

HAM RADIO 2013

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FRIEDRICHSHAFEN

Measurement and Application of Scattering Parameters in RF-Design

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University of
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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*

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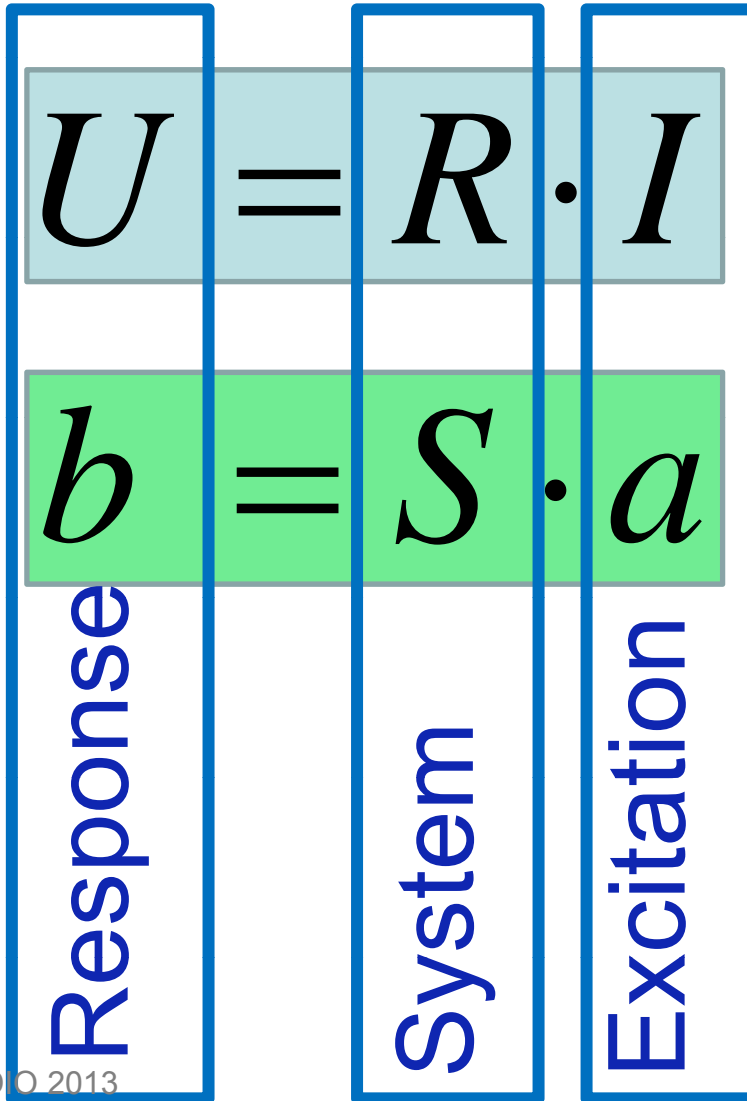


What are Scattering Parameters?

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

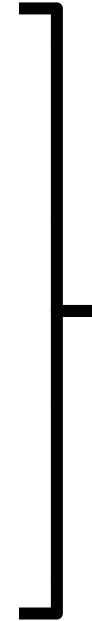


Who is afraid of S-parameters!



Ohm

S-Par.



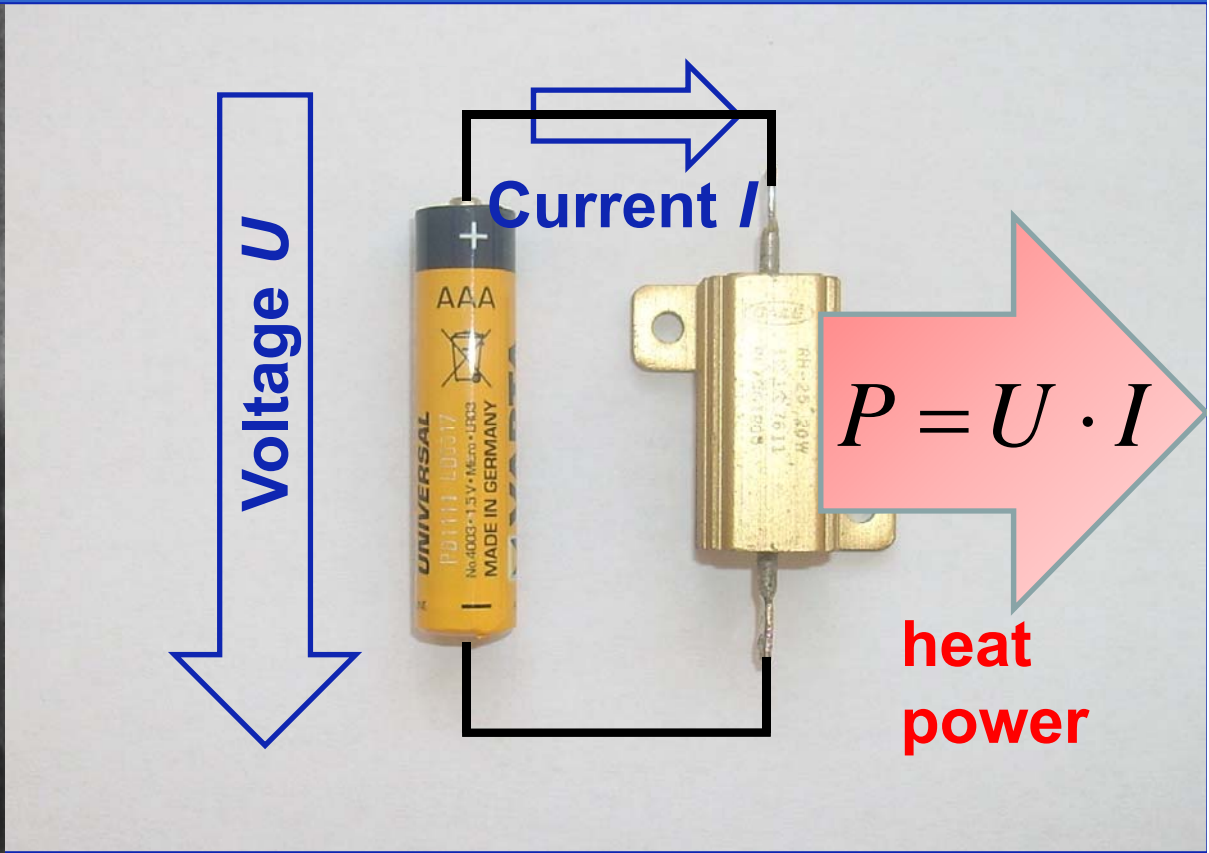
equivalent
description



A different angle to dc Ohms' Law (1)



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

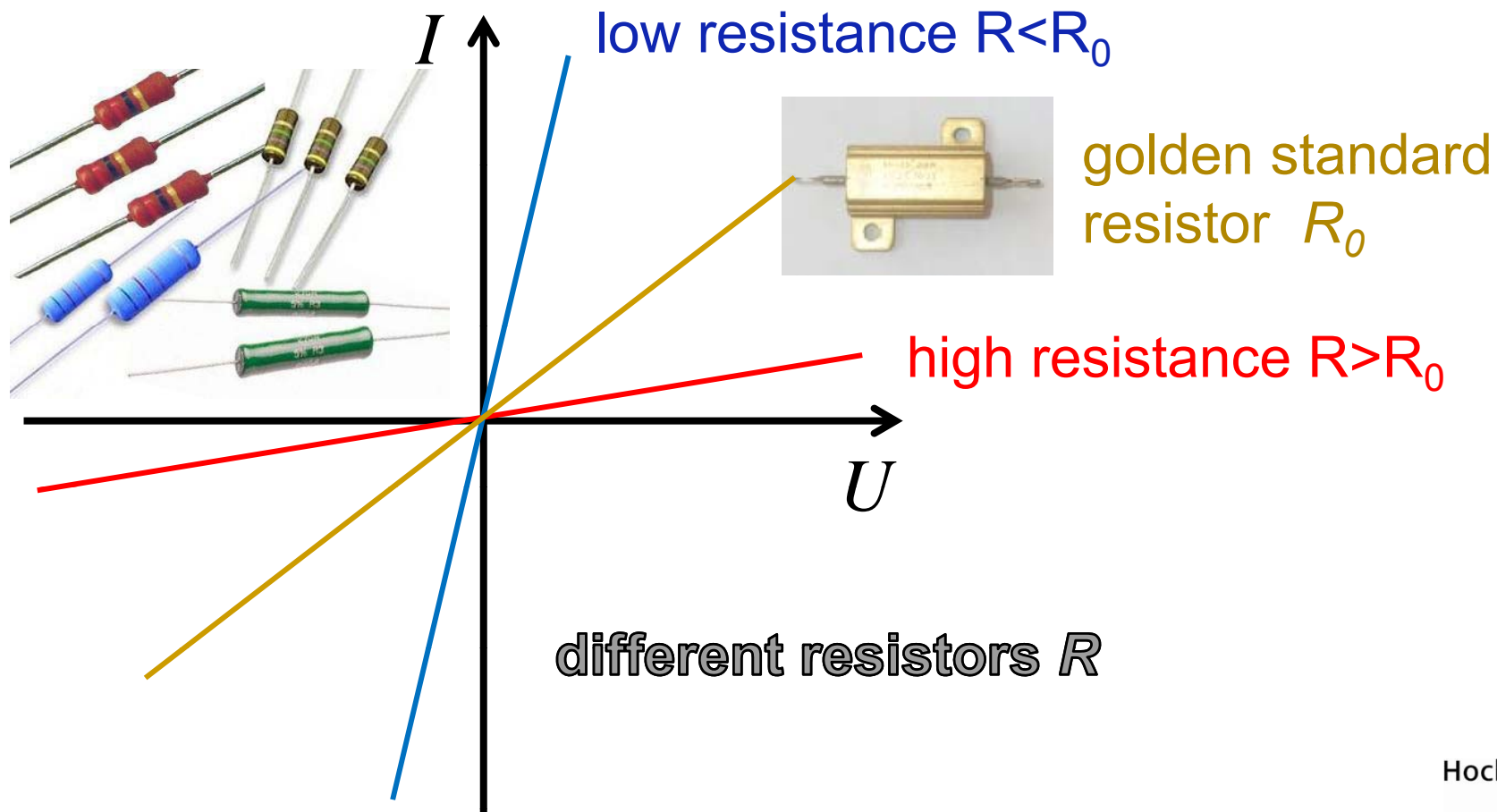


$$U = R \cdot I$$

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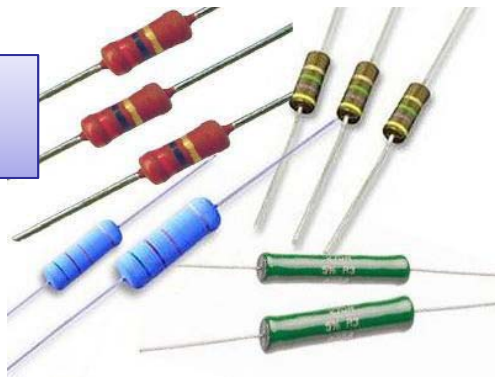
Ohms' Law (2)



Normalizing Resistor R to Reference Resistor R_0

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

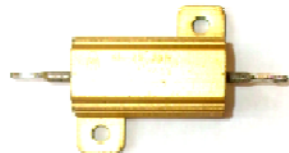
Resistor R



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

normalized r

Resistor R_0



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

normalized 1



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

Focus on power P dissipated in R_0 :

$$\begin{aligned}\sqrt{P} &= \sqrt{U \cdot I} = \sqrt{\frac{U^2}{R_0}} = \frac{U}{\sqrt{R_0}} \equiv u \\ &= \sqrt{I^2 \cdot R_0} = I \cdot \sqrt{R_0} \equiv i\end{aligned}$$

Resistor R_0 in circuit



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 $\sqrt{\text{Watt}}$

Resistor R_0 in circuit

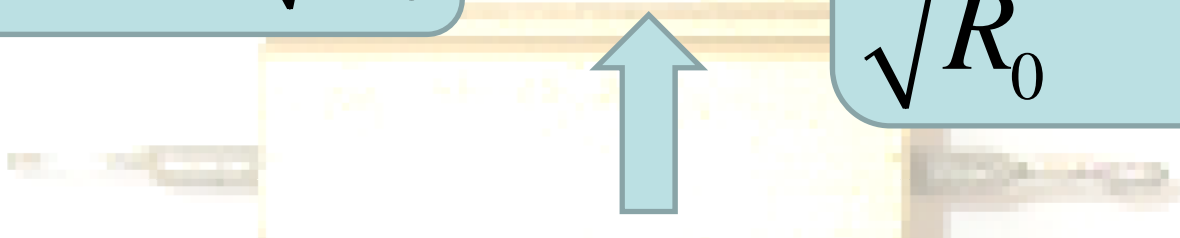


New Units for Voltage and Current:

$$I \rightarrow i$$

$$U \rightarrow u$$

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. $U = R_0 \cdot I$

Resistor R_0 in circuit



Now arbitrary Resistor R instead of R_0

Ohm's Law still applies:

$$u = r \cdot i$$

because:

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

Normalized resistance! ↓

Now arbitrary resistor $R!!!$



Dissipated Power in arbitrary Resistor

$$P = u \cdot i$$

still applies

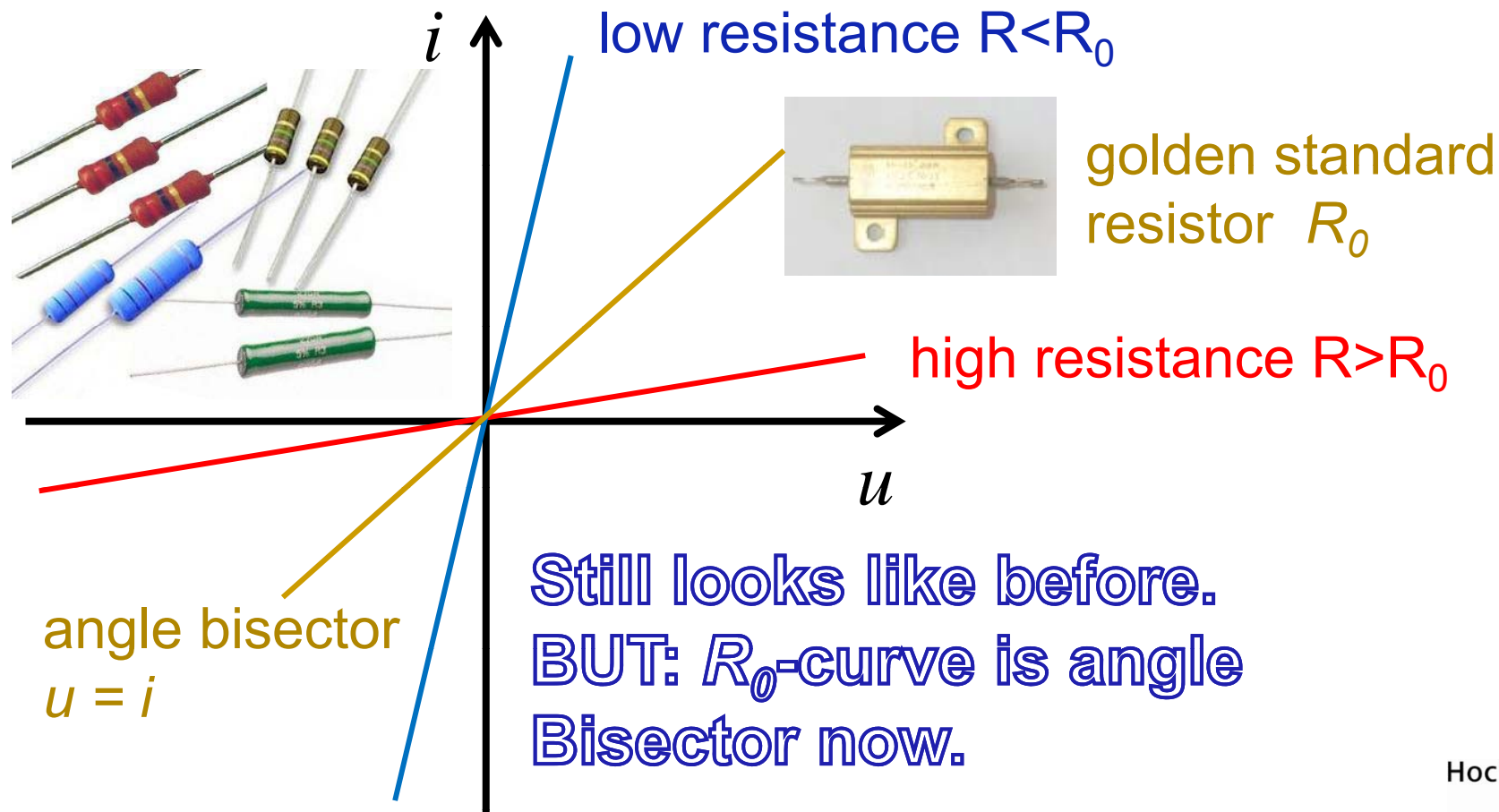
because:

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

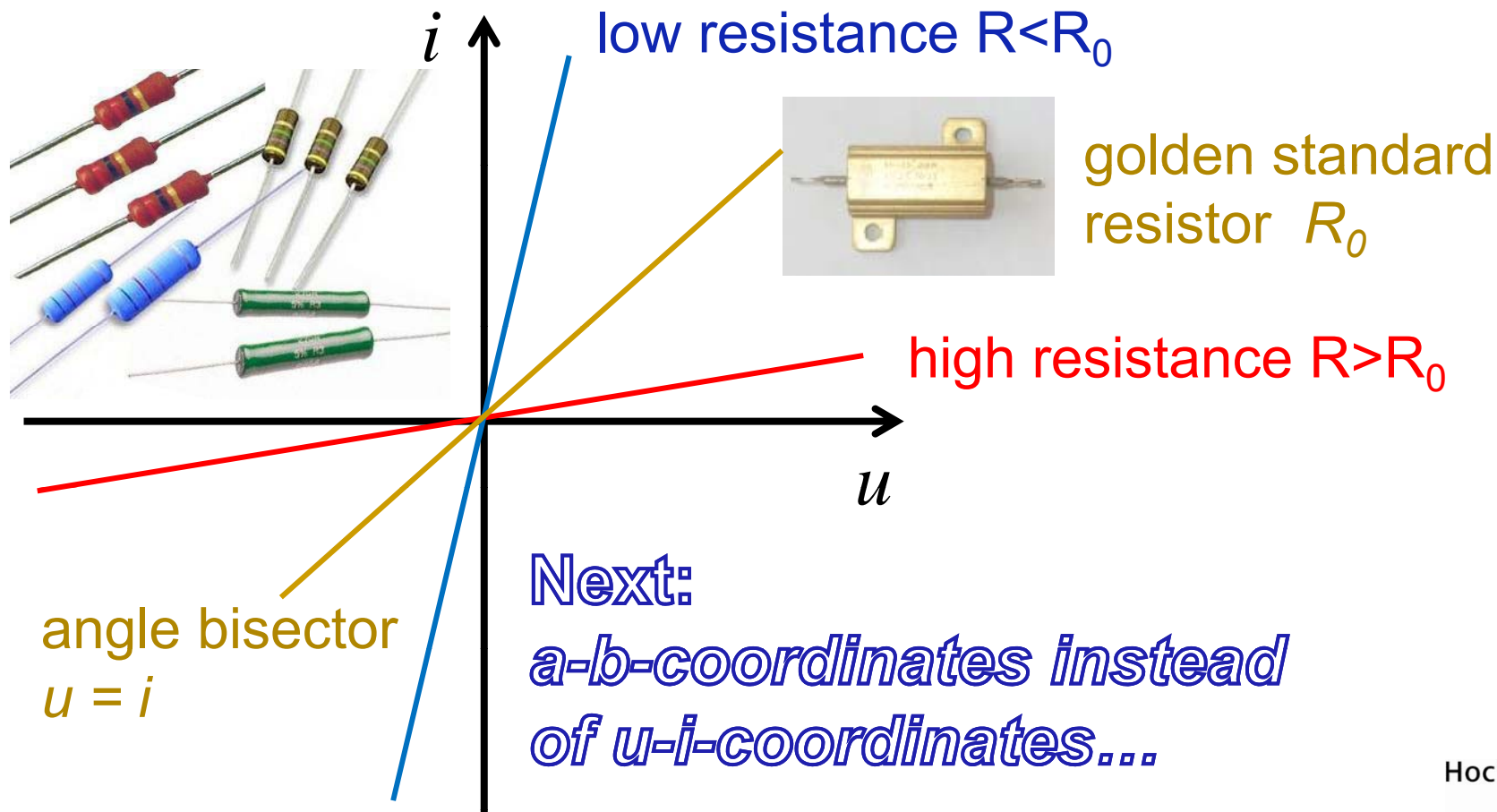
reduce!

Now arbitrary resistor $R!!!$

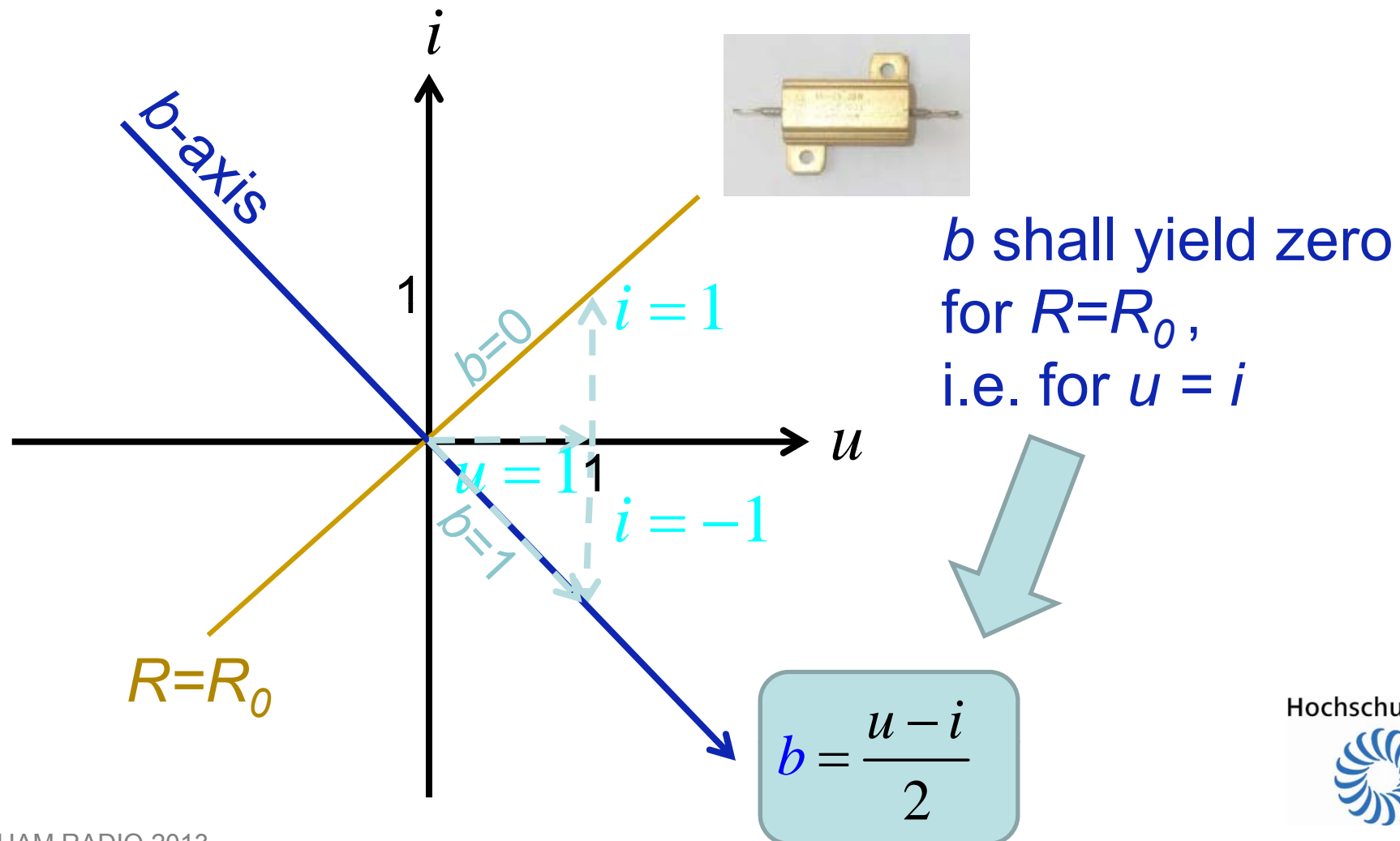
Ohm's Law with new Voltage and Current Units



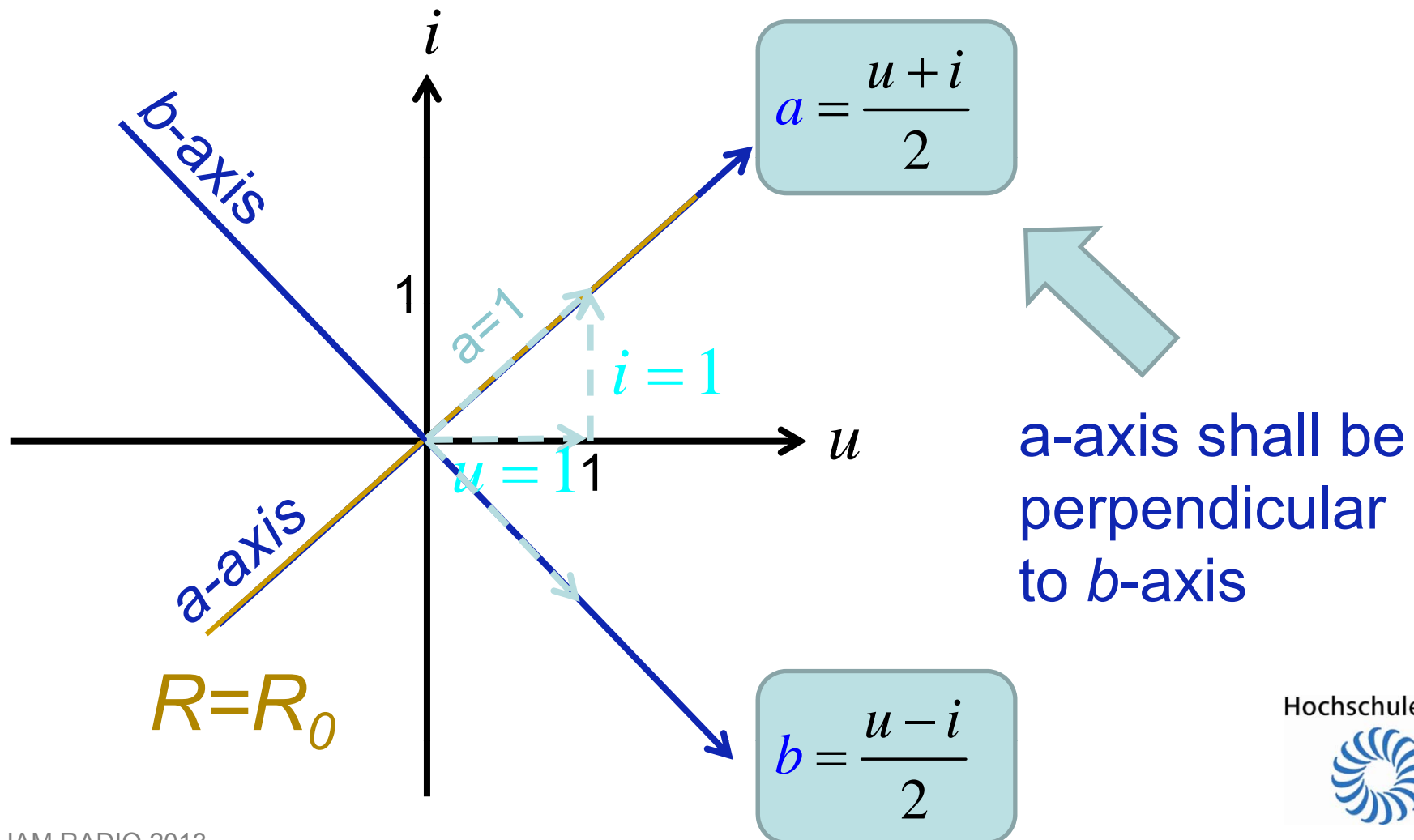
Now we get down to business: A different angle to dc...



