HAM RADIO 2013

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FRIEDRICHSHAFEN

Measurement and Application of Scattering Parameters in RF-Design

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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*

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

Hochschule Ulm

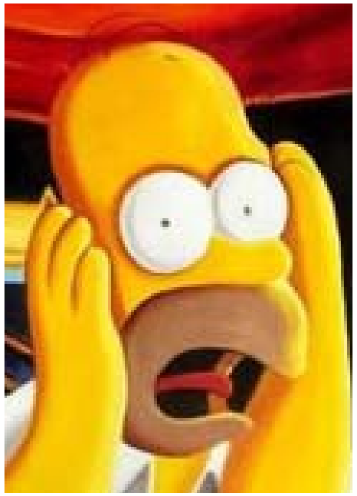
Who is afraid of S-parameters!

$$U = R \cdot I$$ Ohm

$$b = S \cdot a$$ S-Par.

Response | System | Excitation

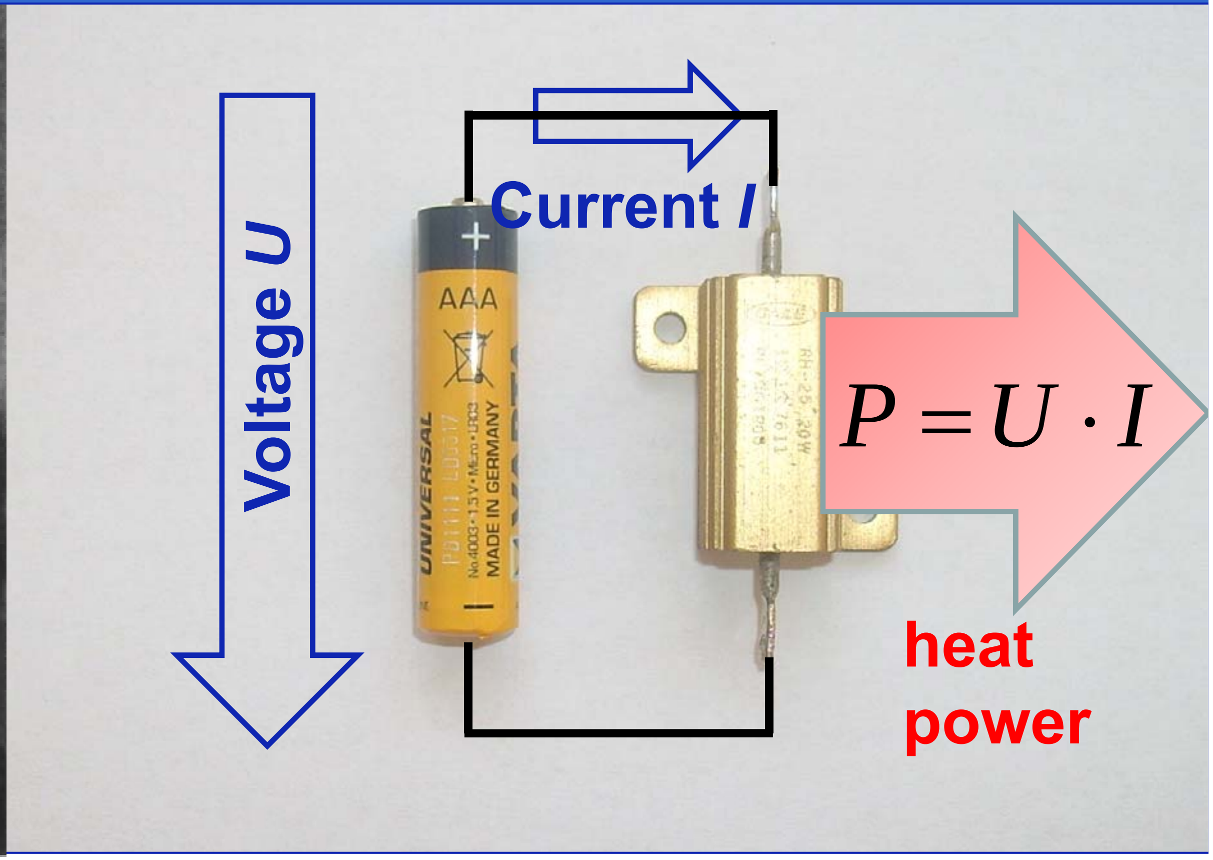
equivalent description



Hochschule Ulm

A different angle to dc
Ohms‘ Law (1)

