,6$$

Complex Reflection Coefficient $S = b/a$

Calculus Example: Antenna Voltage



$$a = 1\sqrt{\text{W}}$$

$$b = 0,1\sqrt{\text{W}} + j0,2\sqrt{\text{W}}$$

Effective Voltage at Antenna:

$$u = a + b = 1,1\sqrt{\text{W}} + j0,2\sqrt{\text{W}}$$

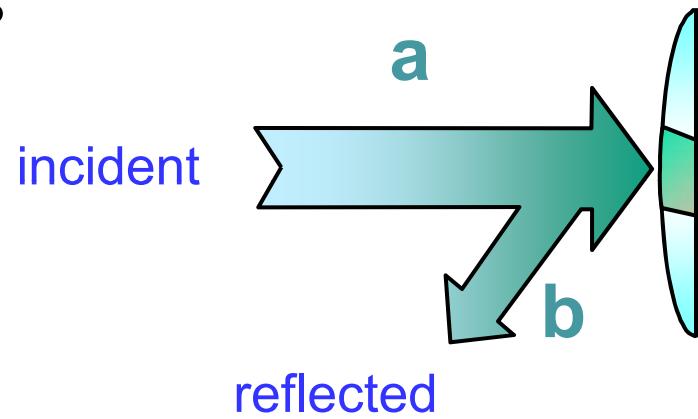
$$U = u \cdot \sqrt{Z_0} = u \cdot \sqrt{50 \Omega} \approx 7,8 \text{ V} + j1,4 \text{ V}$$

$$U_{eff} = |U| = \sqrt{7,8^2 + 1,4^2} \text{ V} \approx 7,9 \text{ V}$$

Complex Reflection Coefficient $S = b/a$

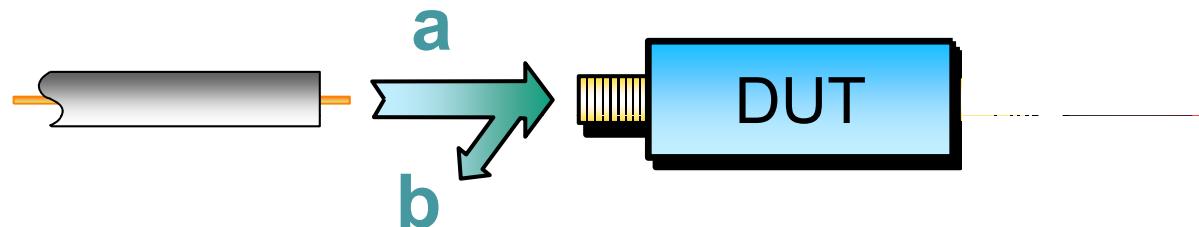
We call it Scattering Parameter now!

Optics



Scattering and absorption of waves at one port

Elektrical



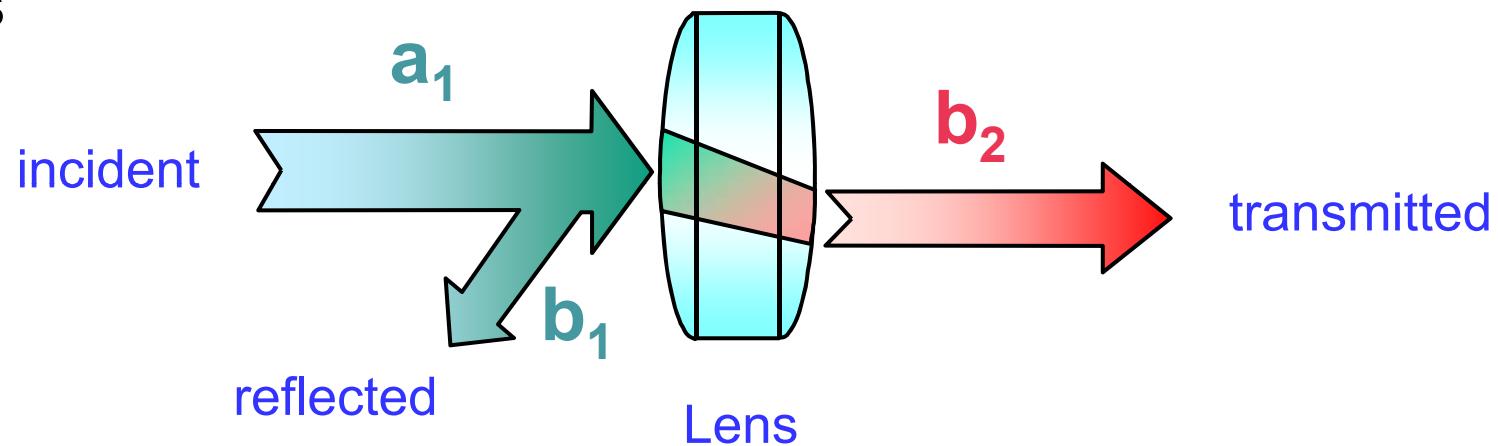
DUT : DEVICE UNDER TEST

Hochschule Ulm

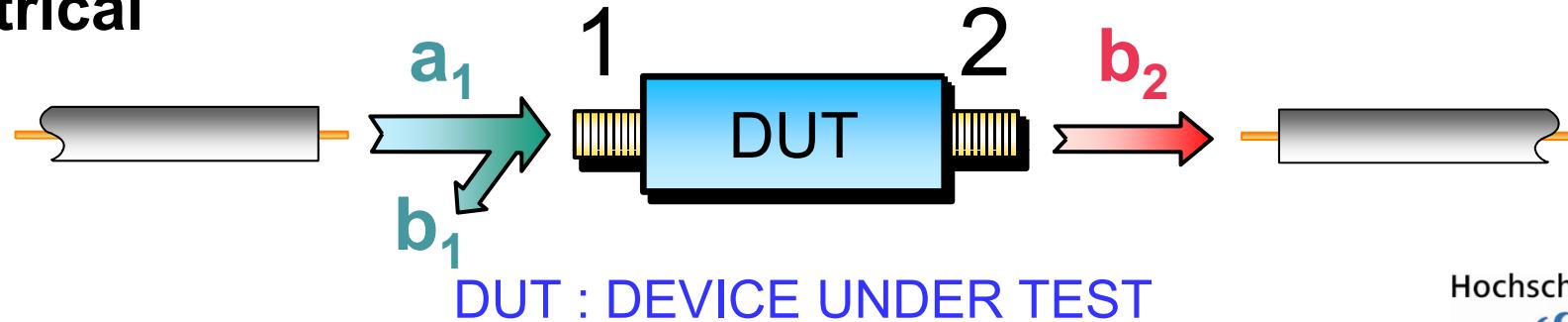


Scattering Parameters or short S-Parameters: Now two Ports!

Optics



Electrical

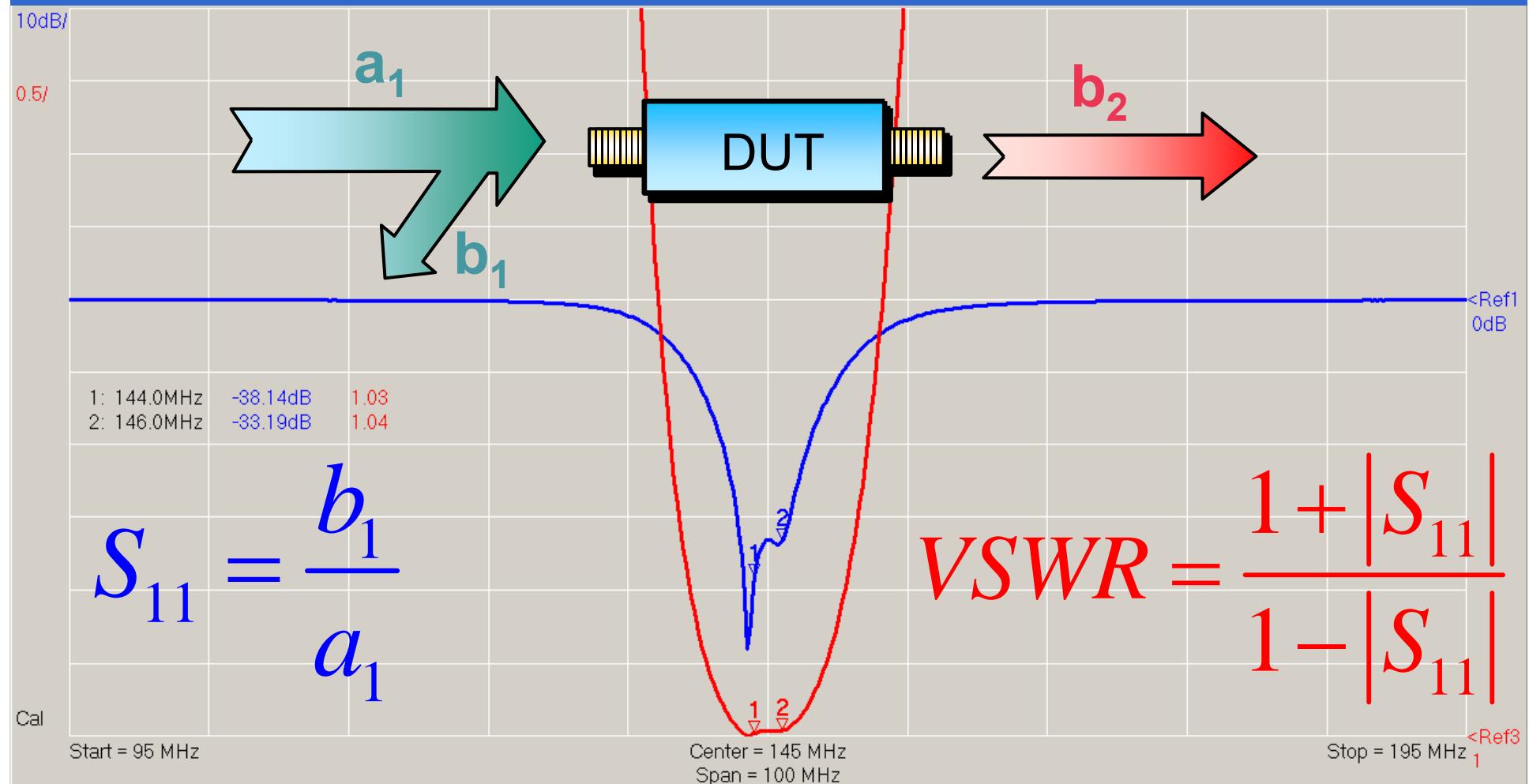


DUT : DEVICE UNDER TEST

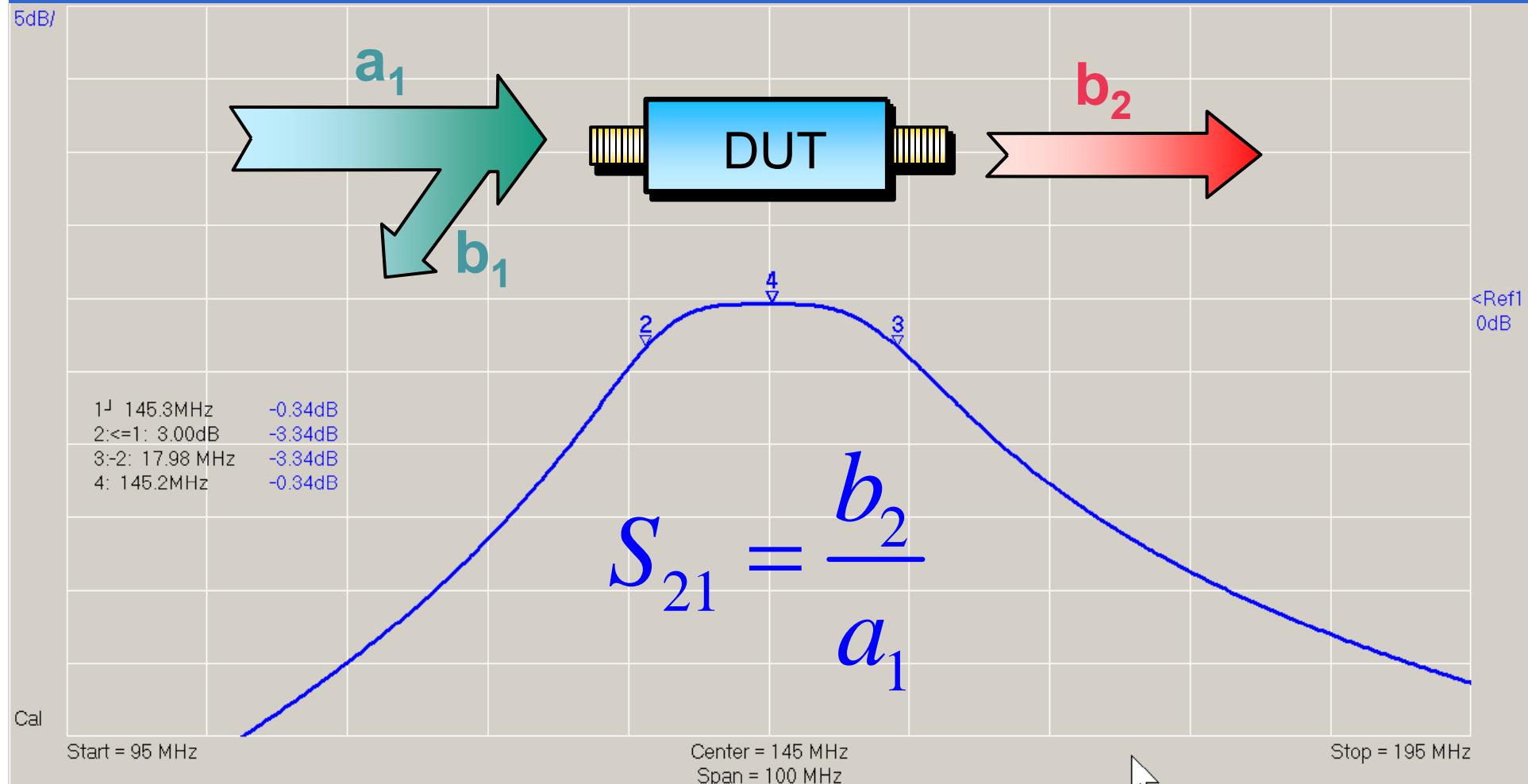
Hochschule Ulm



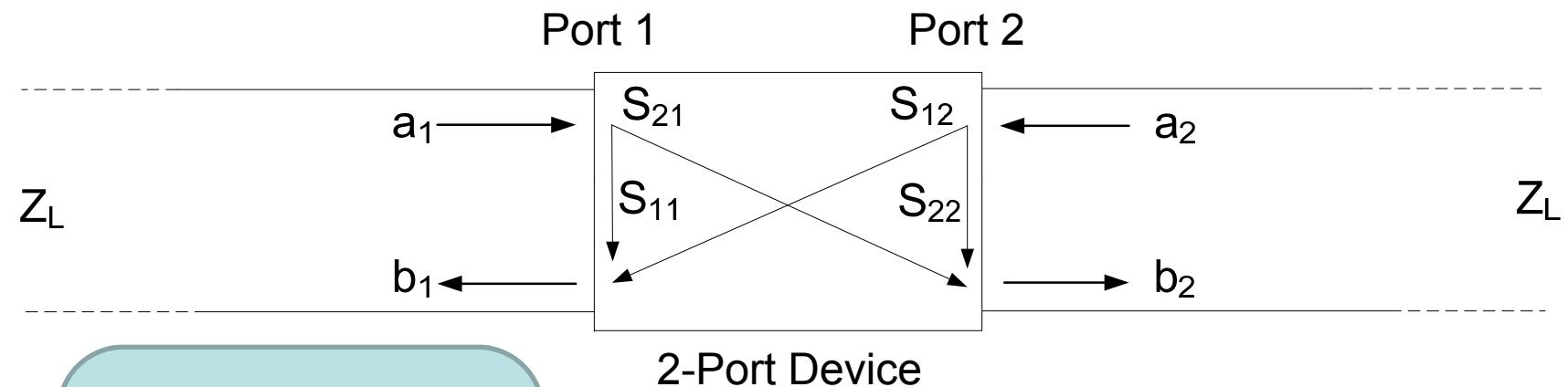
S-Parameter S_{11} (used to be S)
→ $|S_{11}| \rightarrow$ Return Loss



S-Parameter S_{21}
➡ $| S_{21} | = \text{Transmission Gain}$



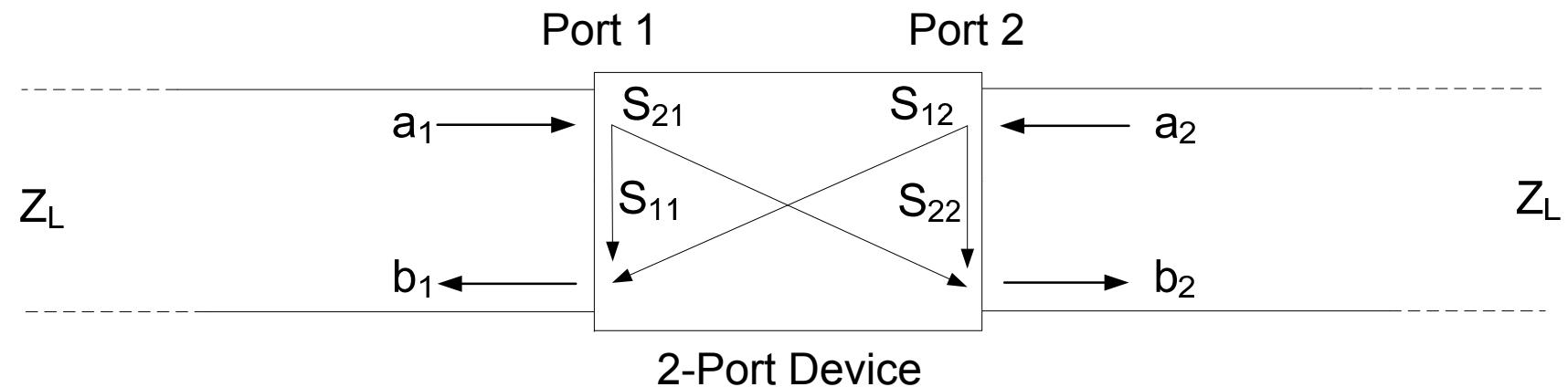
General: S-Parameters S_{ik}



$$S_{ik} = \frac{b_i}{a_k}$$

$i, k = 1 \dots$ number of ports

General: S-Parameters S_{ik}



Scattering parameters $S_{11}, S_{21}, S_{12}, S_{22}$
completely describe linear two port device!
=> useful for simulations

BREAK ???



HAM RADIO 2013

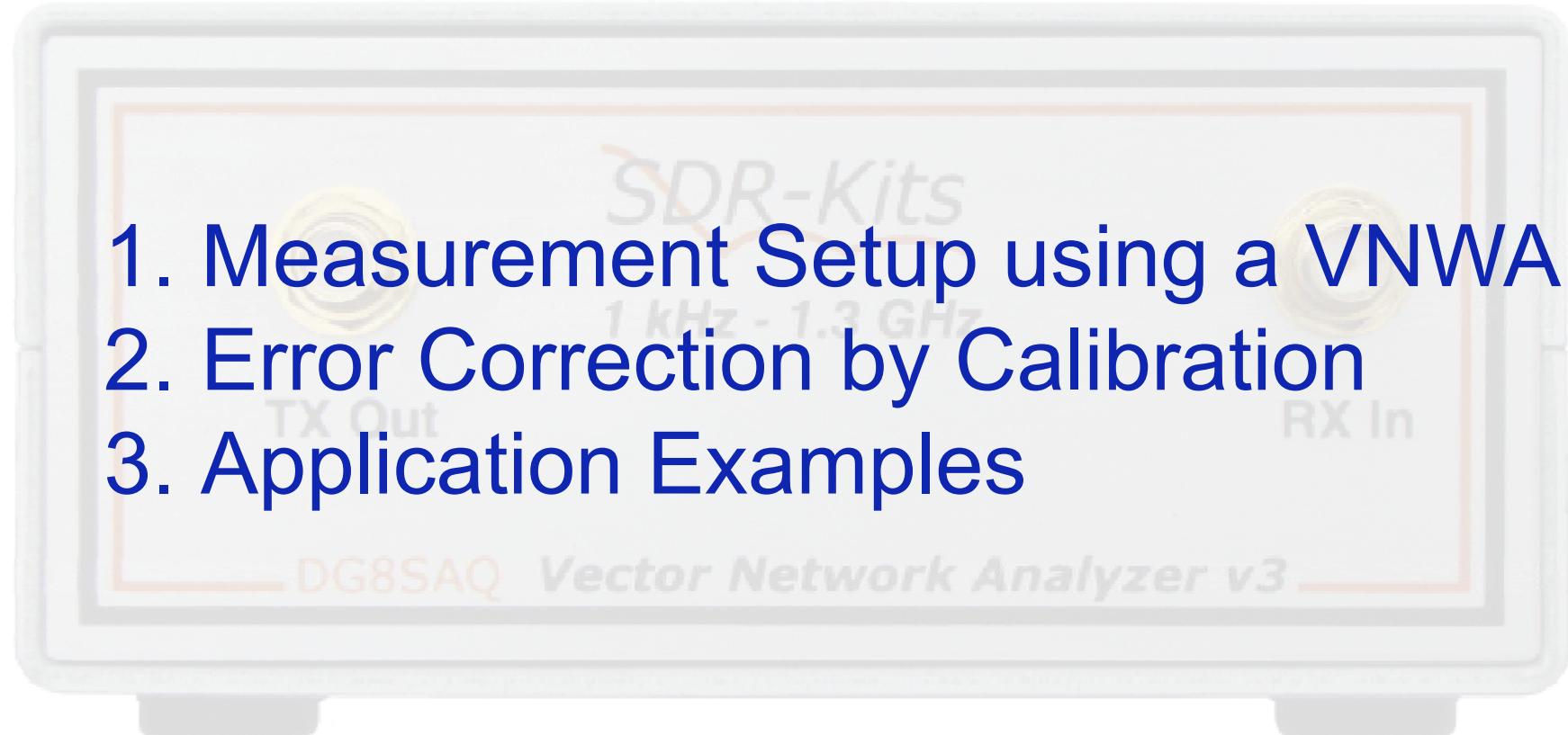
Hochschule Ulm



37

37

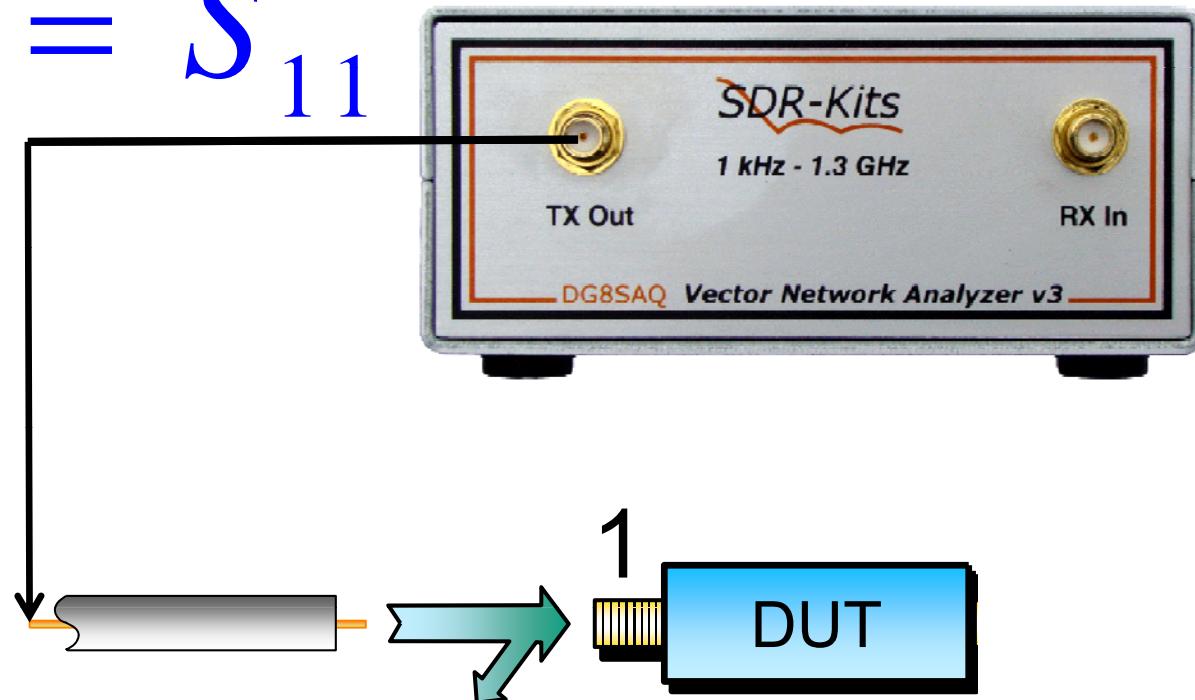
Measuring S-Parameters using a Vector-Network Analyzer