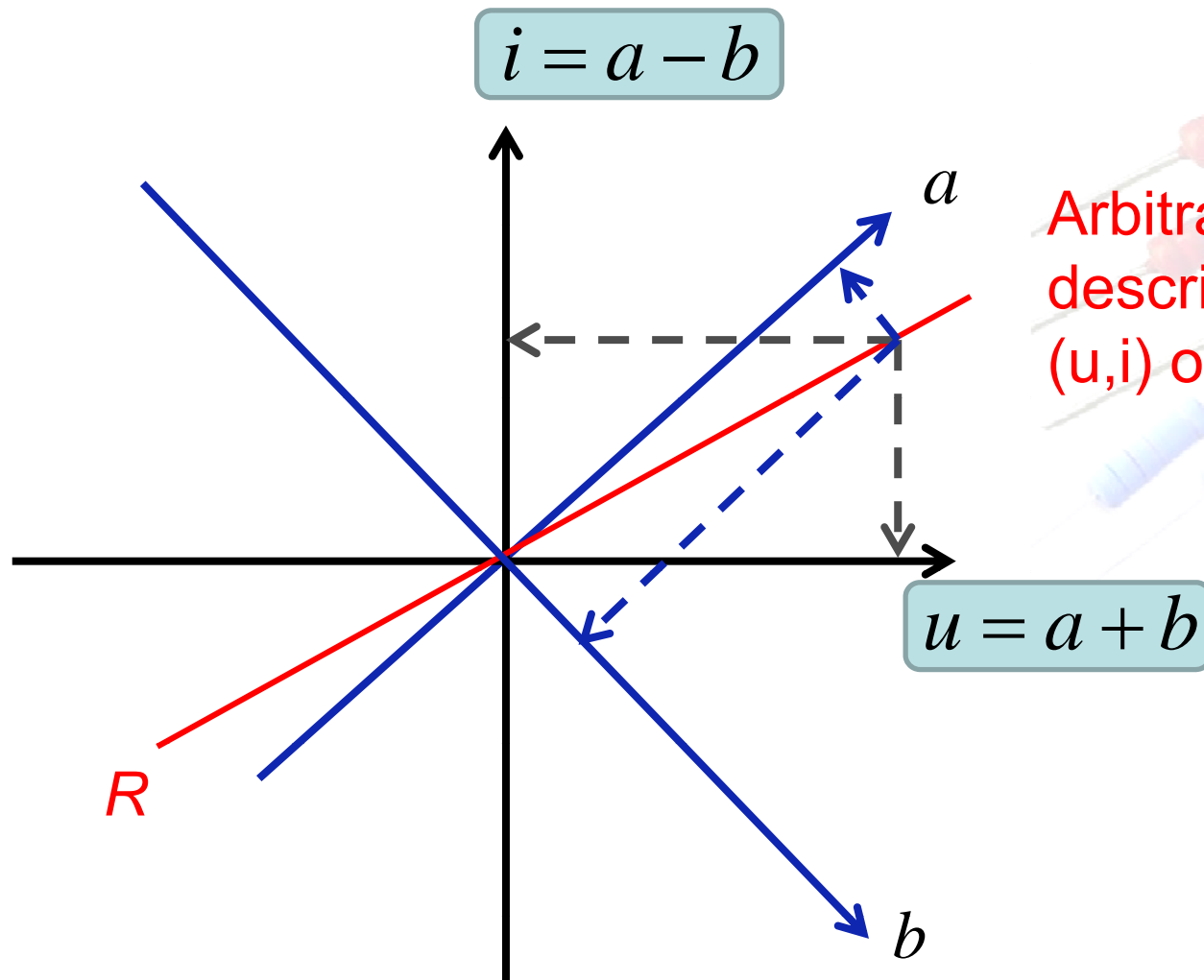
From Voltage and Current... ...to b ...



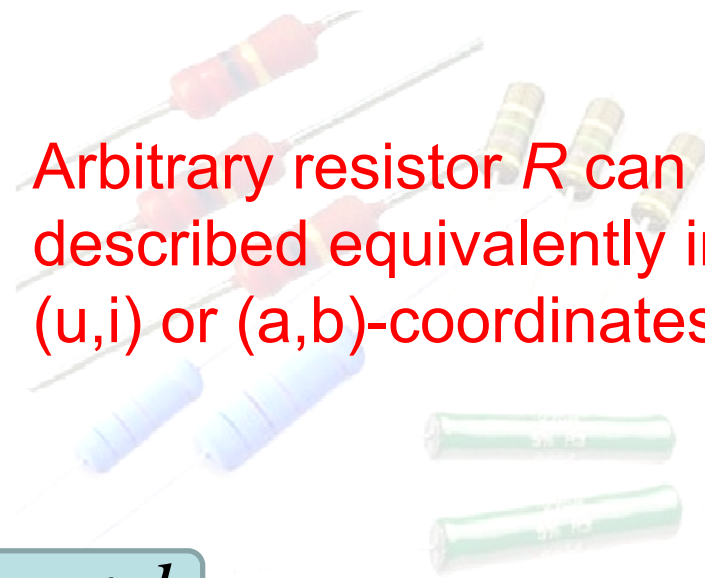
From Voltage and Current... ...to b ...and a !



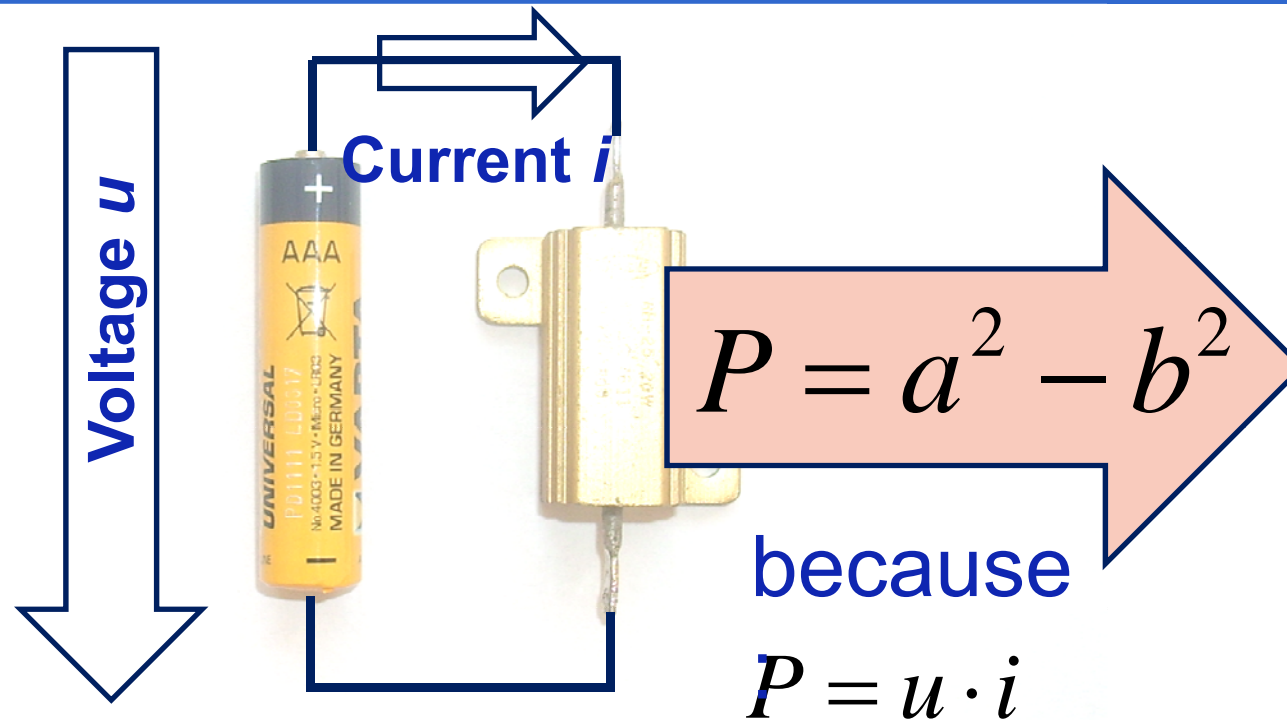
This works the other way round, too: Voltage and Current from a and b



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



A different angle to dc: Dissipated power in resistor R



$$\text{if } R = R_0 \Rightarrow b = 0 \quad = (a + b) \cdot (a - b)$$

$$\Rightarrow P = a^2 \quad = a^2 - b^2$$

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 :

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



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!*

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

$$\left\{ \begin{array}{l} P = |a|^2 - |b|^2 \\ \text{and } b = 0 \\ \text{if } Z = Z_0 \end{array} \right.$$

Now we apply ac!

Complex Reflection Coefficient $S = b/a$



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

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

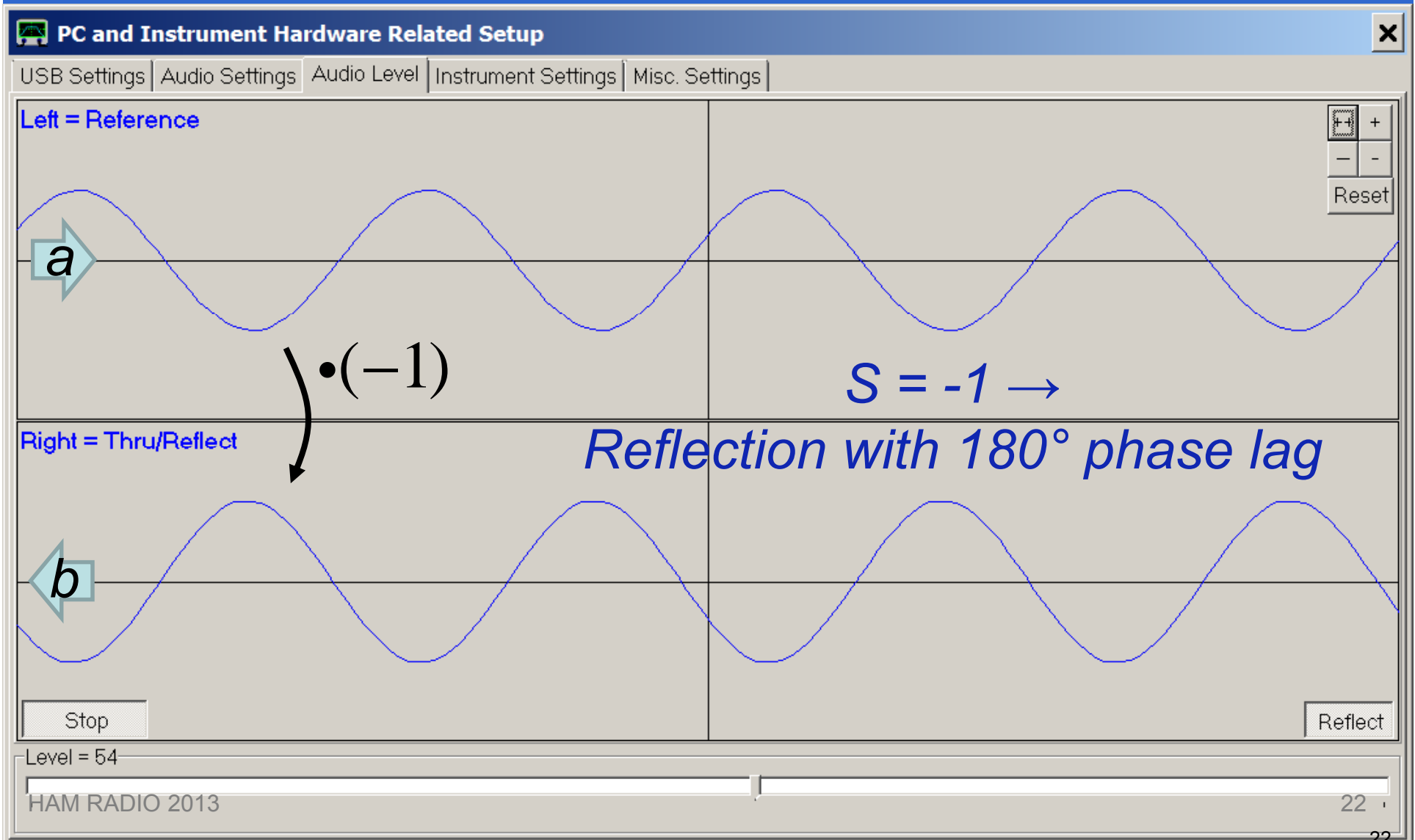
with $z = \frac{Z}{Z_0}$

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

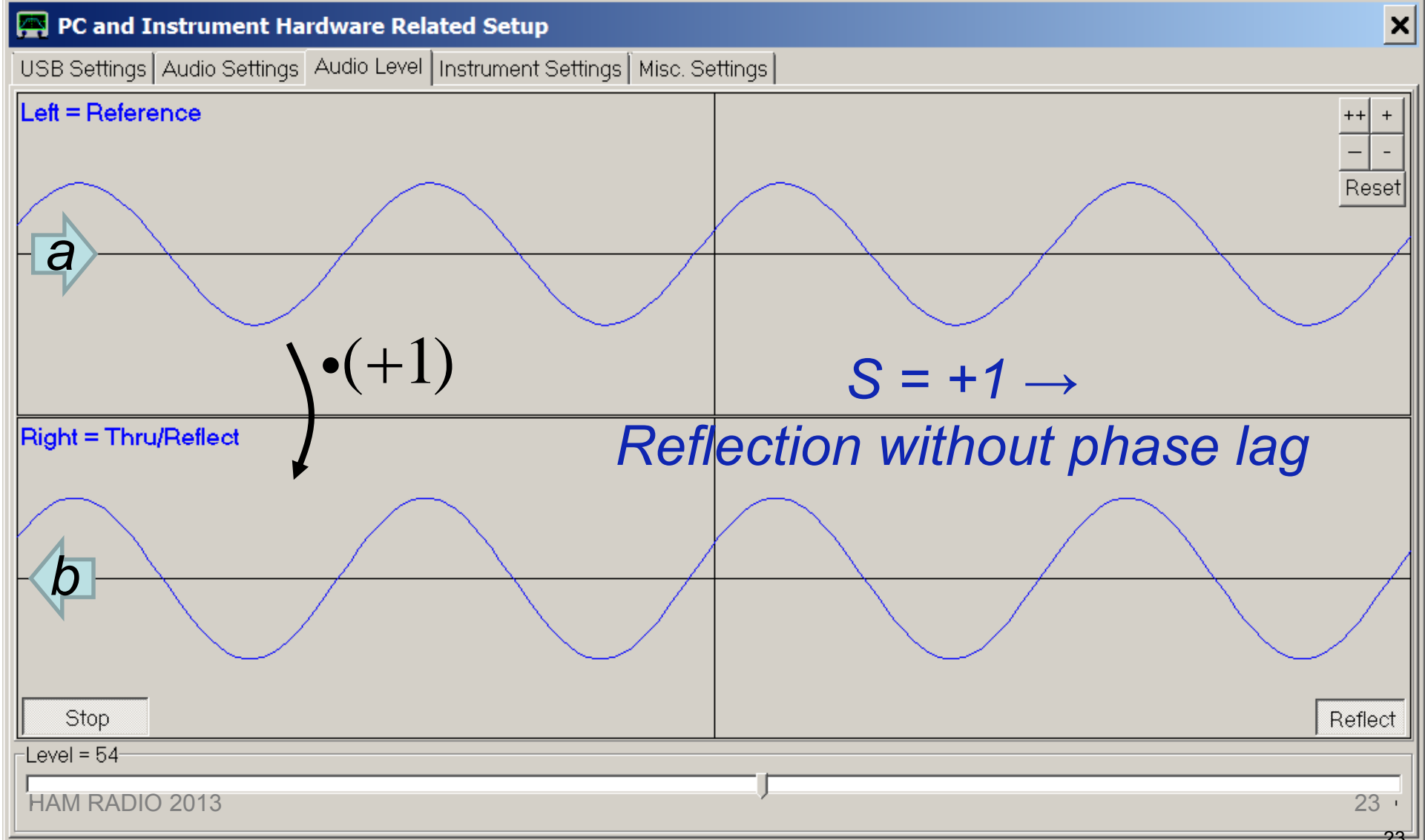


We can see a and b using the VNWA

E.g. Short Circuit $S=-1$

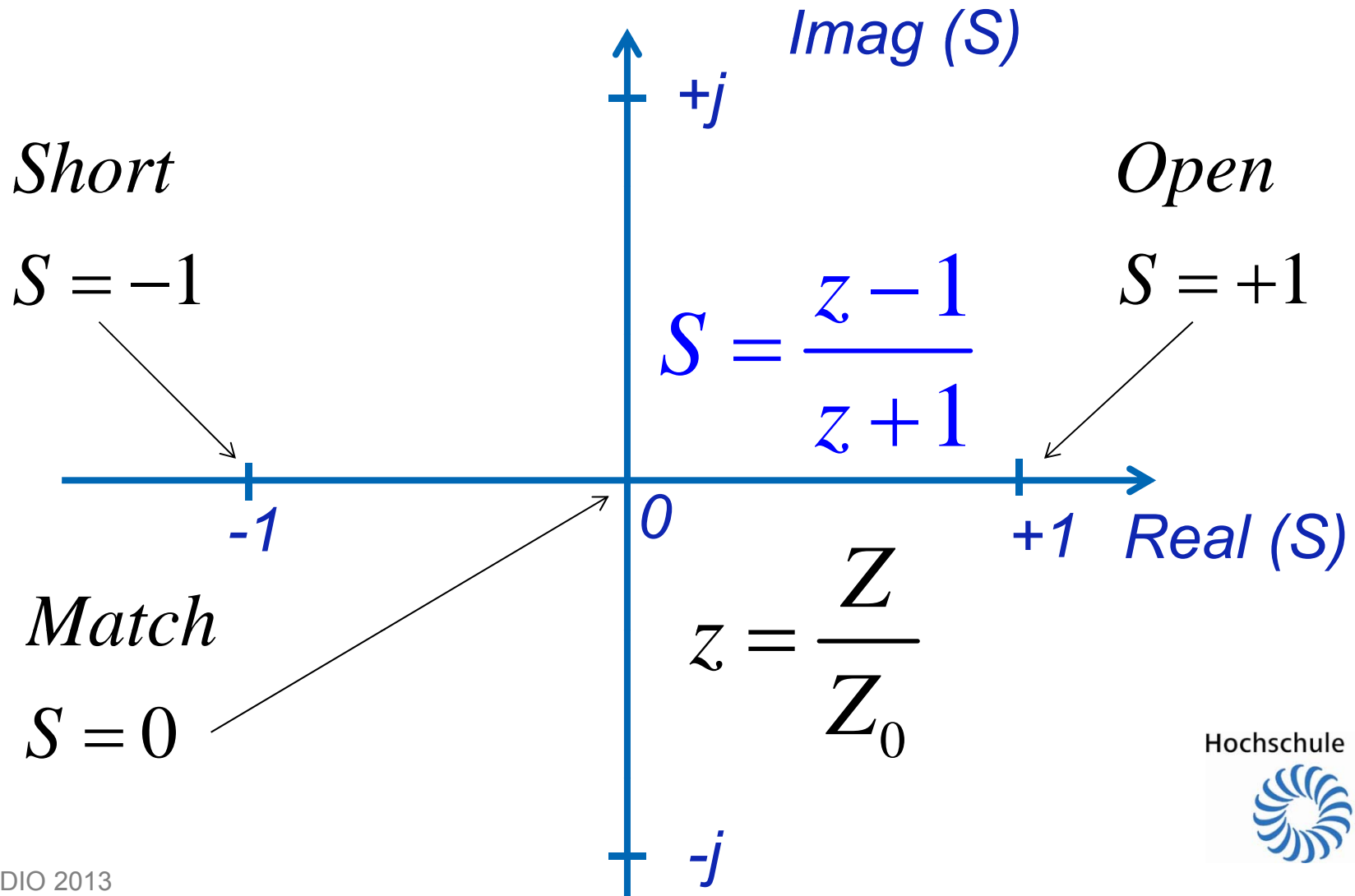


We can see a and b using the VNWA
E.g. Open Circuit $S=+1$:



Complex Reflection Coefficient $S = b/a$

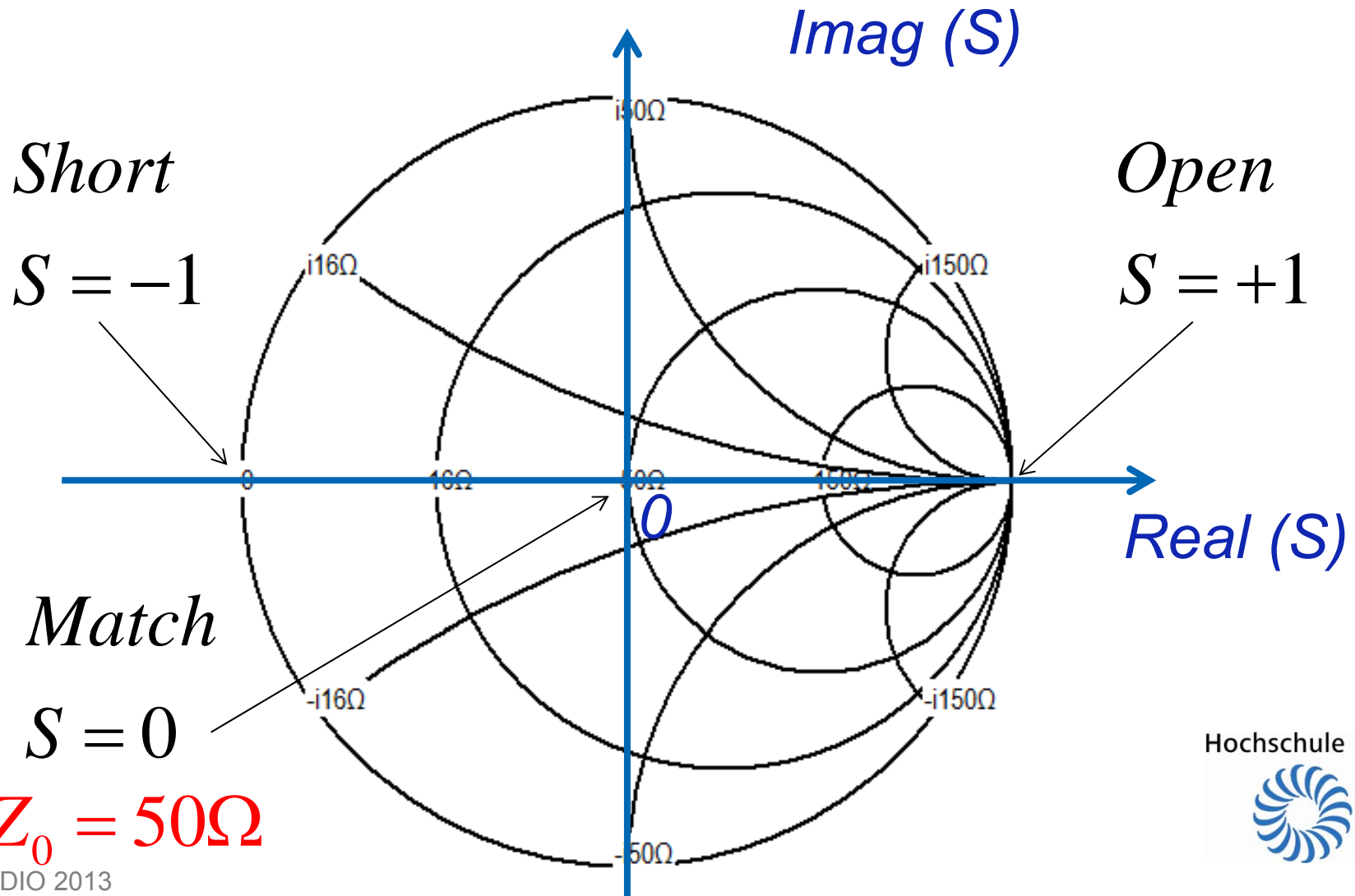
...



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

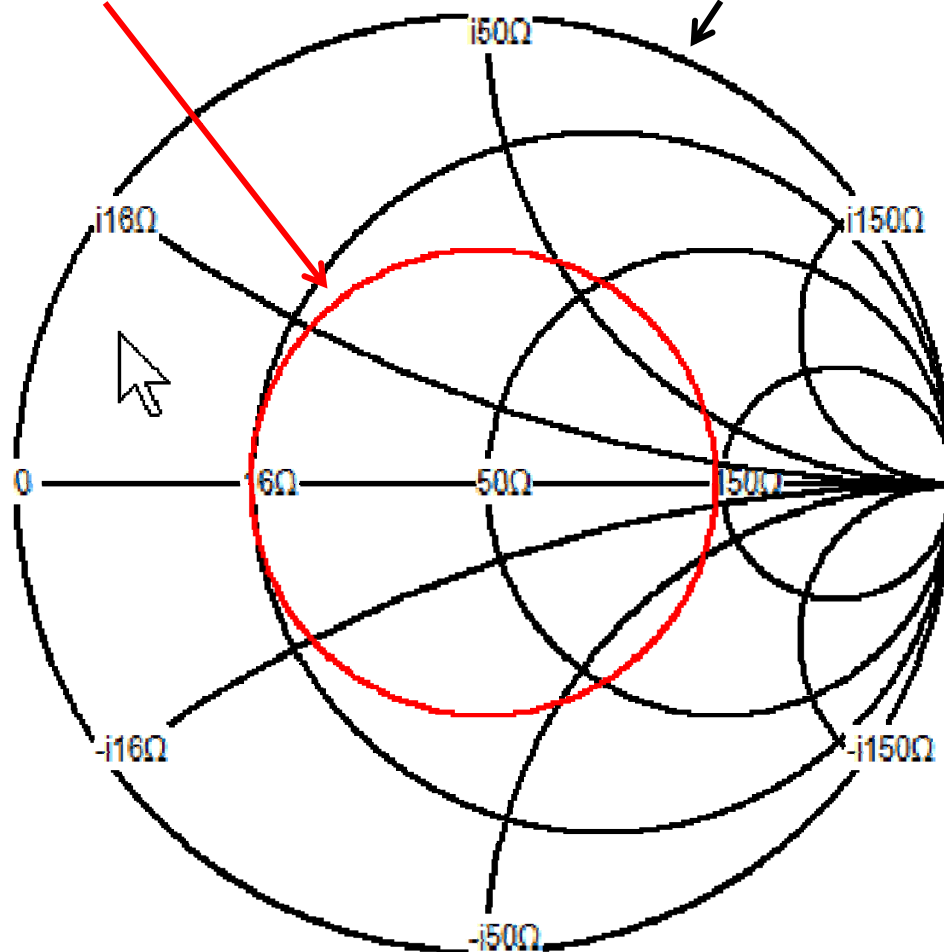


Complex Reflection Coefficient $S = b/a$ and Voltage Standing Wave Ratio VSWR

$|S| = 0,5$ $VSWR = 3$

$|S| = 1$ $VSWR = \infty$

0,5 · 0,5 = 25%
reflected power



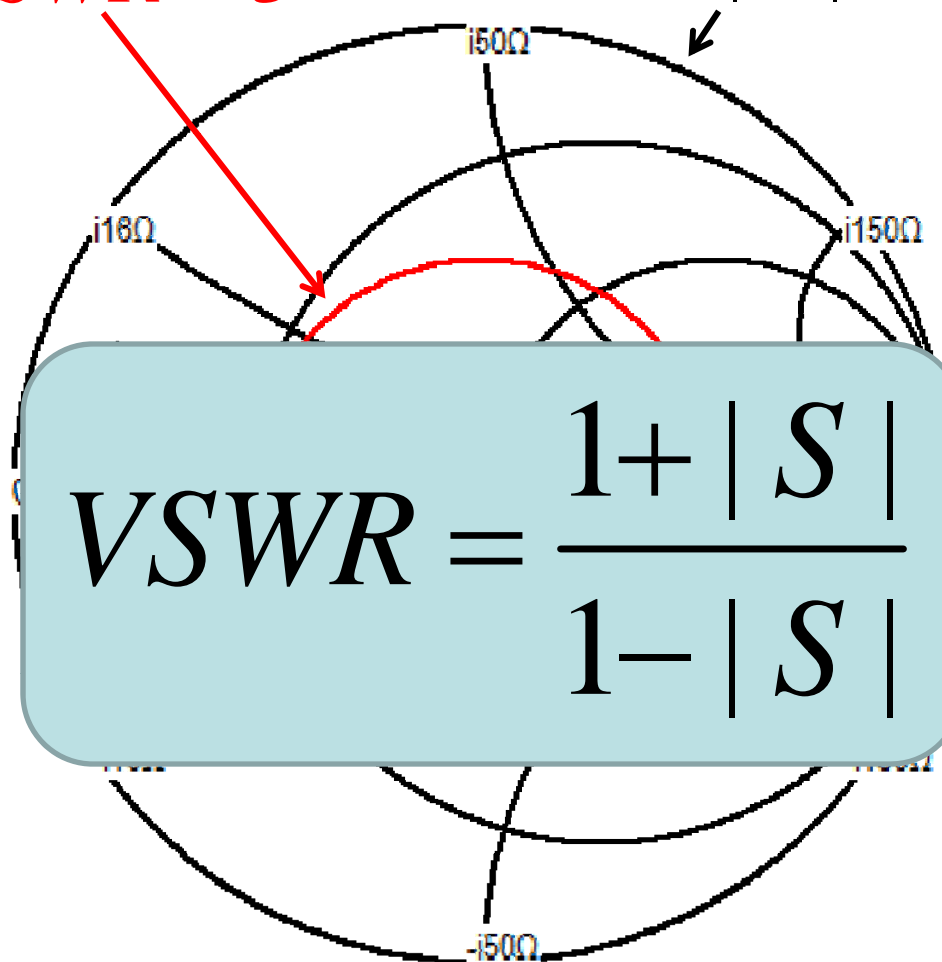
1 · 1 = 100%
reflected power



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

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

$$|S| = 1 \quad VSWR = \infty$$

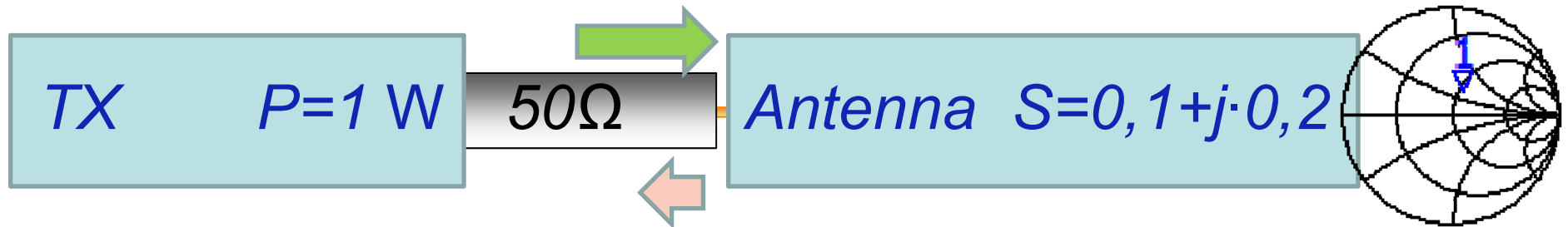


$$VSWR = \frac{1 + |S|}{1 - |S|}$$



Complex Reflection Coefficient $S = b/a$

Calculus Example: Reflected Power



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

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

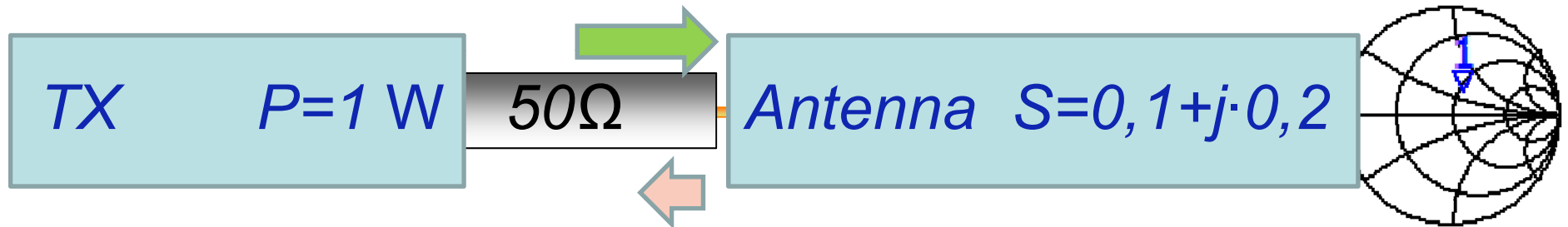
Reflected Power:

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



Complex Reflection Coefficient $S = b/a$

Calculus Example: VSWR



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

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

VSWR:

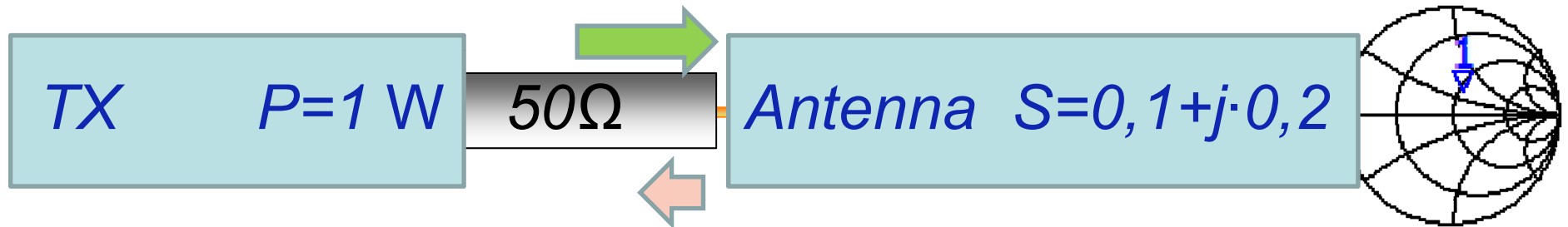
$$|S| = \sqrt{0,1^2 + 0,2^2} \approx 0,22$$

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



Complex Reflection Coefficient $S = b/a$

Calculus Example: Antenna Voltage



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

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

Effective Voltage at Antenna:

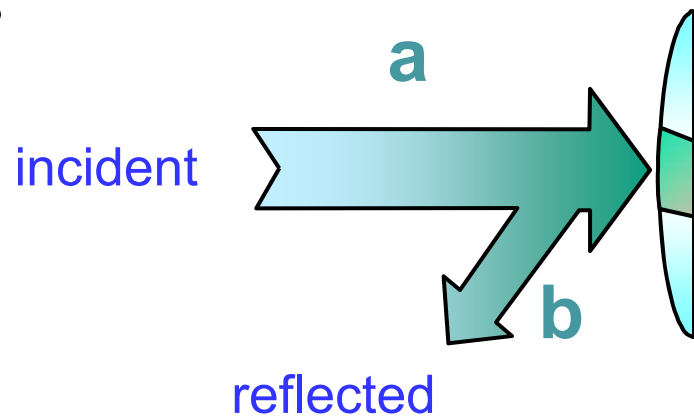
$$u = a + b = 1,1\sqrt{W} + j0,2\sqrt{W}$$

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

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

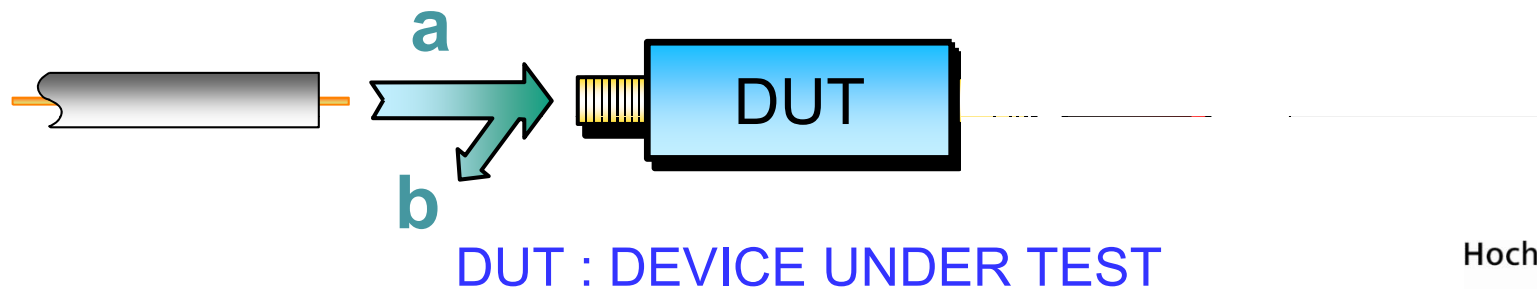
Complex Reflection Coefficient $S = b/a$ We call it Scattering Parameter now!

Optics



Scattering and absorption of waves at one port

Elektrical

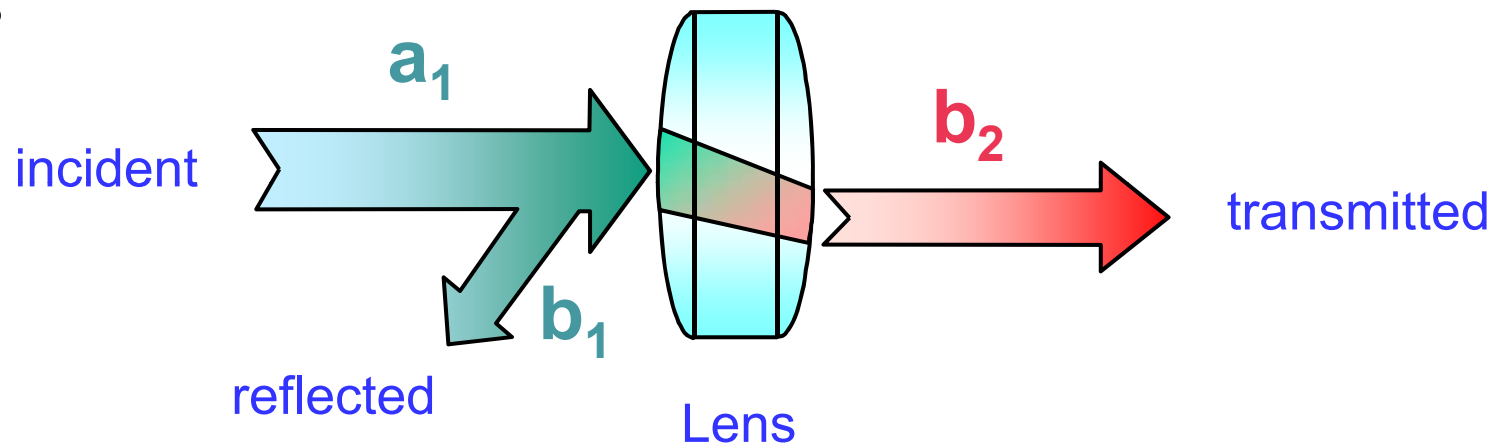


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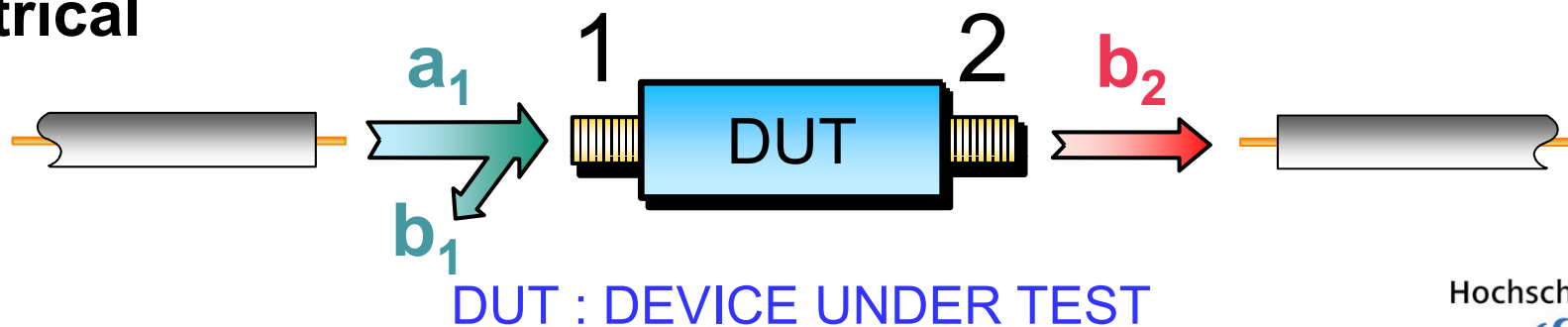


Scattering Parameters or short S-Parameters: Now two Ports!

Optics



Electrical

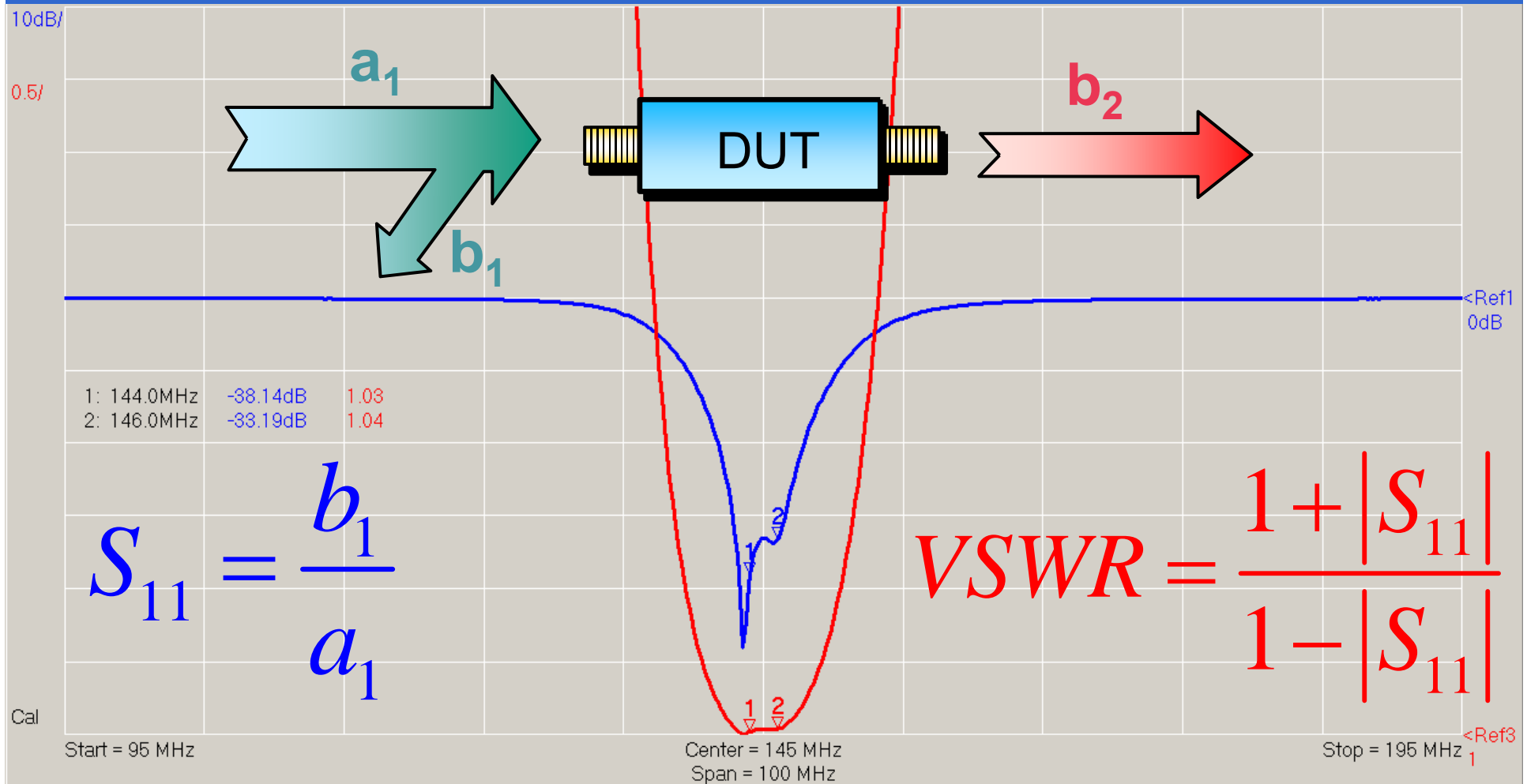


Hochschule Ulm



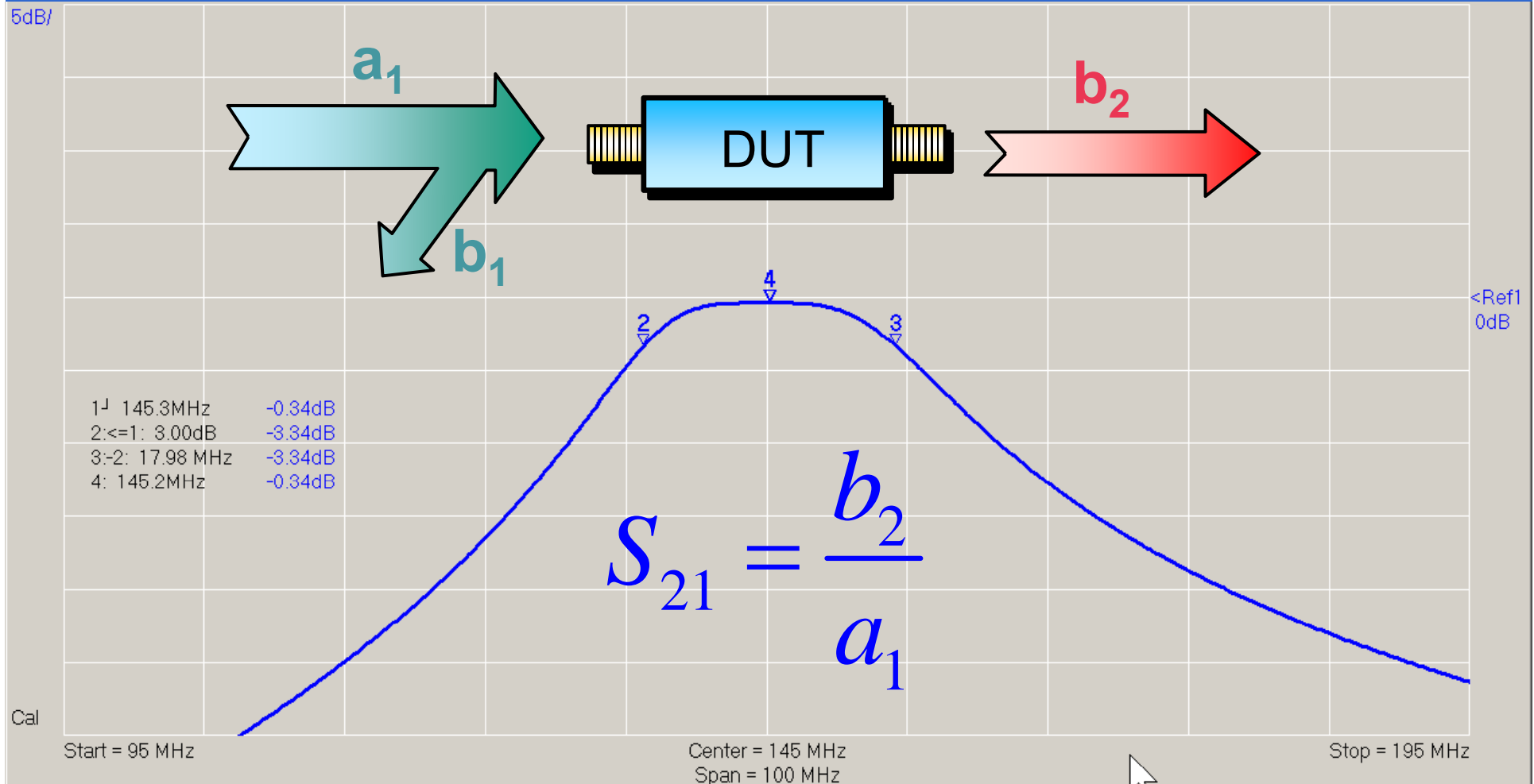
S-Parameter S_{11} (used to be S)

→ $|S_{11}|$ → Return Loss

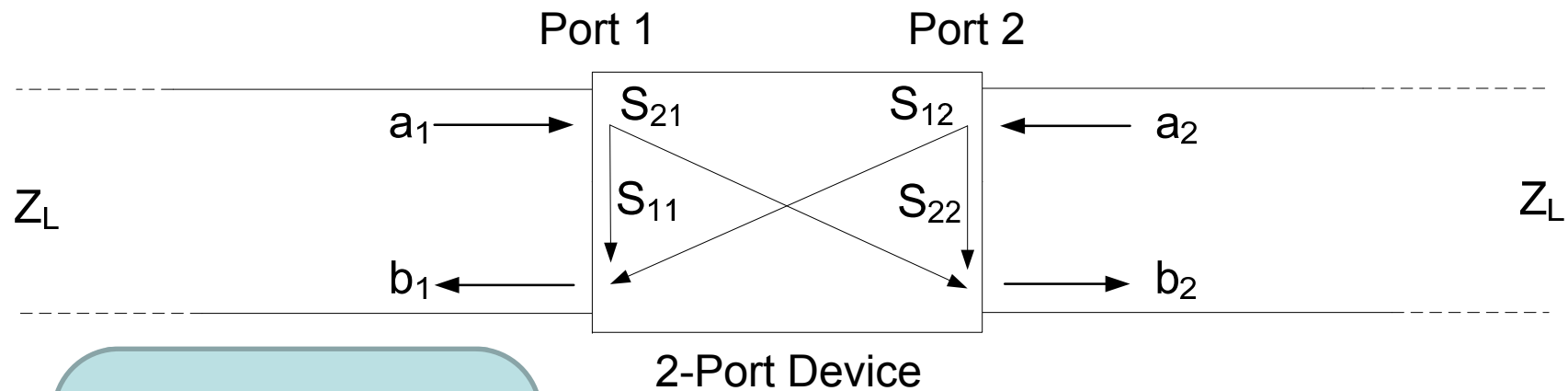


S-Parameter S_{21}

→ $|S_{21}| = \text{Transmission Gain}$



General: S-Parameters S_{ik}

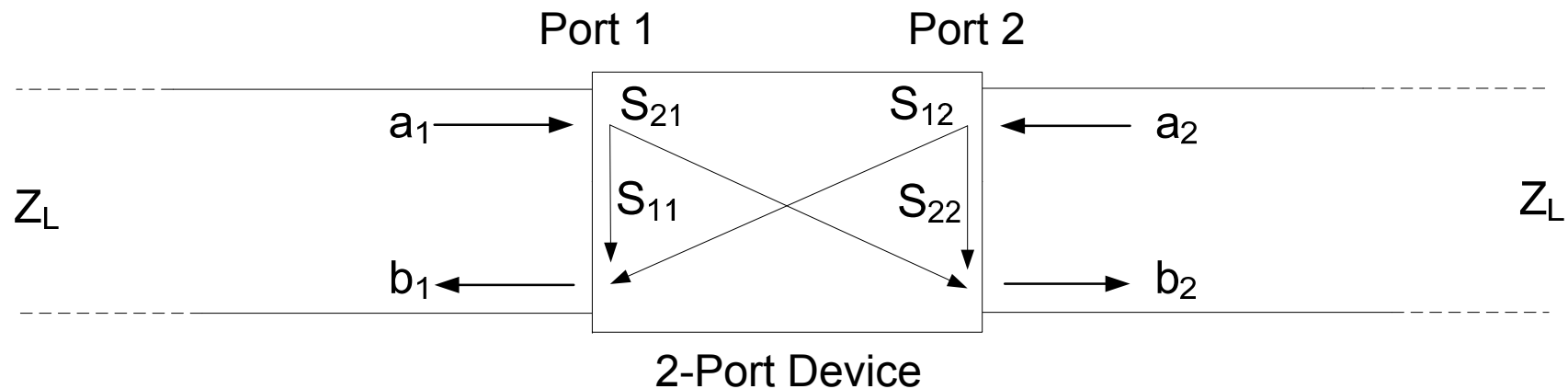


$$S_{ik} = \frac{b_i}{a_k}$$

$i, k = 1 \dots$ 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

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BREAK ???



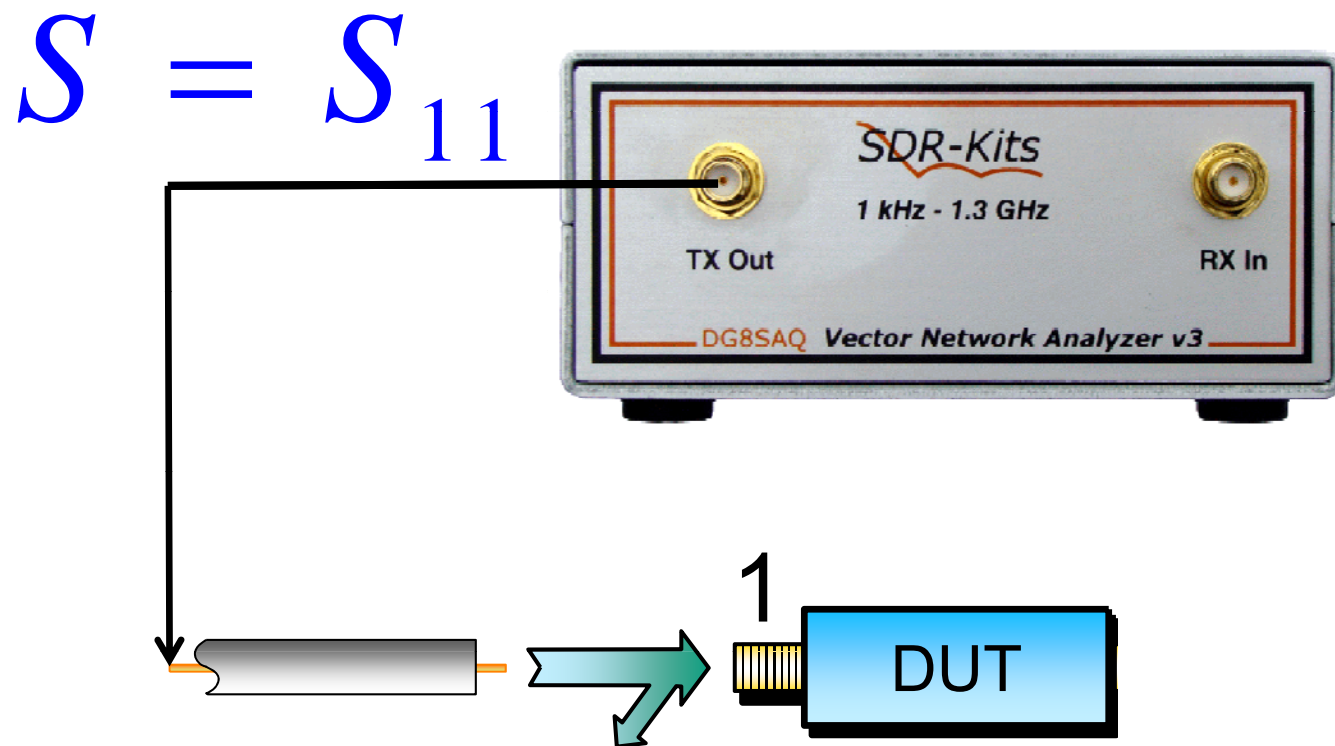
Measuring S-Parameters using a Vector-Network Analyzer

1. Measurement Setup using a VNWA
2. Error Correction by Calibration
3. Application Examples



Measurement Setup using a VNWA

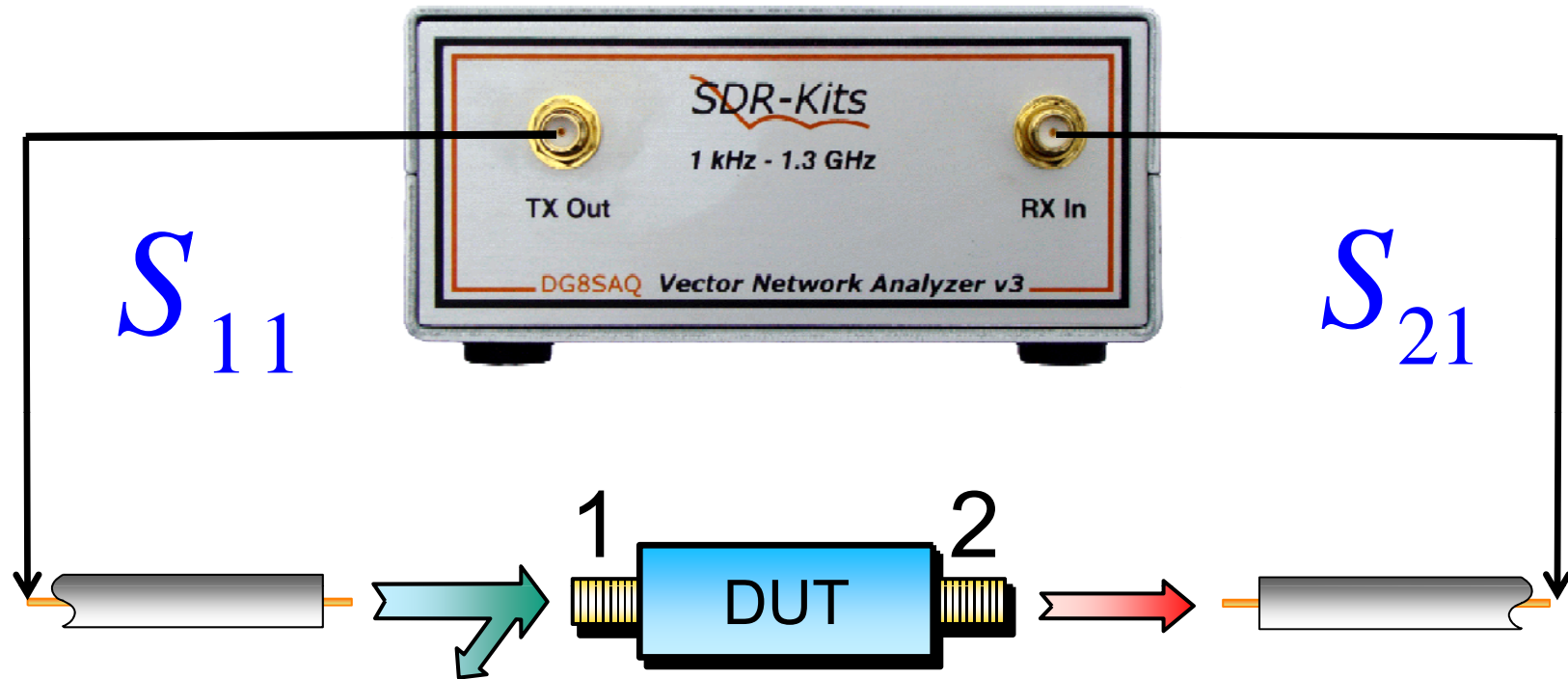
Example 1-Port Device:



DUT : DEVICE UNDER TEST

Measurement Setup using a VNWA

Example 2-Port Device forward:



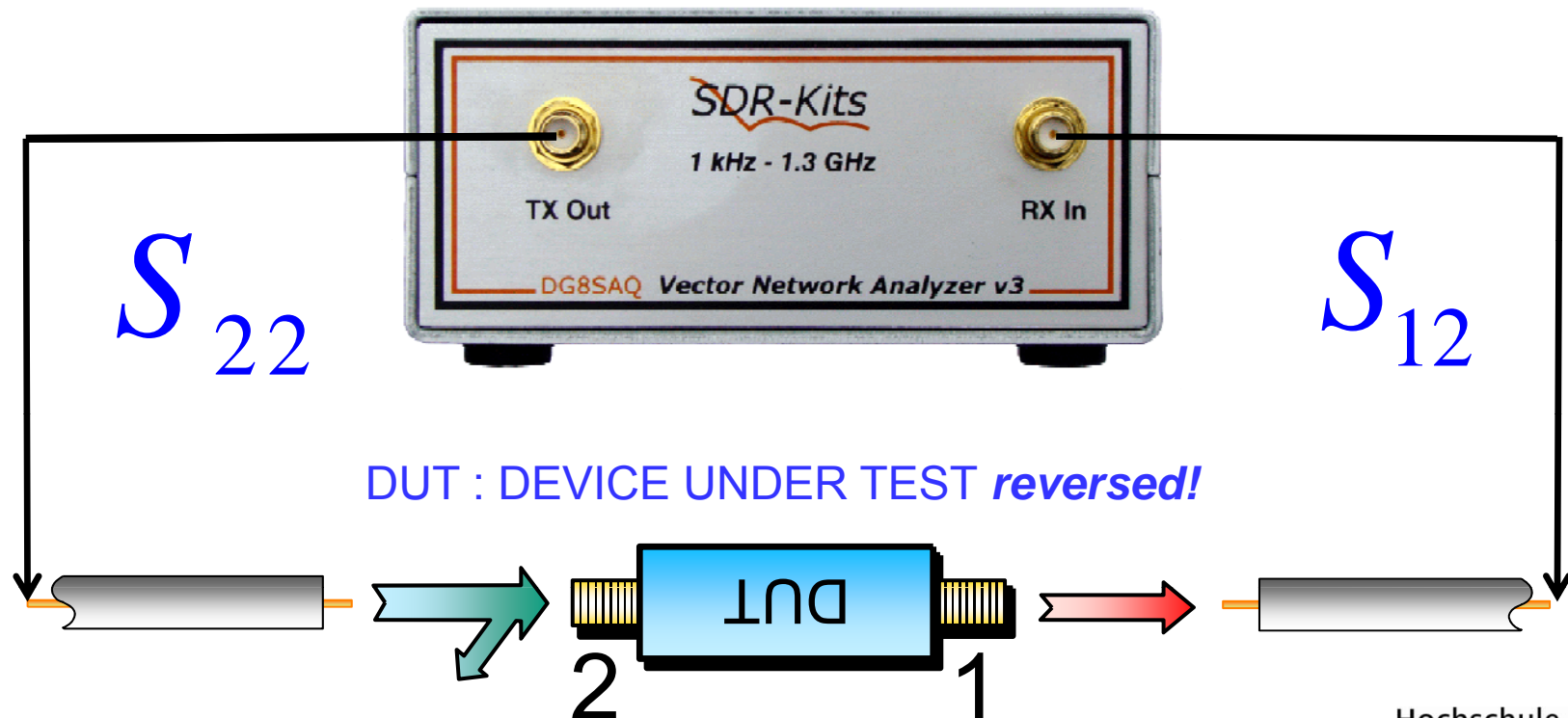
DUT : DEVICE UNDER TEST

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Measurement Setup using a VNWA

Example 2-Port Device reverse:

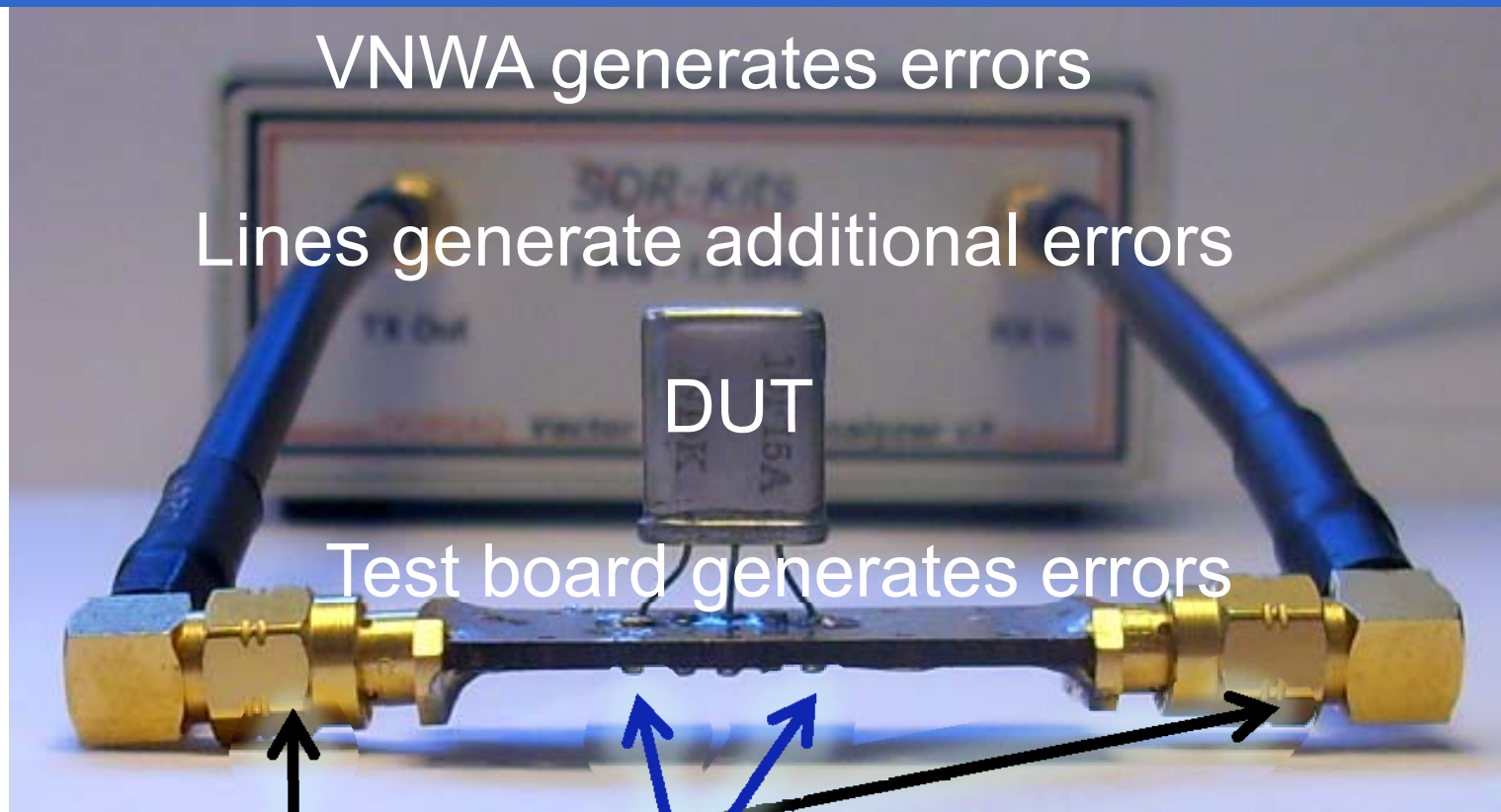


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Error Correction by Calibration

Error Sources



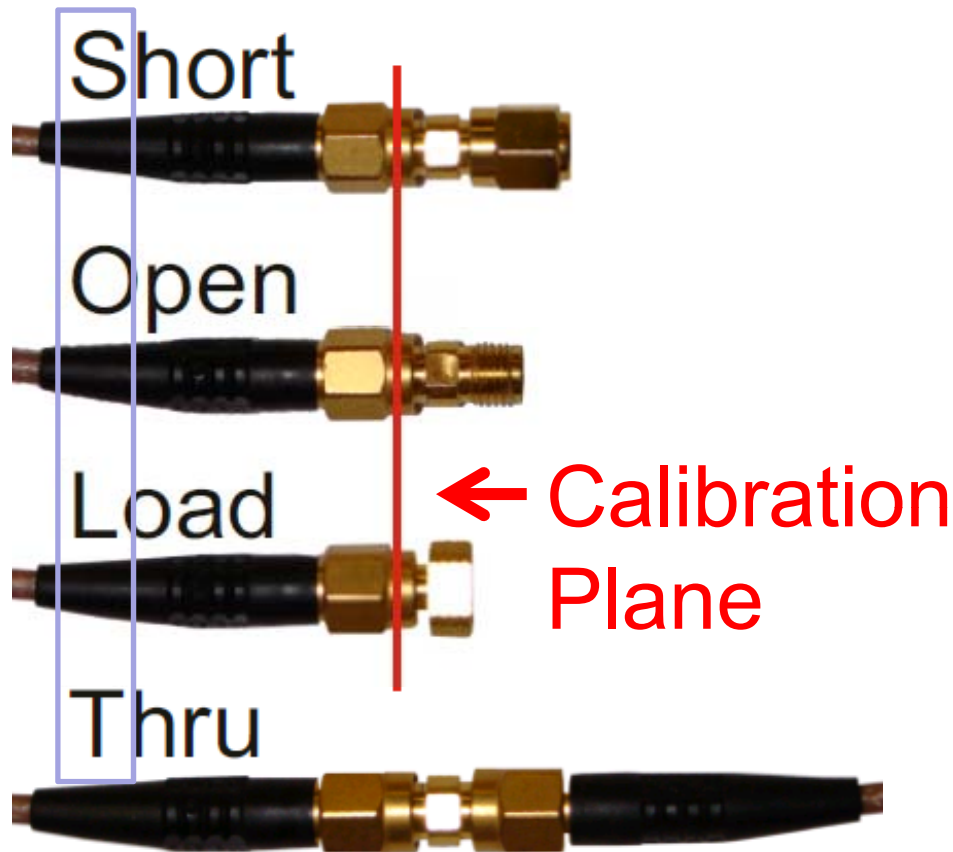
We calibrate here!

We want to measure here!

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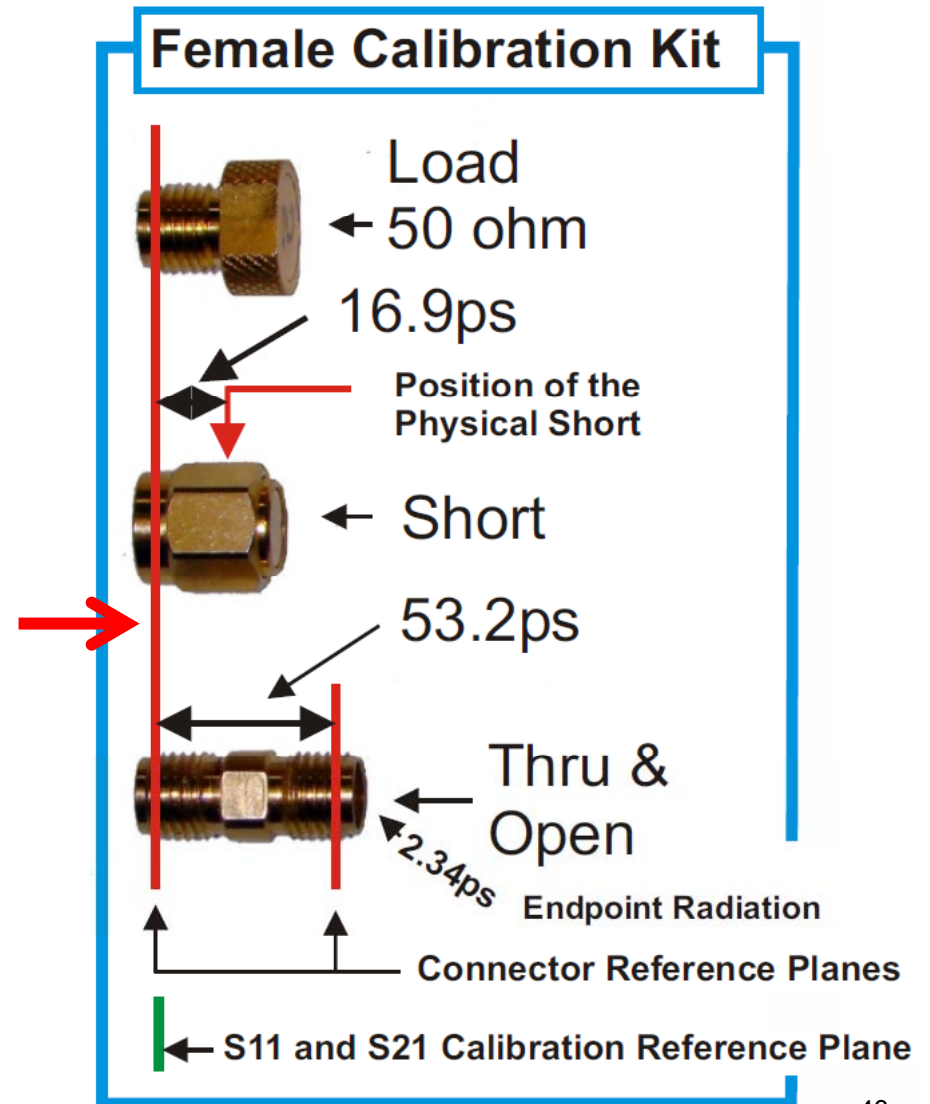


SOLT-Calibration removes Errors from VNWA and Test Cables...



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

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

Calibration Settings

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

OSL Calibration Standard Setup

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

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

LOAD: R = Ohms C || = 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

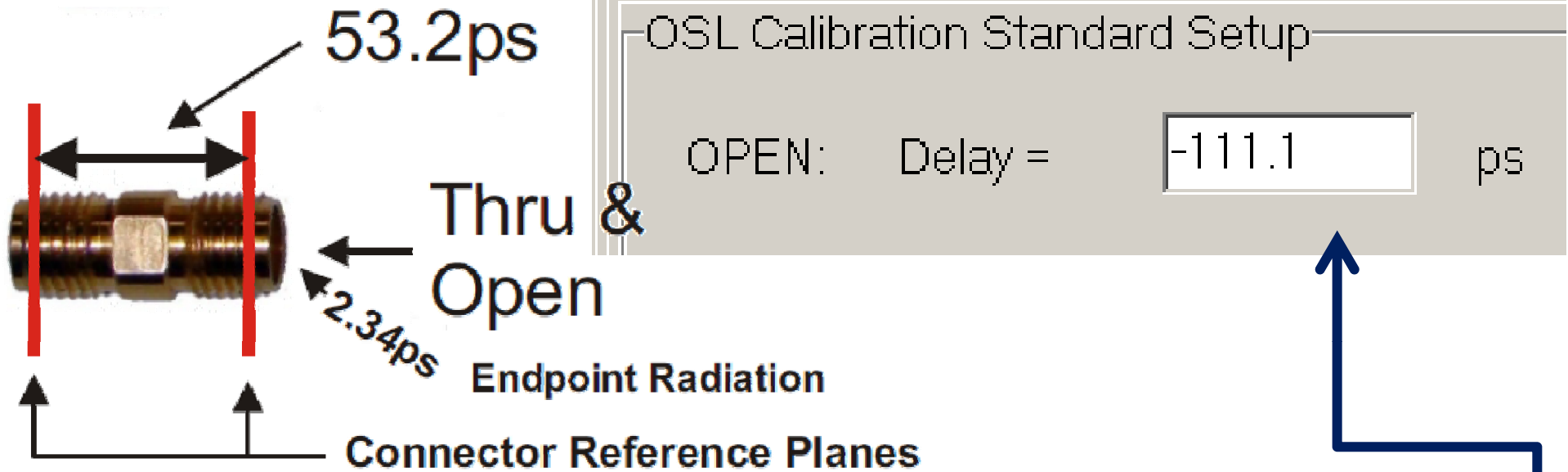
THRU: Transmission Delay = ps => electrical length = 11.172 mm

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Example: Open Standard



Signal travels standard twice, namely forth and back:

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



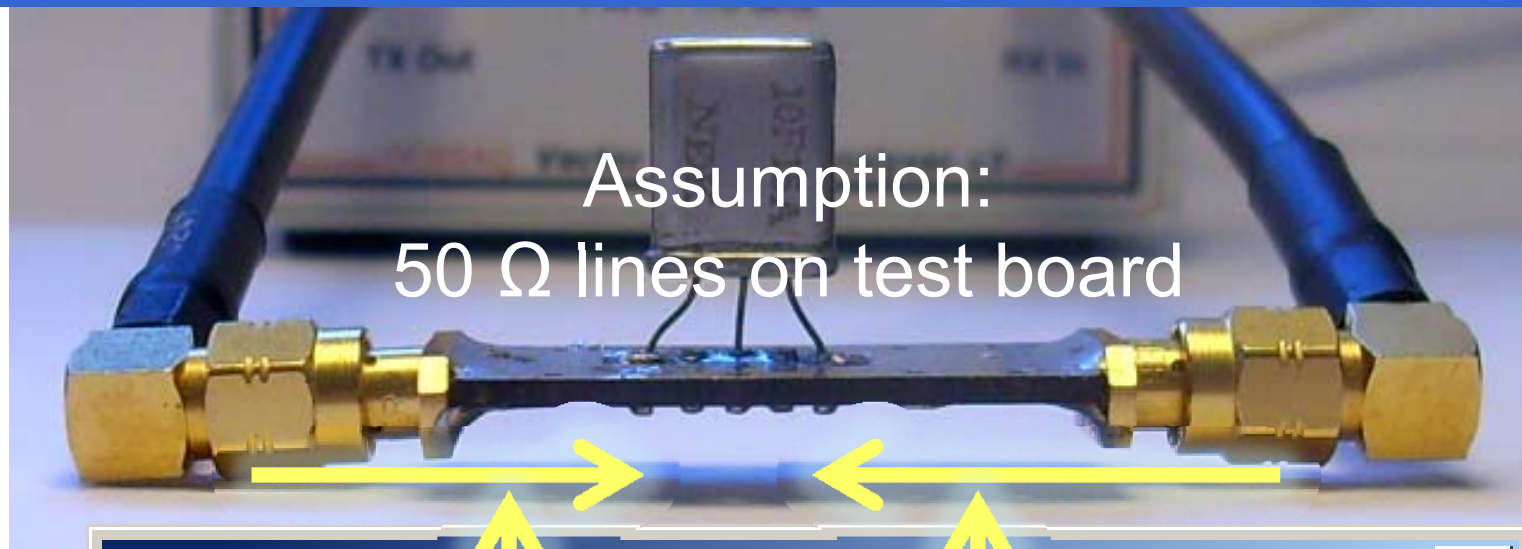
Now, connect standards to VNWA and calibrate

The screenshot shows the 'Full Calibration' window with the following elements and annotations:

- needed for**: A blue box pointing to the 'Correction' tab.
- S_{11}, S_{22}** : A blue box pointing to the 'Reflect Cal' section.
- S_{21}, S_{12}** : A blue box pointing to the 'Thru Calibra' section.
- usually omit**: Vertical text on the right side of the interface.
- Annotations**: Blue rounded rectangles highlight the 'Short', 'Open', 'Load', and 'Cal' buttons in the Reflect Cal section, and the 'Crosstalk Cal', 'Thru Cal', and 'Thru Match Cal' buttons in the Thru Calibra section. A red circle with an arrow points to the 'Crosstalk Cal' button.
- Buttons and Controls**:
 - Reflect Cal: Short, Open, Load, Cal (checked on/off).
 - Thru Calibra: Crosstalk Cal (red circle), Thru Cal (checked on/off), Thru Match Cal (checked on/off).
 - Invalidate All Thru Calibrations button.

UIm

Delay Correction with Port Extensions



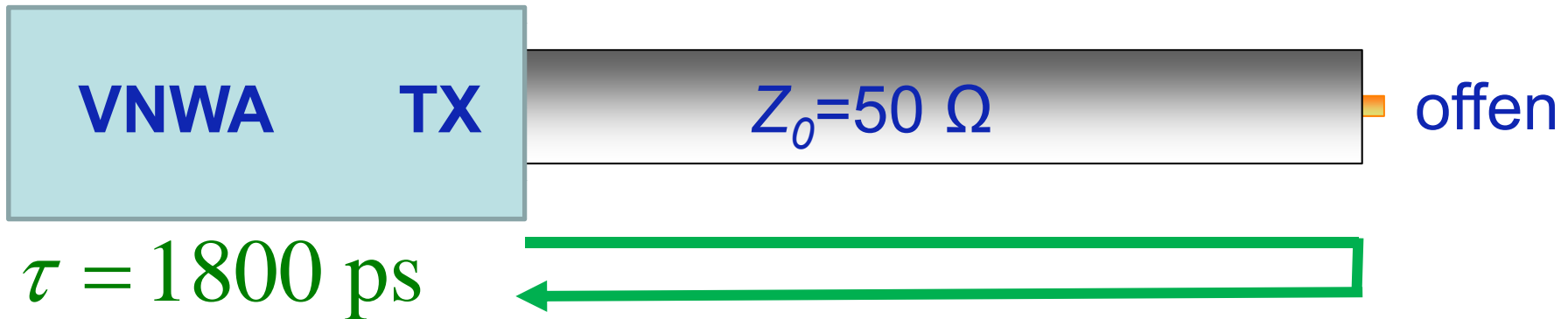
S_{11}
 S_{22}

Port Extensions [X]

Ext. Port 1	<input type="text" value="105"/>	ps <input type="button" value="v"/>	= 22 mm
Ext. Port 2	<input type="text" value="132"/>	ps	= 27.7 mm
Velocity Factor:	<input type="text" value="0.7"/>	<input checked="" type="checkbox"/> Port Ext. ON	

Wrong Cal Parameters cause Port Mismatch

Example: open 50 Ohms – Line (1)



Calibration Settings We can simulate this:

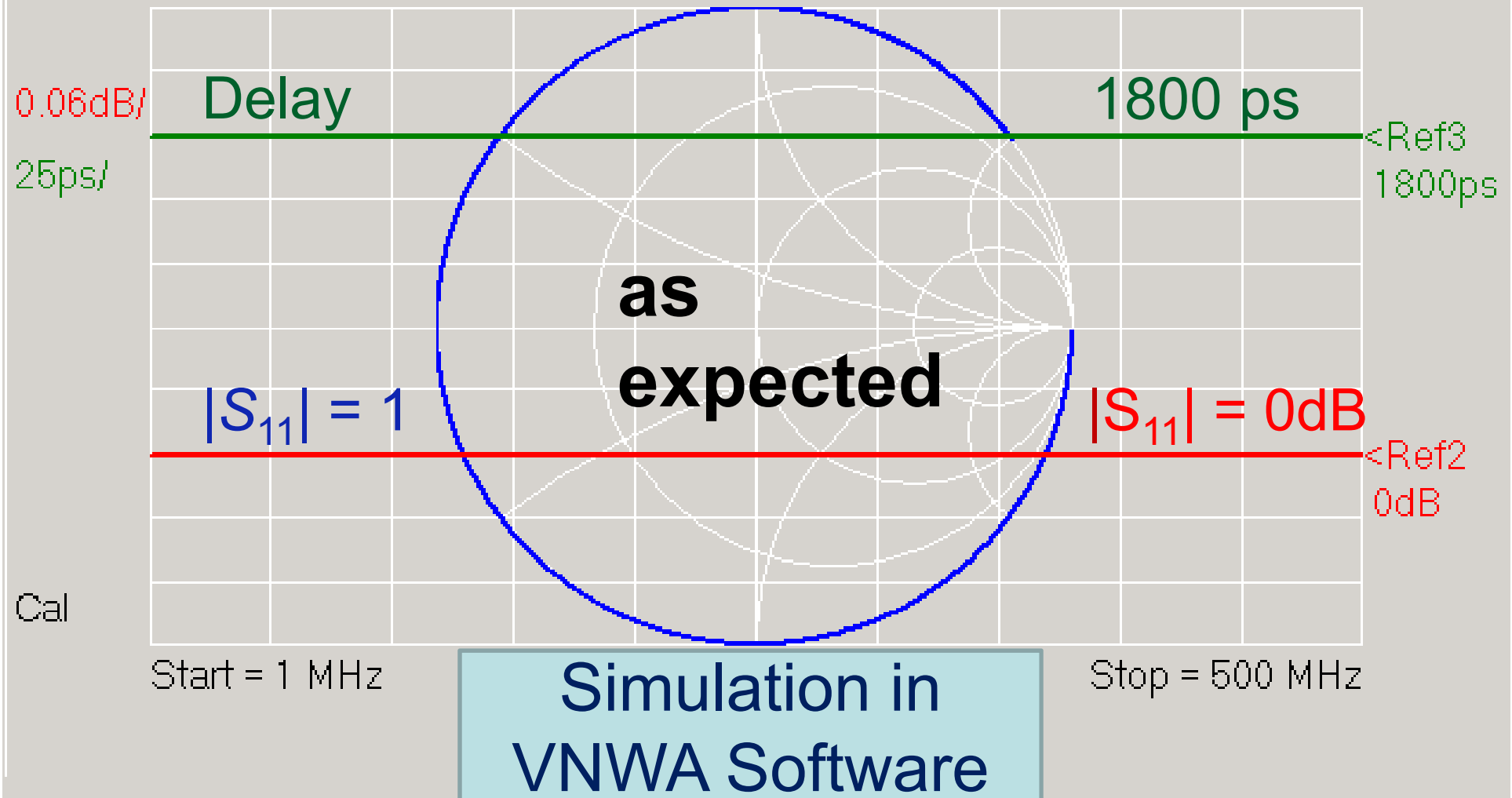
SOLT Simulation Settings | Special Settings | **Measurement Simulation**

$S_{11} = \exp(-j \cdot \omega \cdot 1800 \text{e-12})$

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

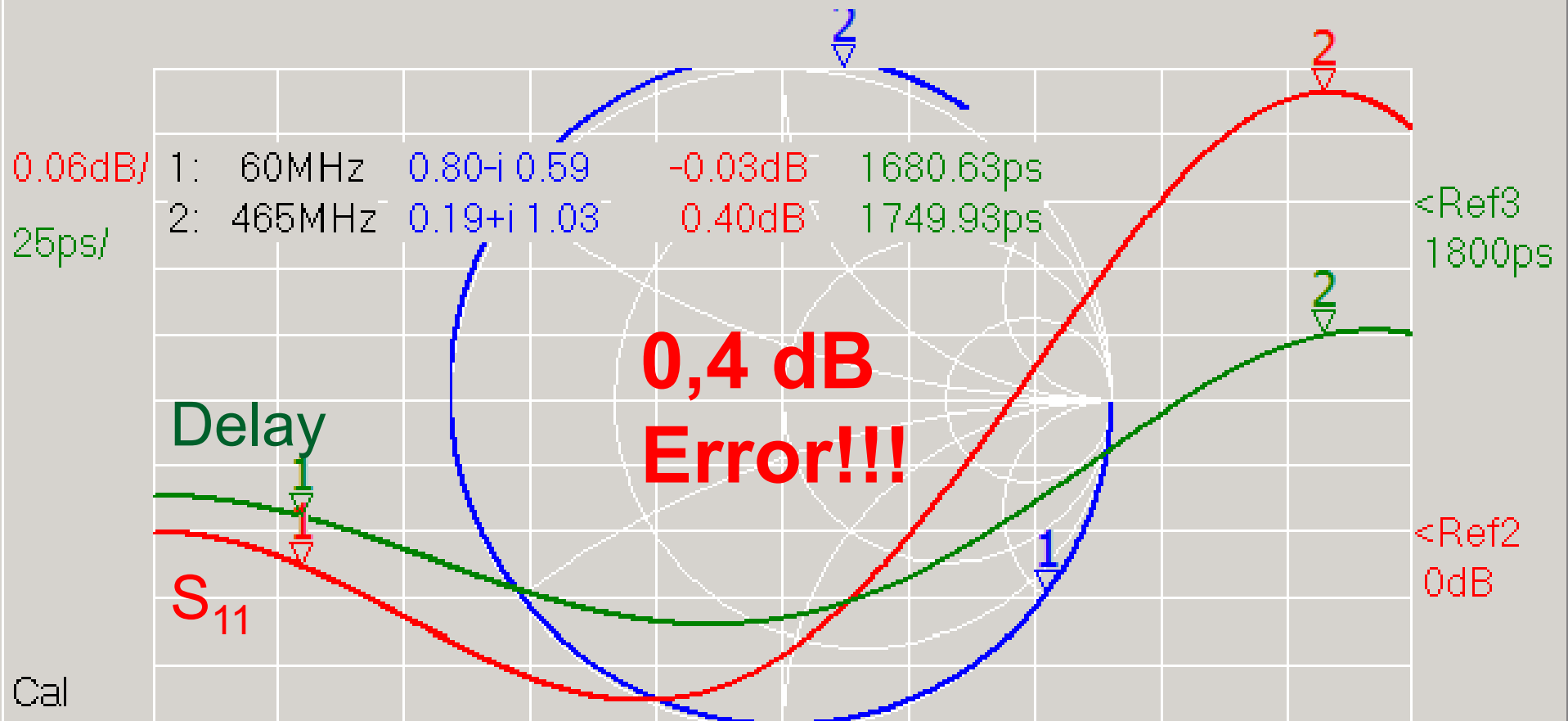


Example: open 50 Ohms – Line (2) Simulated with Amphenol Female Parameters



HAM RADIO 2013 simulate 2-port measurement and do 12 term correction

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

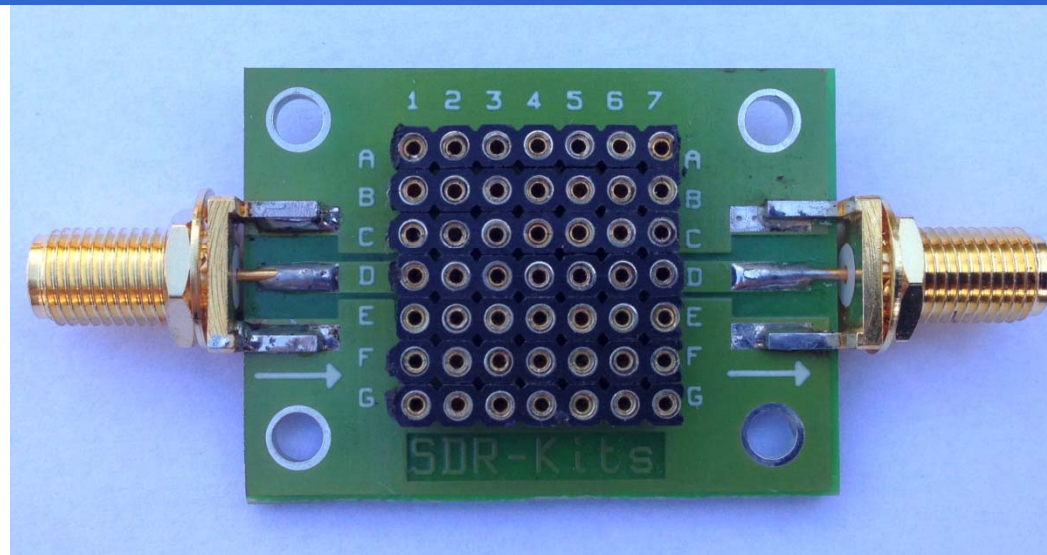
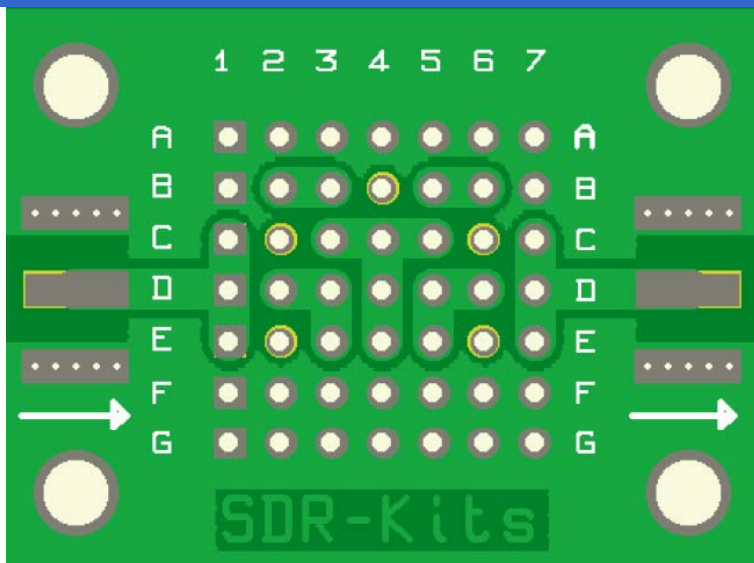


Previously simulated measurement data corrected again using ideal cal parameters

Applications ...