Georg Simon Ohm
(1789-1854)



$$U = R \cdot I$$

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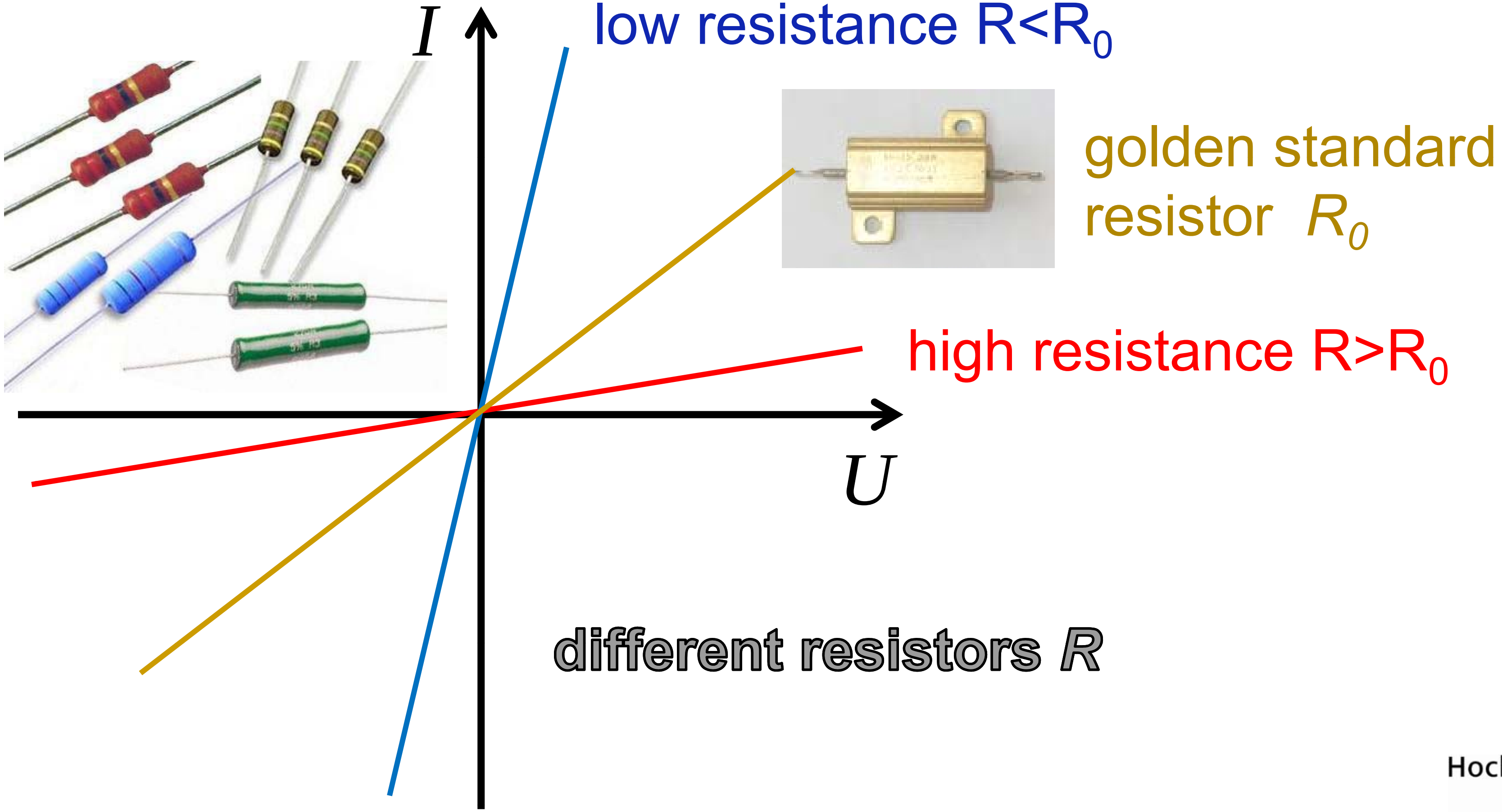
Ohms‘ Law (2)