Measurement Setup using a VNWA

Example 1-Port Device:

$$S = S_{11}$$



DUT : DEVICE UNDER TEST

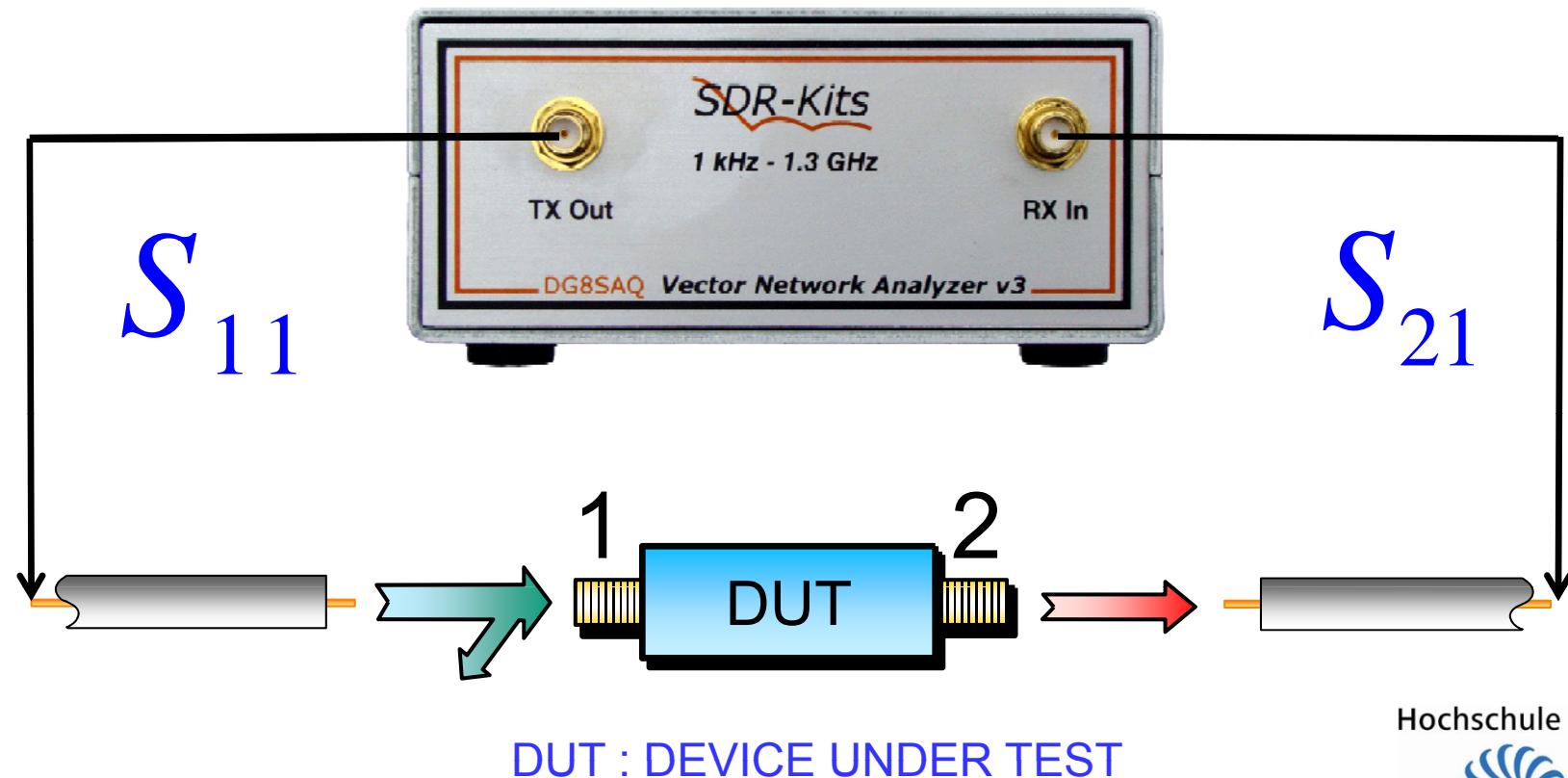
Hochschule Ulm



39

Measurement Setup using a VNWA

Example 2-Port Device forward:



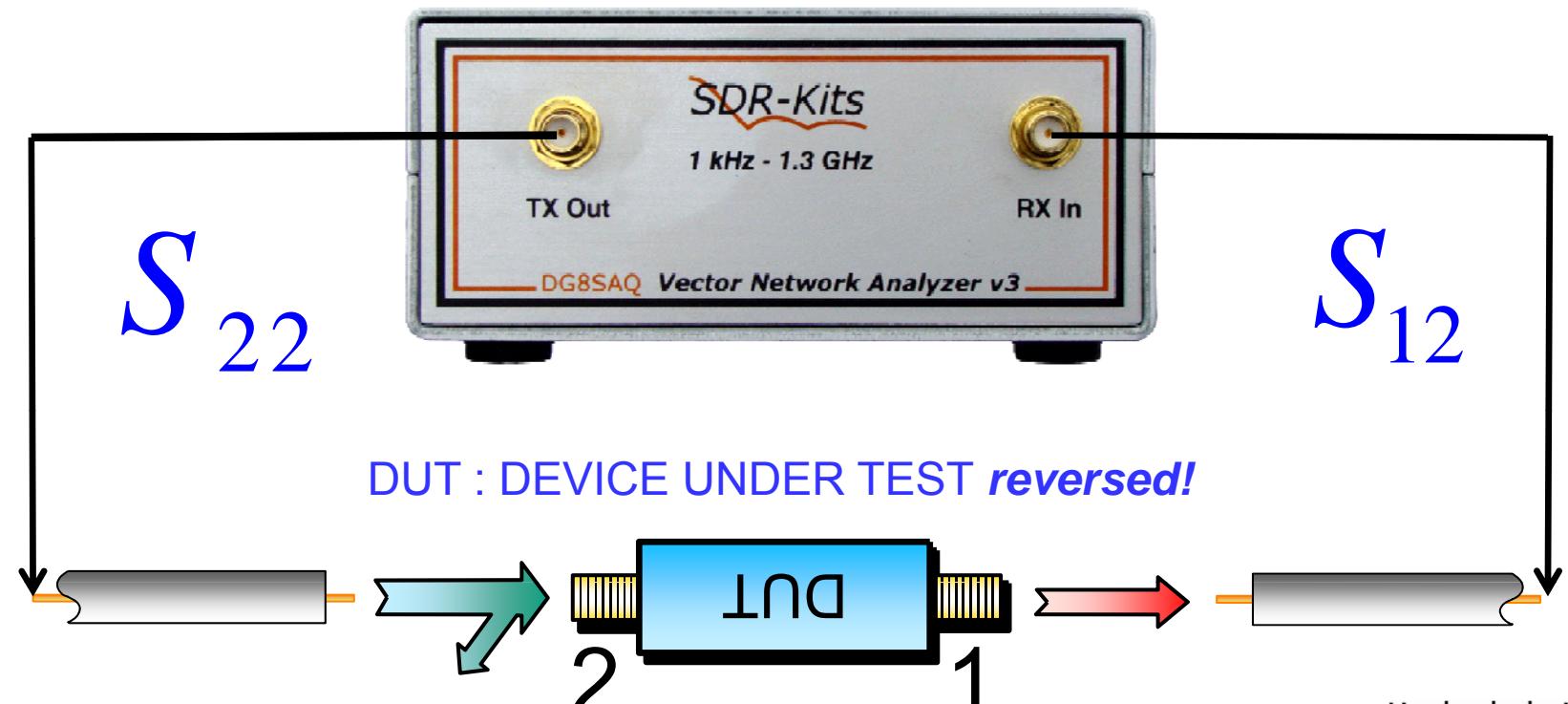
DUT : DEVICE UNDER TEST

Hochschule Ulm



Measurement Setup using a VNWA

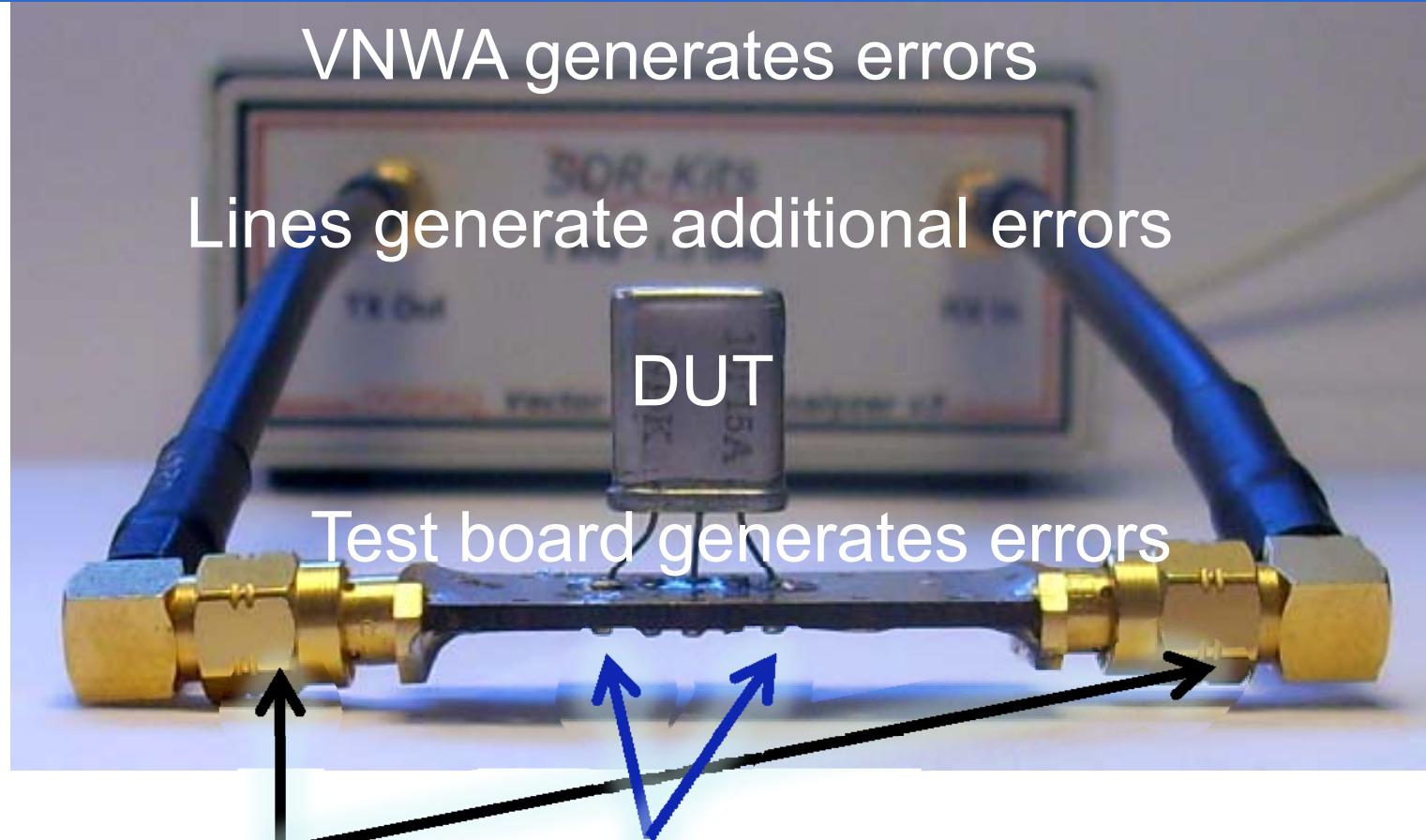
Example 2-Port Device reverse:



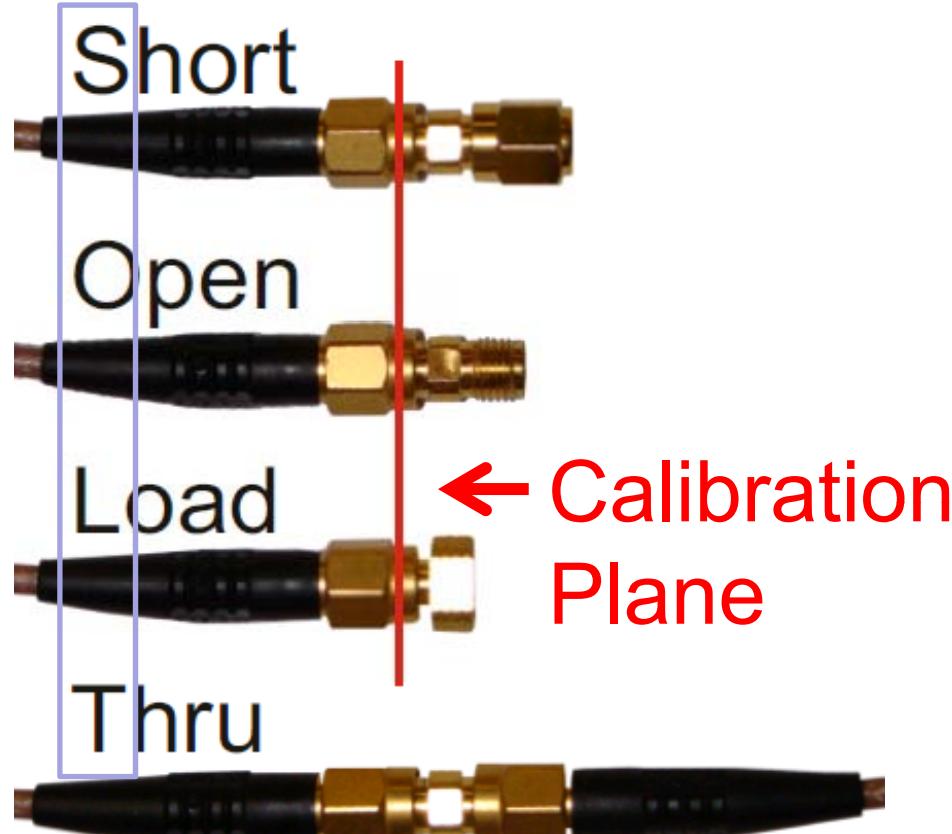
Hochschule Ulm



Error Correction by Calibration Error Sources

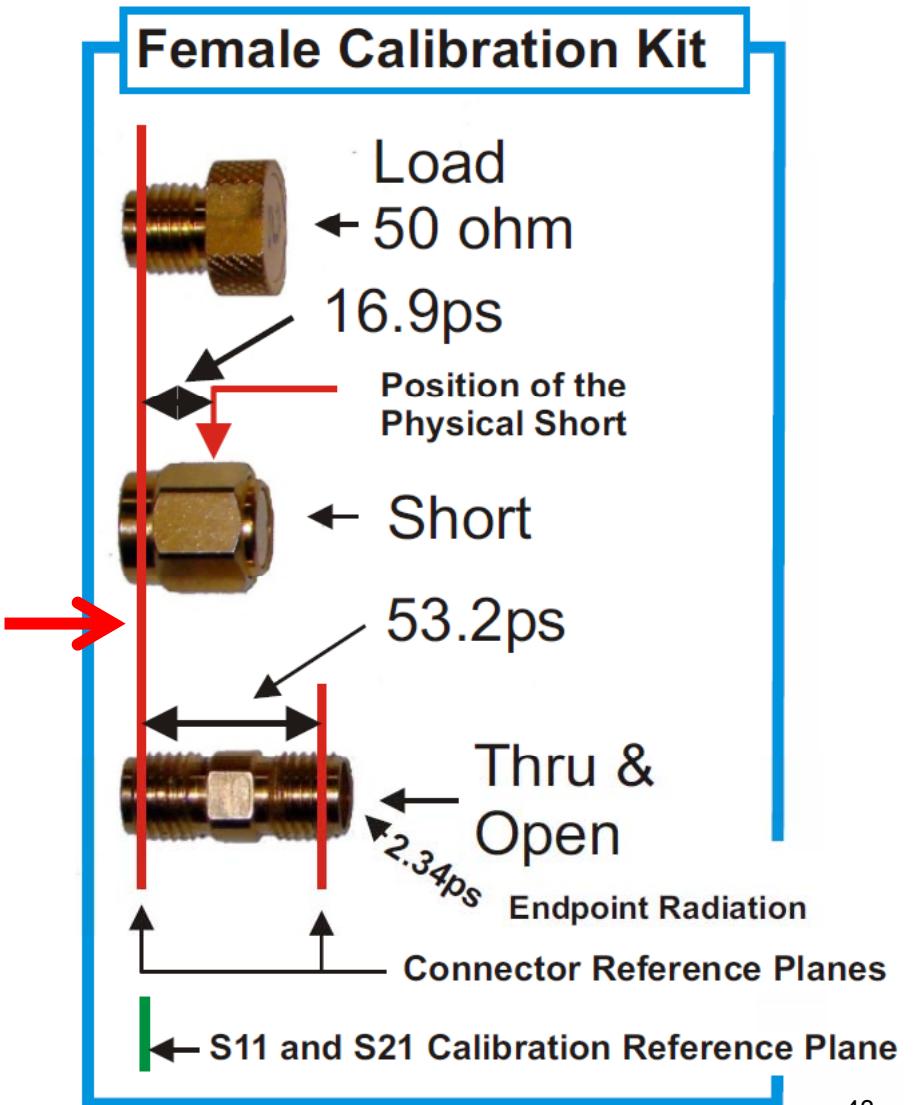


SOLT-Calibration removes Errors from VNWA and Test Cables...



<http://www.hamcom.dk/VNWA/>

HAM RADIO 2013



... as long as the Properties of the Calibration Standards are known!

Calibration Settings

General Settings Simple SOLT Model Settings SOLT Simulation Settings Special Settings **I** **<** **>** **X**

OSL Calibration Standard Setup

OPEN: Delay = **-111.1** ps => one way electrical length = -11.665 mm

SHORT: Delay = **-140.2** ps => one way electrical length = -14.721 mm

LOAD: R = **50** Ohms C II = **30** fF

Note: The Delays above are correction values, i.e. the NEGATIVE of the delays of the standards!

THRU Calibration Standard Setup

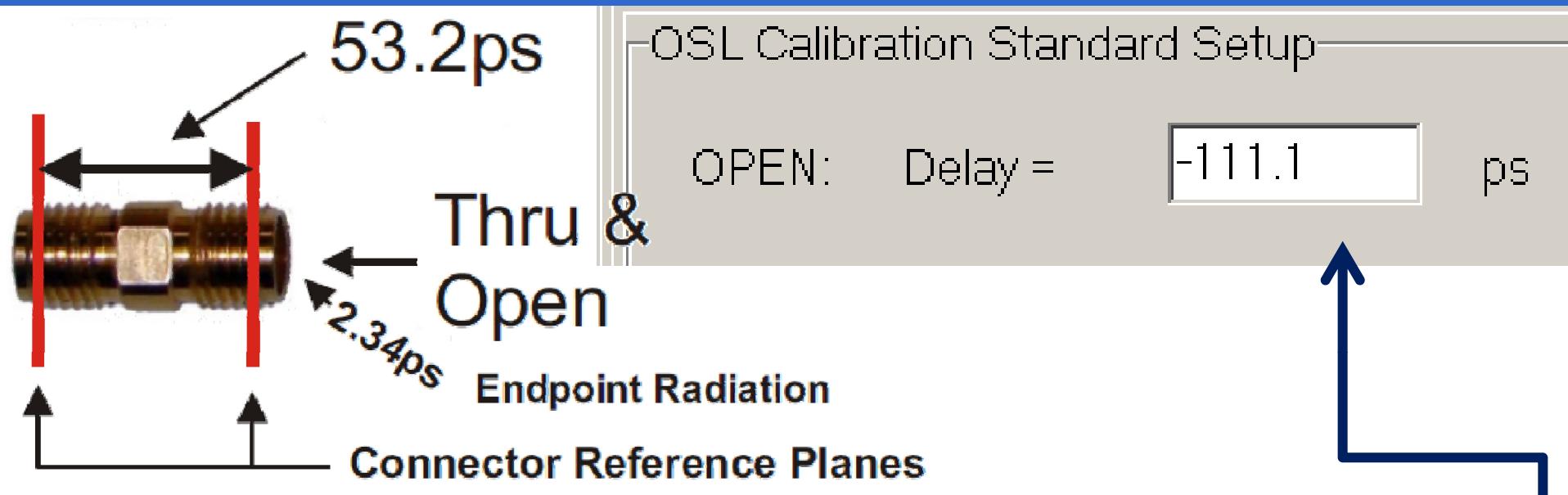
THRU: Transmission Factor = **1** => attenuation = 0.000 dB