Test Board for HF Experiments



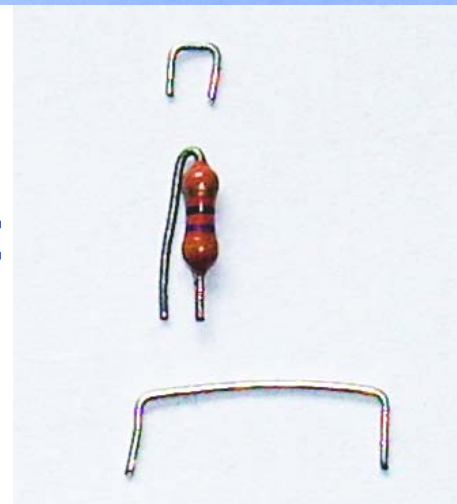
**Calibration
Standards:**

Open = n.c.

Short:

Load = 47Ω :

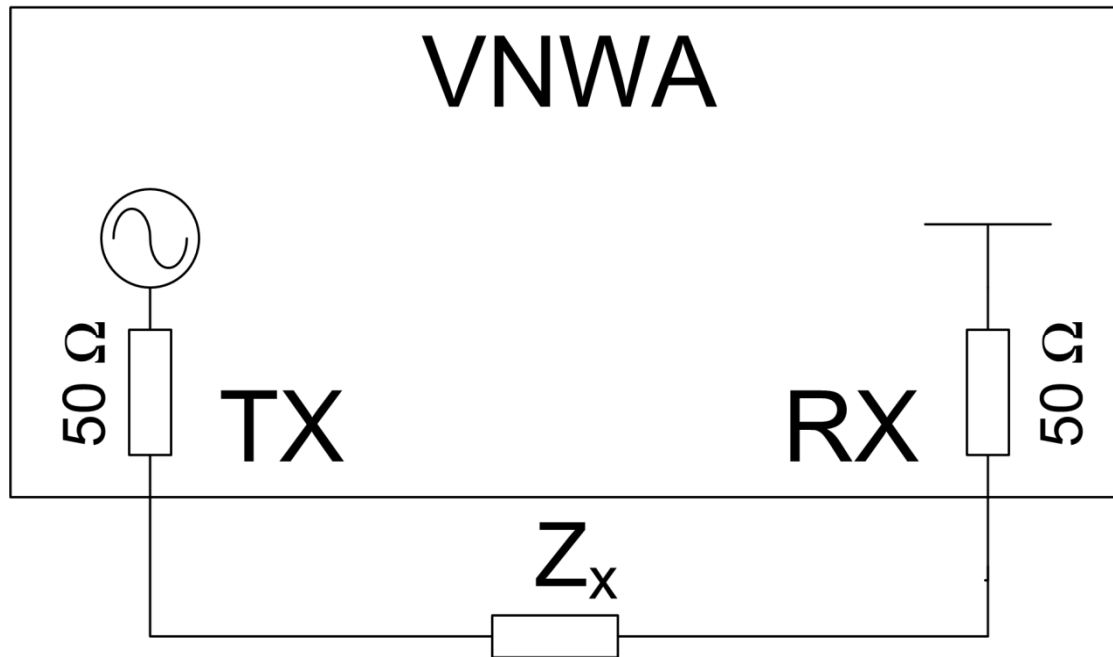
Thru:



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Measuring „Load“-Resistor without SOL-Calibration?

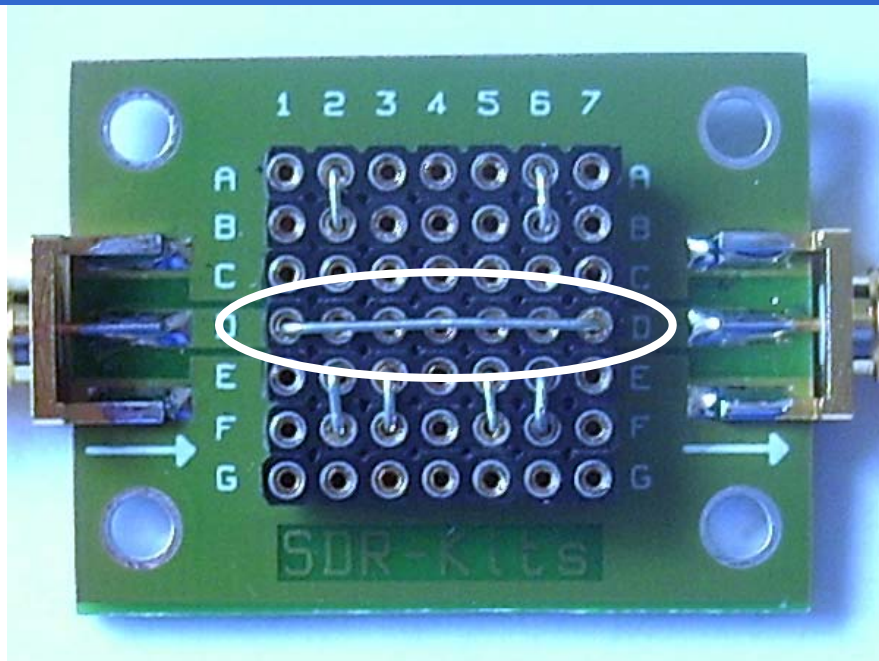


$Z_x = 47 \Omega$ yield $\approx 3,4$ dB insertion loss.

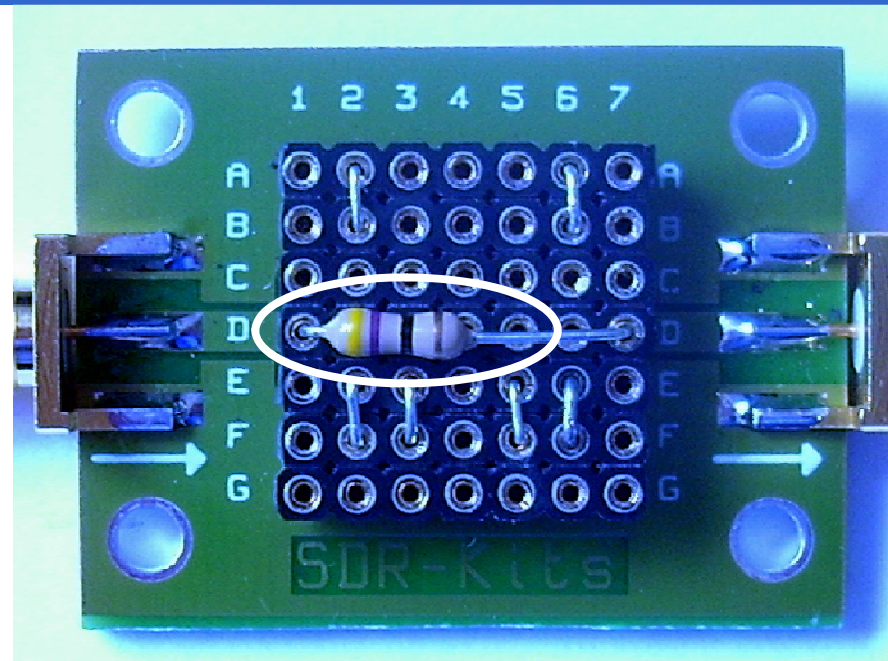
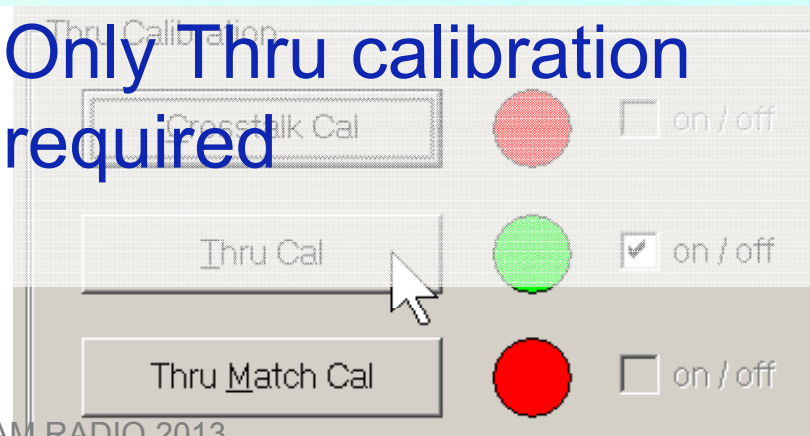
Works, because VNWA TX and RX port impedances are exactly 50Ω .

➤ only Thru calibration required!

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



Only Thru calibration
required



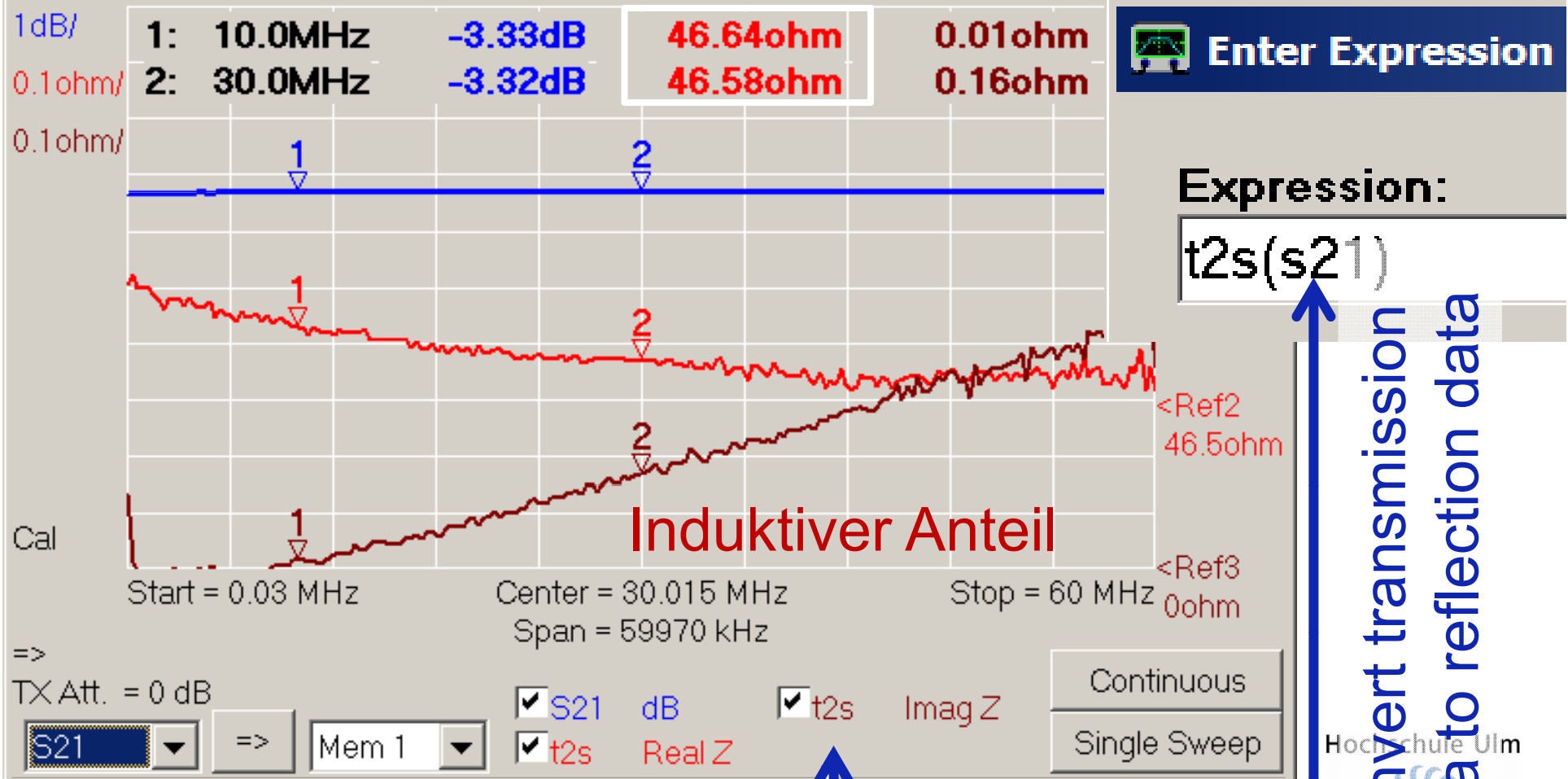
Measurement:
Resistor between
TX and RX

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Measuring „Load“-Resistor

Result = 46,6 Ω




Induktiver Anteil

<Ref2
46.5ohm
<Ref3
0ohm

Convert transmission data to reflection data

Analysis with Custom Trace

Simple Calibration Standard Model: Only measured Load-Resistance

 **Calibration Settings** ✕

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 || = fF

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

THRU Calibration Standard Setup

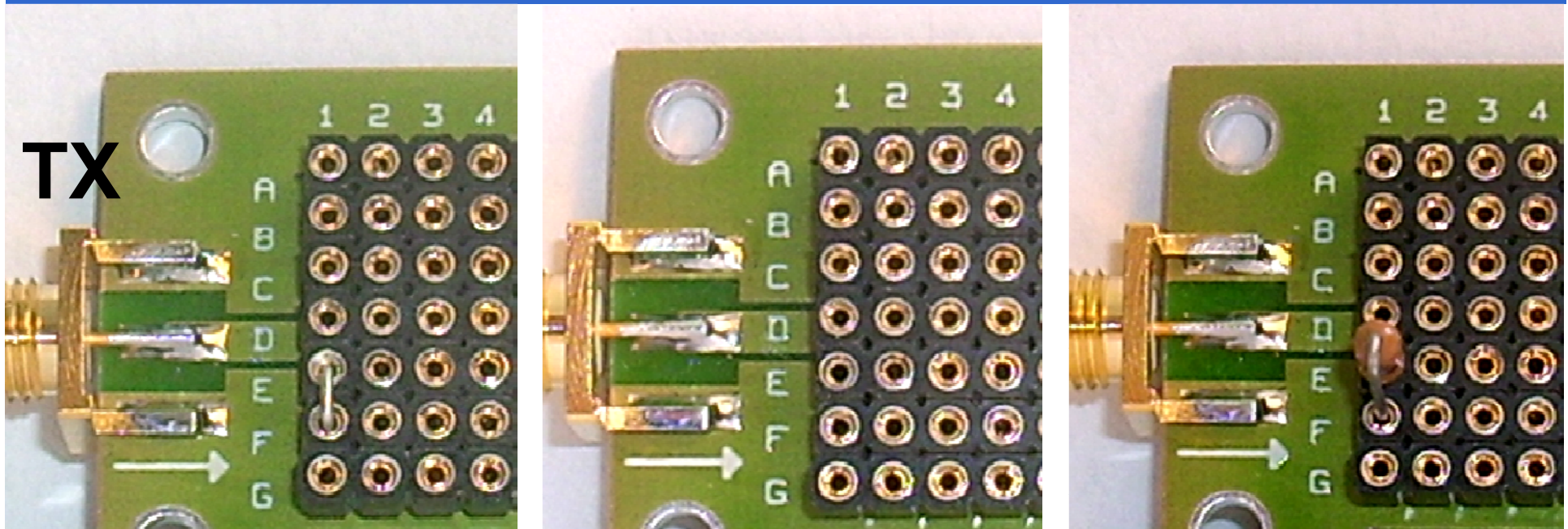
THRU: Transmission Factor = => attenuation = 0.000 dB

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

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SOL-Calibration for S_{11} -Measurement



Reflect Calibration

Short

Open

Load

HAMRAD on/off

Thru Calibration

Crosstalk Cal on/off

Thru Cal on/off

Thru Match Cal on/off

Invalidate All Thru Calibrations

Load

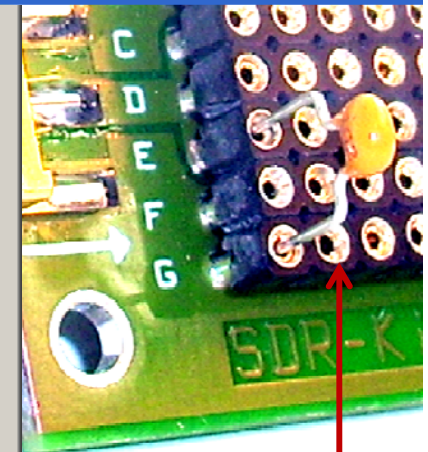
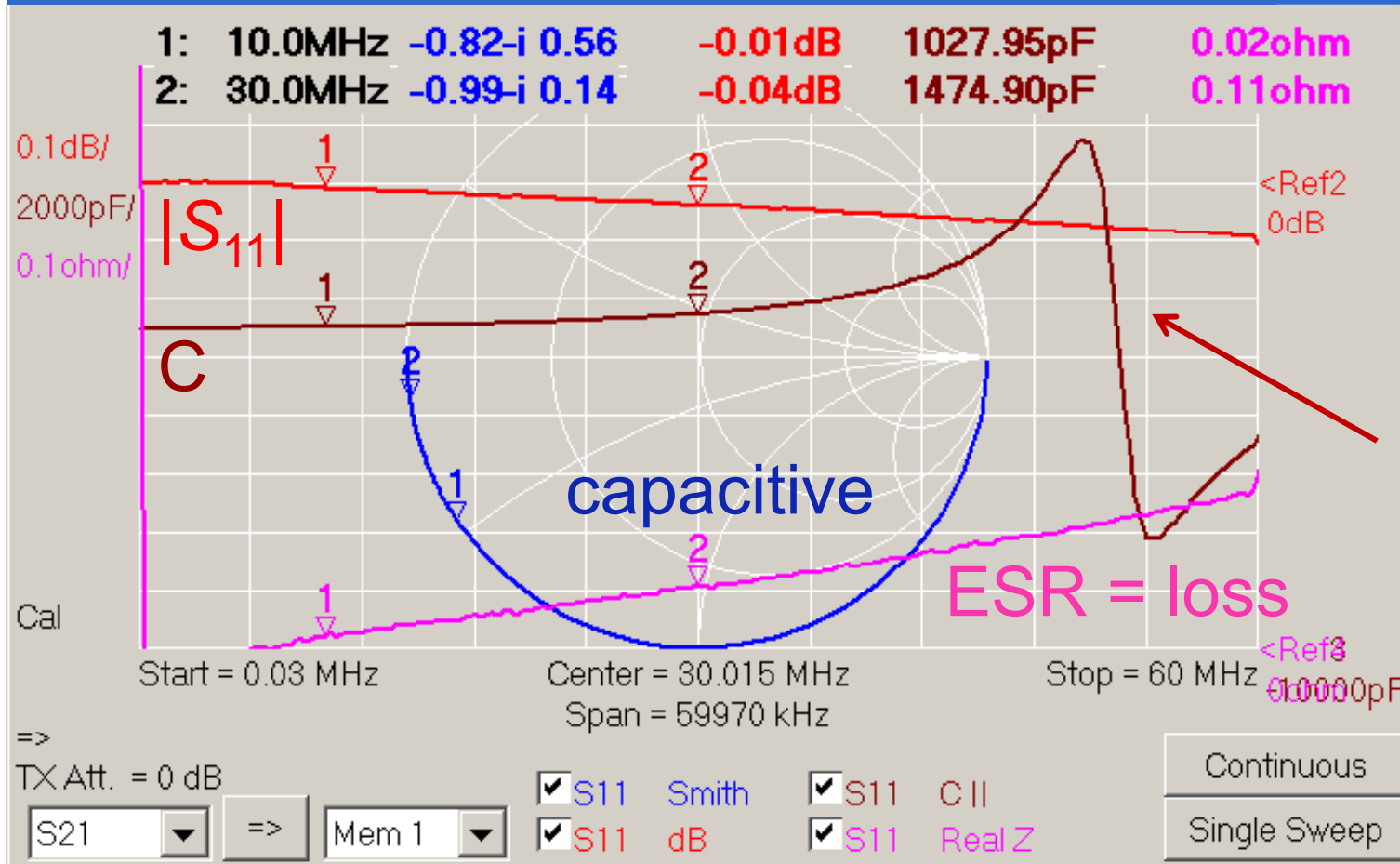
Hochschule Ulm



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



Resonance due to component wires

Hochschule Ulm



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

Modelling of Measurement Result in VNWA using Custom-Trace

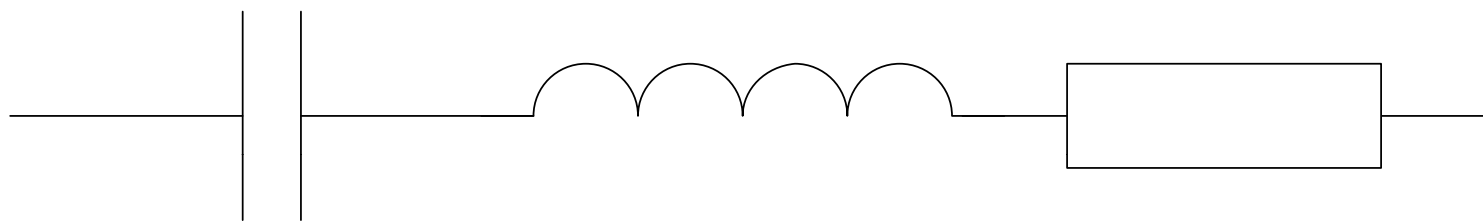


Enter Expression 2 for trace 2:

Expression:

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

Impedance to Reflecion coefficient



0,984 nF

9,3 nH

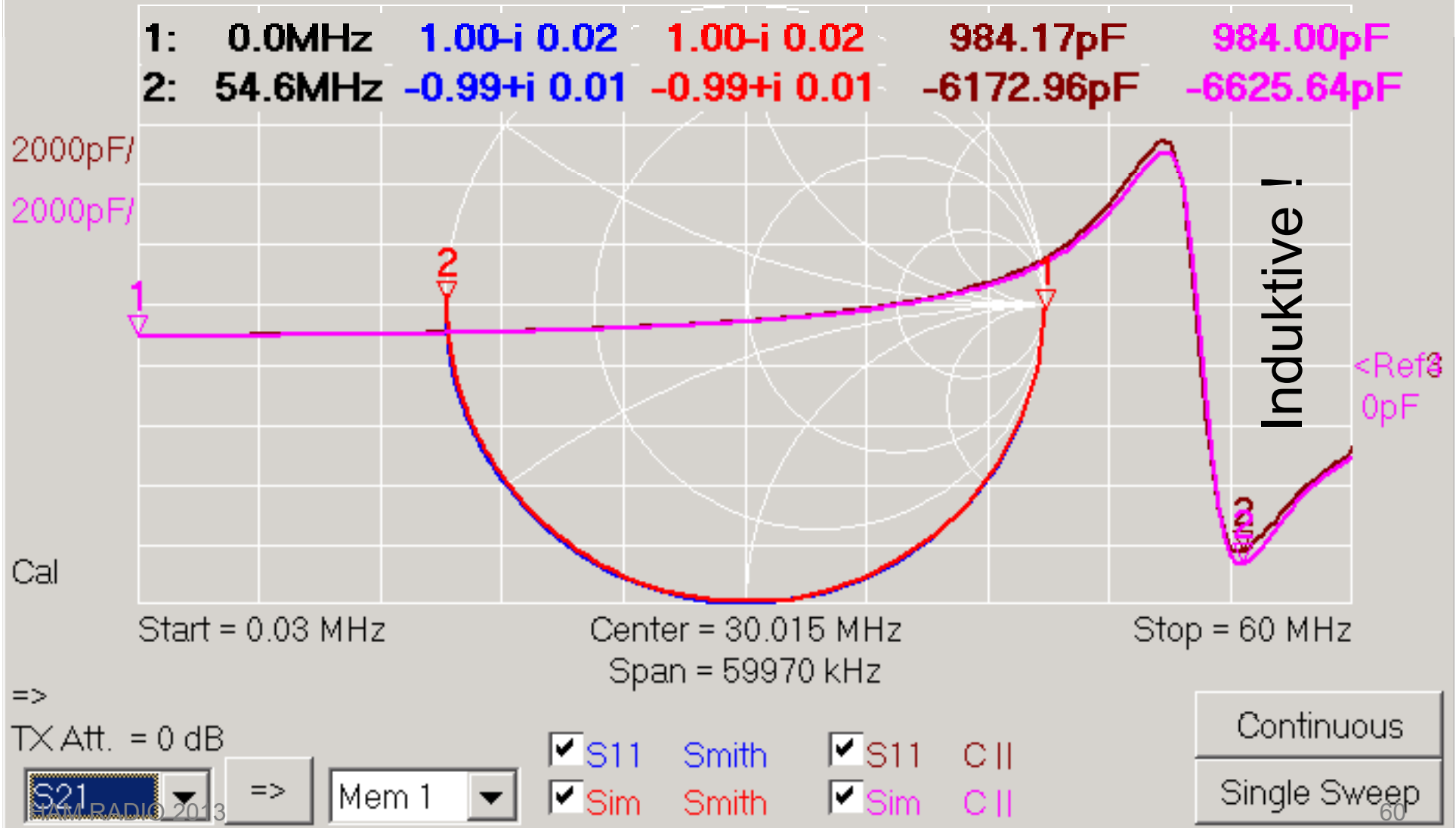
0,22 Ω

einfaches Modell

Hochschule Ulm

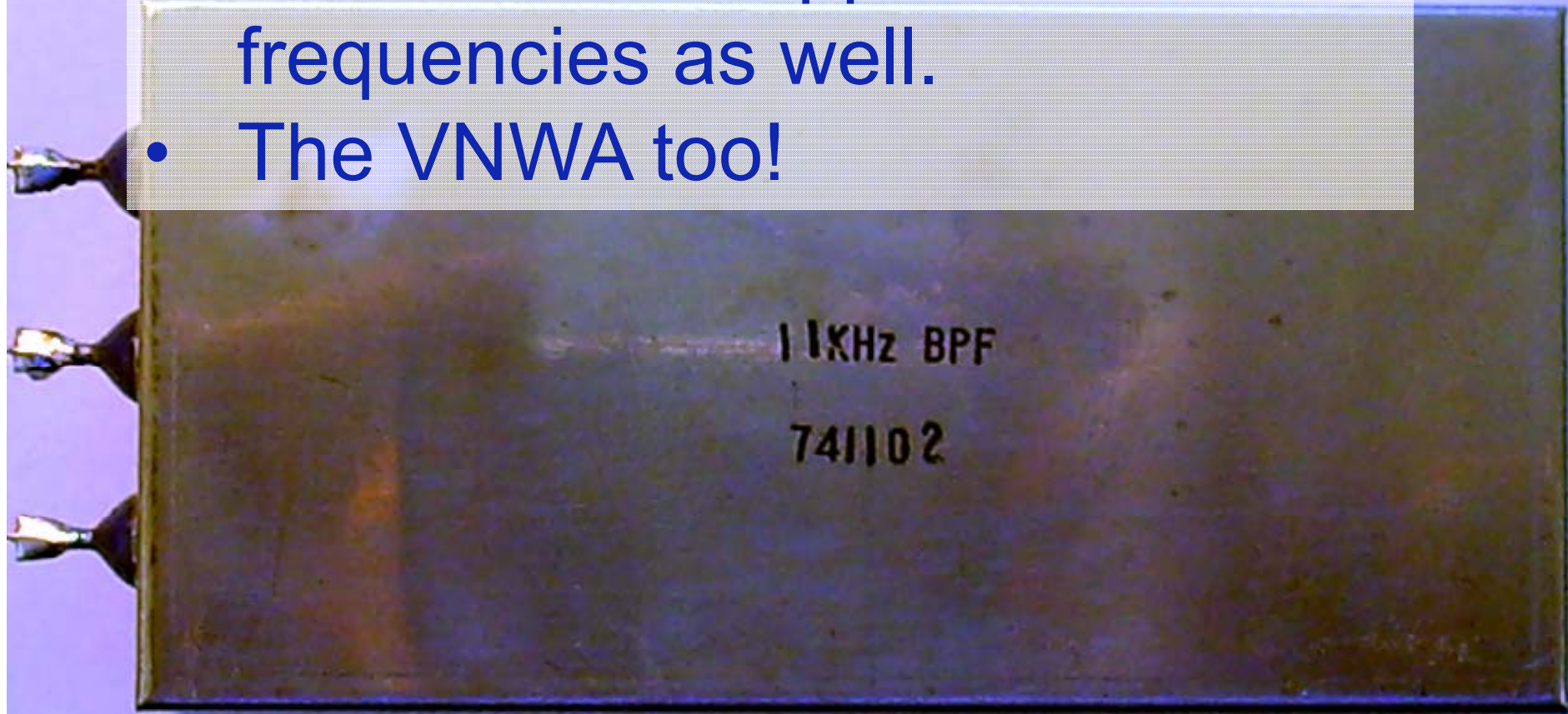


The Model is quite accurate!