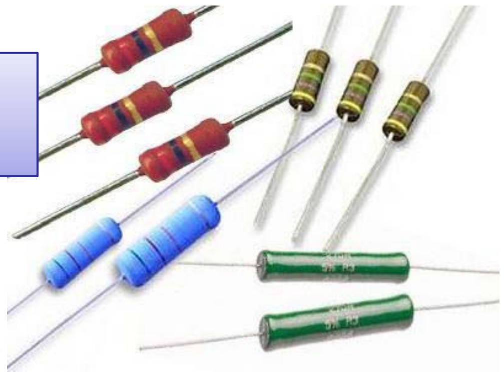


Hochschule Ulm

Normalizing Resistor *R to* Reference Resistor R_0

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

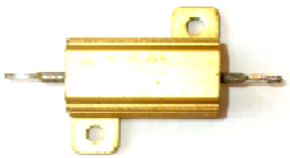
Resistor *R*



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

normalized *r*

Resistor R_0



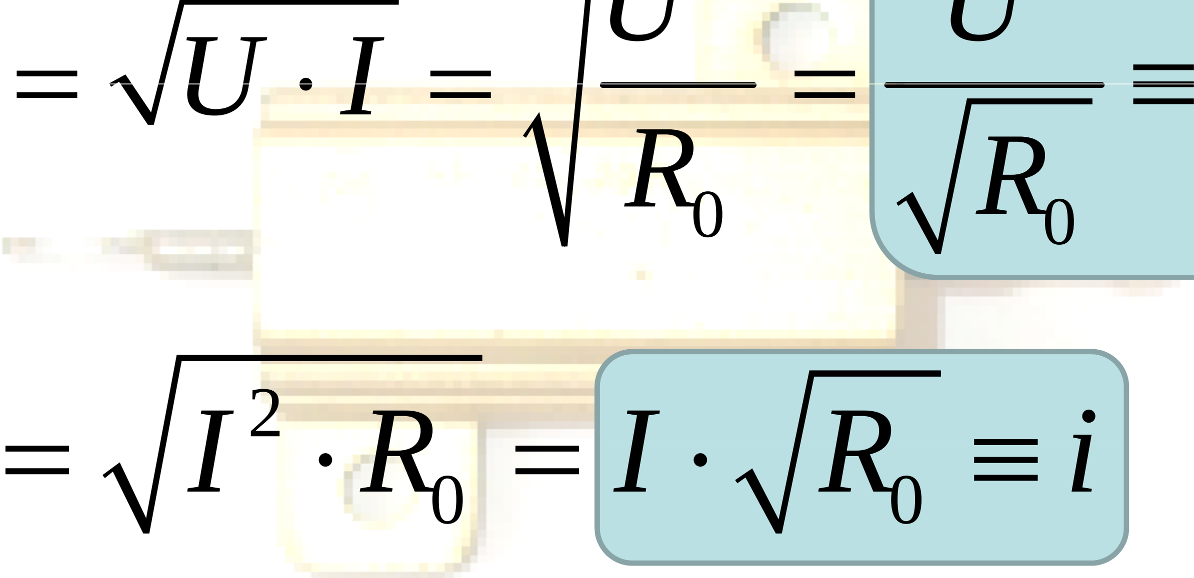
$$r_0 = \frac{R_0}{R_0} = 1$$

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:



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

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

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Resistor R_0 in circuit

New Units for Voltage and Current:
$I \rightarrow i$ $\qquad$ $U \rightarrow u$

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 $\sqrt{Watt}$

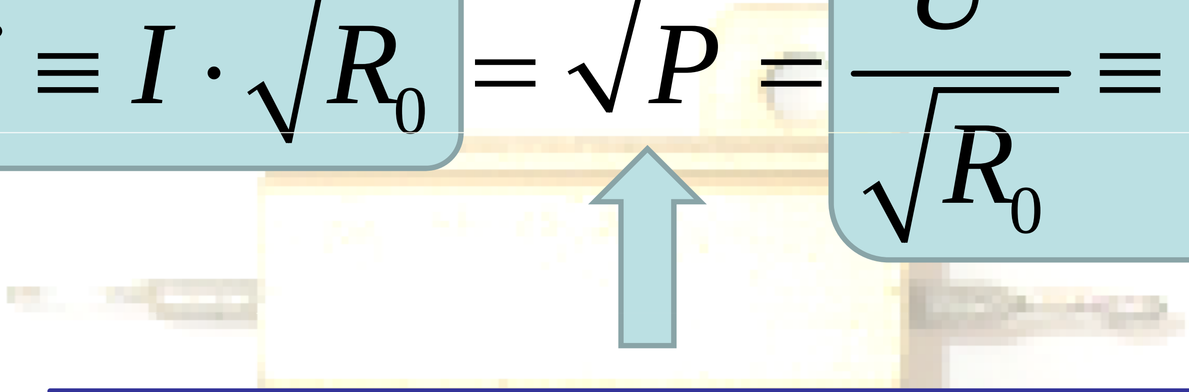
Resistor R_0 in circuit

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

Hochschule Ulm

Now arbitrary Resistor *R* instead of R_0

Ohm's Law still applies:

$$u = r \cdot i$$

because:

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

Normalized resistance! ↓

Now arbitrary resistor *R!!!*

Hochschule Ulm

Dissipated Power in arbitrary Resistor

$$P = u \cdot i$$

still applies

because:

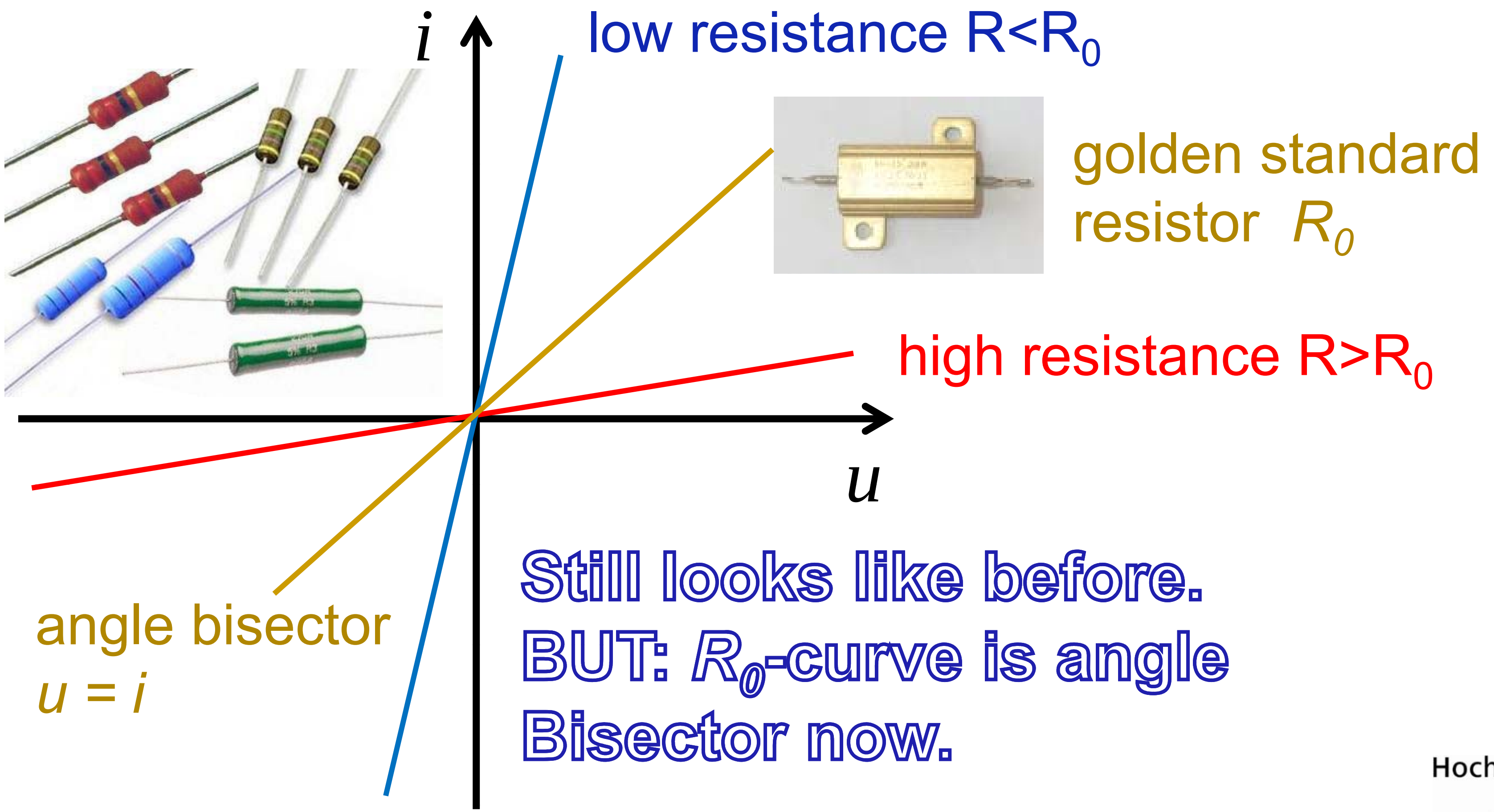
$$u \cdot i = \frac{U}{\sqrt{R_0}} \cdot I \cdot \sqrt{R_0} = U \cdot I = P$$