THRU: Transmission Delay = **53.2** ps => electrical length = 11.172 mm

HAM RADIO 2013

Ulm

Example: Open Standard

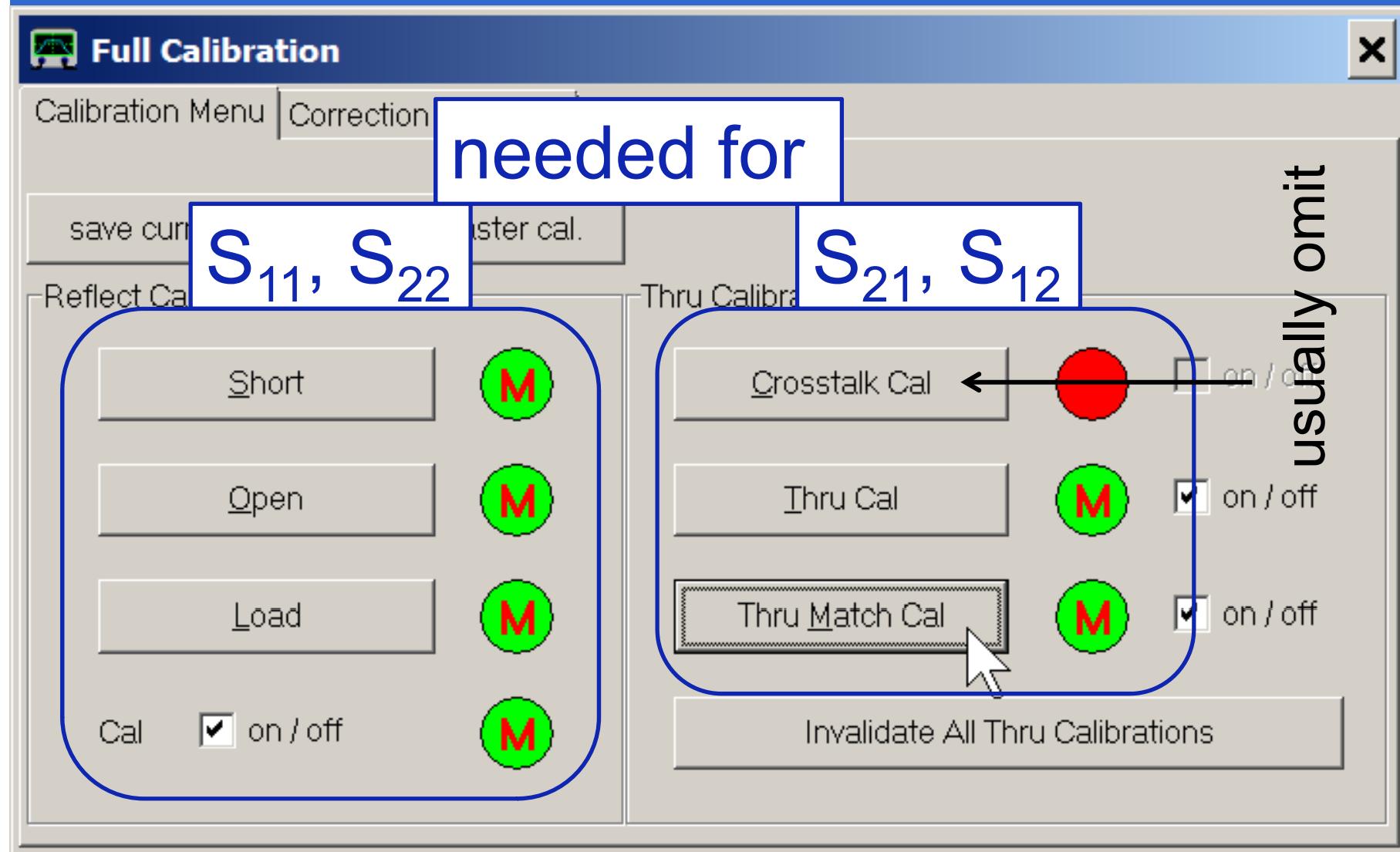


Signal travels standard twice, namely forth and back:

$$\tau = -2 \times (53,2 \text{ ps} + 2,34 \text{ ps}) = -111.08 \text{ ps}$$



Now, connect standards to VNWA and calibrate

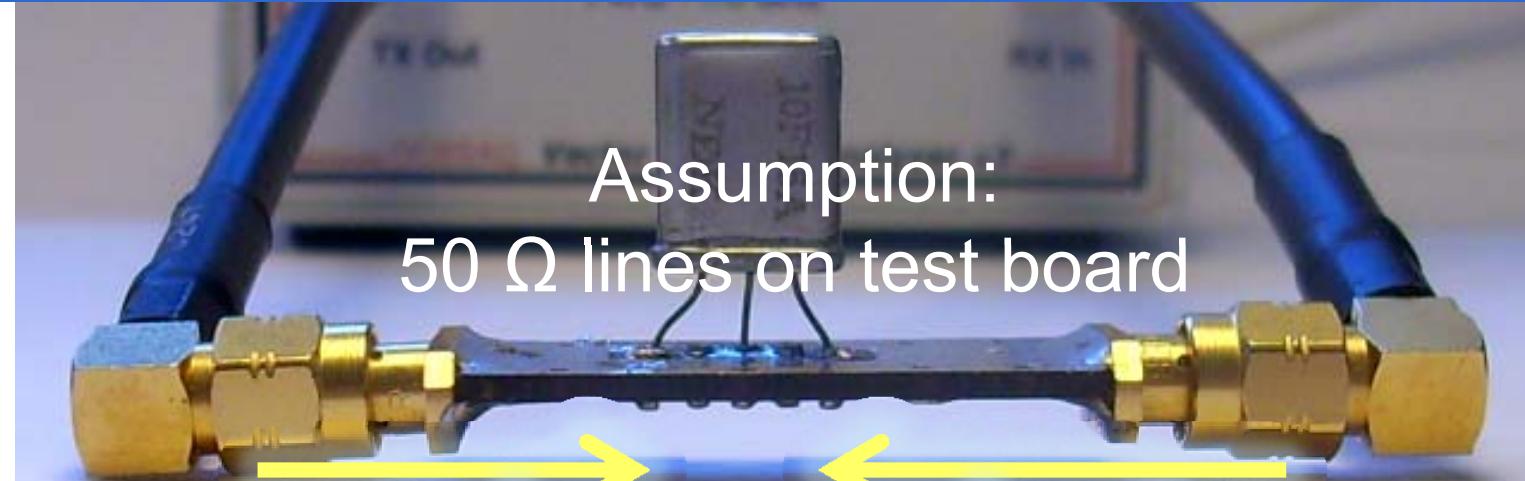


Jlm

46

46

Delay Correction with Port Extensions



S_{11}
 S_{22}

Assumption:
50 Ω lines on test board

Port Extensions

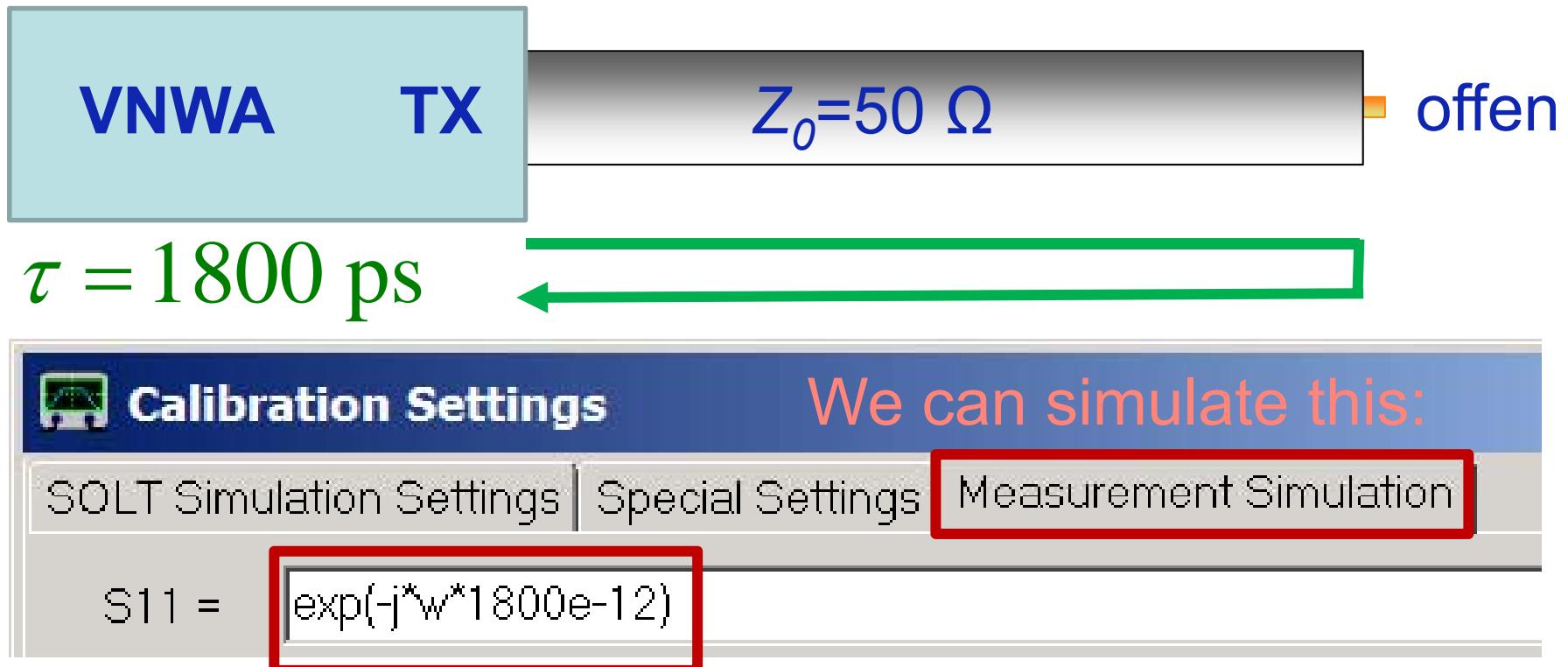
Ext. Port 1	105	ps	= 22 mm
Ext. Port 2	132	ps	= 27.7 mm

Velocity Factor: 0.7 Port Ext. ON

chule Ulm

Wrong Cal Parameters cause Port Mismatch

Example: open 50 Ohms – Line (1)

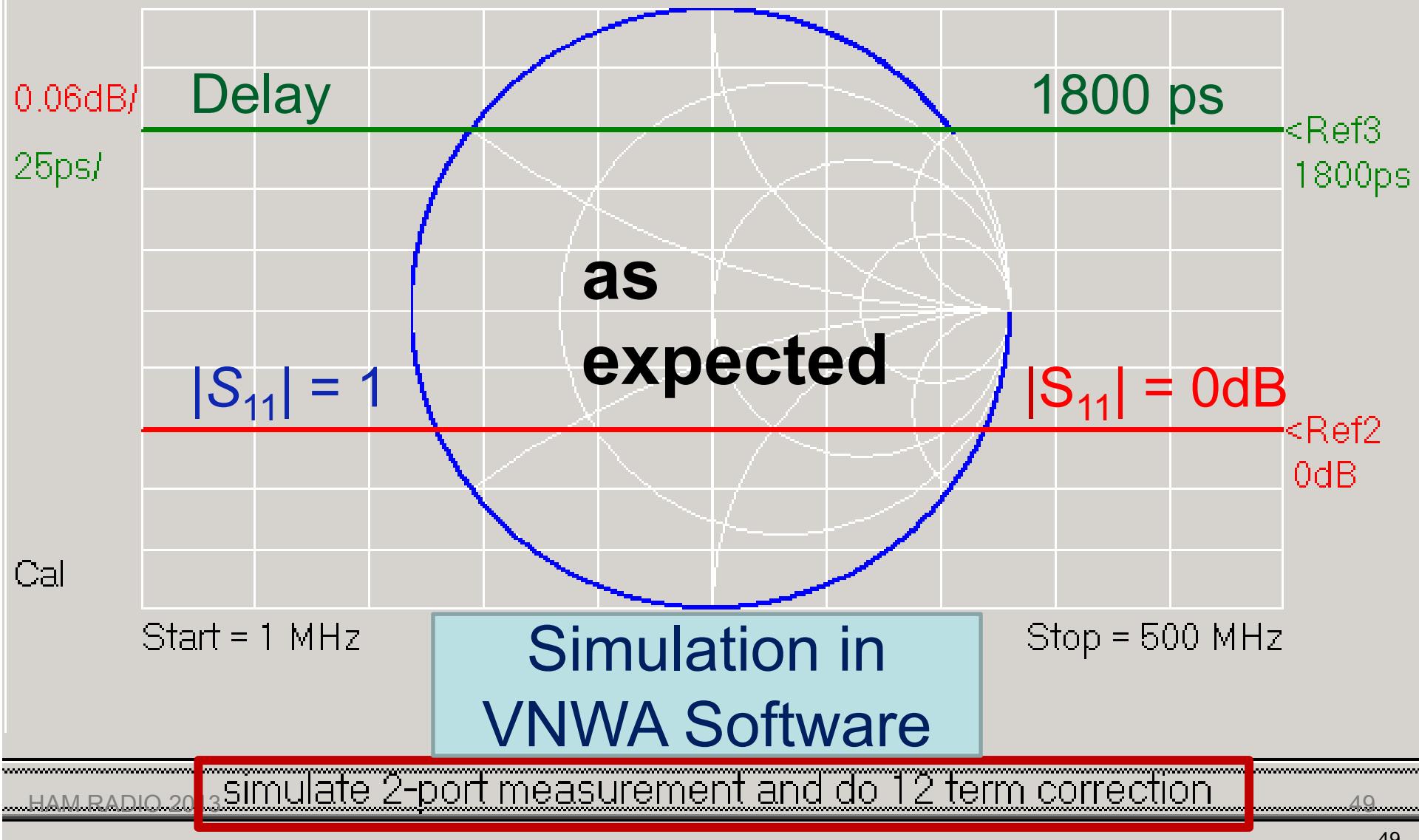


i.e. $|S_{11}| = 1$ total power reflected
 $\text{Phase}(S_{11}) = -\omega \cdot 1800 \text{ ps}$

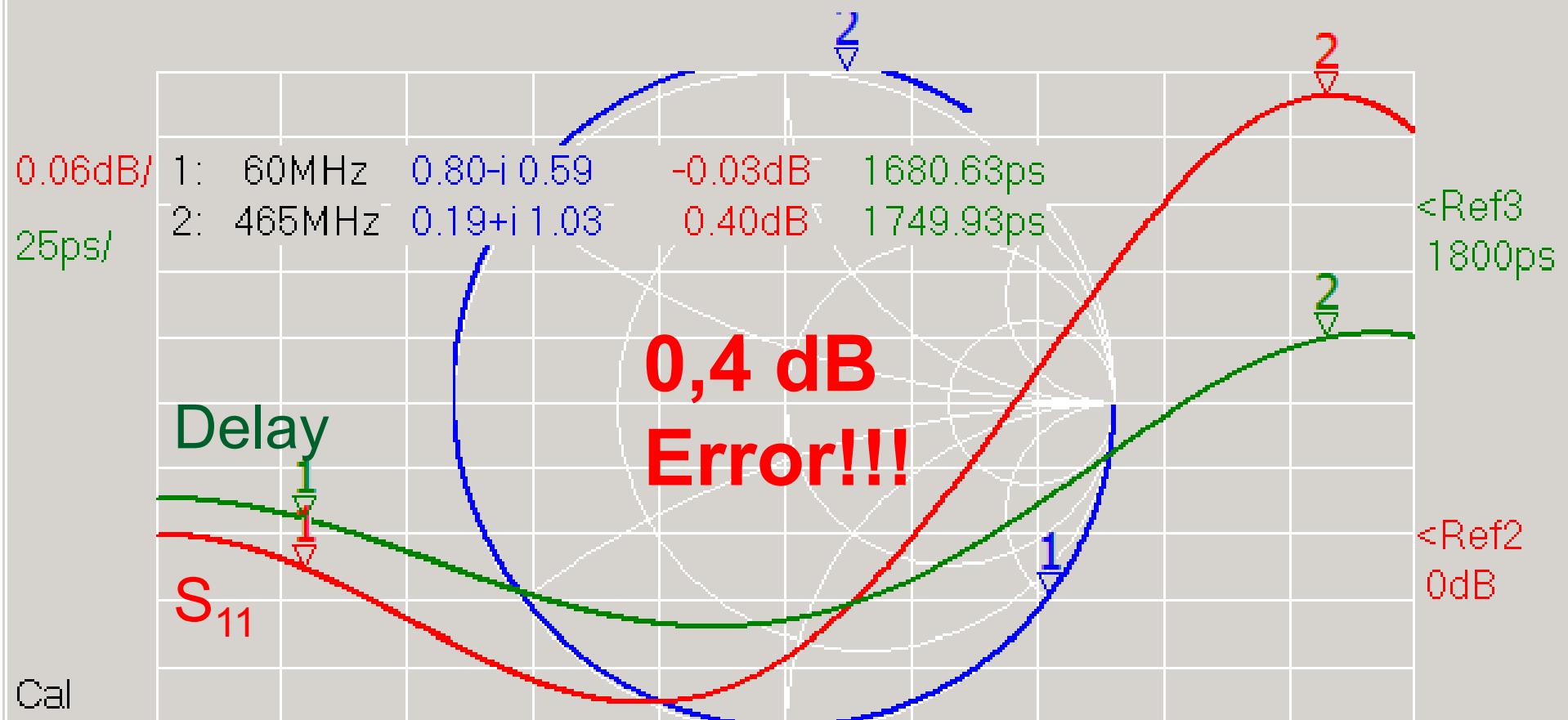
Hochschule Ulm



Example: open 50 Ohms – Line (2) Simulated with Amphenol Female Parameters



Example: open 50 Ohms – Line (3)
Let software think standards are ideal:

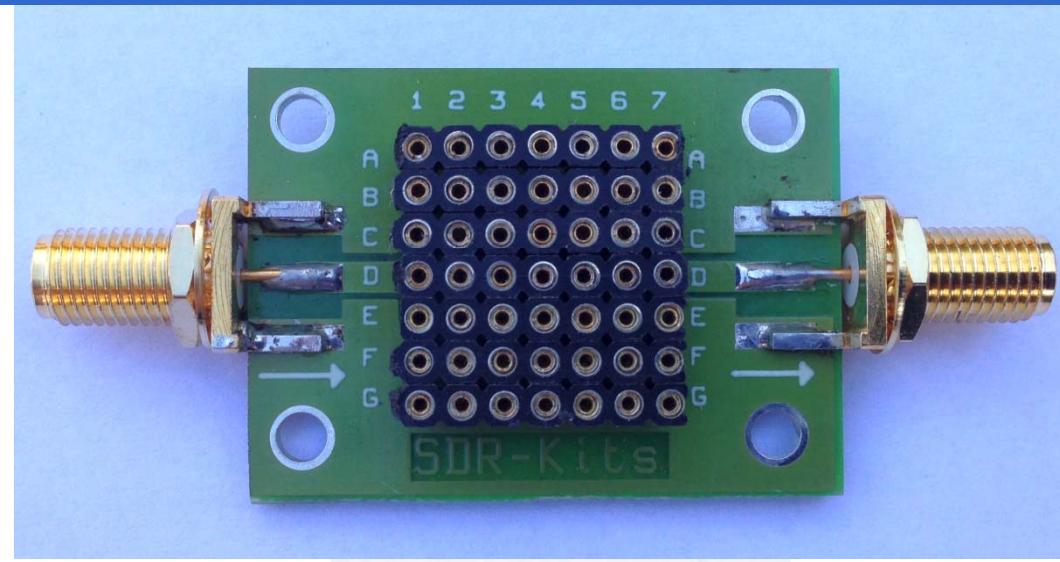
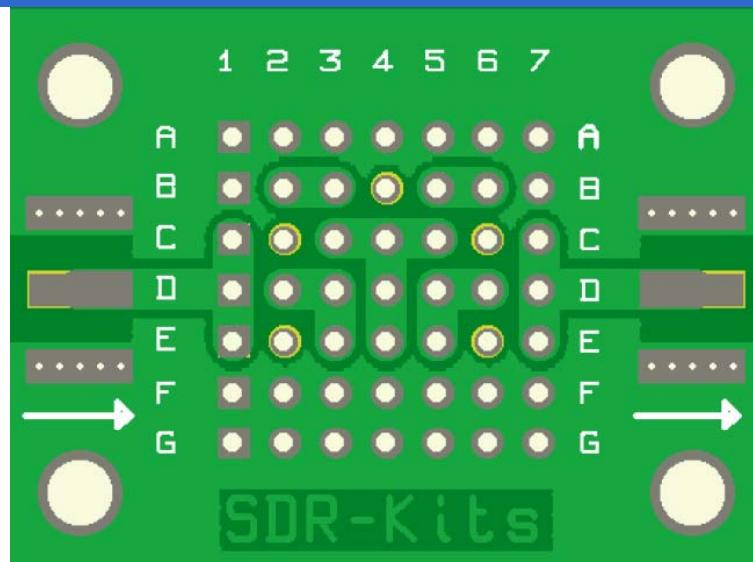


Previously simulated measurement data
corrected again using ideal cal parameters

Applications ...



Test Board for HF Experiments



**Calibration
Standards:**

Open = n.c.

Short:



Load = 47Ω:



Thru:

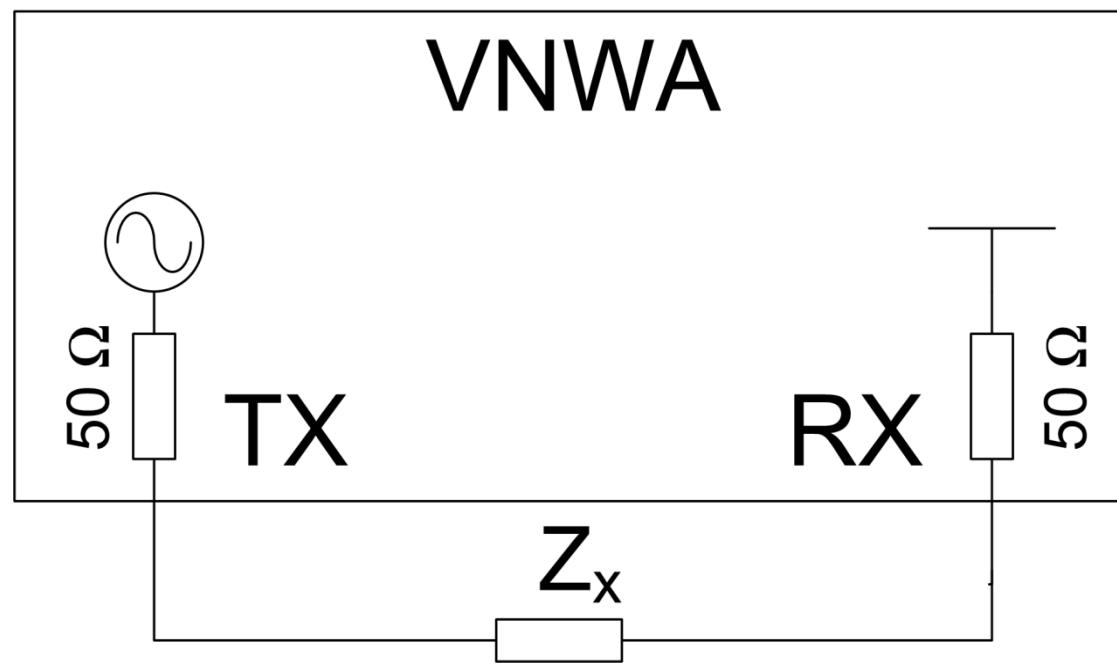


Hochschule Ulm



52

Measuring „Load“-Resistor without SOL-Calibration?