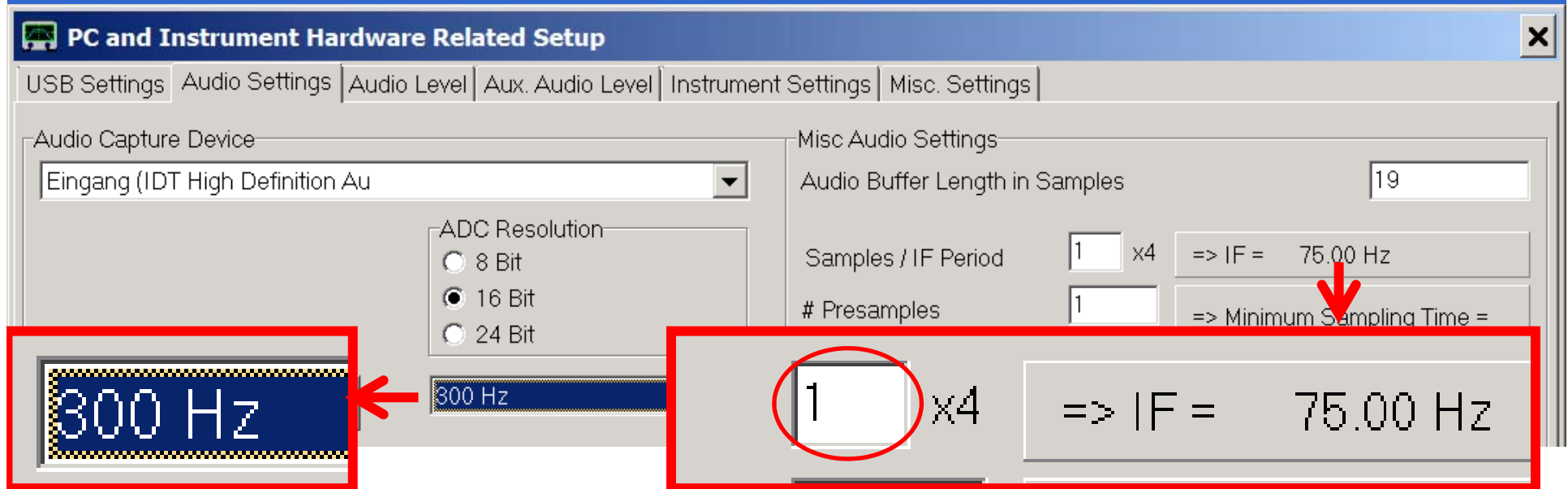


Two Port Measurement of a 12 kHz Band Pass Filter

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



Special VNWA Settings for low Frequencies



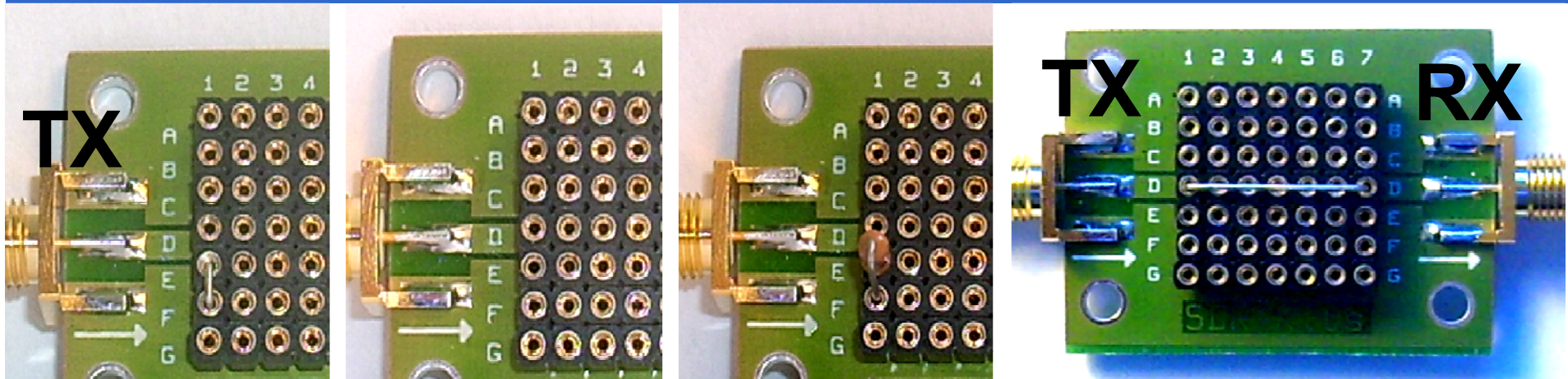
Lowest sample rate 300 Hz → Nyquist limit 150 Hz
→ Measurements down to ≈ 150 Hz possible








IF must be within Codec frequency range (20 Hz...16kHz)

Hochschule Ulm

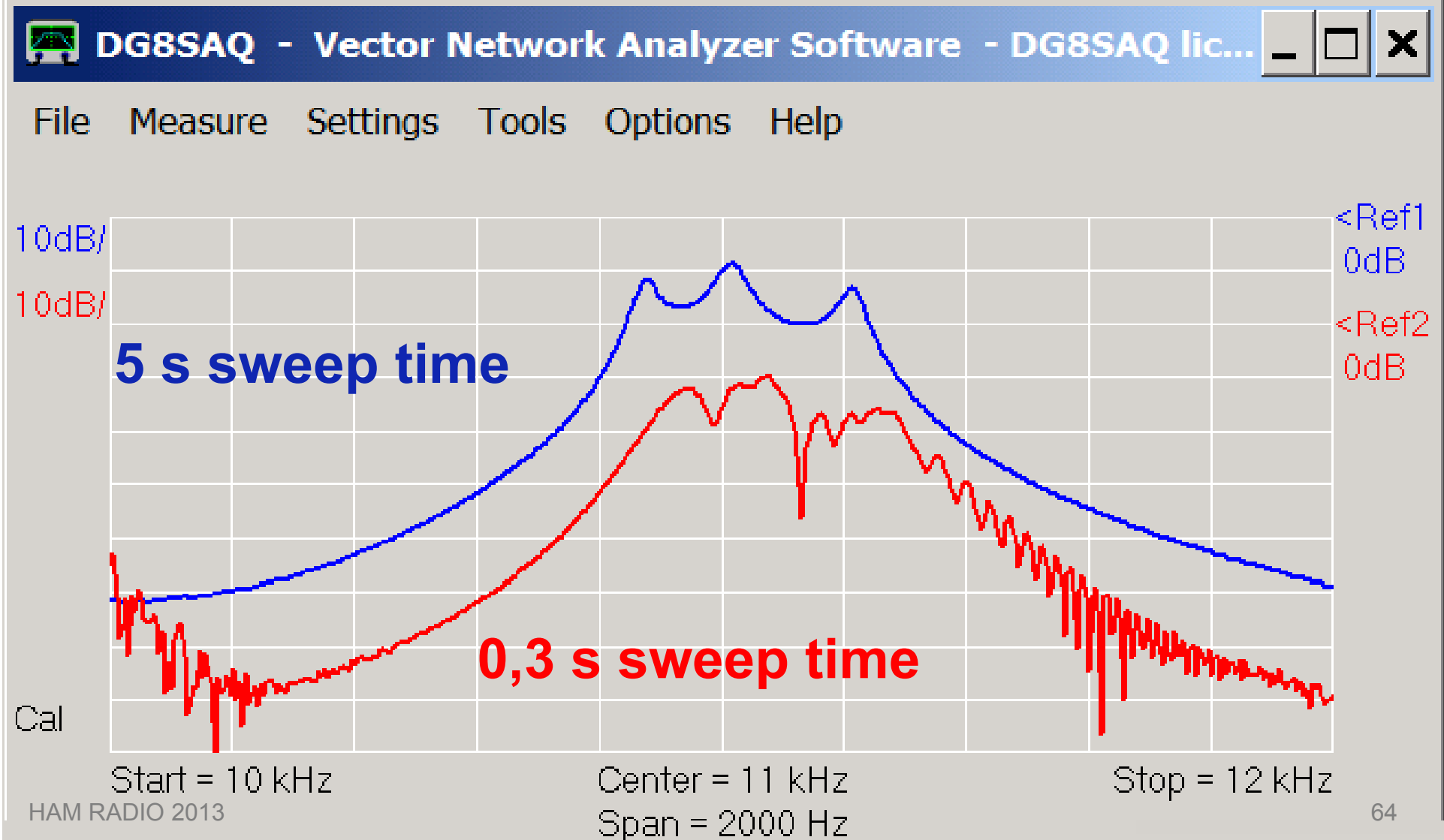


SOLT-Calibration for 2-Port Measurements

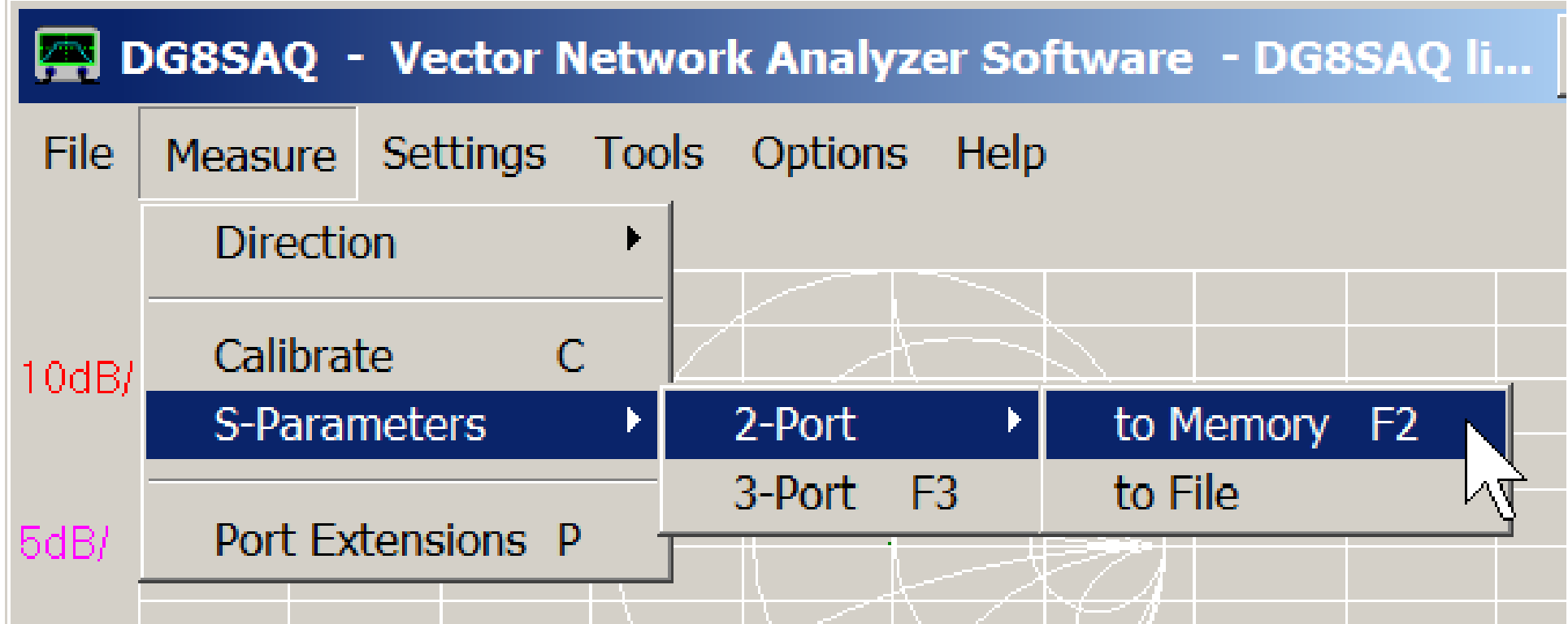


Reflect Calibration		Thru Calibration	
Short	Open	Load	Thru
Short		Crosstalk Cal	 <input type="checkbox"/> on / off
Open		Thru Cal	 <input checked="" type="checkbox"/> on / off
Load		Thru Match Cal	 <input checked="" type="checkbox"/> on / off
Cal <input checked="" type="checkbox"/> on / off		Invalidate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

TX

RX

1

2

S_{11} , S_{21} measured

Multiport S-Parameter Measurement

Terminal 1 => Terminal 2

OK

Abbrechen

Hochschule Ulm

66

66

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

Multipoint S-Parameter Me

Terminal 2 => Terminal 1

OK

2

1

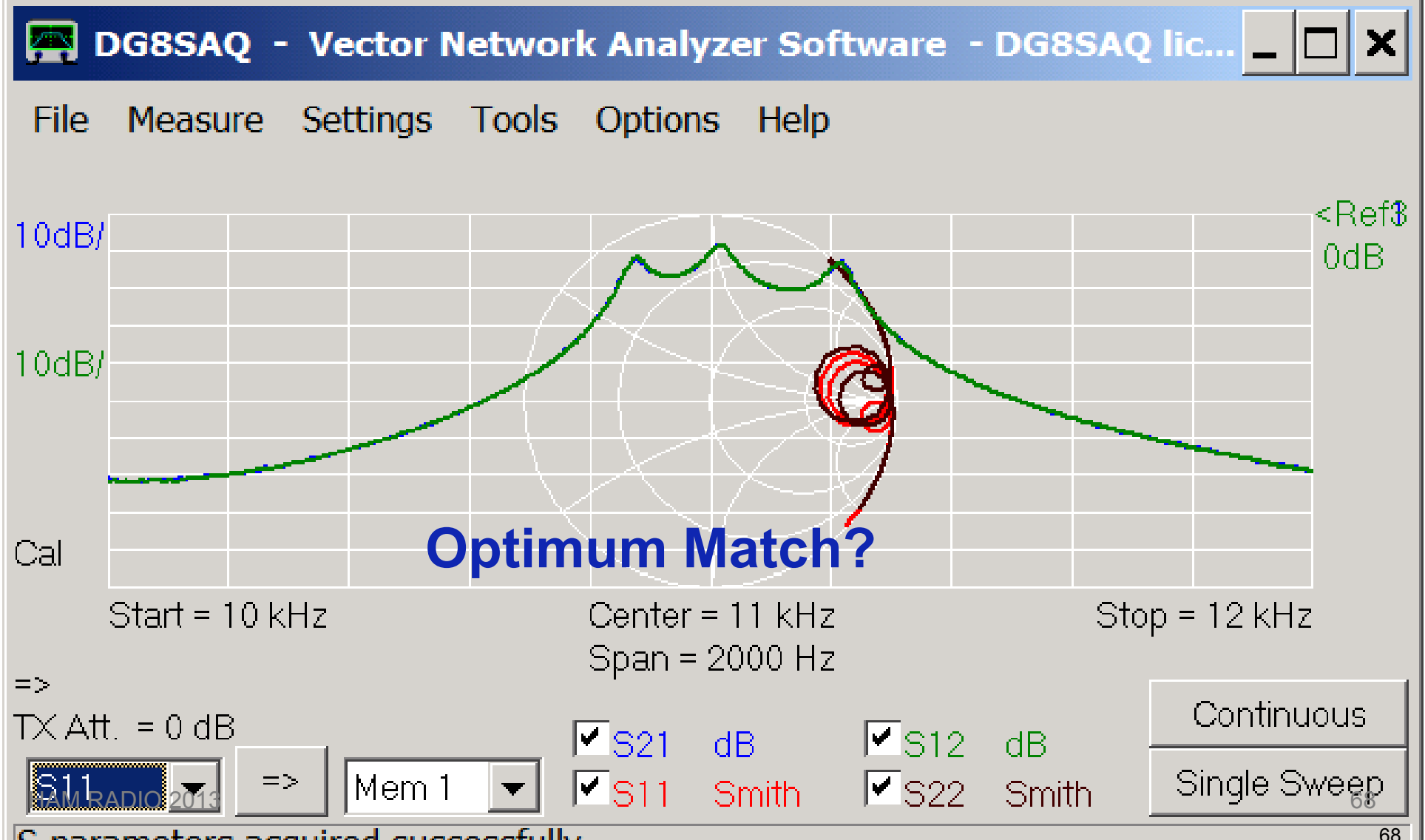
TX

RX

S_{12} , S_{22} measured

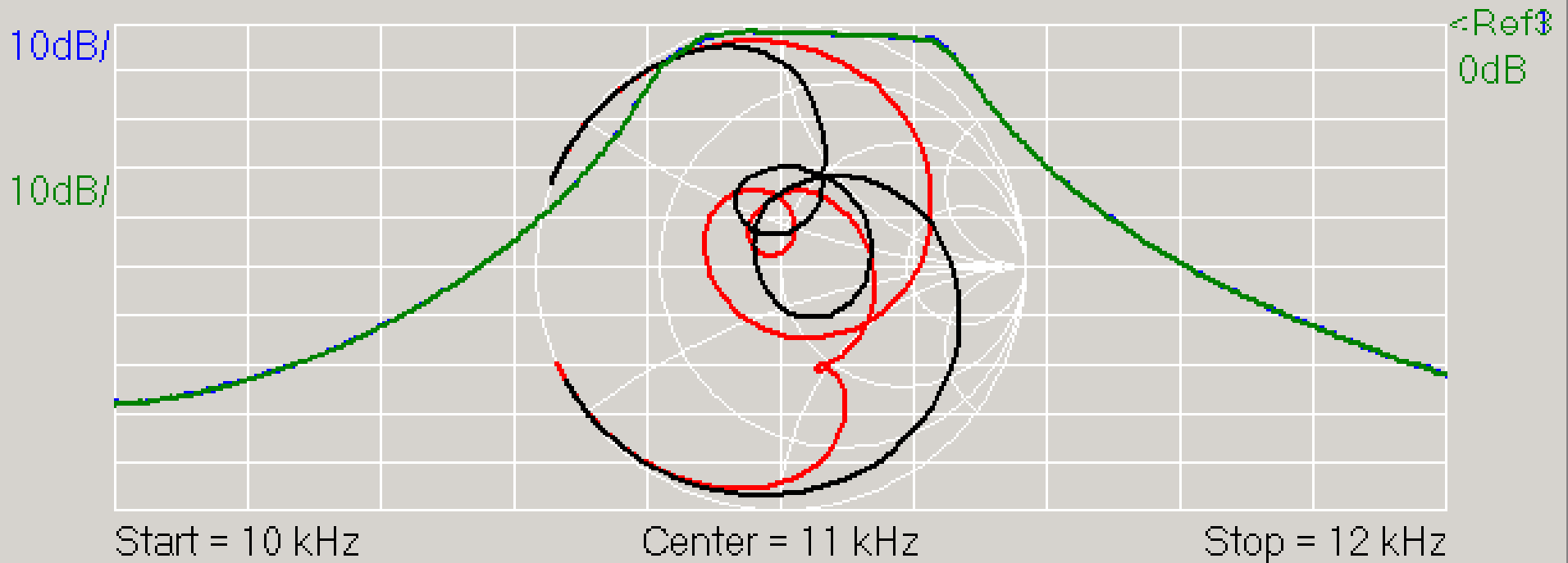


What are measured 2-Port S-Parameters good for?

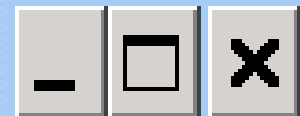


Matching Analysis: VNWA Matching Tool

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



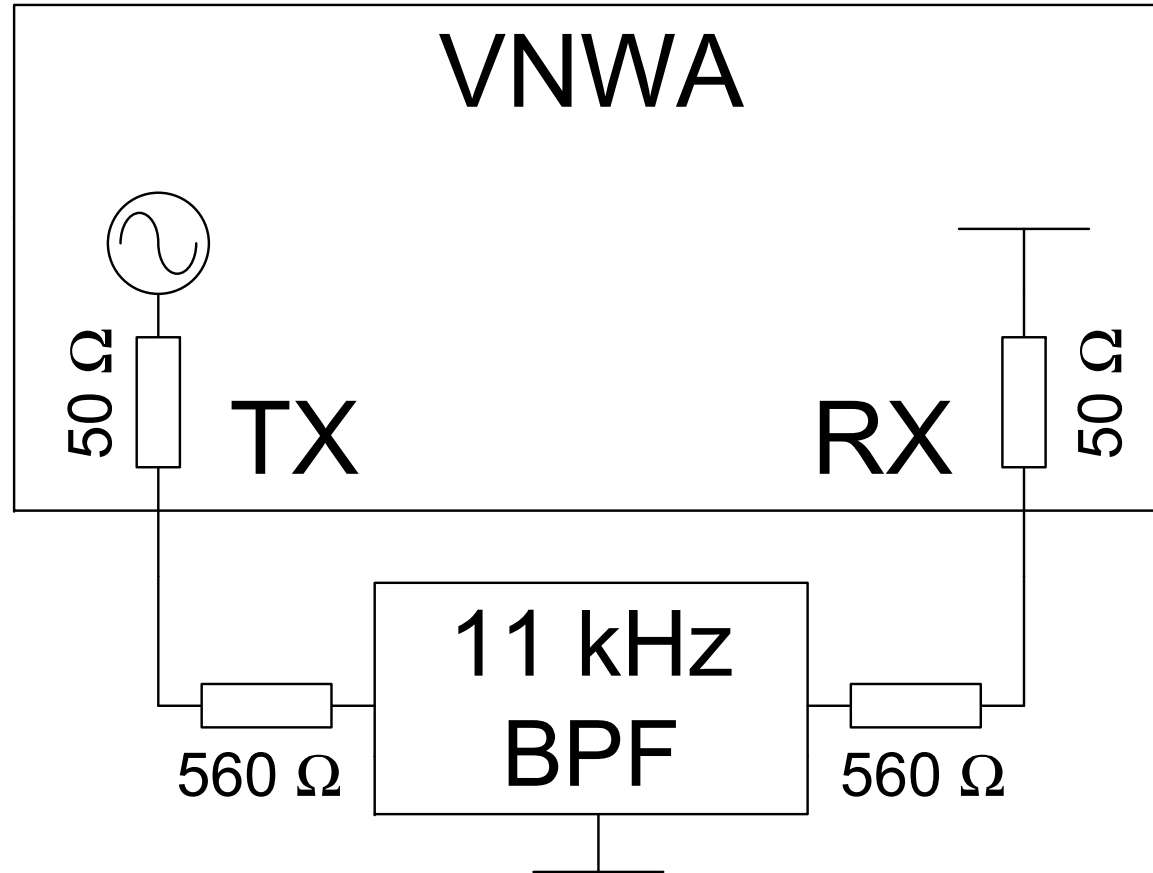
C parallel
(neg. possible)

0

pF



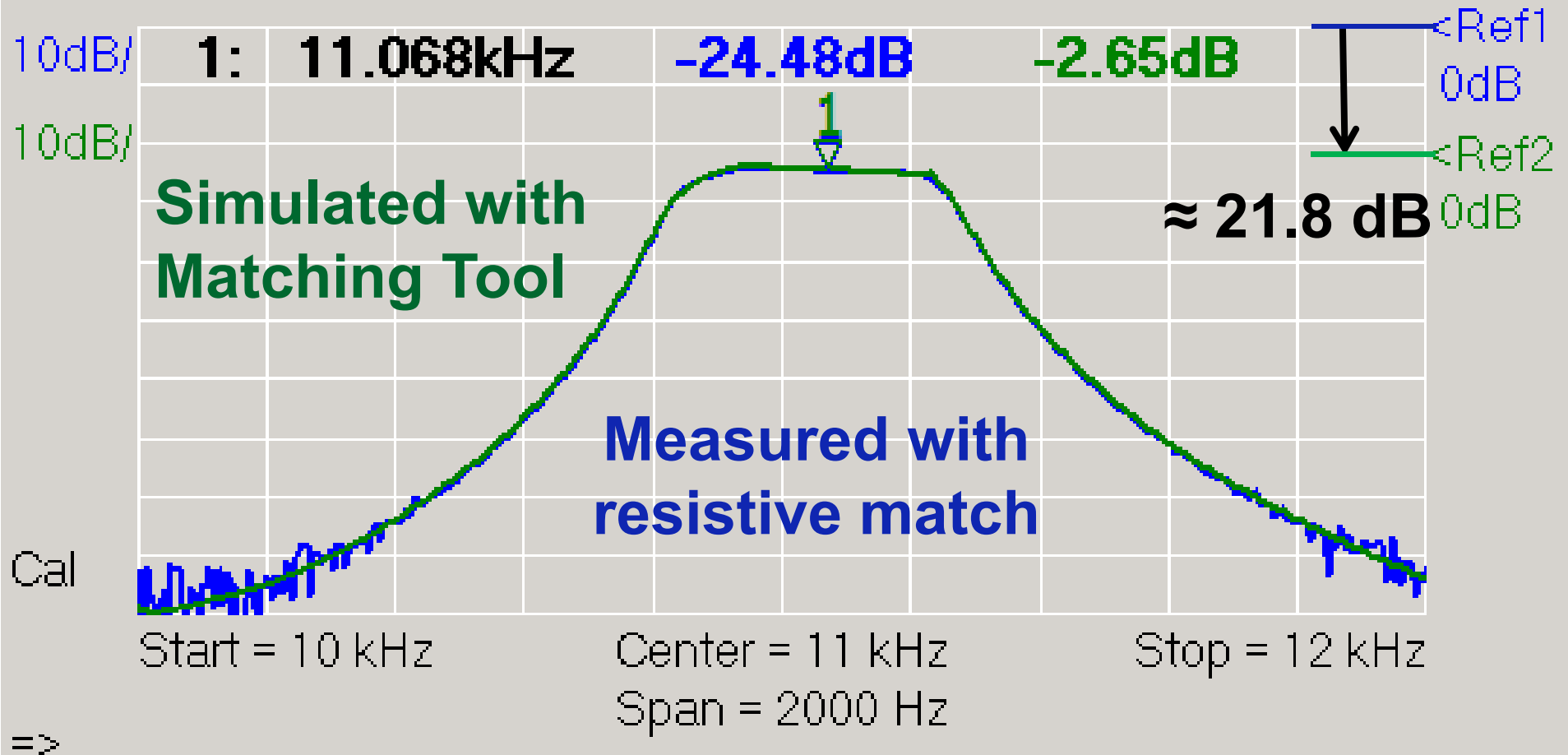
Forced Impedance Match using Resistors



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



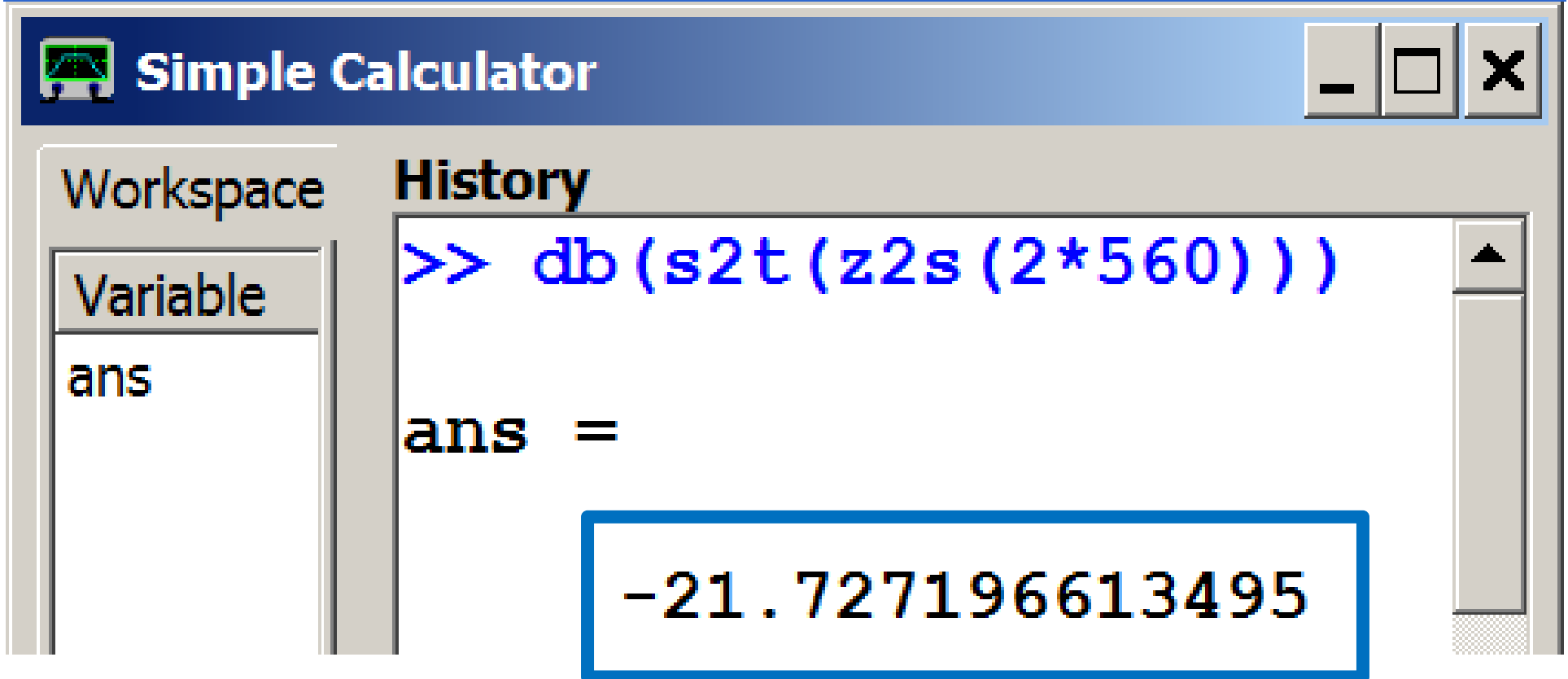
Match works except for increased Loss



S21 dB

Mem1 dB

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



The screenshot shows a software window titled "Simple Calculator". On the left, there is a "Workspace" panel with a "Variable" section containing the variable "ans". The main "History" panel shows the command `>> db (s2t (z2s (2*560)))` and the result `ans =` followed by a large blue-bordered box containing the value `-21.727196613495`.