reduce!

Now arbitrary resistor *R!!!*

Hochschule Ulm

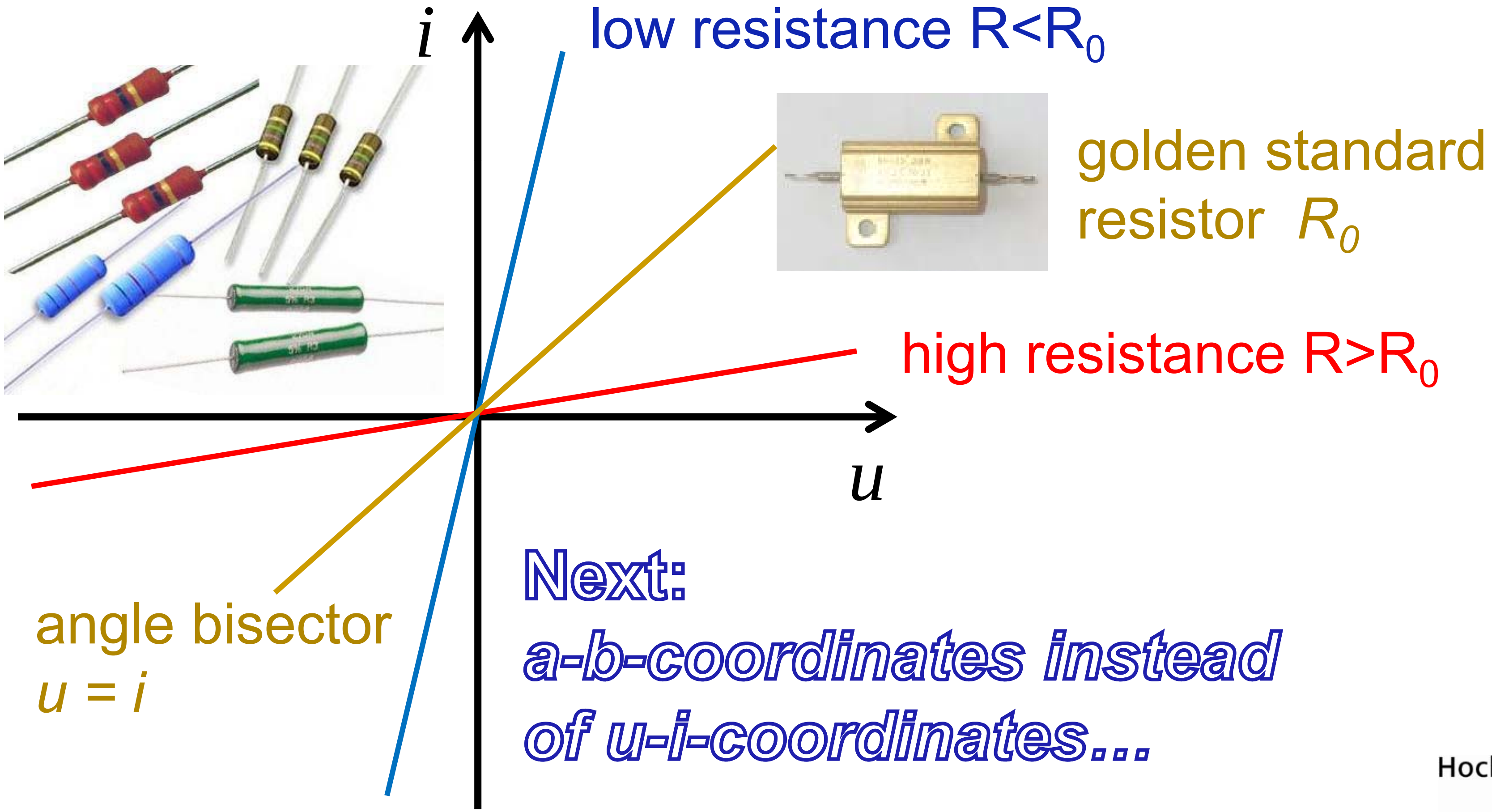
Ohm‘s Law with new Voltage and Current Units