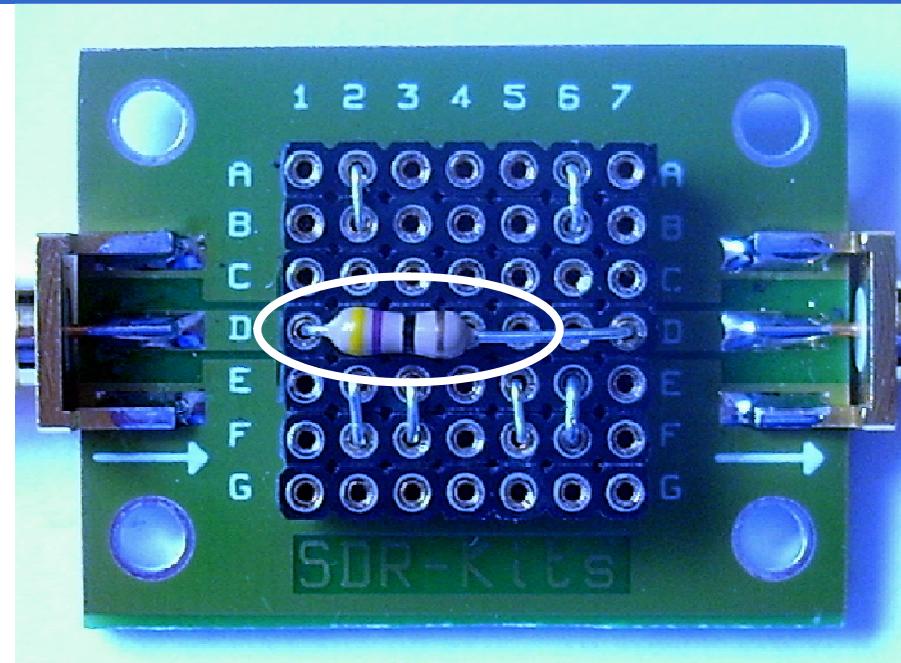
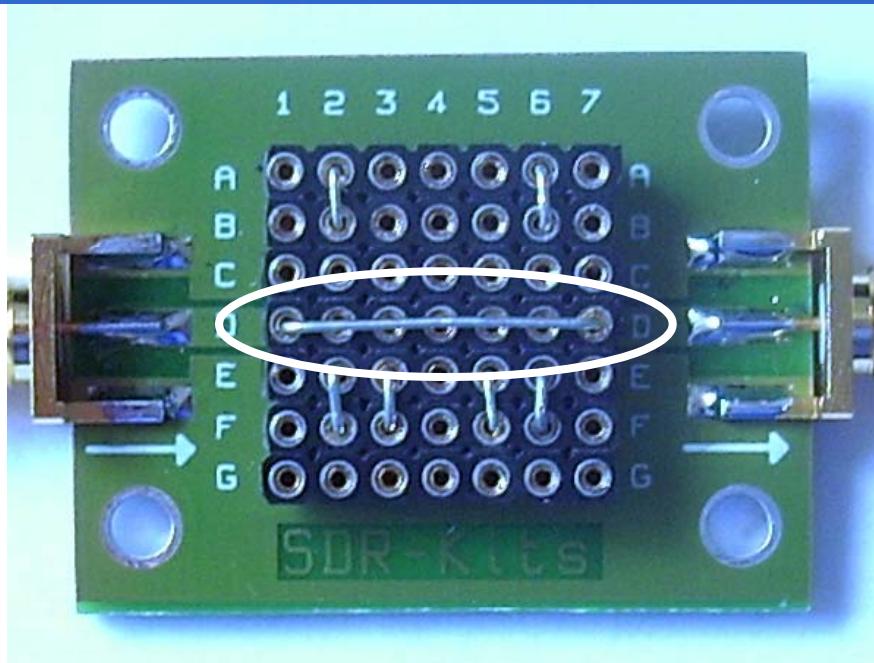


$Z_x = 47 \Omega$ yield $\approx 3,4$ dB
insertion loss.

Works, because
VNWA TX and RX
port impedances
are exactly 50Ω .

➤ only Thru
calibration
required!

Measuring „Load“-Resistor in Transmission ($=S_{21}$ -Measurement)



Measurement:
Resistor between
TX and RX

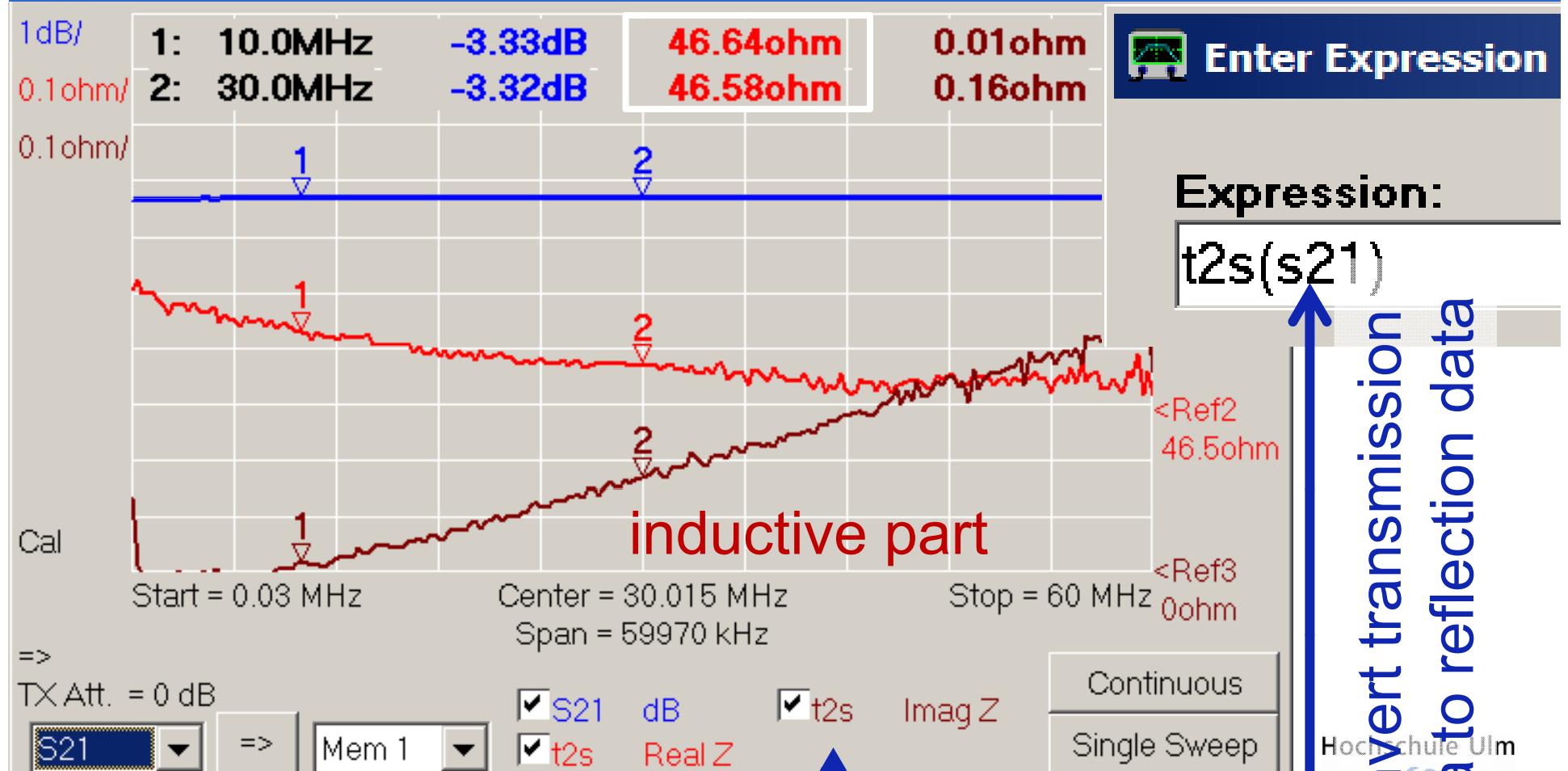
Hochschule Ulm



54

Measuring „Load“-Resistor

Result = 46,6 Ω



Analysis with Custom Trace

Simple Calibration Standard Model: Only measured Load-Resistance

 **Calibration Settings** X

General Settings | Simple SOLT Model Settings | SOLT Simulation Settings | Special Settings

OSL Calibration Standard Setup

OPEN: Delay = ps => one way electrical length = 0.000 mm

SHORT: Delay = ps => one way electrical length = 0.000 mm

LOAD: R = Ohms C_{II} = fF

Note: The Delays above are correction values, i.e. the NEGATIVE of the delays of the standards!

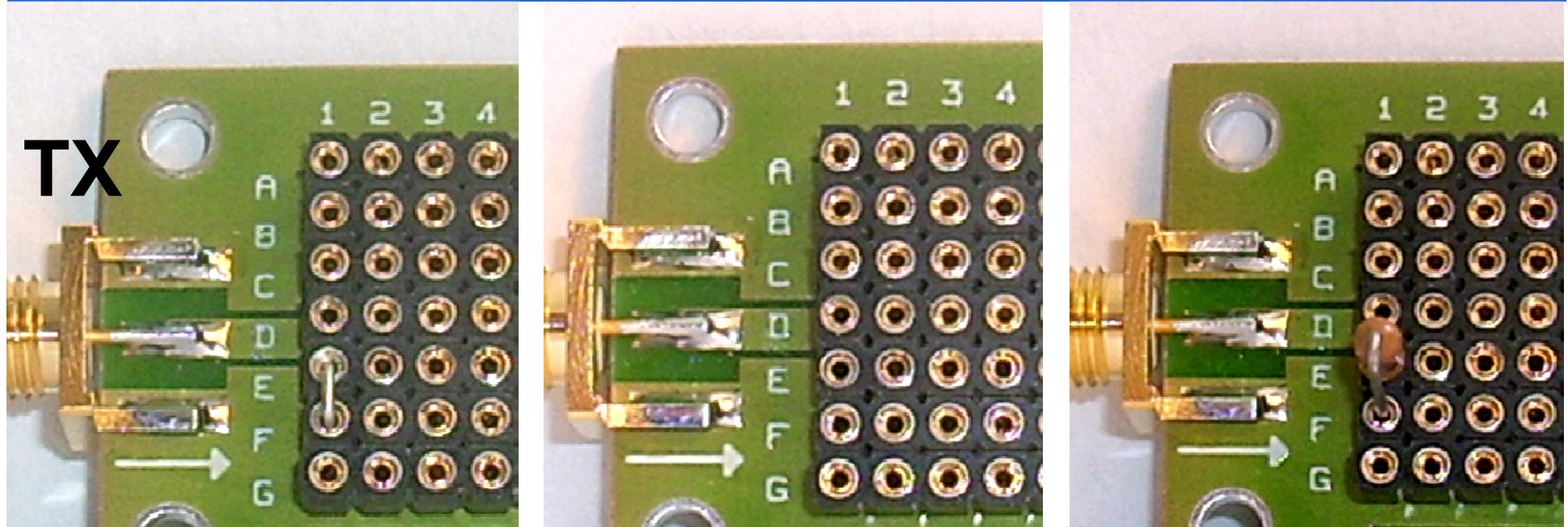
THRU Calibration Standard Setup

THRU: Transmission Factor = => attenuation = 0.000 dB

THRU: Transmission Delay = ps => electrical length = 0.000 mm

HAM RADIO 2013

SOL-Calibration for S_{11} -Measurement



Reflect Calibration

Thru Calibration

Load

Short

Open

Open



Load



HAMRAD 2018 off

Invalidate All Thru Calibrations

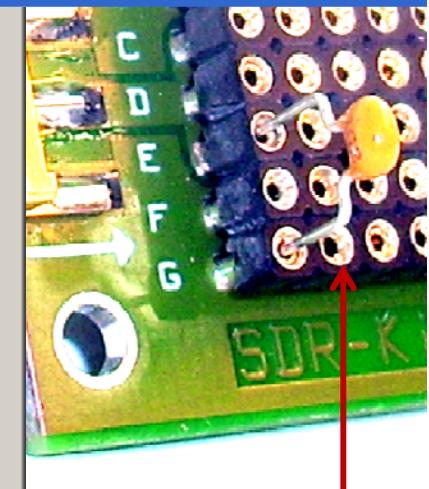
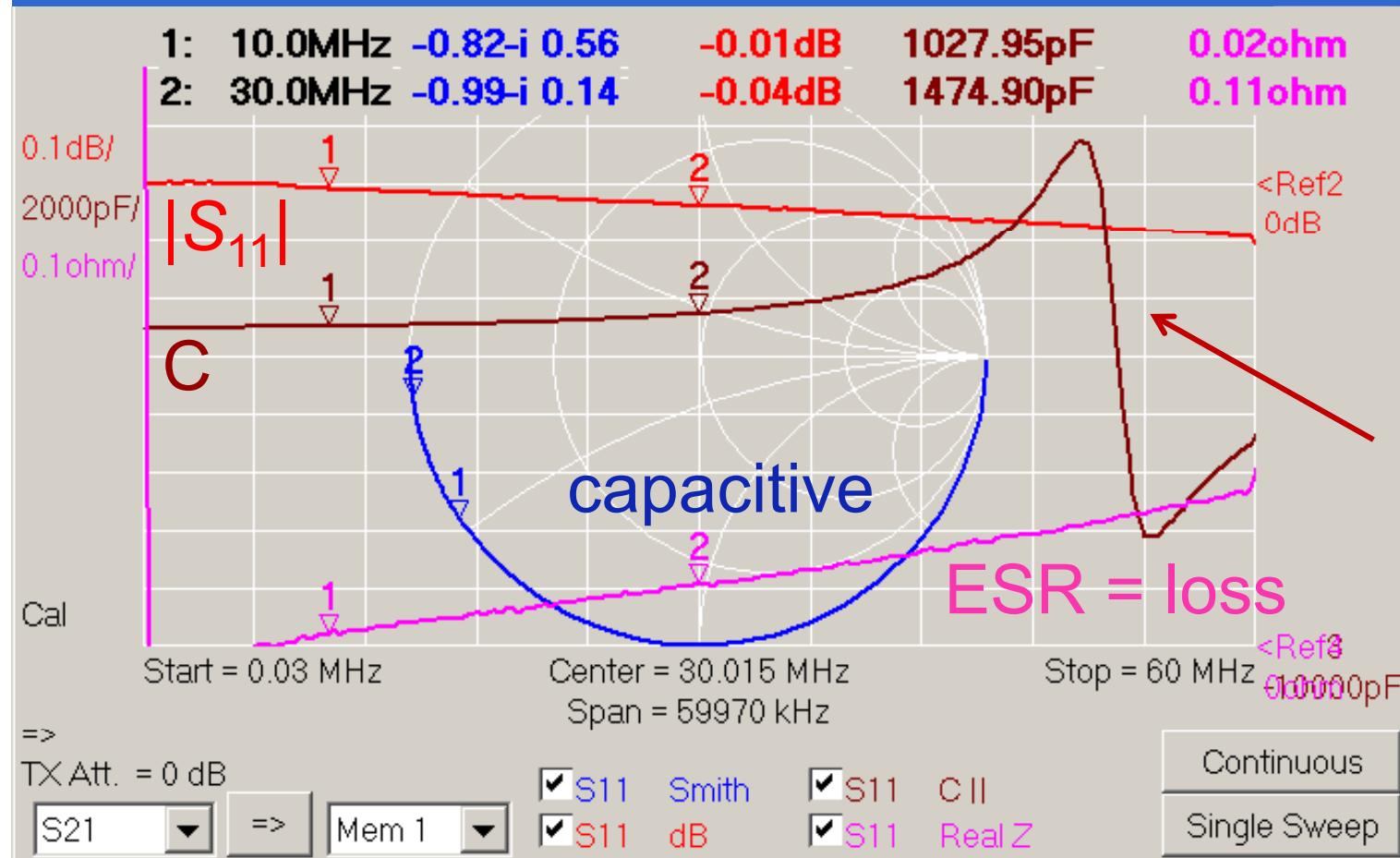
Hochschule Ulm



57

57

Reflexion Measurement (S_{11}) of a 1 nF Capacitor



Resonance
due to
component
wires

Hochschule Ulm



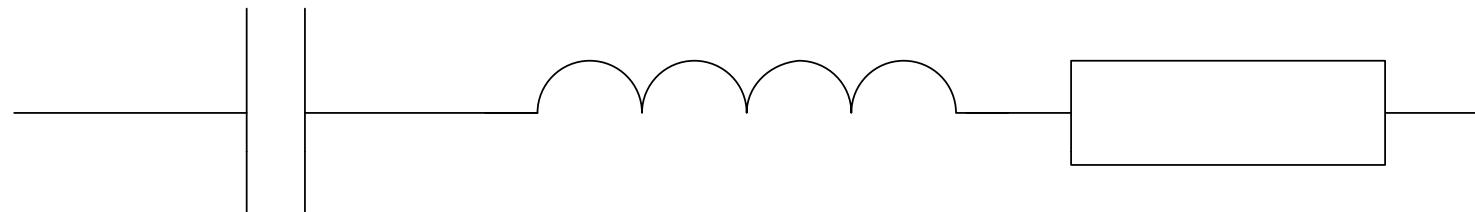
Capacitor reflects almost total power, $|S_{11}| \approx 0 \text{ dB}$

Modelling of Measurement Result in VNWA using Custom-Trace

 Enter Expression 2 for trace 2:

Impedance to Reflecion coefficient
Expression:

`z2s(1/(j*w*0.984e-9)+j*w*9.3e-9+0.22)`



0,984 nF

9,3 nH

0,22 Ω

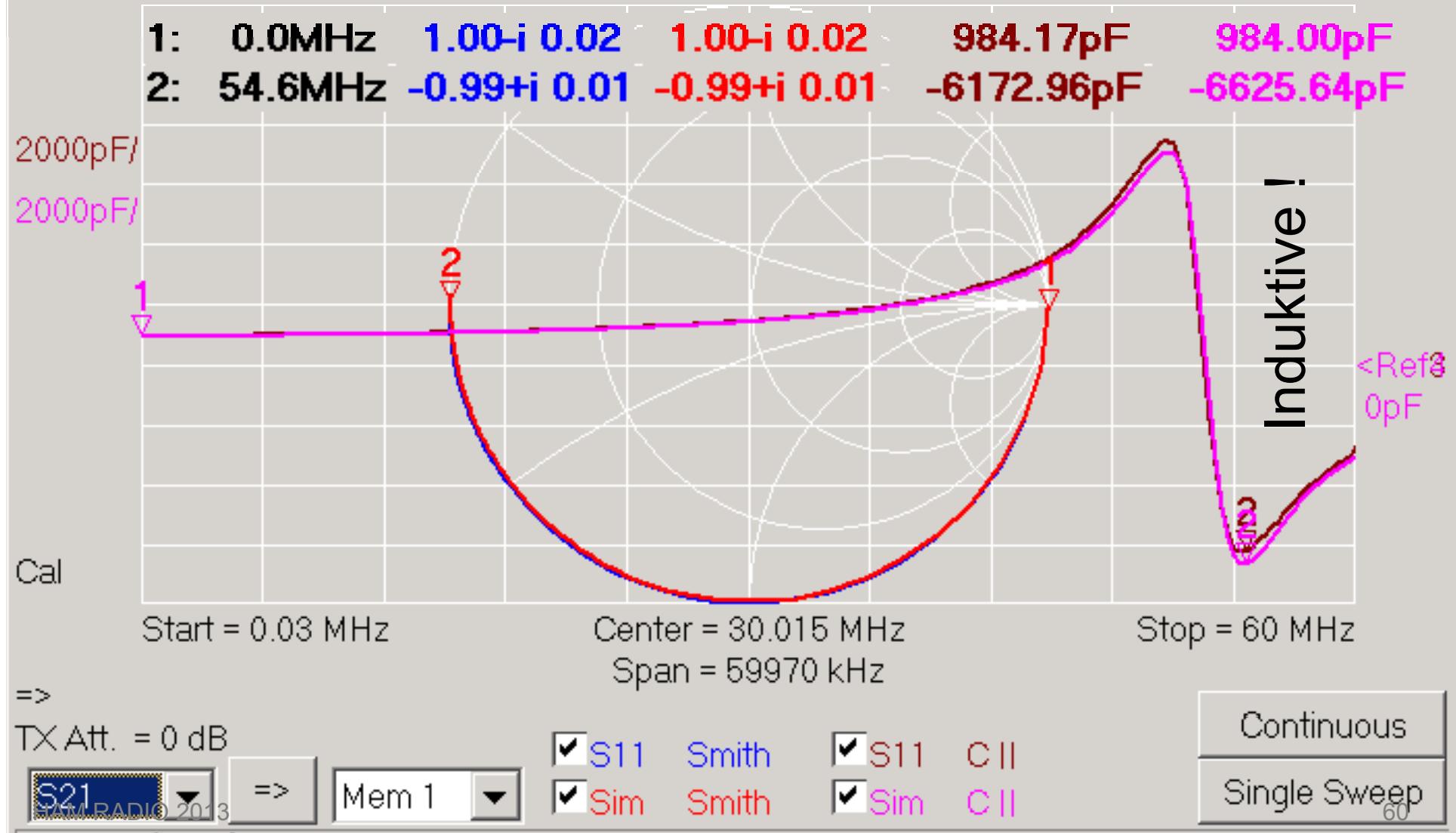
einfaches Modell

Hochschule Ulm



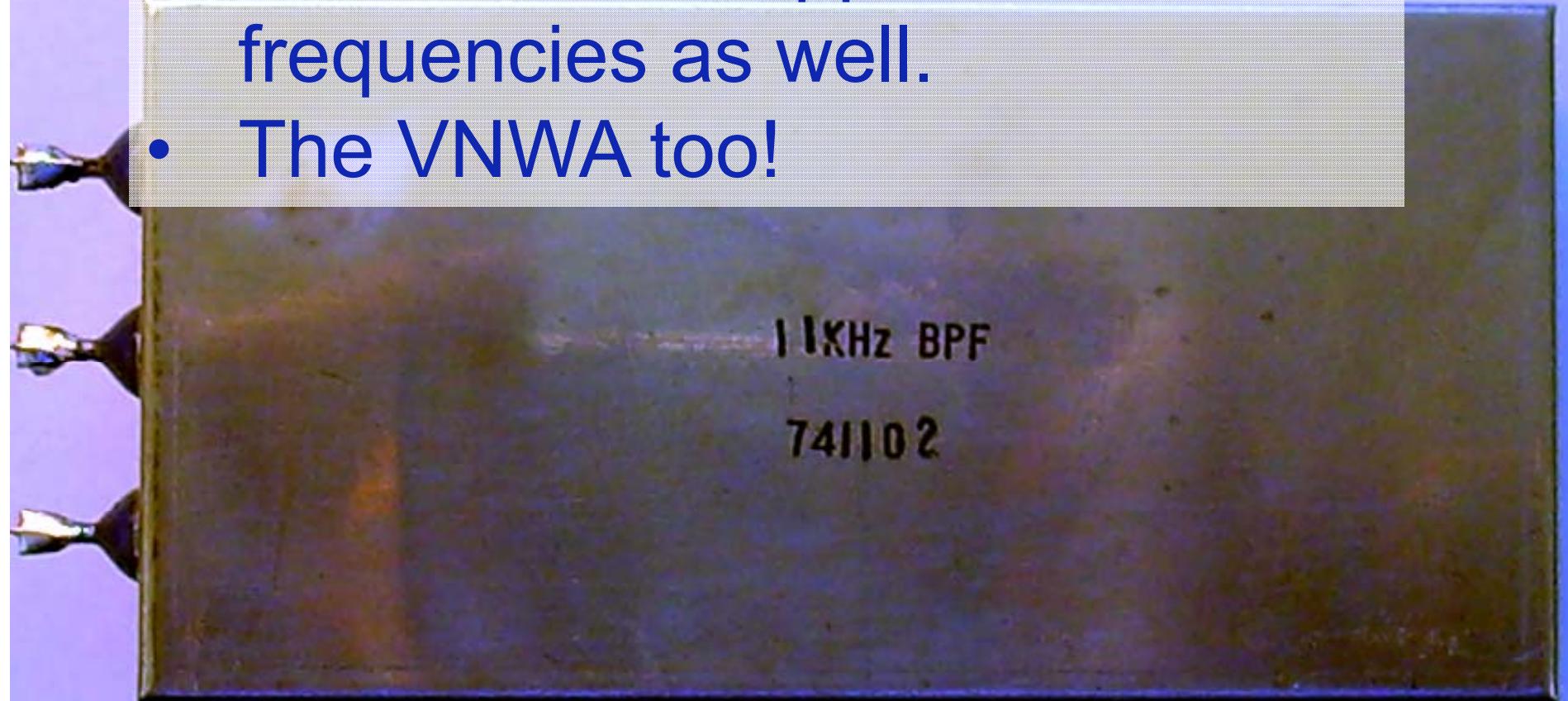
59

The Model is quite accurate!