21,7 dB additional attenuation ✓



This can also be „properly“ simulated!

Simulation Tool QUCS



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



Measured S-Parameters in QUCS

The screenshot shows the QUCS 0.0.16 software interface. The title bar reads "Qucs 0.0.16 - Project: 11kHzBPF". The menu bar includes "File Edit Positioning Insert Project Tools Simulation View Help". The toolbar contains various icons for file operations, simulation, and editing. The left sidebar shows a tree view with "simulations" selected, and "S-parameter simulation" is highlighted in blue. The main workspace displays a circuit diagram on a grid background. The circuit consists of a series connection of components: a port P1 (Num=1, Z=50 Ohm), a resistor R1 (R=560 Ohm), a component X1 (File=11kHz_BPF.s2p, Ref), a resistor R2 (R=560 Ohm), and a port P2 (Num=2, Z=50 Ohm). A blue box labeled "S parameter simulation" is positioned above the circuit, with a blue arrow pointing from it to the X1 component. The simulation parameters are listed as: SP1, Type=lin, Start=10 kHz, Stop=12 kHz, Points=400. The status bar at the bottom right shows "no warnings 0:0".

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
Z=50 Ohm

R1
R=560 Ohm

R2
R=560 Ohm

P2
Num=2
Z=50 Ohm

Matching Simulation in QUCS

Qucs 0.0.16 - Project: 11kHzBPF

File Edit Positioning Insert Project Tools Simulation View Help

11kHzBPF.sch 11kHzBPF.dpl

Simulate (F2)

diagrams

Projects
Cartesia Polar Tabular

Content
n
Smith Admittan
Chart ce Smith

Components
Polar-S Smith-P
mith olar
Combi Combi
3D-Carte Locus
sian Curve
Timing Truth
Diagram Table

Gain

0.1

0.01

1e-03

1e-04

1e-05

1e04 1.02e04 1.04e04 1.06e04 1.08e04 1.1e04 1.12e04 1.14e04 1.16e04 1.18e04 1.2e04

**Standard diagramm
output a bit strange**

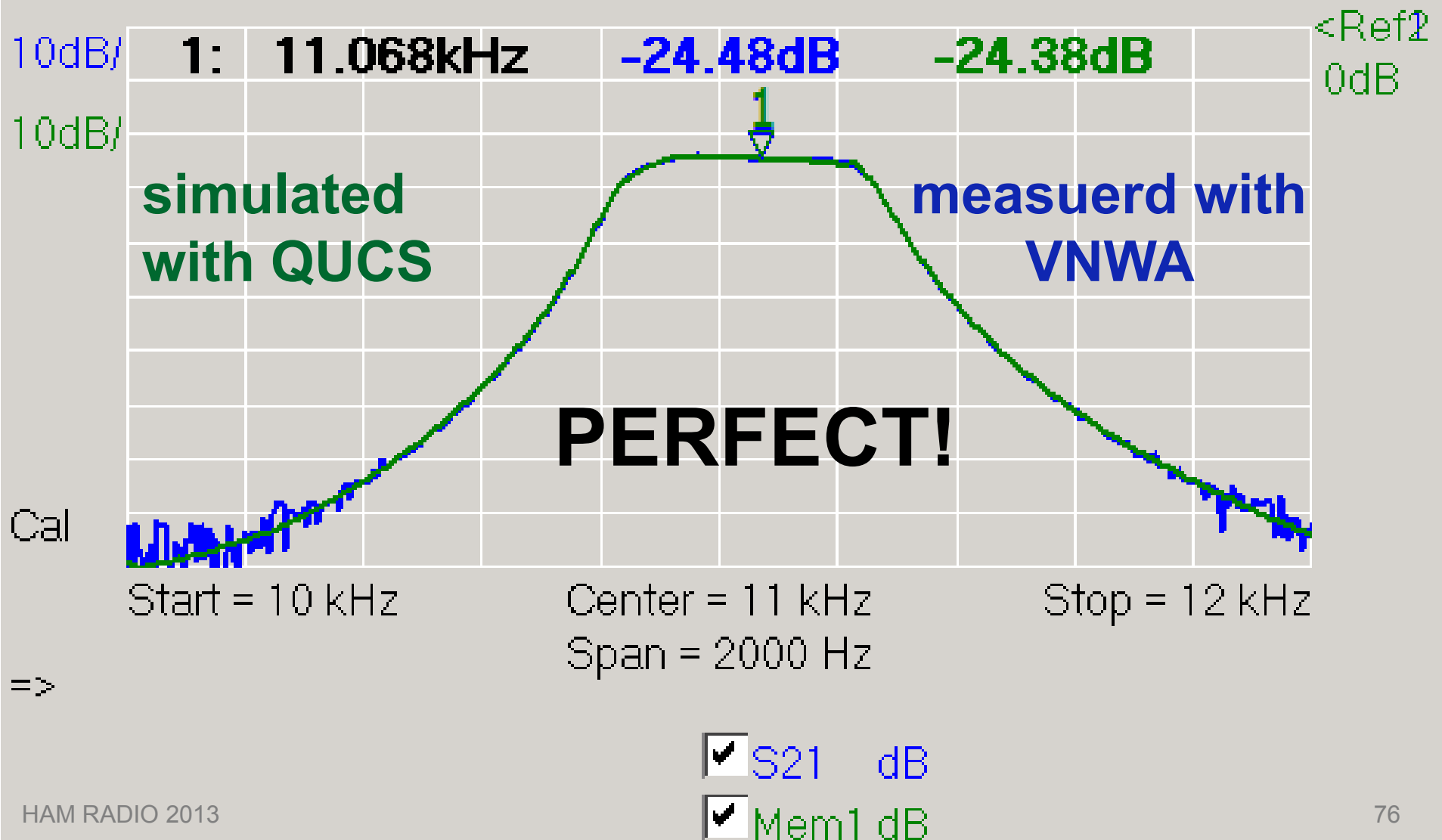
→ **Export simulation result
to VNWA**

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no warnings 0 : 0

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Comparison QUCS-Simulation vs. Measurement



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

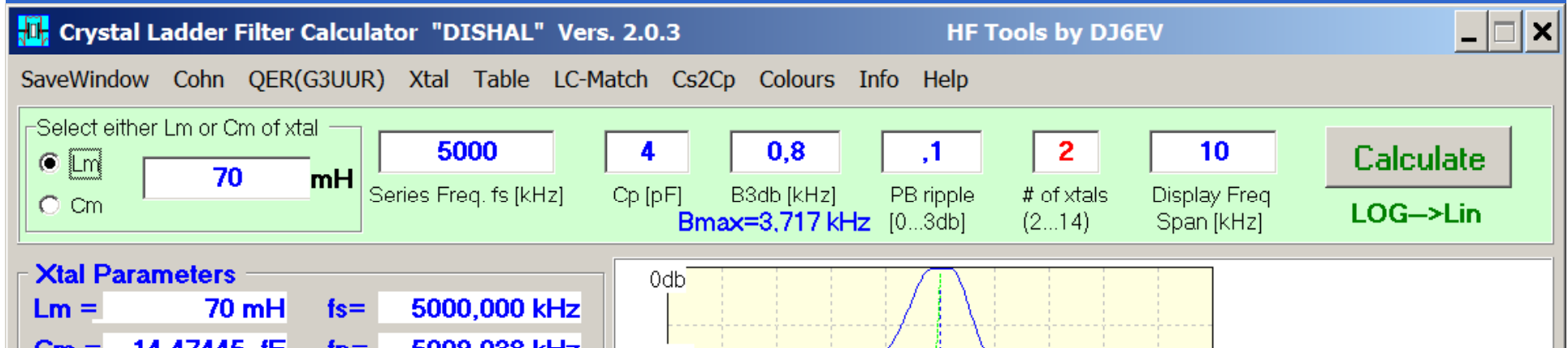
 Elsie Student Edition - Welcome !

This is the Student Edition of
Elsie

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



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



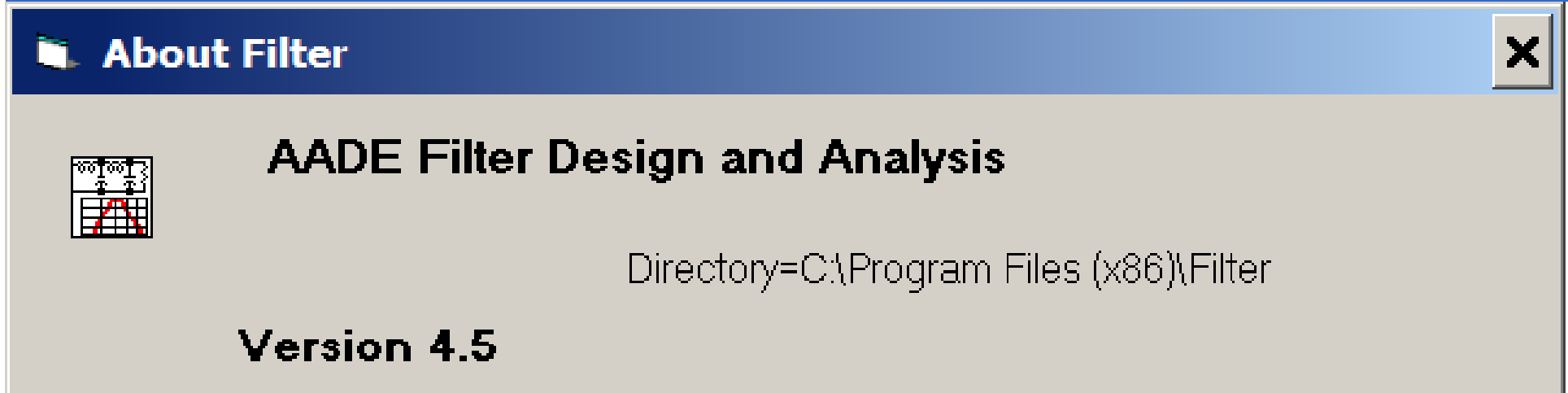
- <http://www.bartelsos.de/dk7jb.php/quarzfilter-horst-dj6ev>
- **Crystal filter designer and analyzer**
- **Simulates without crystal losses**
- **S_{21} -simulation results can be exported**

Hochschule Ulm



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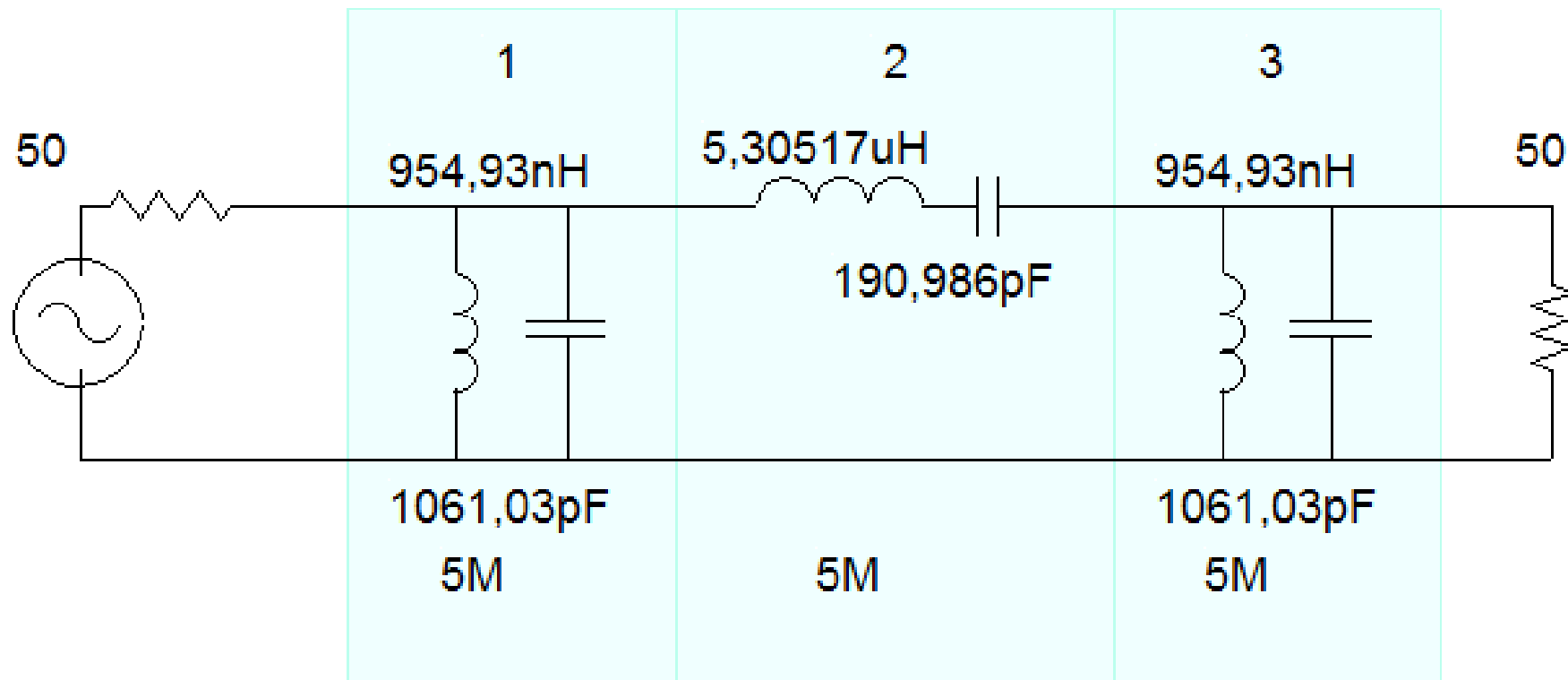
Free Filter Design Software (3): AADE Filter Design - for all filters



- <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**



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



Filter Design with Elsie

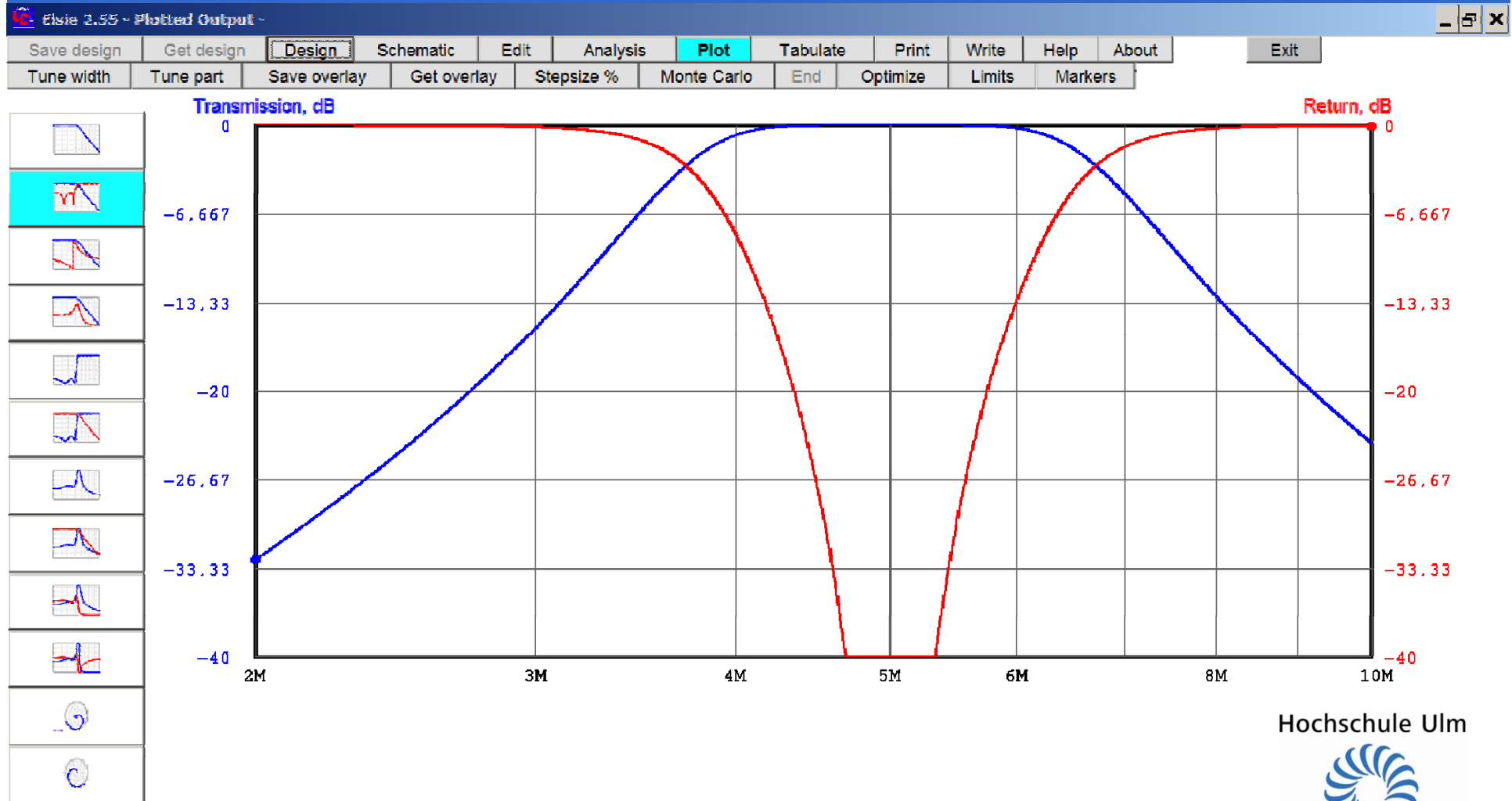
Hochschule Ulm



80

80

Elsie Simulation Result



Hochschule Ulm



Modify Components to standard Values and finite Q ...