Still looks like before.
BUT: R_0-curve is angle Bisector now.

Hochschule Ulm

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

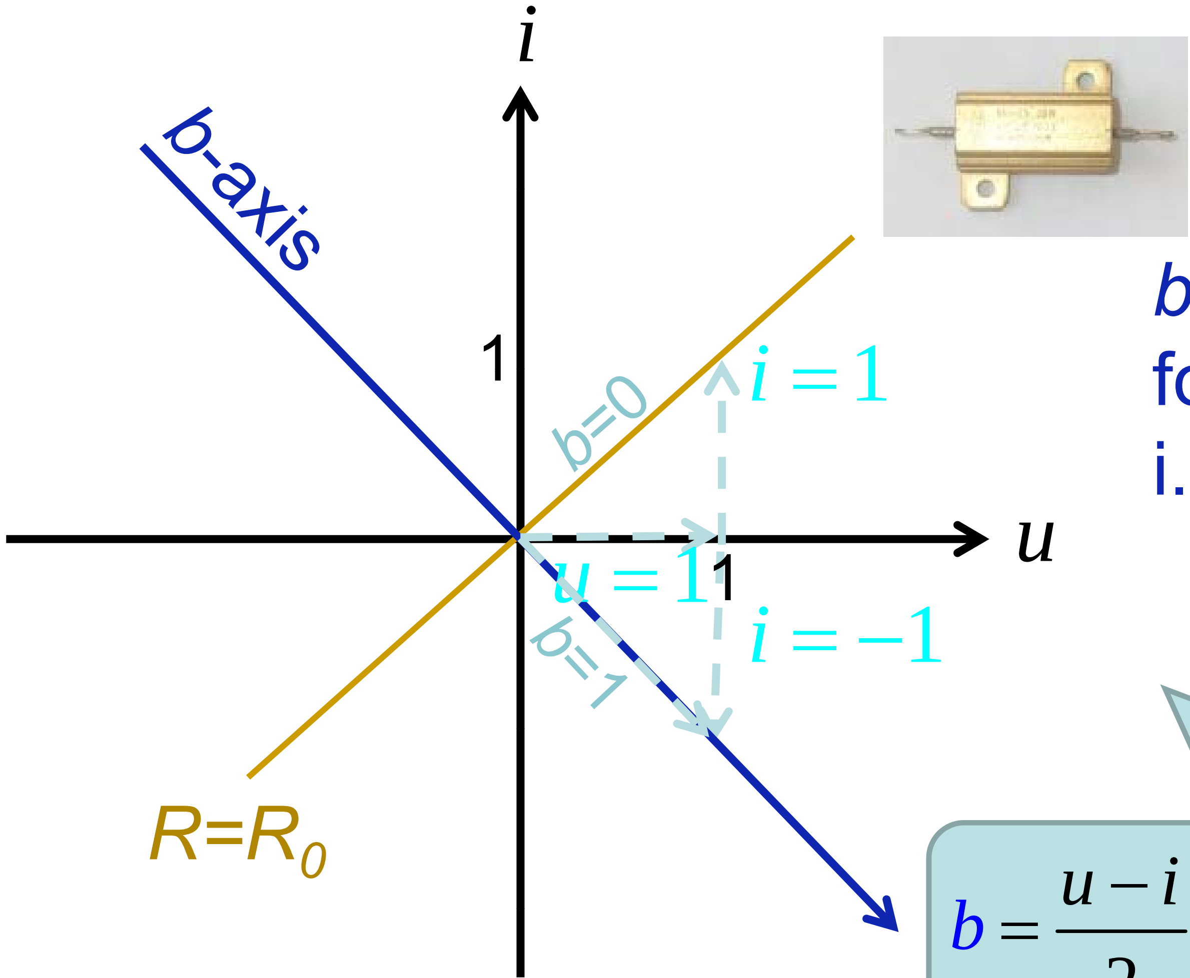


Next:

a-b-coordinates instead of u-i-coordinates...