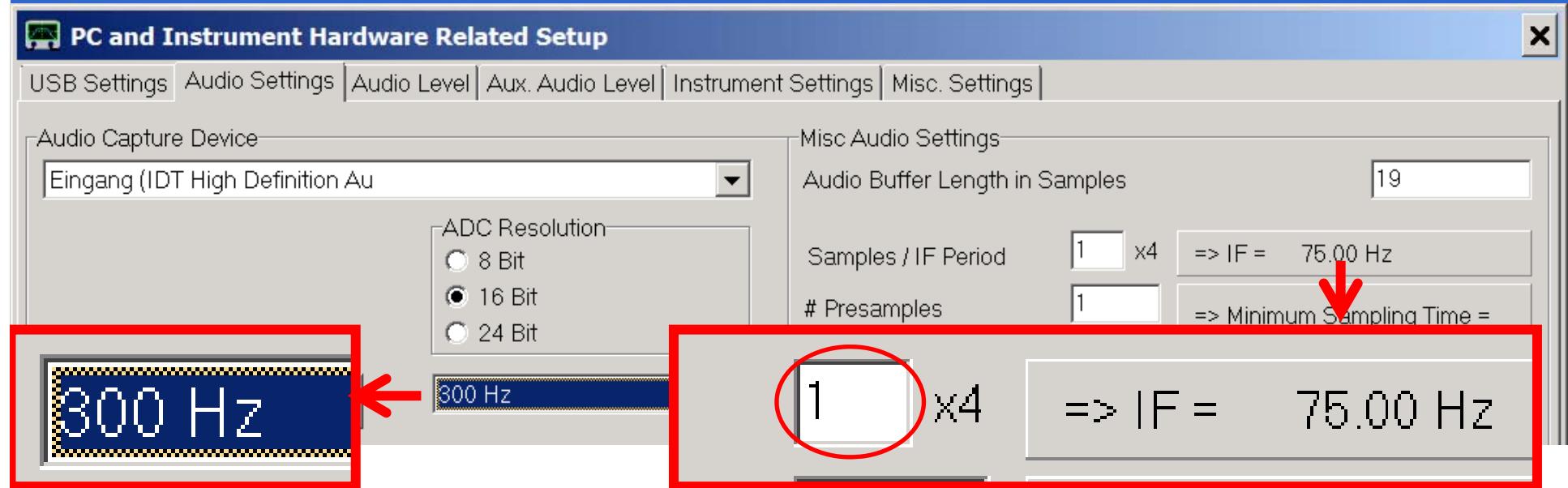


Two Port Measurement of a 12 kHz Band Pass Filter

- S-Parameters applicable to low frequencies as well.
- The VNWA too!

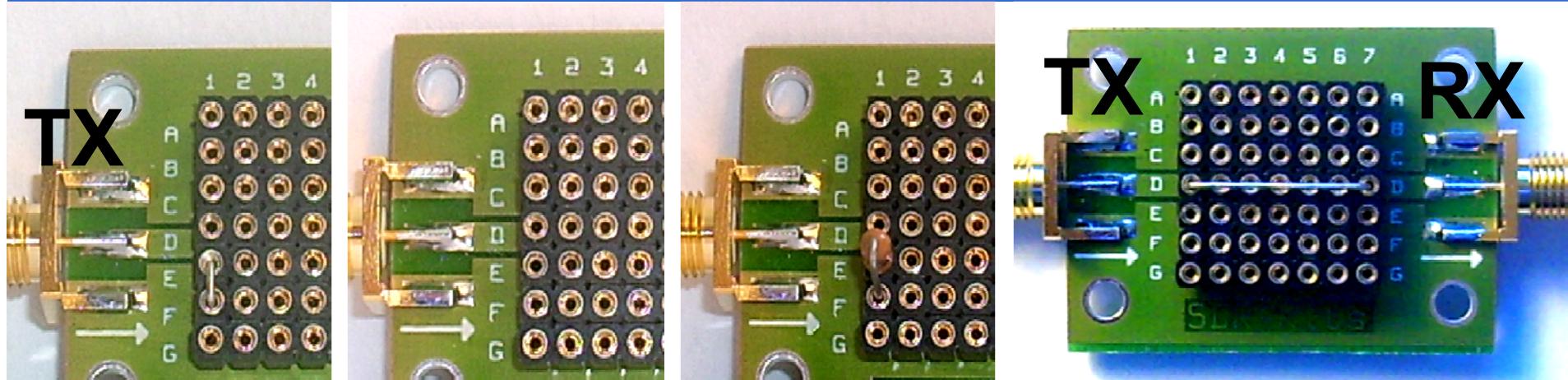


Special VNWA Settings for low Frequencies



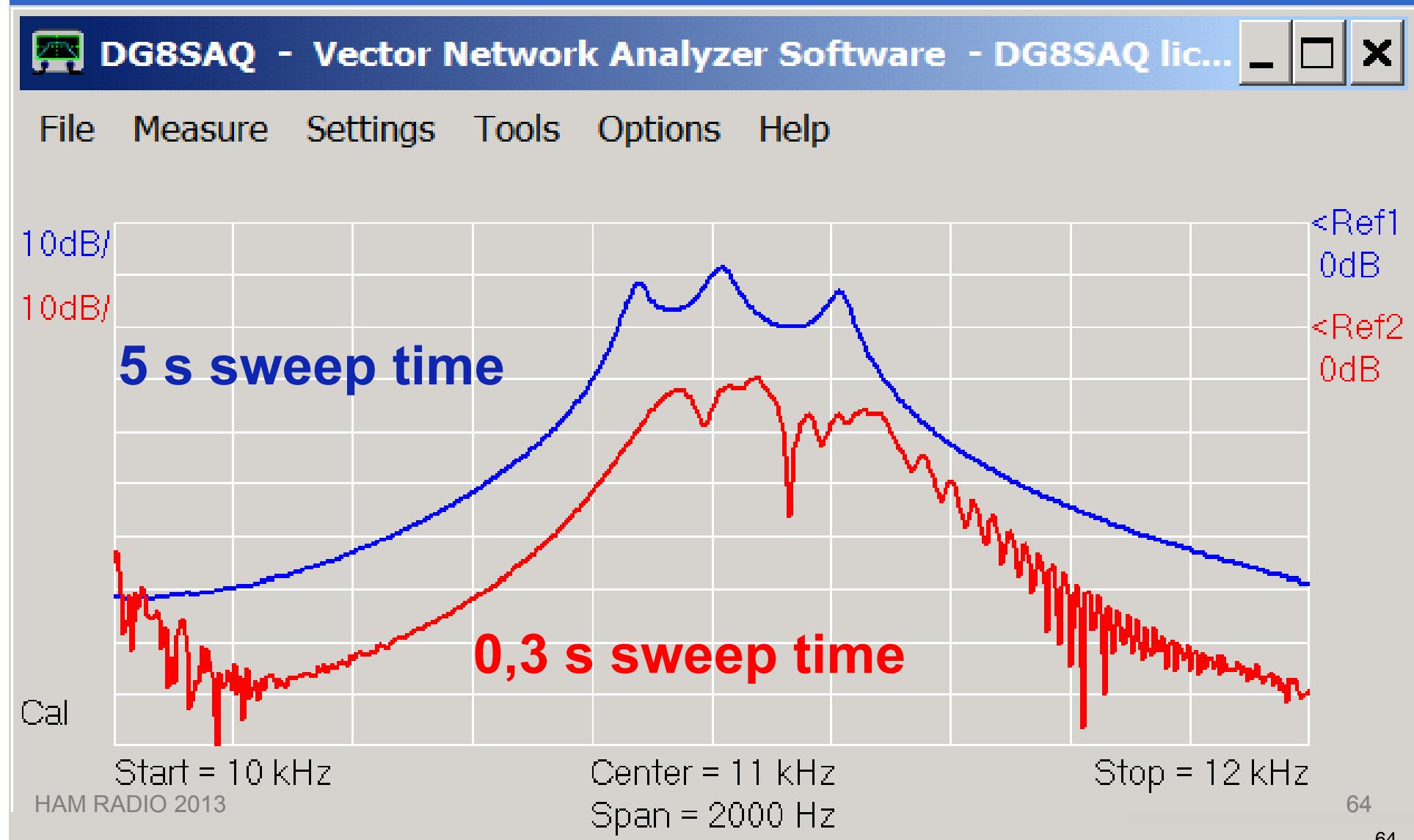
**Lowest sample rate 300 Hz IF must be within Codec
→ Nyquist limit 150 Hz frequency range
→ Measurements down to (20 Hz...16kHz)
≈150 Hz possible**

SOLT-Calibration for 2-Port Measurements

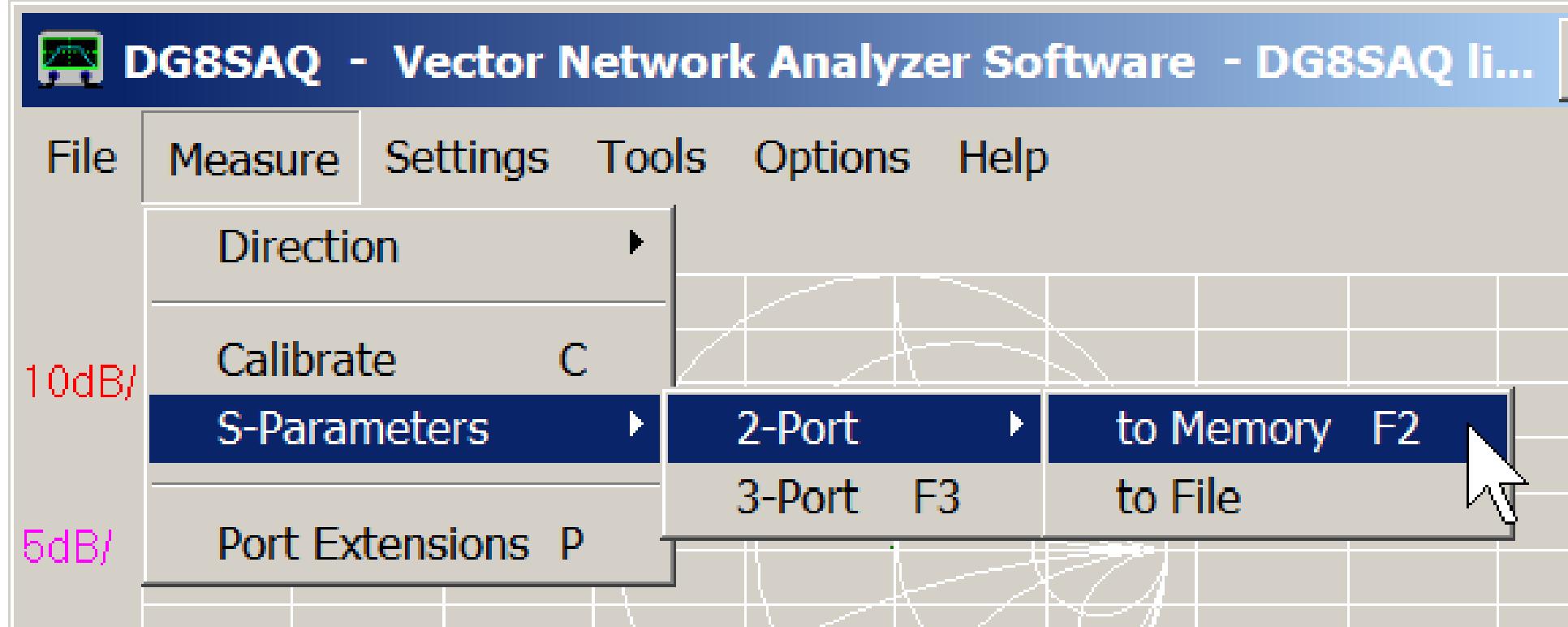


Reflect Calibration	Open	Thru Calibration	Thru
Short	Open	Load	Thru
<input type="button" value="Short"/>	<input type="button" value="Open"/>	<input type="button" value="Crosstalk Cal"/>	<input type="checkbox"/> on / off
<input type="button" value="Open"/>	<input type="button" value="M"/>	<input type="button" value="Thru Cal"/>	<input checked="" type="checkbox"/> on / off
<input type="button" value="Load"/>	<input type="button" value="M"/>	<input type="button" value="Thru Match Cal"/>	<input checked="" type="checkbox"/> on / off
<input type="checkbox"/> Cal	<input checked="" type="checkbox"/> on / off	<input type="button" value="Invalidate All Thru Calibrations"/>	

Beware: Steep Skirt Filters require Time to settle to changing Stimulus!

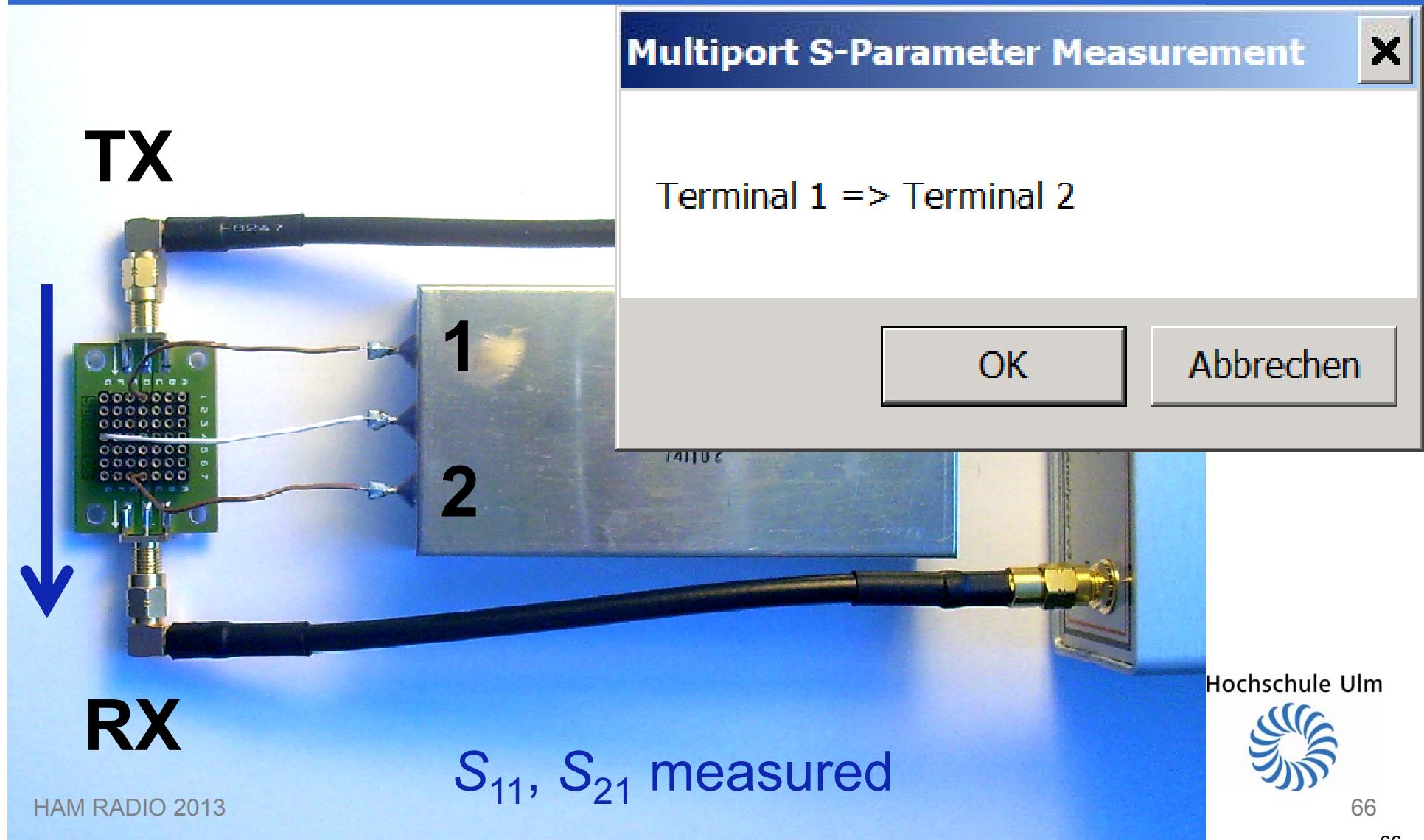


Two Port Measurement of a 12 kHz Band Pass Filter



We need to measure all four S-parameters
(S_{11} , S_{21} , S_{12} , S_{22}) ...

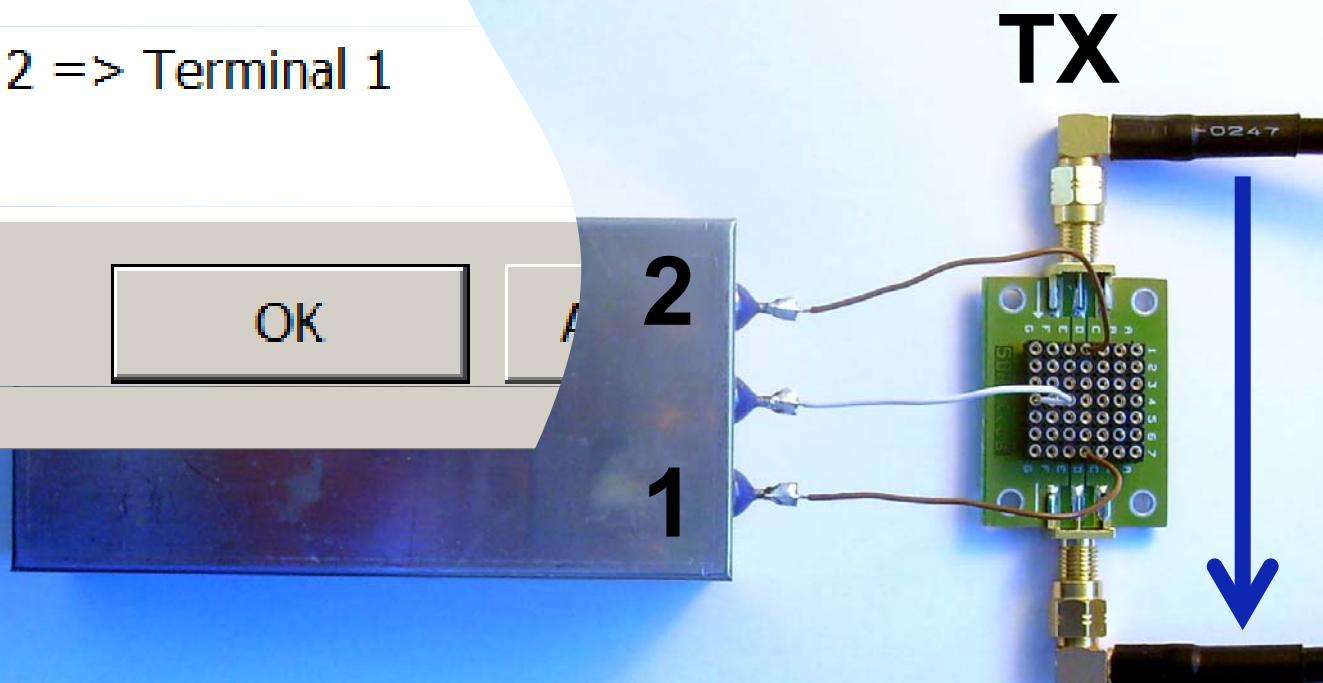
Two Port Measurement of a 12 kHz Band Pass Filter: Forward Measurement