Schematic

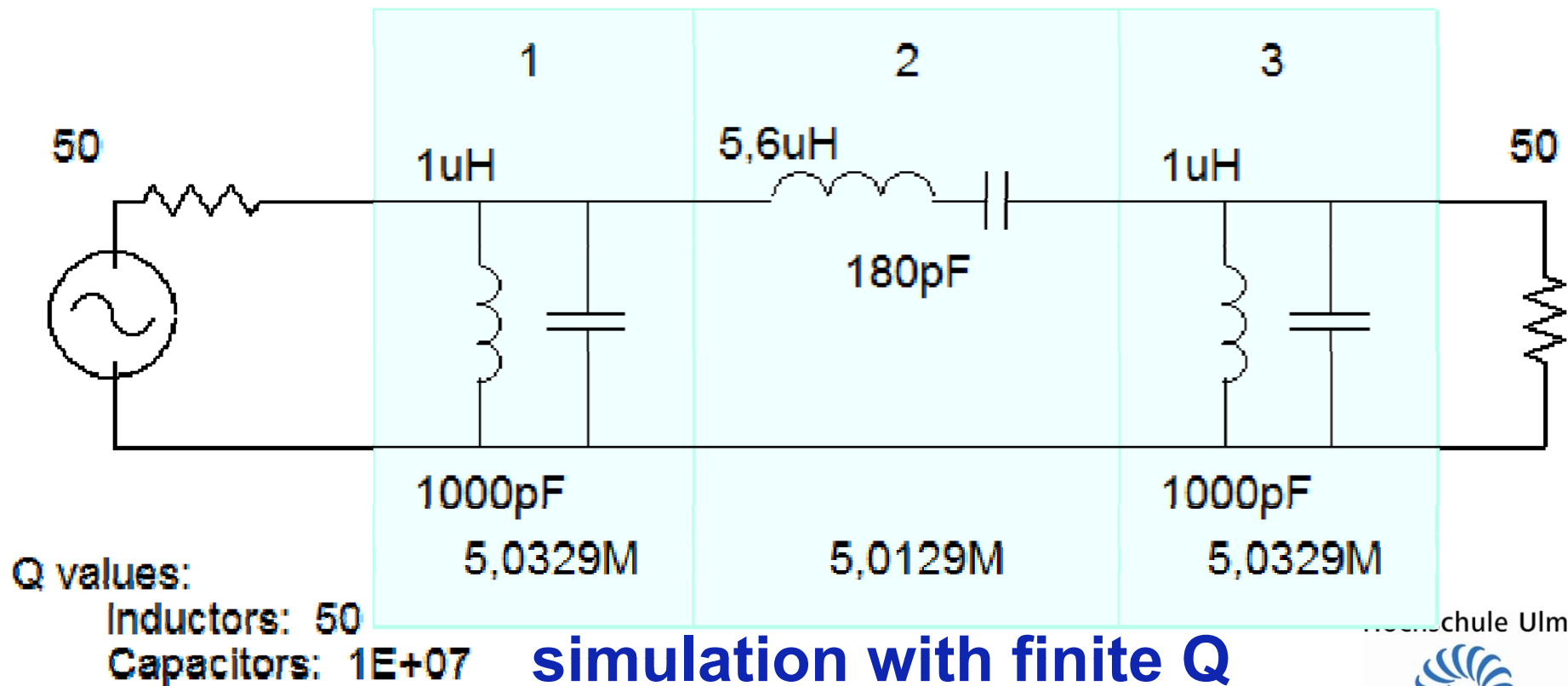
Edit

Analysis

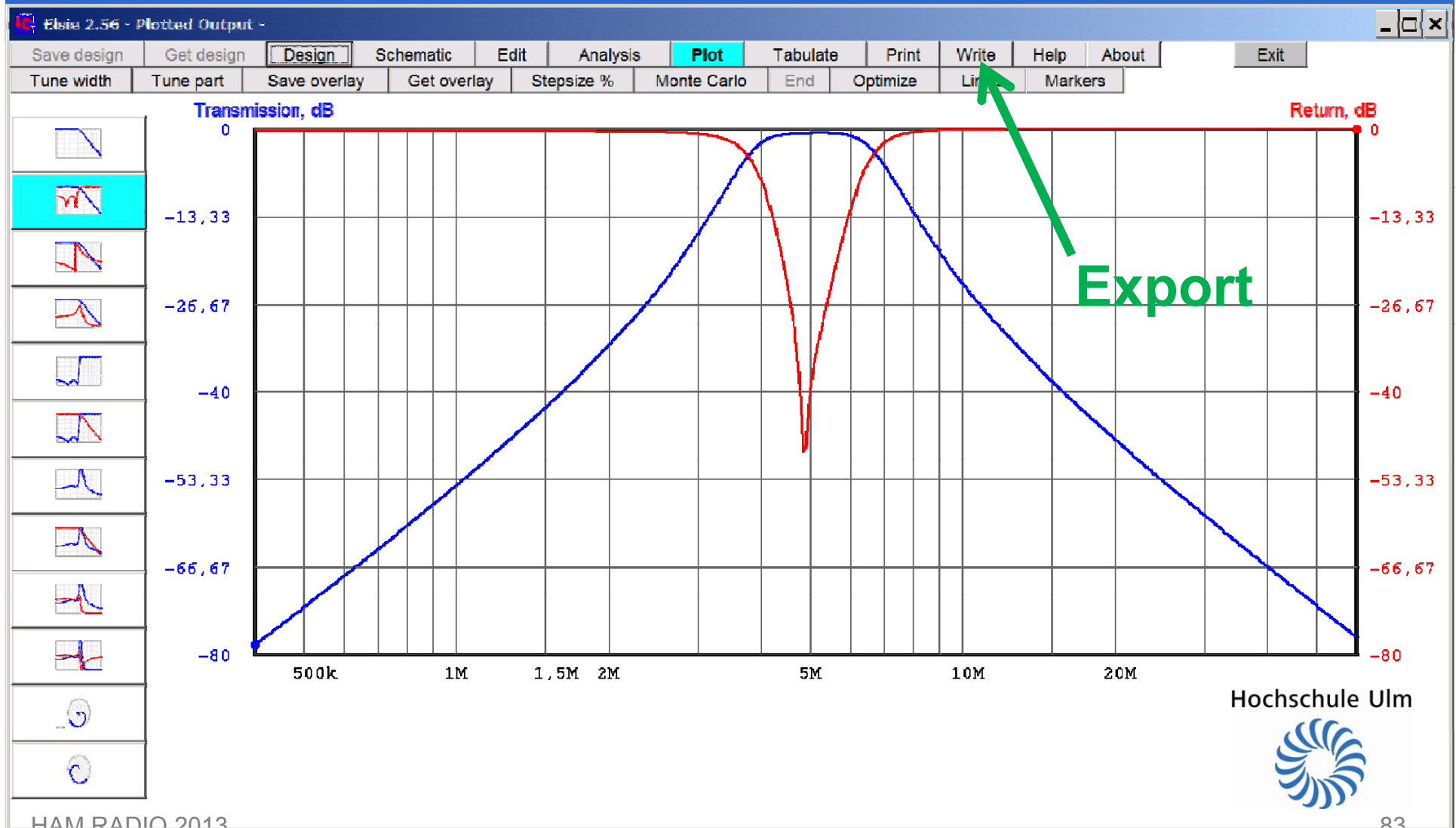
Plot

Tabulate

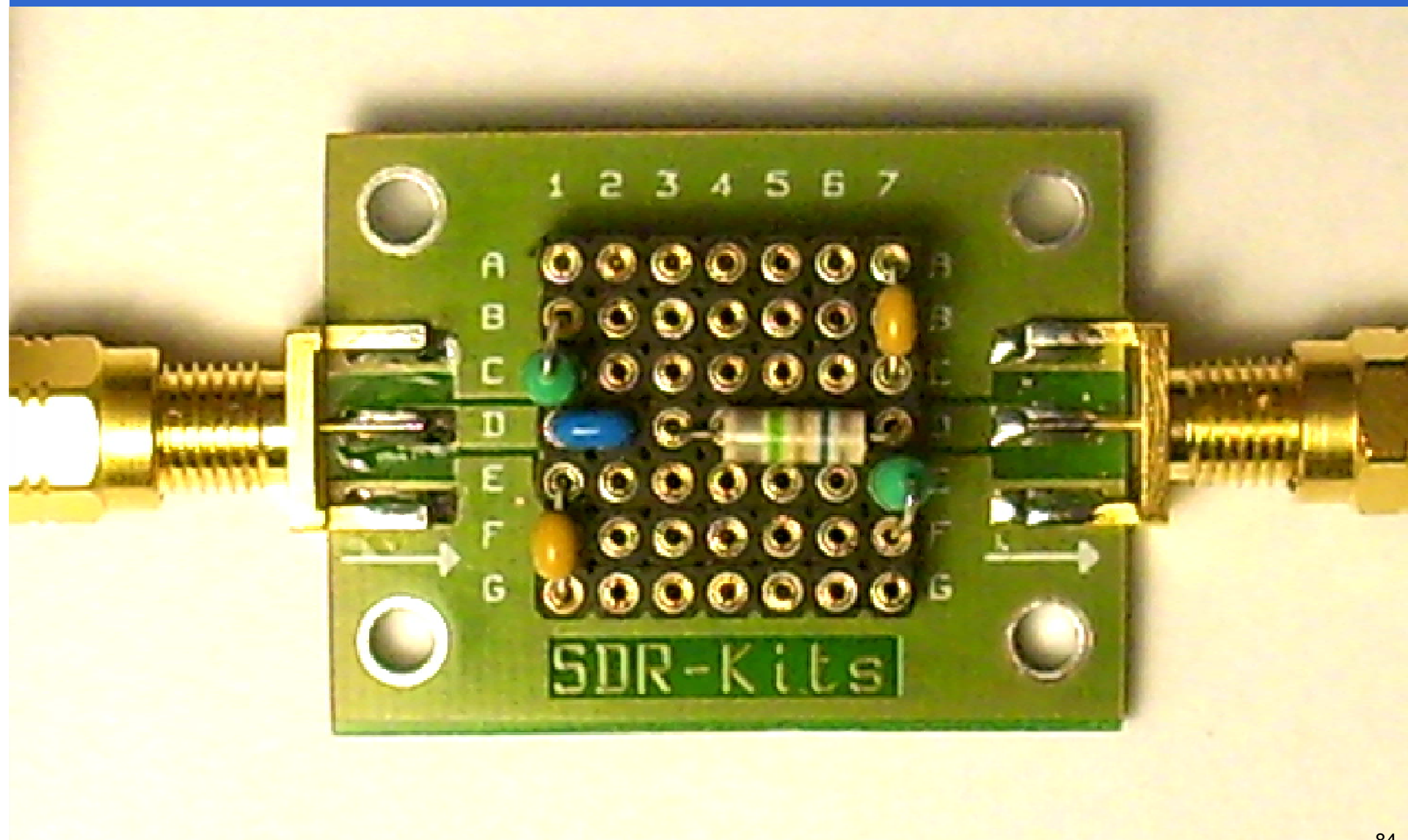
Print



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

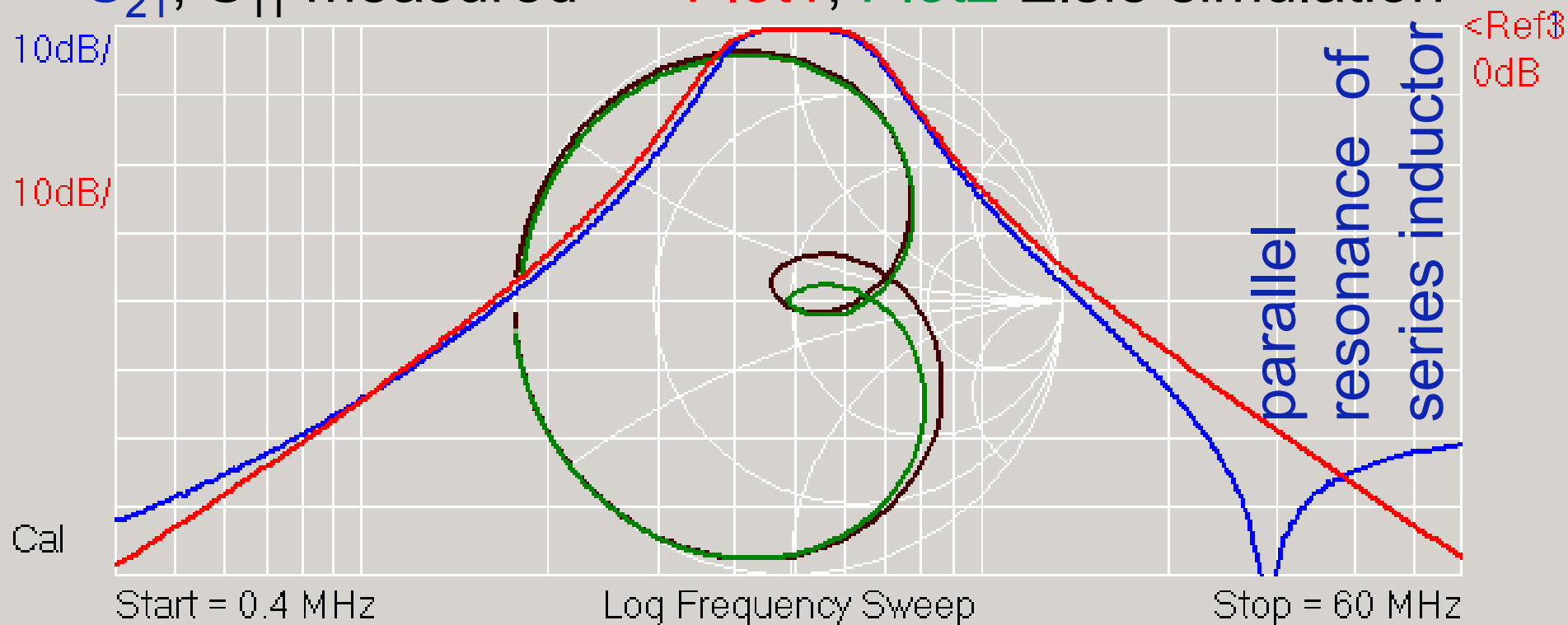


Filter Hardware



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

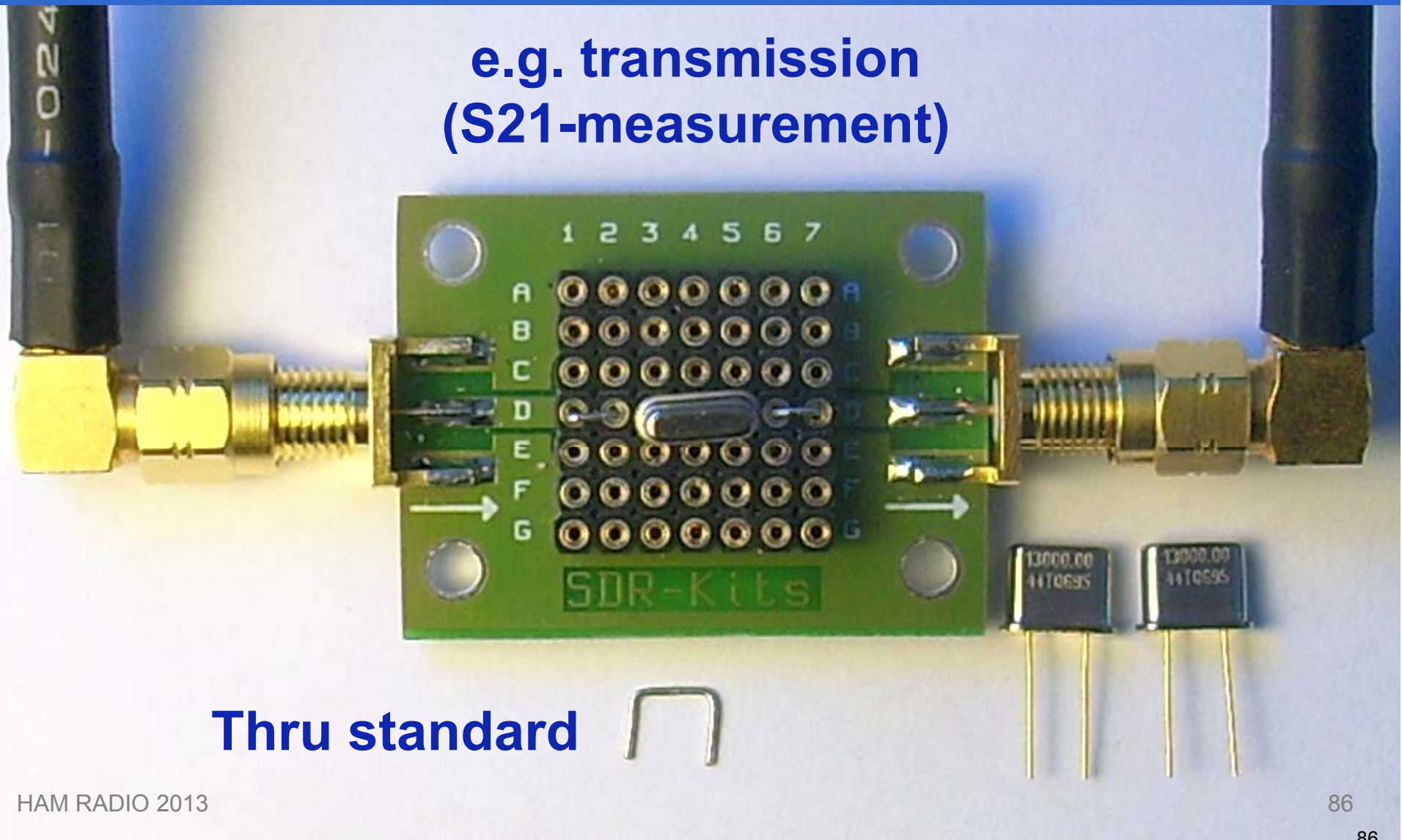
Single Sweep

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Measuring / Selecting Crystals: VNWA Crystal Analyzer

e.g. transmission
(S21-measurement)

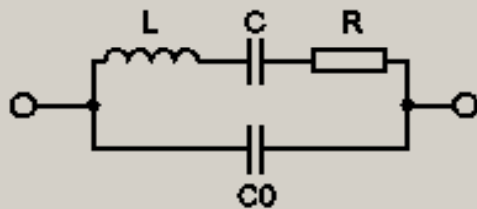


Thru standard

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

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

Equivalent Circuit



L = 23.22917 mH

C = 6.456461 fF

R = Ohm

C0 = pF

$f = 1/2\pi\sqrt{L \cdot C}$ = MHz

$R \cdot Q = \sqrt{L/C}$ = x1000

Q = 69517

source = S21

Test Jig Impedances = 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

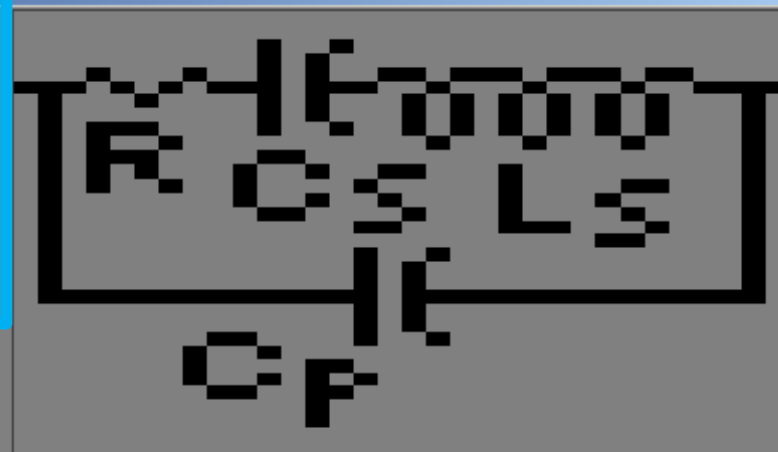
With these we want to build a Crystal Filter → Enter Crystal Parameters into AADE

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	.	√	x ²	μ	
tab	bksp	CLR	n		
ENTER	Cancel	p			

Cp = 2,46804p
 Ls = 23,499m
 Cs = ,00638p
 Qx = 48,842K



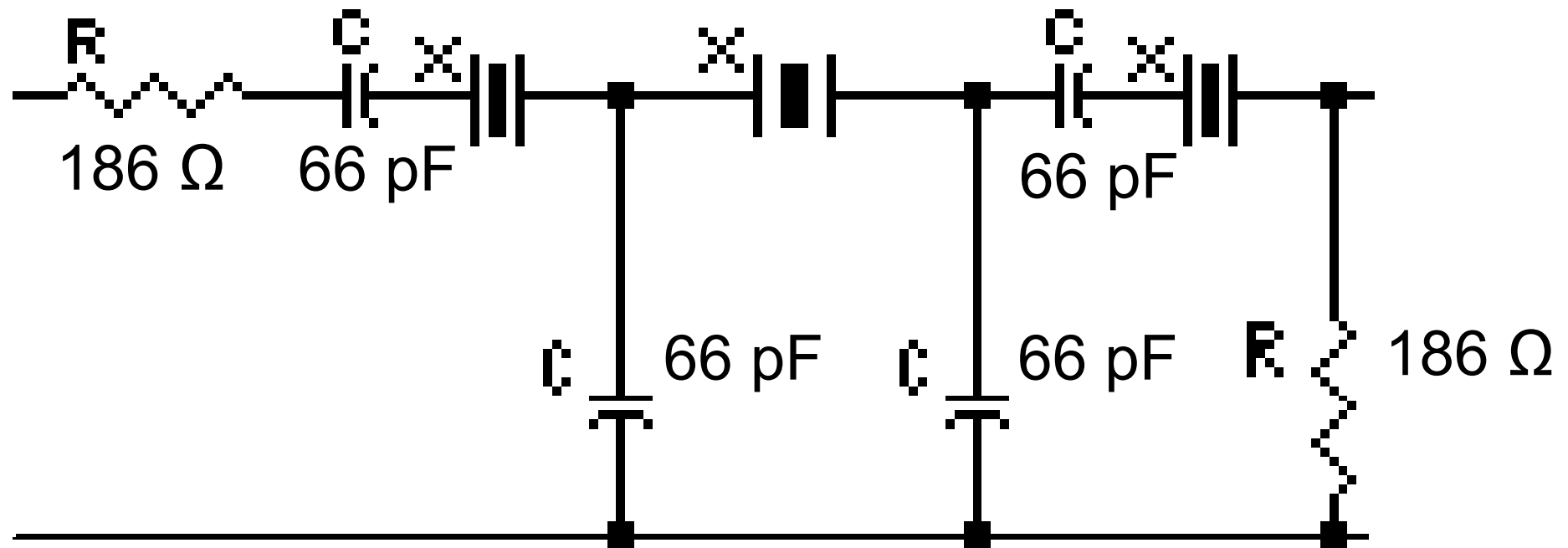
Daten vom
 VNWA
 Crystal
 Analyzer
 übertragen

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

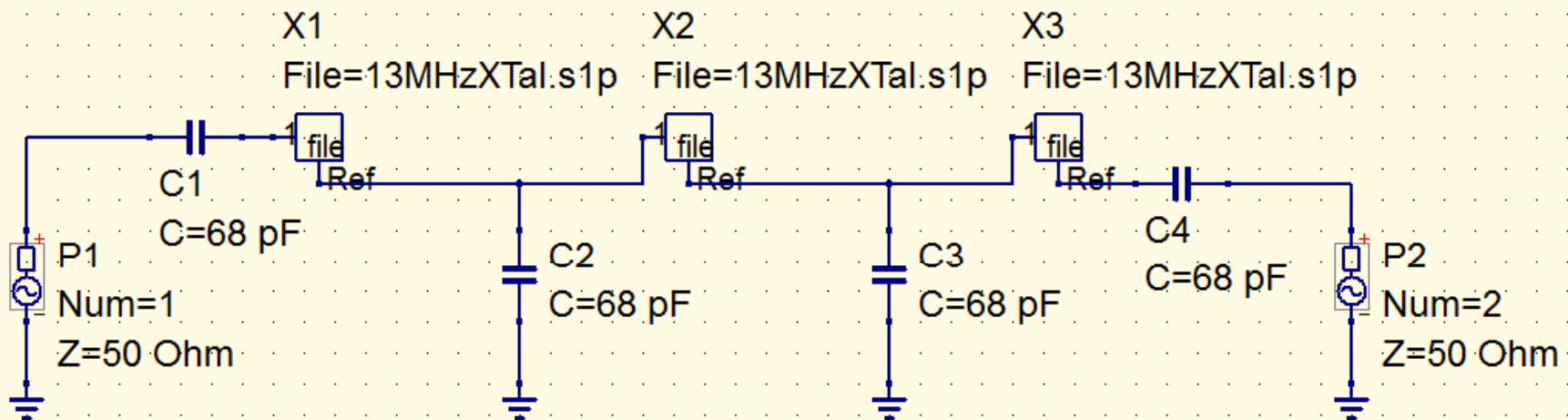


Simulation in QUCS at 50 Ω using standard Component Values

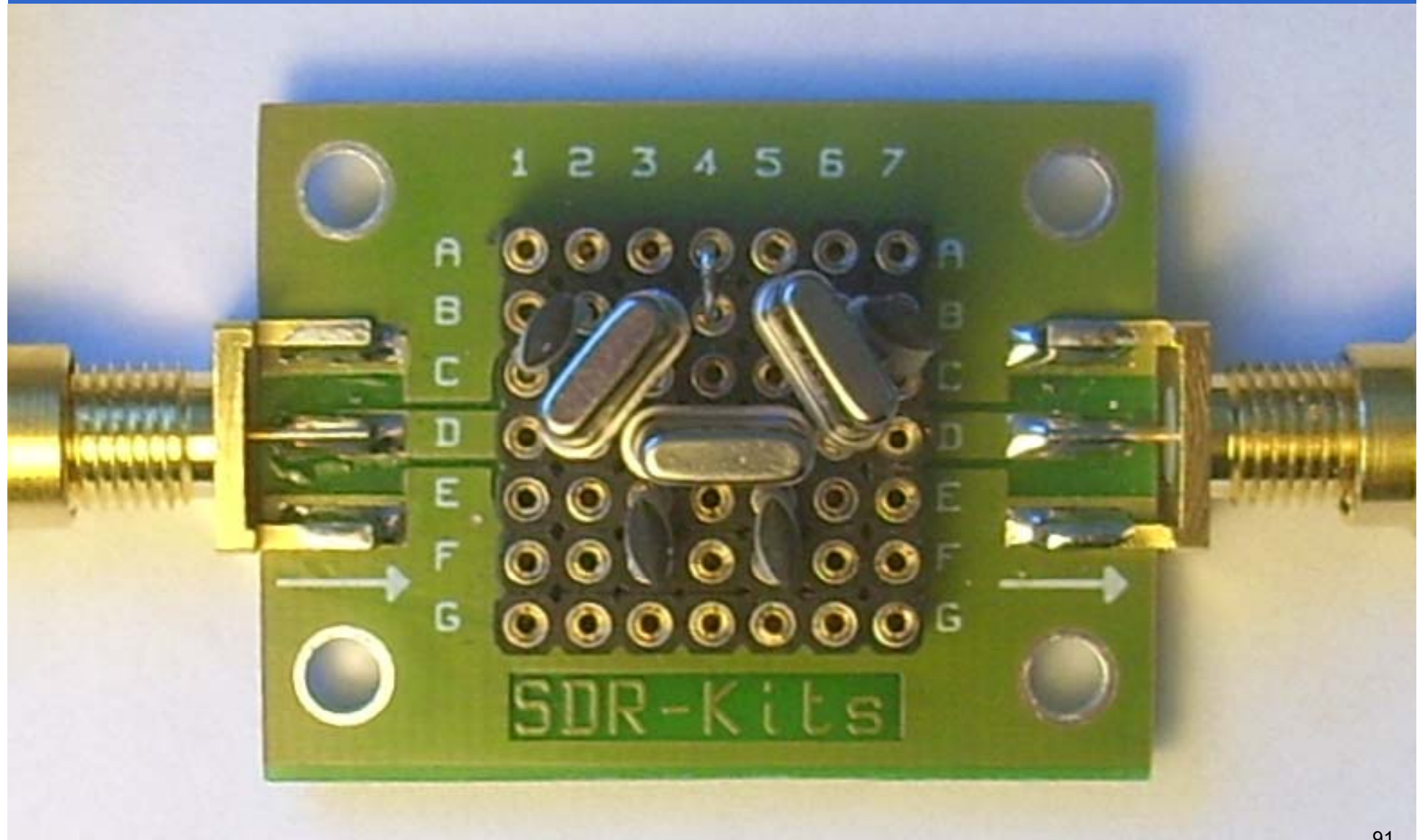
S parameter simulation

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

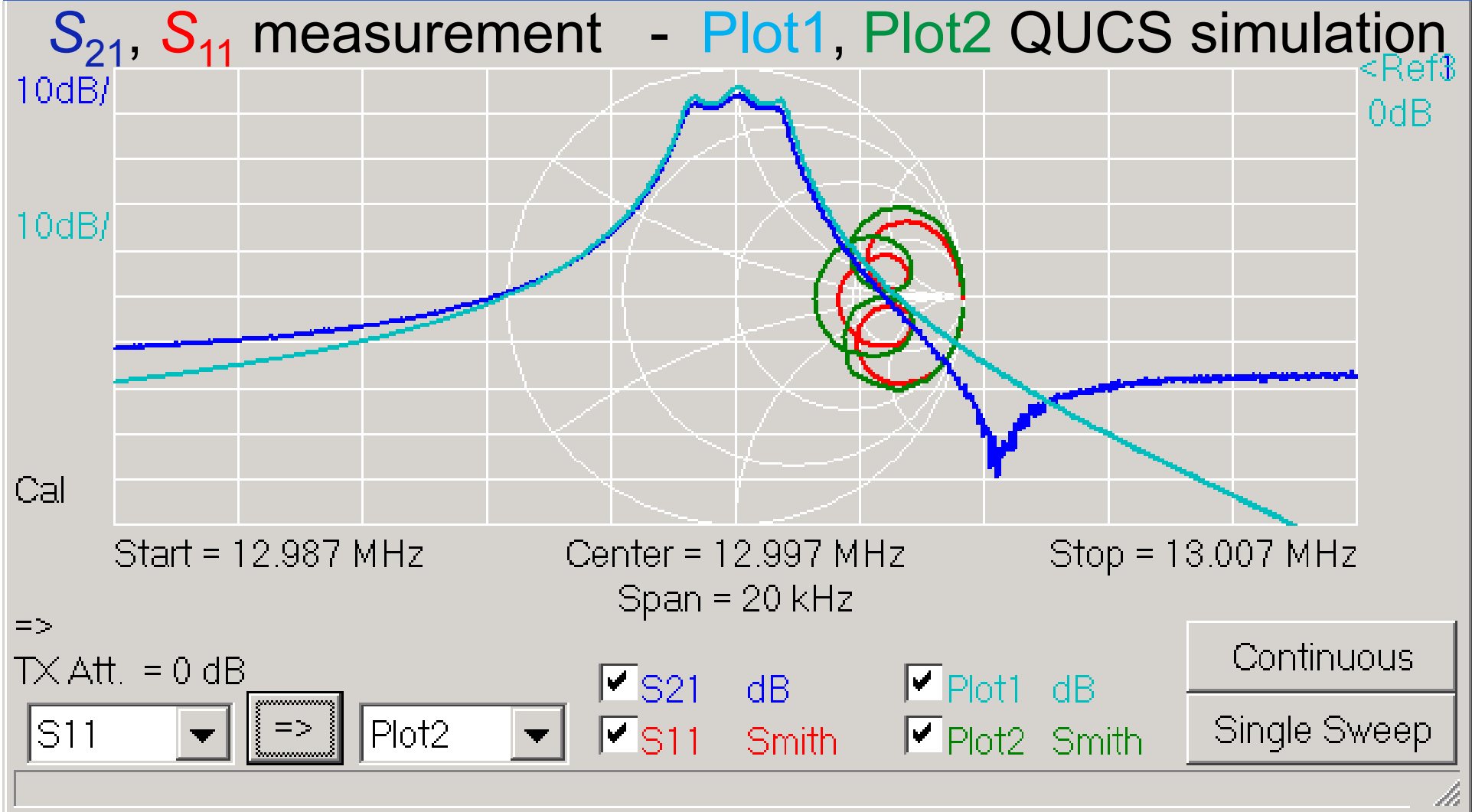
Crystals simulated with s1p-file obtained by VNWA measurement!



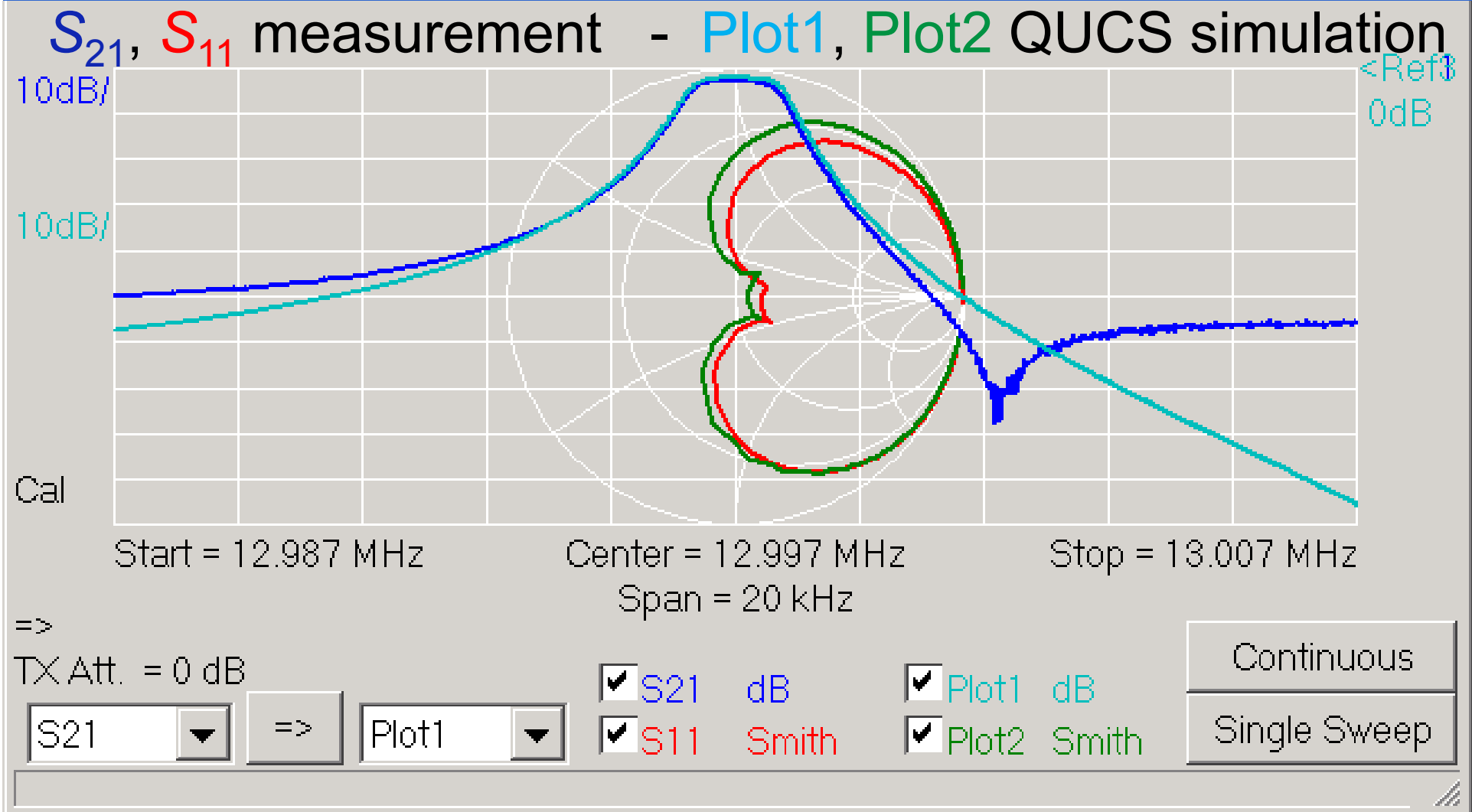
Crystal Filter Hardware



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!

Do I get this right? You tell your wife:
"Sorry dear, not tonight. I have a head-
ache" and then you can sit all night and
work with your Vector Network Analyzer!?!

Dipl. Psychologe
dra. Quin

OMICRON
LAB

Reviews