Two Port Measurement of a 12 kHz Band Pass Filter: Reverse Measurement

Multiport S-Parameter Me

Terminal 2 => Terminal 1



S_{12} , S_{22} measured

HAM RADIO 2013

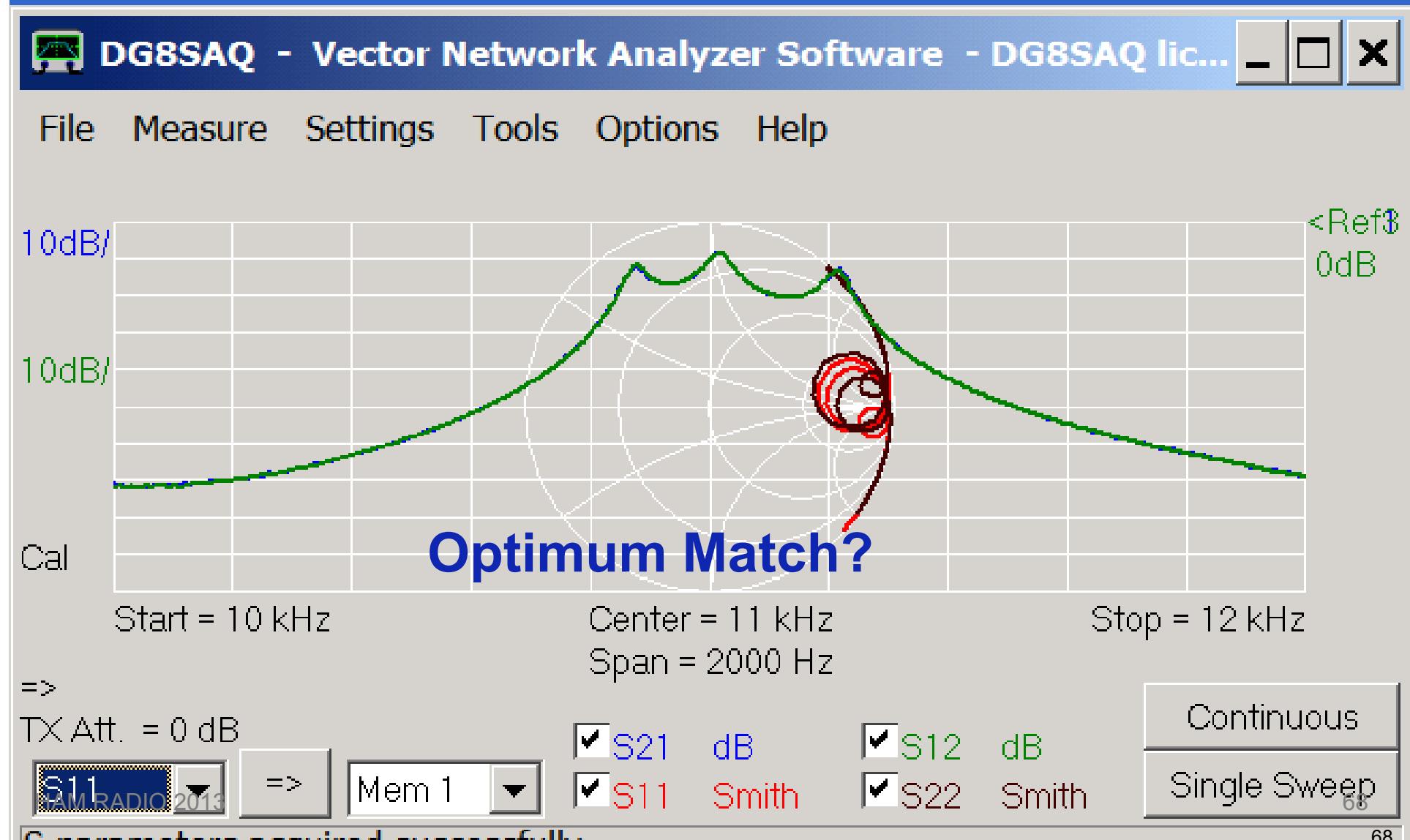
Hochschule Ulm



67

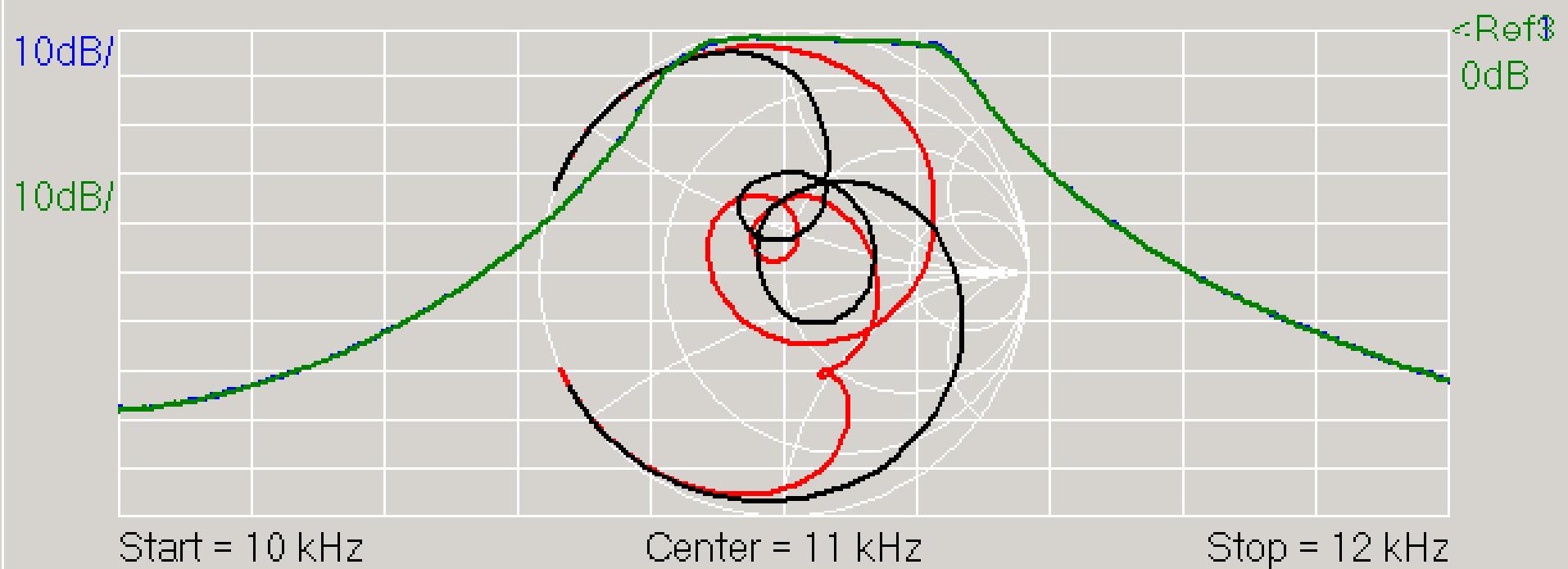
67

What are measured 2-Port S-Parameters good for?

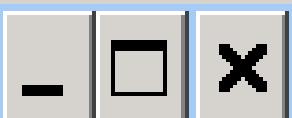


Matching Analysis: VNWA Matching Tool

Optimum: $Z_{in} = Z_{out} = 610 \Omega$



Recalculate to new source and load conditi...



Port 1

Port 1 Impedance

610

Ohm



C parallel
(neg. possible)

0

pF



Port 2

Port 2 Impedance

610

Ohm



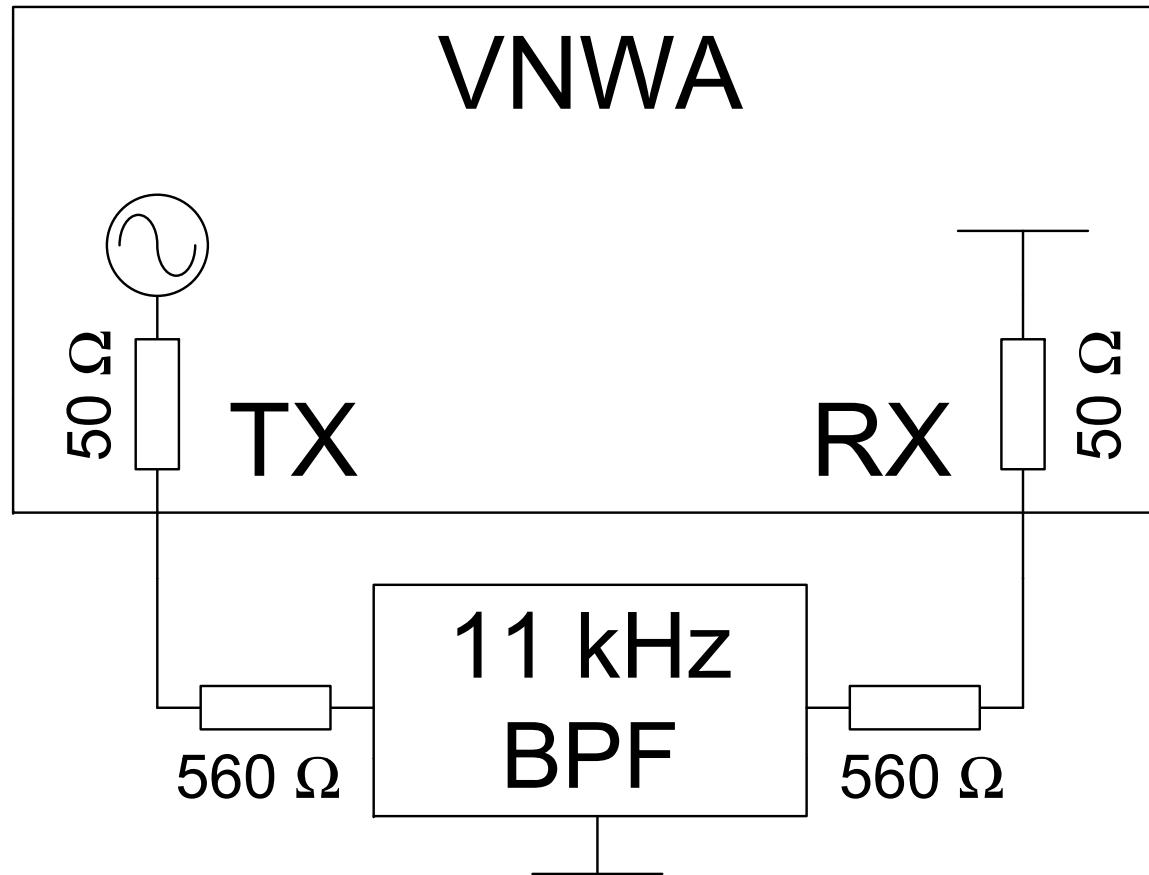
C parallel
(neg. possible)

0

pF



Forced Impedance Match using Resistors



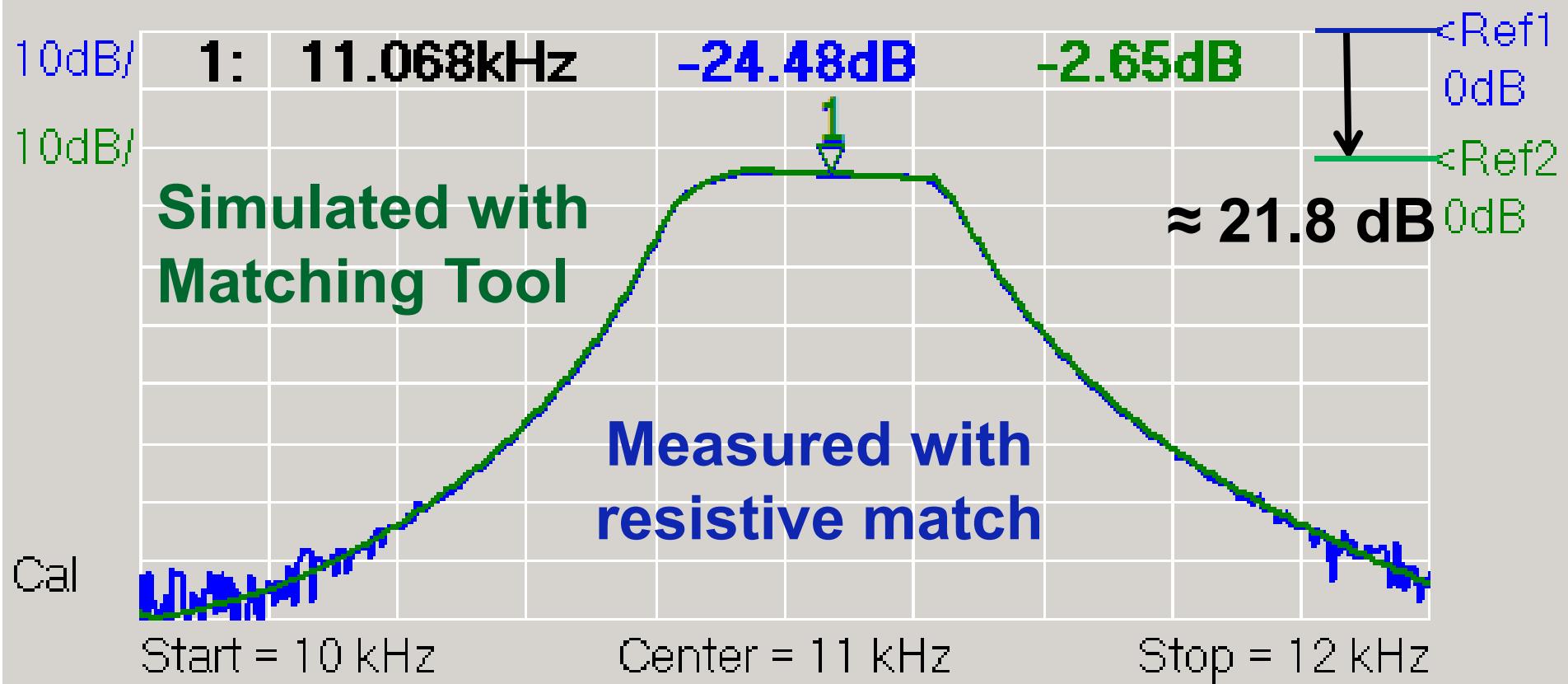
$$50 \Omega + 560 \Omega = 610 \Omega$$

Hochschule Ulm



70

Match works except for increased Loss



Effect of two 560Ω Resistors in Signal Path: VNWA Complex Calculator

The screenshot shows a window titled "Simple Calculator". On the left, there's a toolbar with icons for workspace, variable, and ans. The main area has tabs for "Workspace" and "History". In the History tab, the command `>> db(s2t(z2s(2*560)))` is entered, and the result is displayed as `ans = -21.727196613495`. The result is highlighted with a blue border.

```
>> db(s2t(z2s(2*560)))  
ans =  
-21.727196613495
```

21,7 dB additional attenuation ✓

Hochschule Ulm



This can also be „properly“ simulated!
Simulation Tool QUCS



- <http://qucs.sourceforge.net/>
- **Universal circuit simulator**
- **Free**
- **No restrictions**
- **Easy to use**
- **Grafics and data export needs
brush up**



Measured S-Parameters in QUCS

Qucs 0.0.16 - Project: 11kHzBPF

File Edit Positioning Insert Project Tools Simulation View Help

simulations

Projects Content Components

11kHzBPF.sch 11kHzBPF.dpl

S parameter simulation

SP1
Type=lin
Start=10 kHz
Stop=12 kHz
Points=400

measured S-parameters from s2p-file

X1
File=11kHz_BPF.s2p

P1 Num=1 R=560 Ohm Z=50 Ohm

R1 Ref

R2

P2 Num=2 R=560 Ohm Z=50 Ohm

HAM RADIO 2013

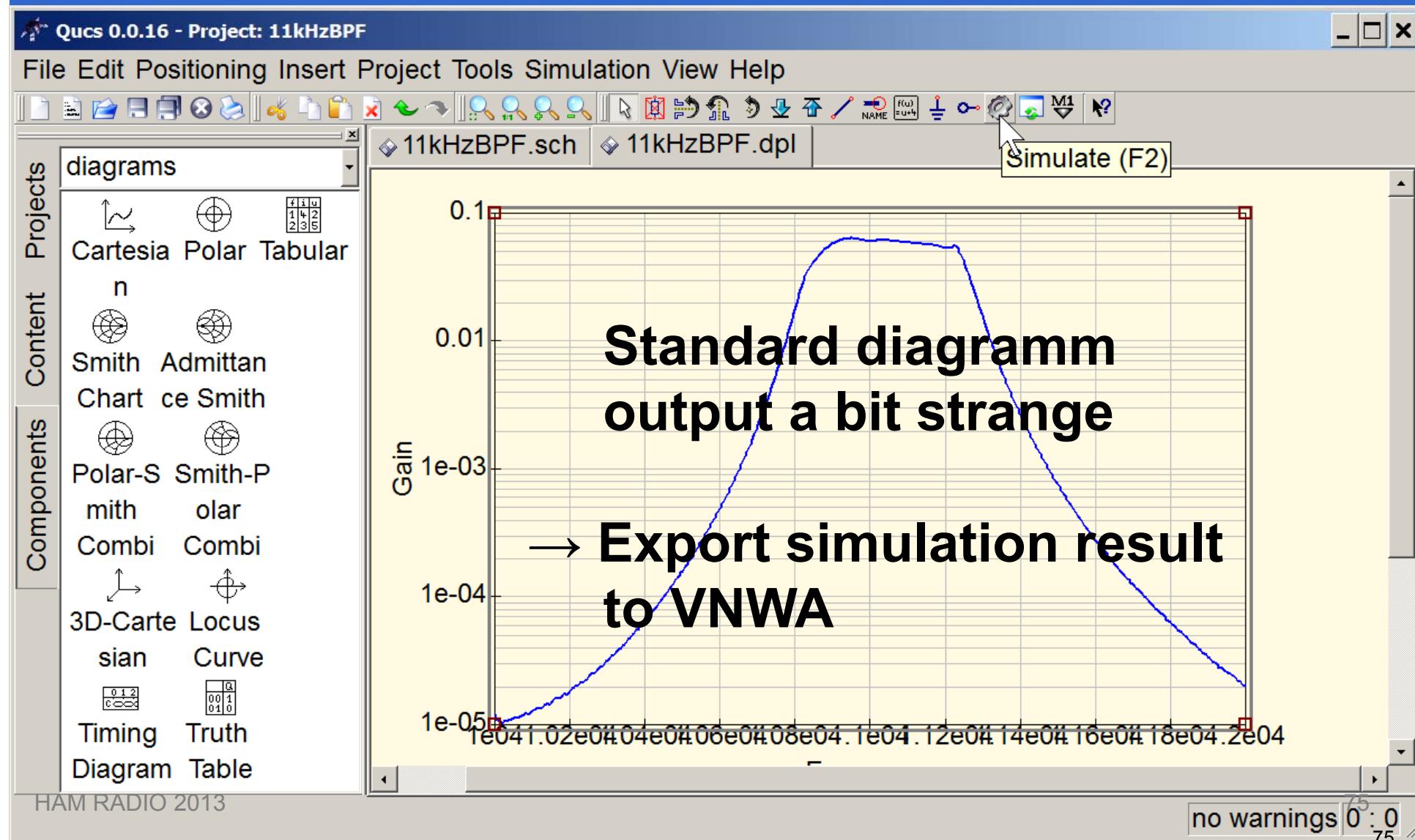
no warnings 0 : 0 74

The screenshot shows the QUCS (Quick Uniform Circuit Simulator) software interface. The main window displays a schematic diagram of a bandpass filter. The circuit consists of two series resistors (R1 and R2, both labeled R=560 Ohm), two shunt loads (P1 and P2, both labeled Z=50 Ohm), and a central reference node (Ref). The input port is labeled X1 and the output port is labeled X2. A blue callout box labeled "S parameter simulation" contains the following parameters:

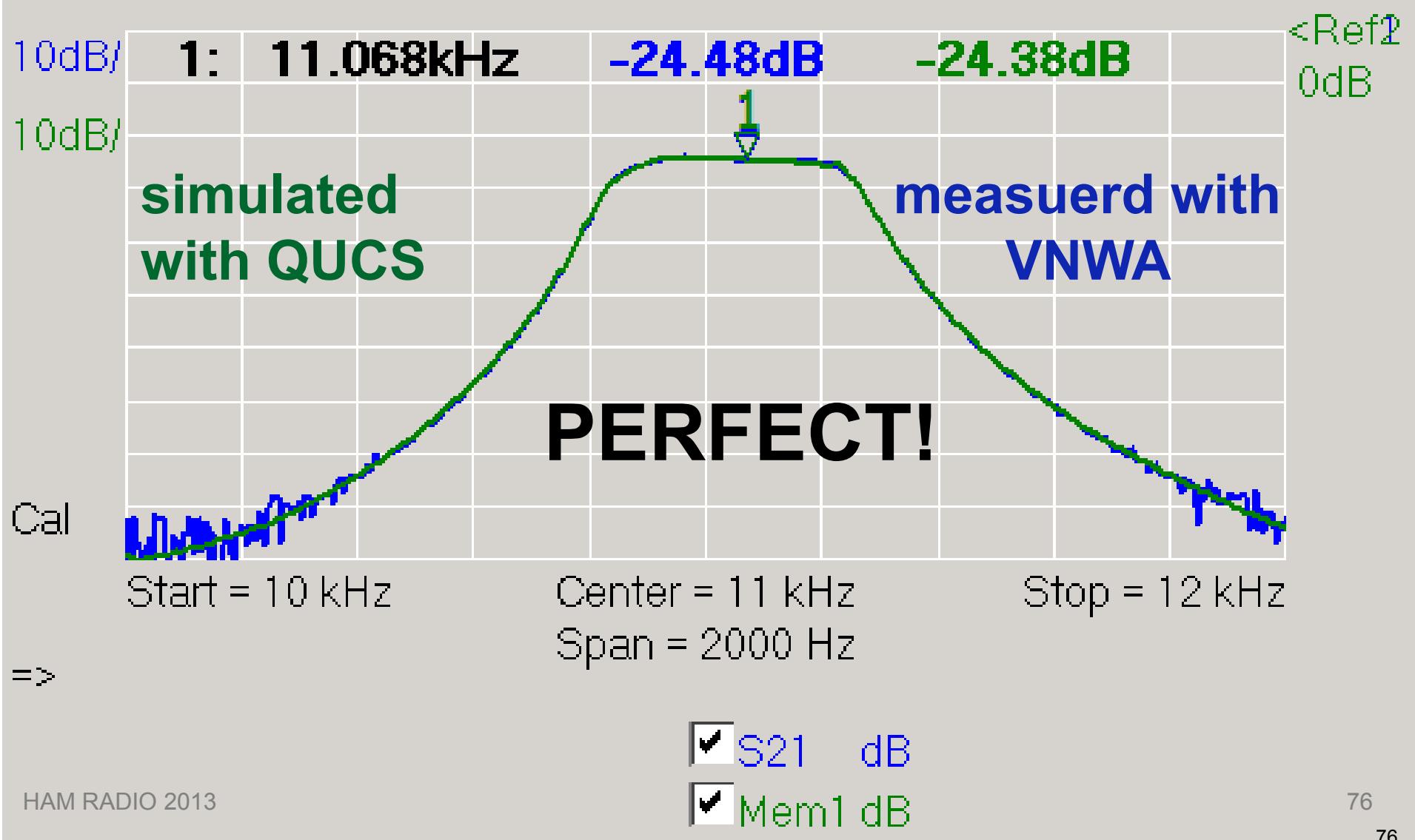
- SP1
- Type=lin
- Start=10 kHz
- Stop=12 kHz
- Points=400

A large blue arrow points from the text "measured S-parameters from s2p-file" to the "File=11kHz_BPF.s2p" entry in the simulation setup. The left sidebar lists various simulation types: DC, Transient, AC, S-parameter simulation, HB, Parametric sweep, and Digital optimization. The bottom status bar indicates "no warnings" and the number "74".

Matching Simulation in QUCS



Comparison QUCS-Simulation vs. Measurement



Free Filter Design Software (1): Elsie – for LC-Filters

 Elsie Student Edition - Welcome !

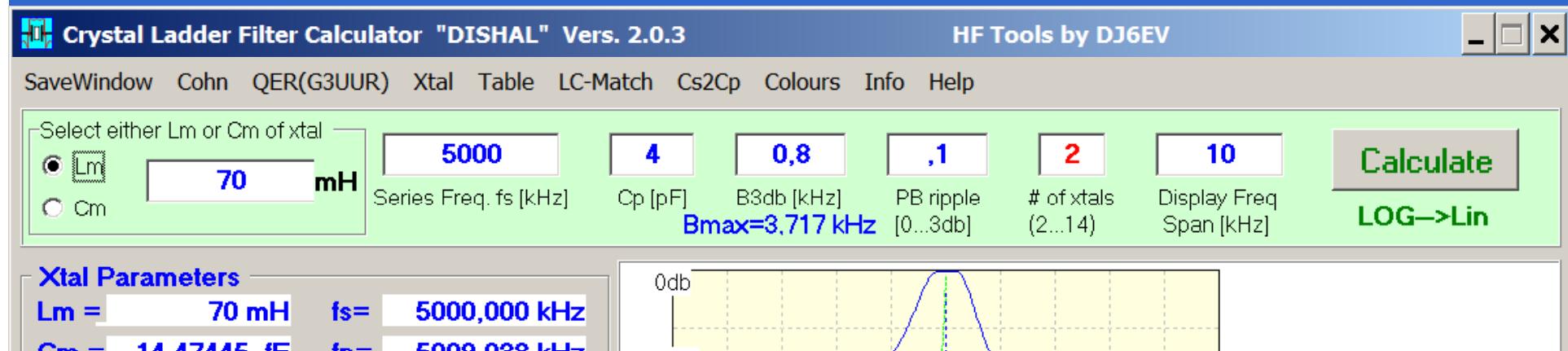
This is the Student Edition of
Elsie

- <http://tonnesoftware.com/elsiedownload.html>
- LC-Filter Designer and Analyzer
- Student version restricted to 7 dipoles
- Numerical simulation results export easily to s2p-file!

Hochschule Ulm

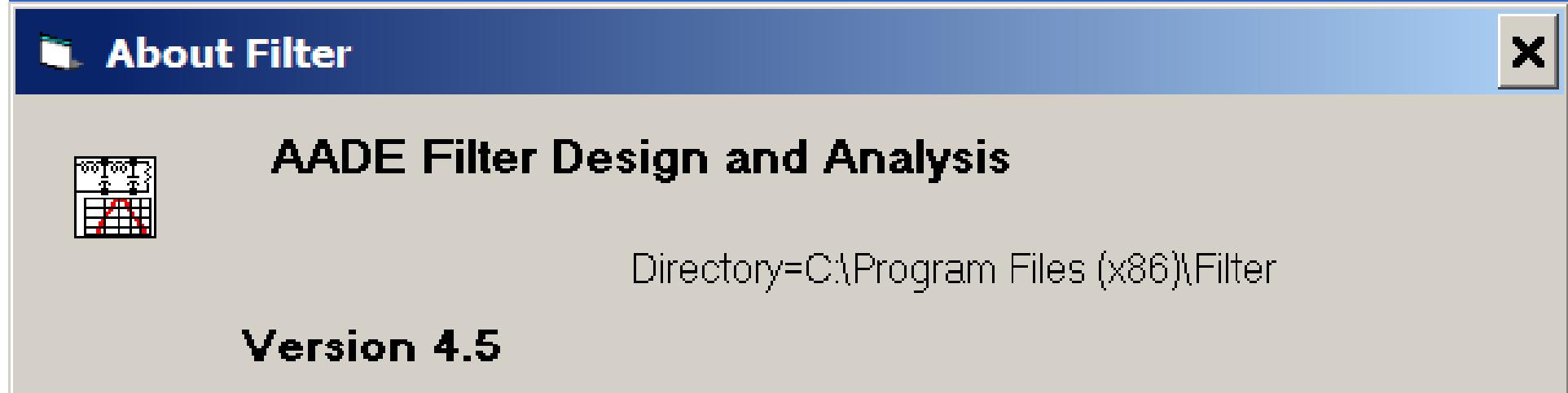


Free Filter Design Software (2): Dishal – for Crystal Filters



- <http://www.bartelsos.de/dk7jb.php/quarzfilter-horst-dj6ev>
- **Crystal filter designer and analyzer**
- **Simulates without crystal losses**
- **S₂₁-simulation results can be exported**

Free Filter Design Software (3): AADE Filter Design - for all filters

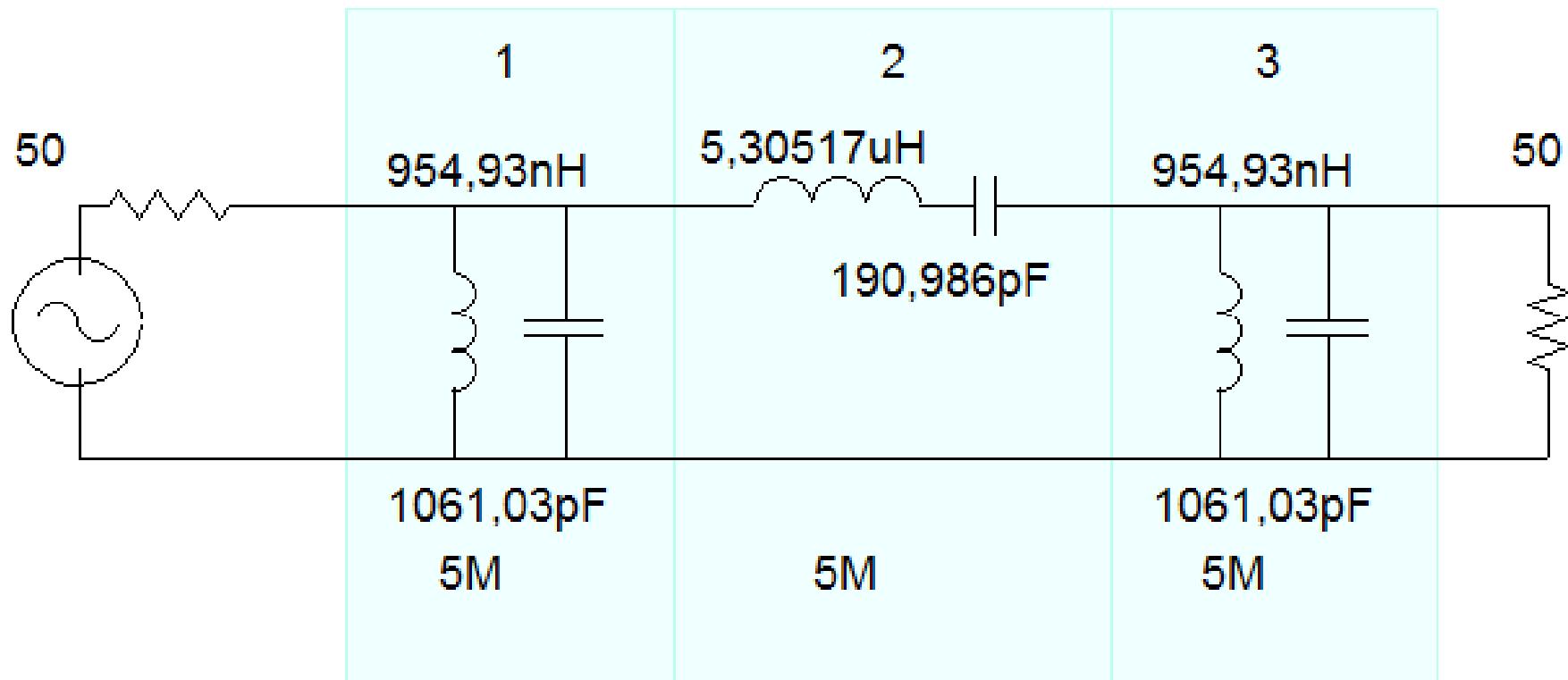


- <http://aade.com/filter32/download.htm>
- **Universal filter designer and analyzer**
- **Free, but with nag screen**
- **Easy to use**
- **Numerical simulation results cannot be exported**

Hochschule Ulm



Design 3 Pole Butterworth π -Band Pass for 5 MHz with 3 MHz Bandwidth at 50Ω



Filter Design with Elsie

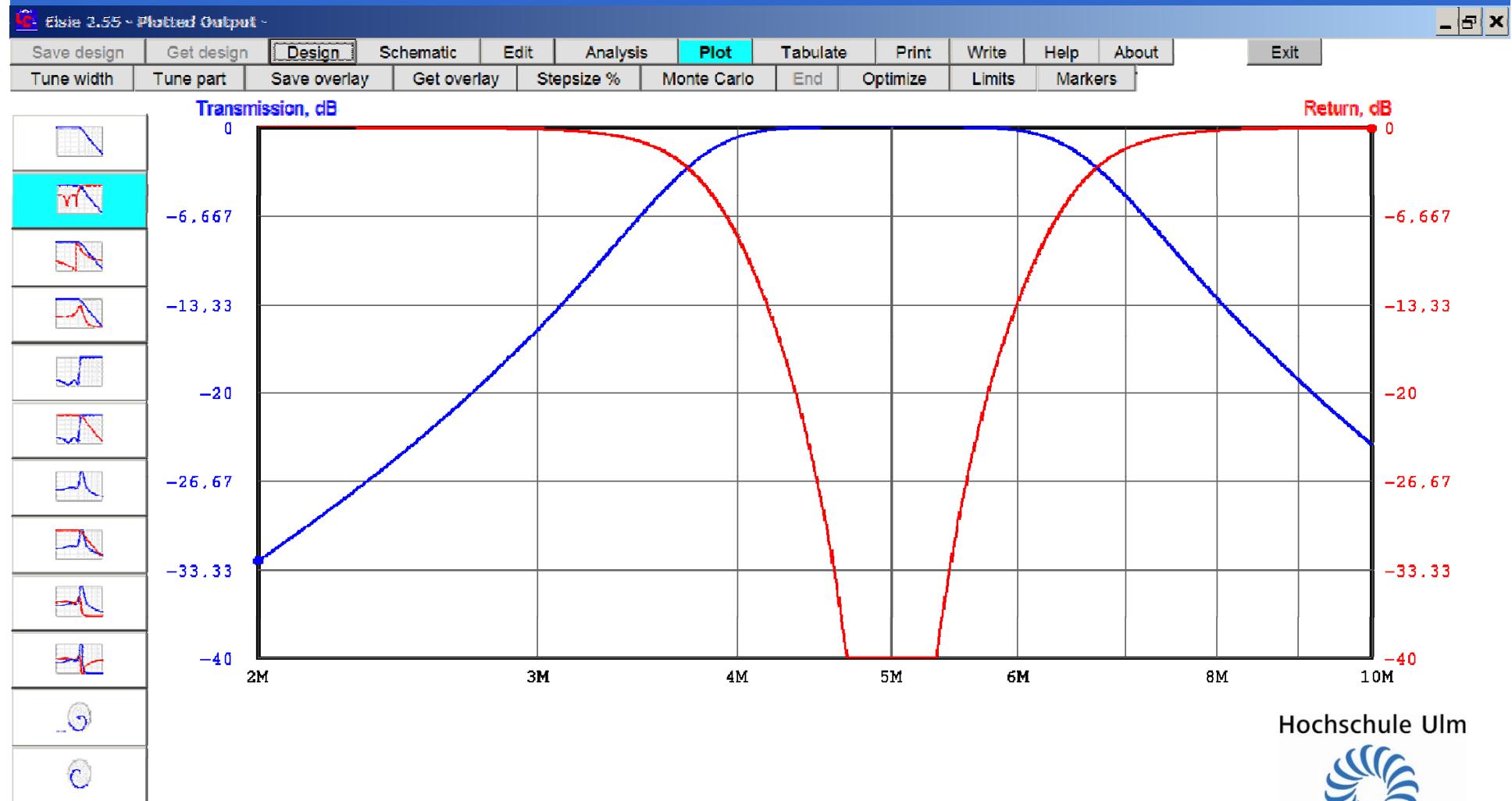
Hochschule Ulm



80

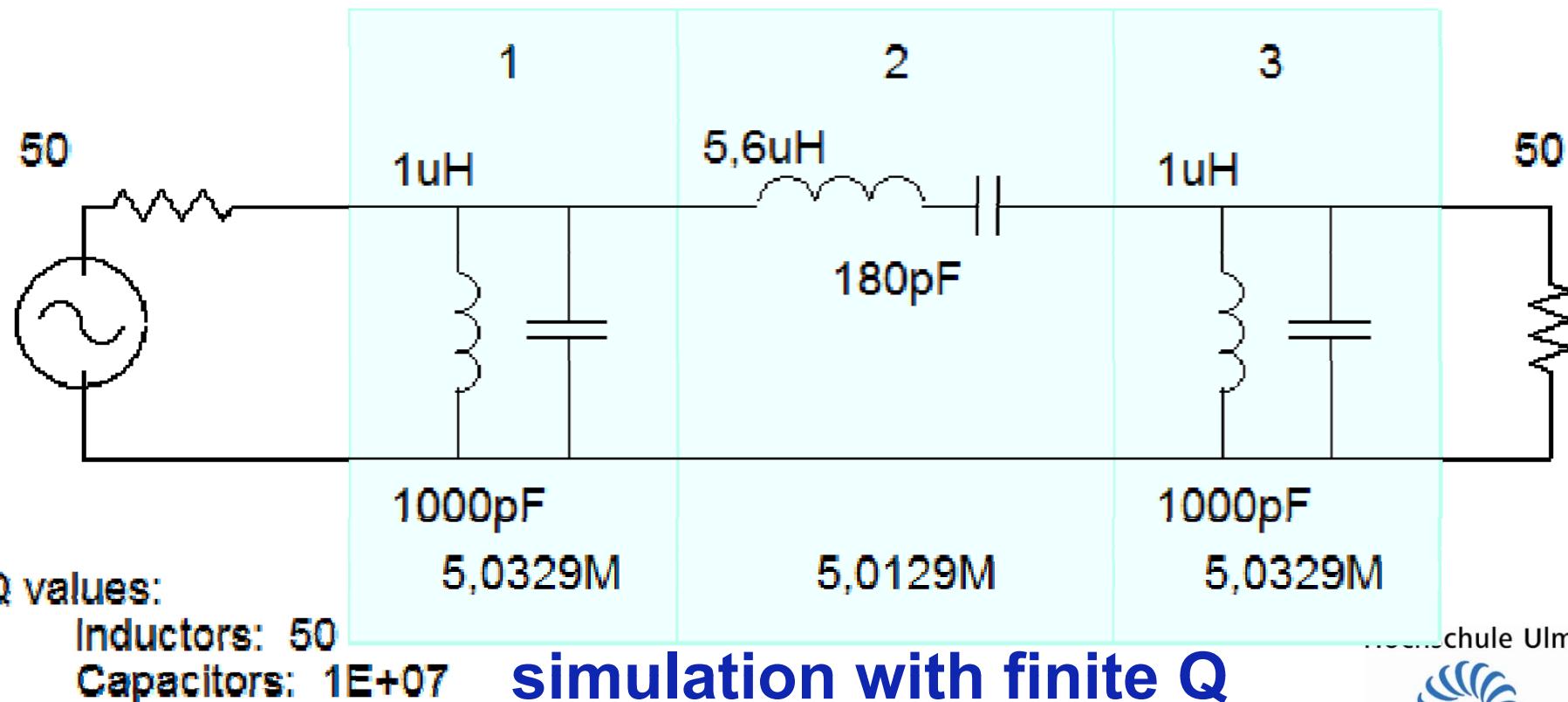
80

Elsie Simulation Result

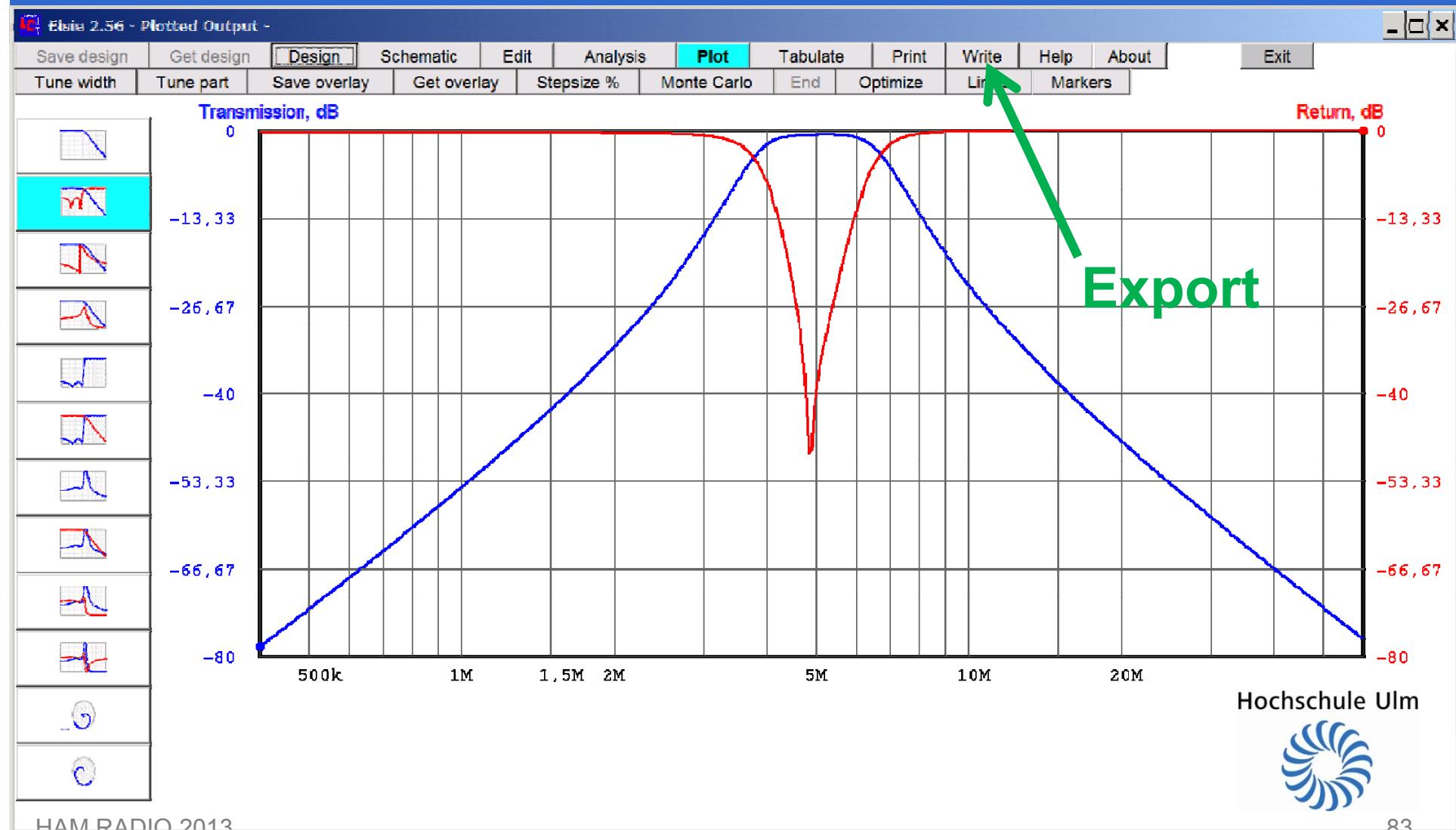


Modify Components to standard Values and finite Q ...

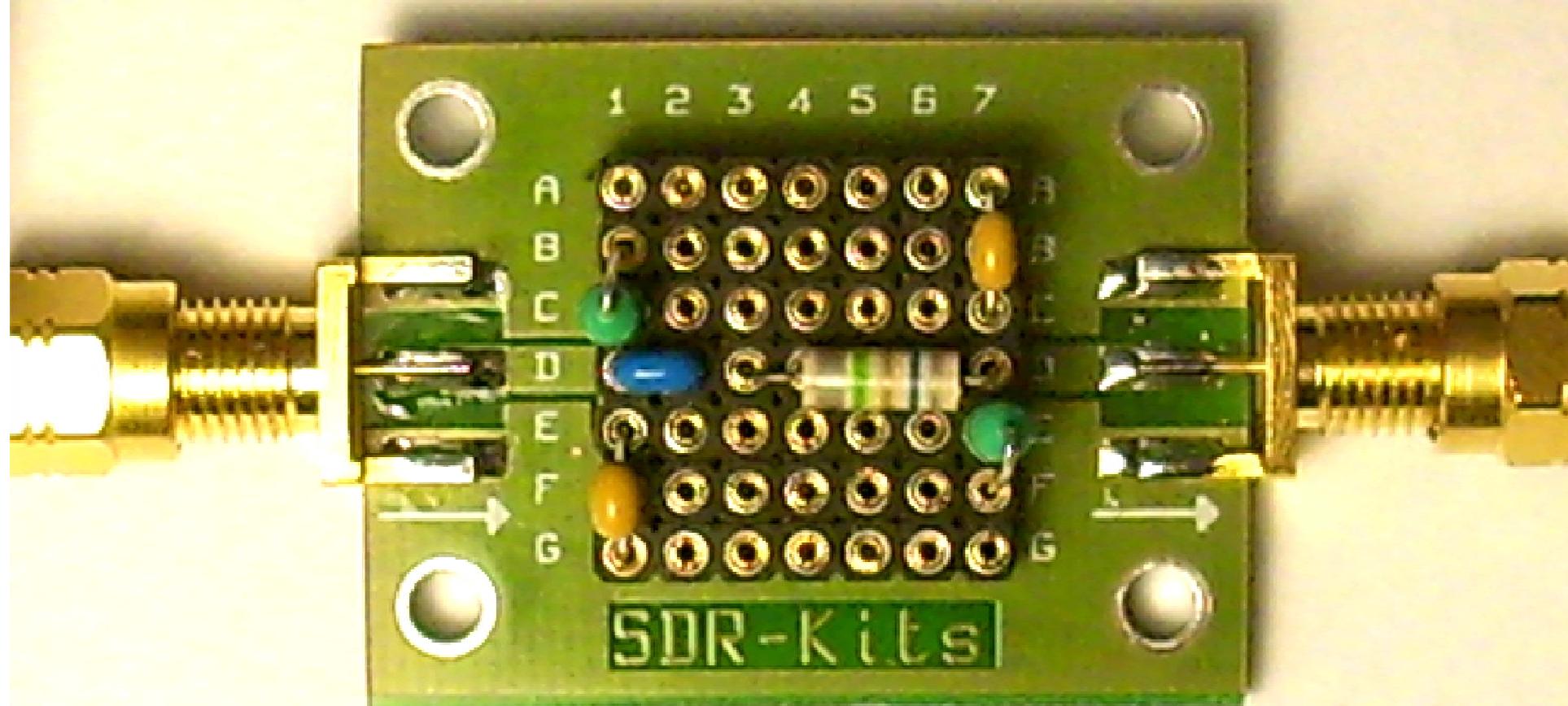
Schematic **Edit** Analysis Plot Tabulate Print



...and export Simulation into s2p-file for Comparison with Measurement.

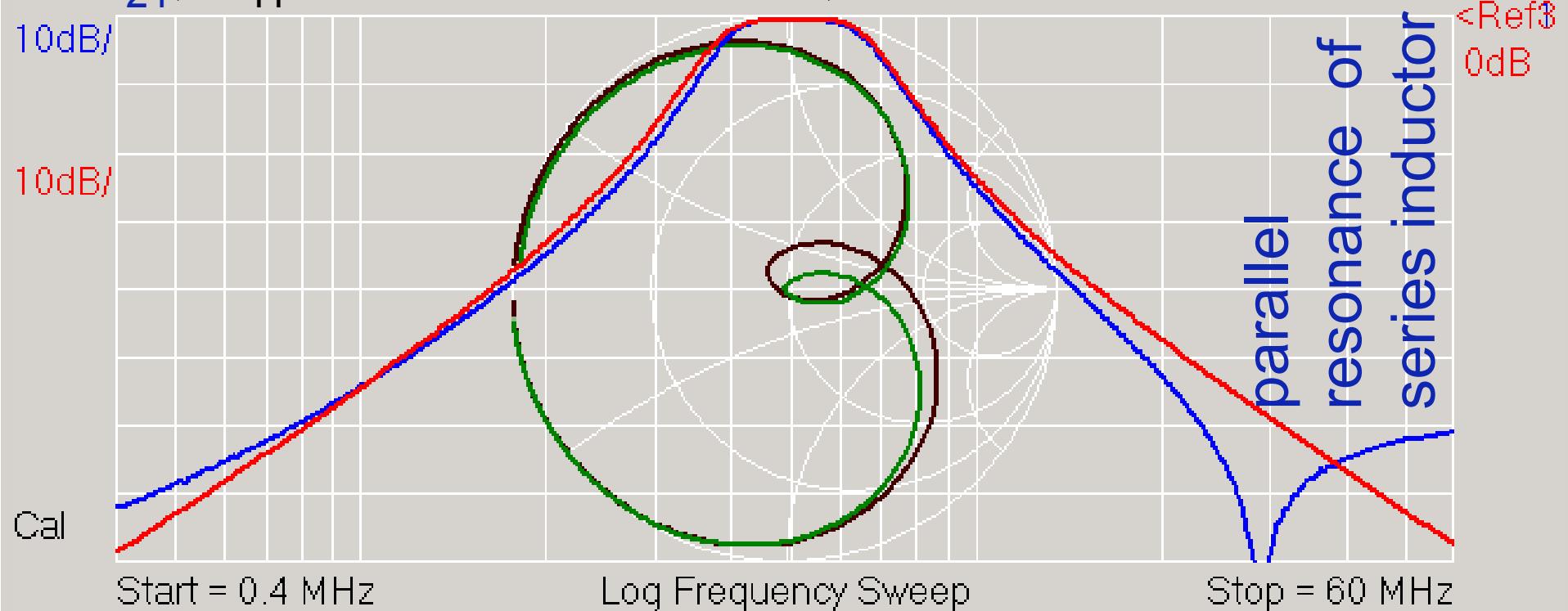


Filter Hardware



Comparison Measurement vs. Elsie Simulation

S_{21} , S_{11} measured - Plot1, Plot2 Elsie simulation



=>

TX Att. = 0 dB

S21

=>

Mem 1

S21 dB

S11 Smith

Plot1 dB

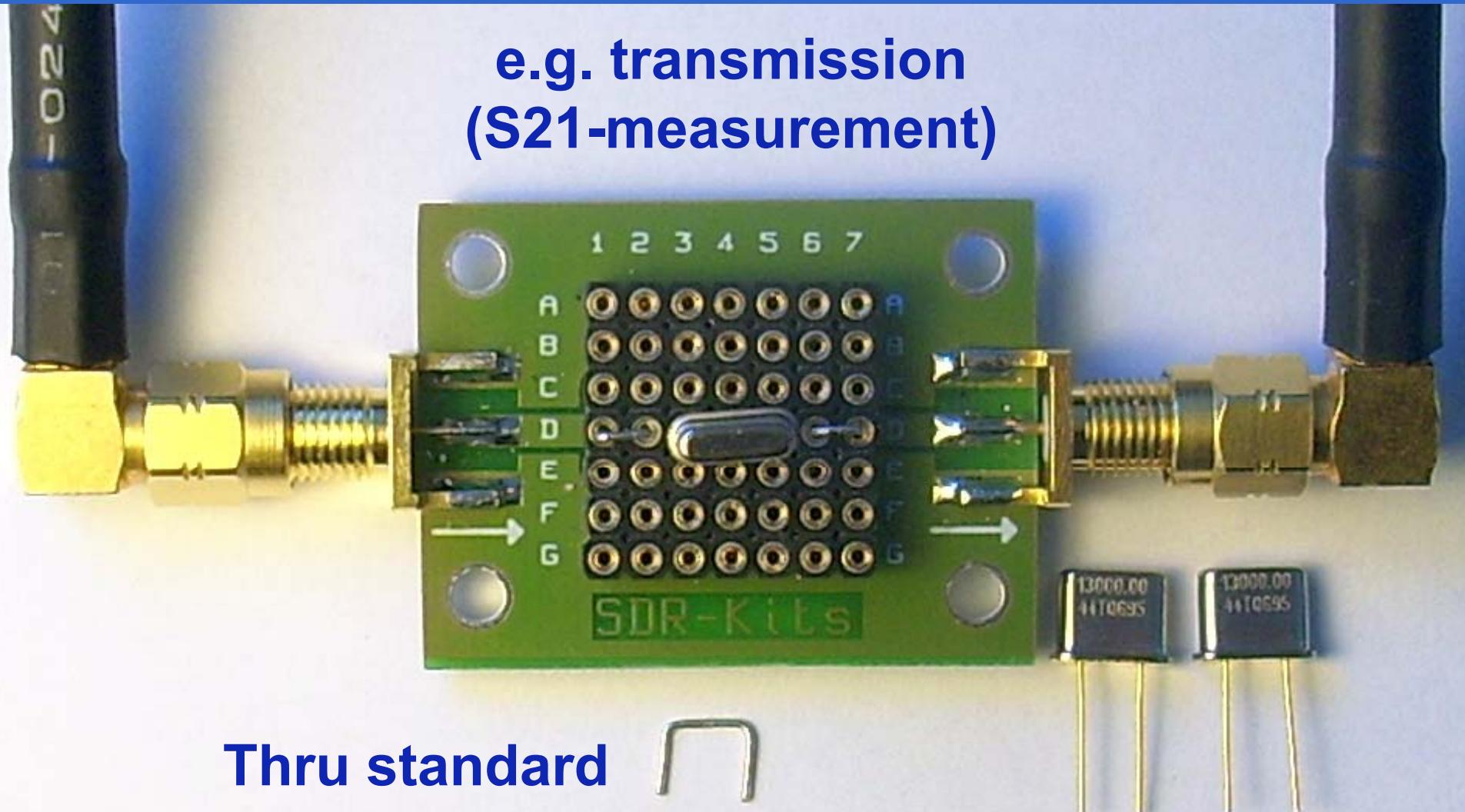
Plot2 Smith

Continuous

Single Sweep

Measuring / Selecting Crystals: VNWA Crystal Analyzer

e.g. transmission
(S21-measurement)



Thru standard

The VNWA Crystal Analyzer Tool: Find 3 similar Crystals...

Crystal Analyzer - Analysis will be performed into 3-port data spaces s_11 an... X

Equivalent Circuit

L = 23.22917 mH
C = 6.456461 fF
R = 27.285283581 Ohm
C0 = 2.4657104121e-12 pF
 $f = 1/2\pi\sqrt{L \cdot C}$ = 12.995886978 MHz
 $R \cdot Q = \sqrt{L/C}$ = 1896.7918117 x1000 Q = 69517

auto-optimize

source = S21 Test Jig Impedances = 50 Ohms

Batch Crystal Analyzer

#	f / Hz	Q	L / H	C / F	R / Ohm	C0 / F	figure of m
1	12995915.37	48842	0.02349916516	6.382253945E-15	39.29	2.468043934E-12	0.000775
2	12995927.72	54196	0.02368969902	6.330910084E-15	35.69	2.420346928E-12	0.00116
3	12995886.98	69517	0.02322917961	6.456461114E-15	27.29	2.465710412E-12	0.0015

With these we want to build a Crystal Filter
 → Enter Crystal Parameters into AADE

Enter data

Enter values from the keyboard or by clicking on the calculator pad shown. Tab advances to the next value.

7	8	9	+	-	M
4	5	6	*	/	K
1	2	3	%	=	m
0	.		$\sqrt{ }$	x^2	μ
tab	bksp	CLR			n
ENTER		Cancel	p		

Daten vom VNA Crystal Analyzer übertragen

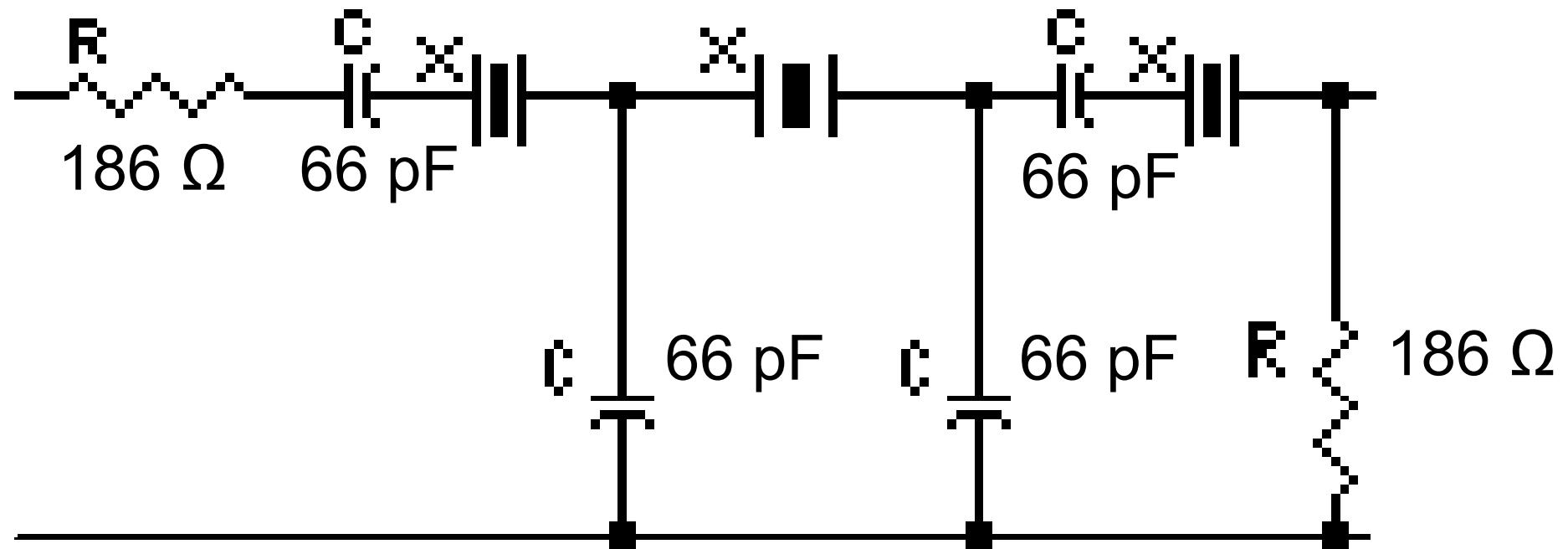
$C_p = 2,46804\text{p}$
 $L_s = 23,499\text{m}$
 $C_s = ,00638\text{p}$
 $Q_x = 48,842\text{K}$

Enter the crystals parallel capacitance in Farads. L/C Meter II will measure it!

#	f / Hz	Q	L / H	C / F	R / Ohm	C0 / F	figure of m
1	12995915.37	48842	0.02349916516	6.382253945E-15	39.29	2.468043934E-12	0.000775



AADE Minimum Loss (Cohn) Design



Hochschule Ulm

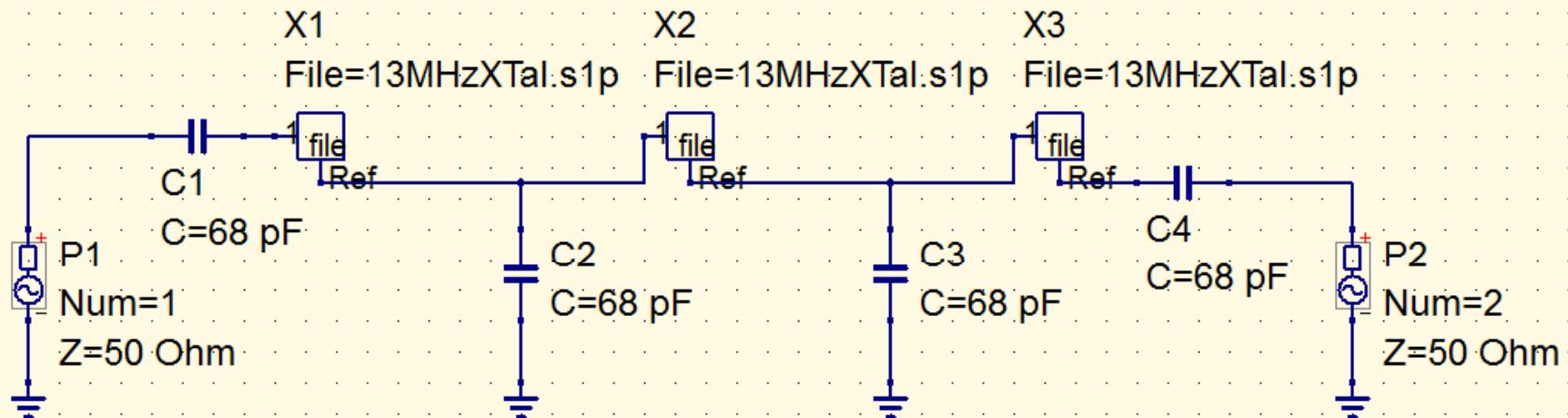


Simulation in QUCS at 50 Ω using standard Component Values

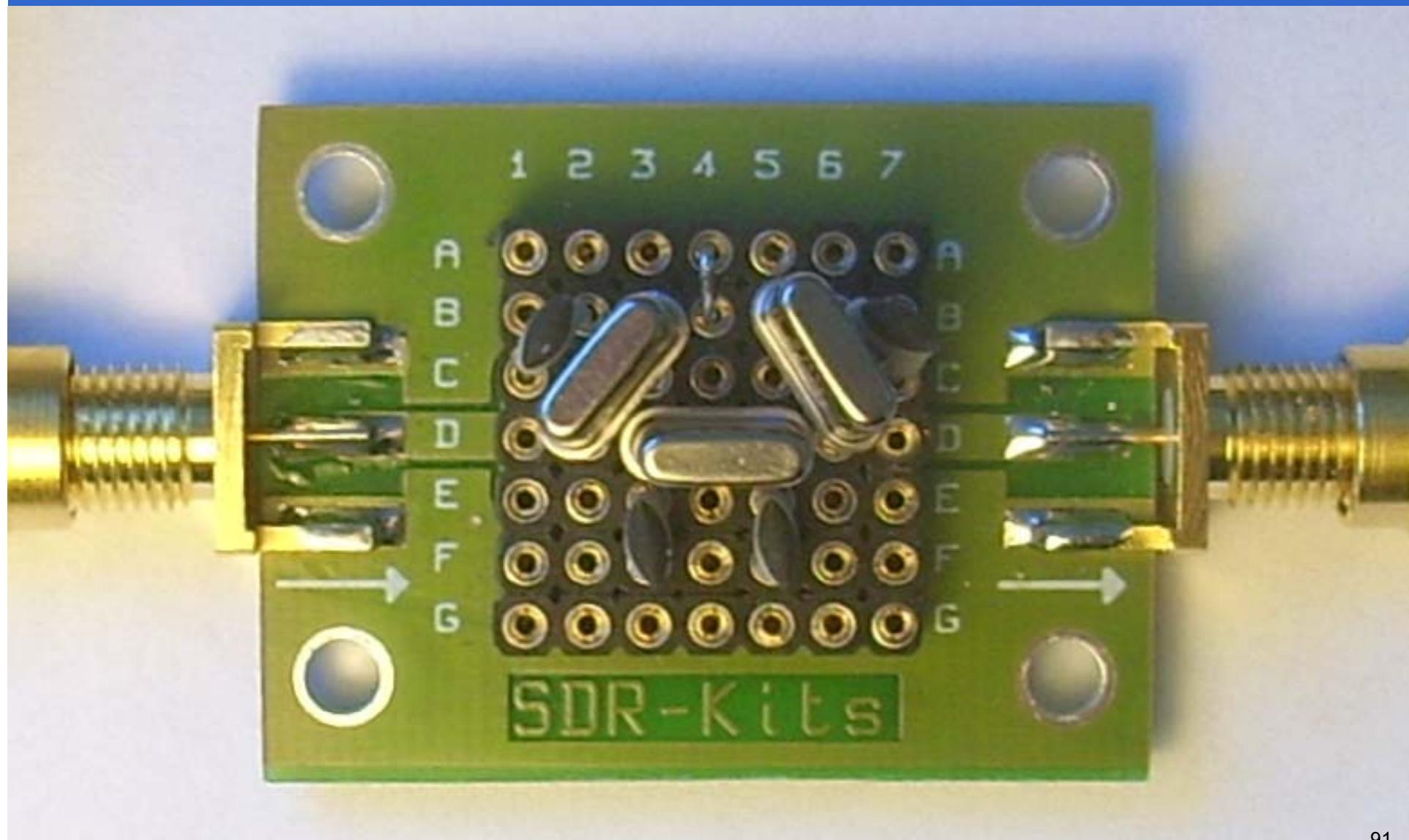
S parameter simulation

SP1
Type=lin
Start=12.987 MHz
Stop=13.007 MHz
Points=800

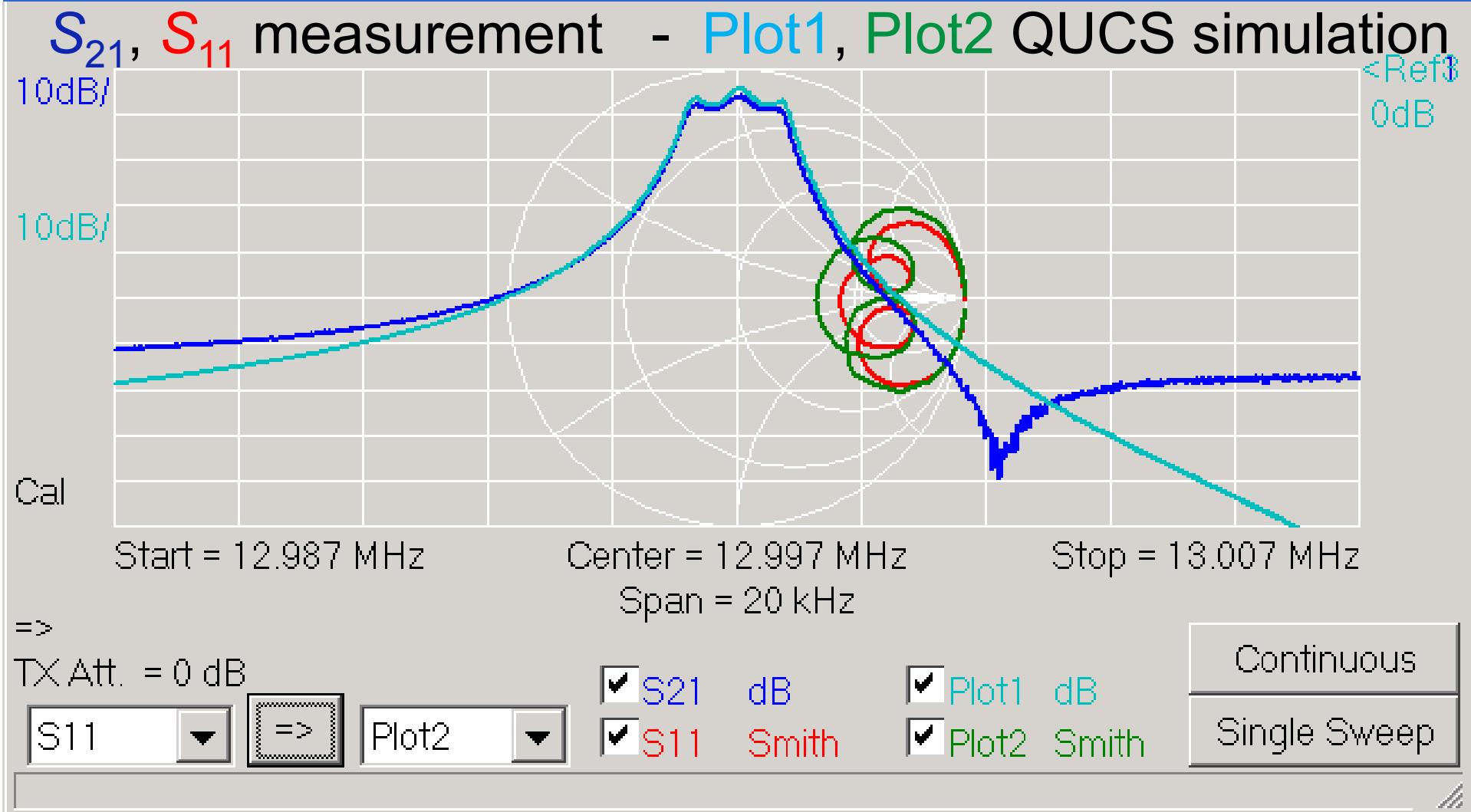
Crystals simulated with
s1p-file obtained by VNWA
measurement!



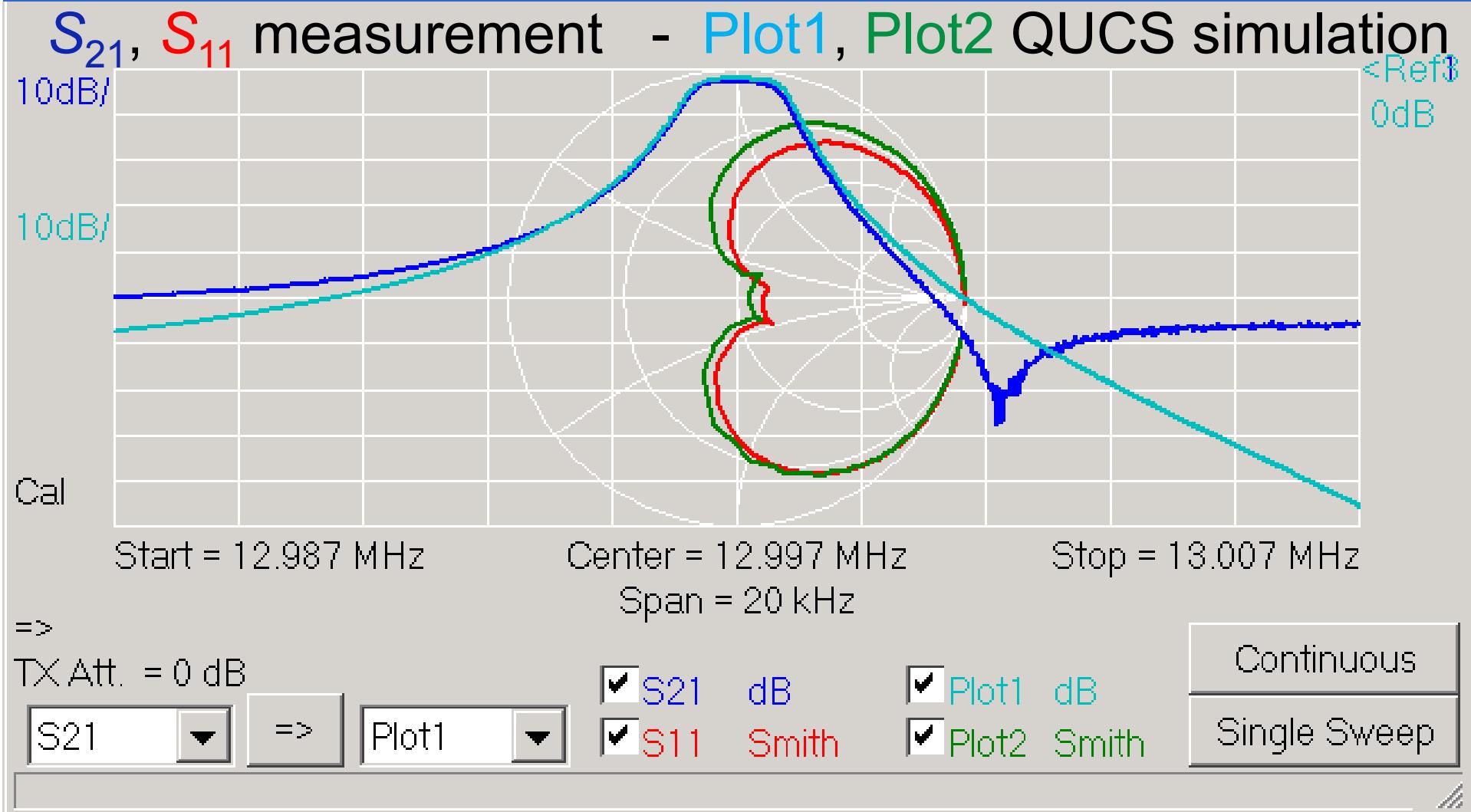
Crystal Filter Hardware



Crystal Filter: Measurement vs. Simulation at 50 Ω



Crystal Filter: Measurement vs. Simulation at 186 Ω



Now, we are able to...

- **Measure components**
- **Design filters**
- **Simulate filters**
- **Measure filters**



Have fun at the workshop!

Many thanks for your attention!