Hochschule Ulm

From Voltage and Current…
…to *b*…

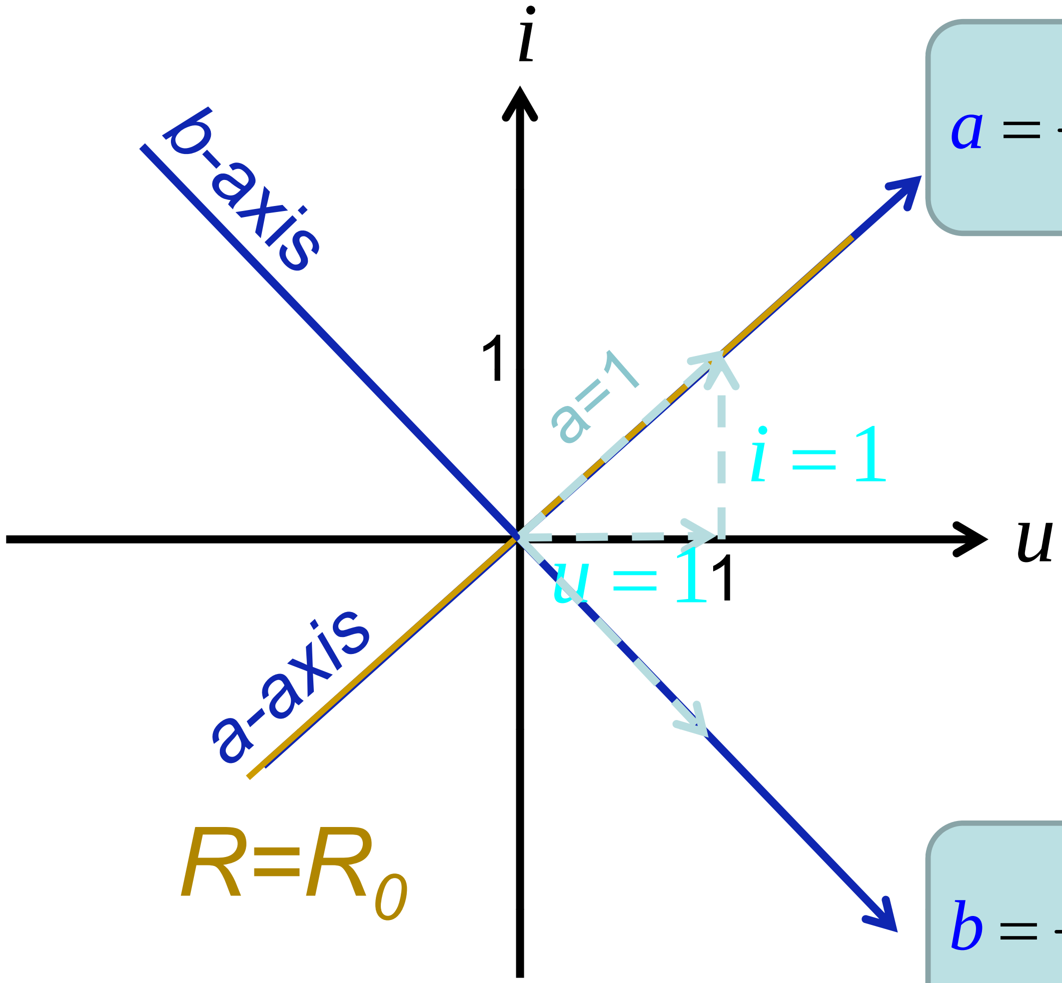


b shall yield zero
for $R=R_0$,
i.e. for $u = i$

$$b = \frac{u-i}{2}$$

Hochschule Ulm

From Voltage and Current…
…to *b*…and *a* !



$$a = \frac{u+i}{2}$$

$$b = \frac{u-i}{2}$$

a-axis shall be perpendicular to *b*-axis

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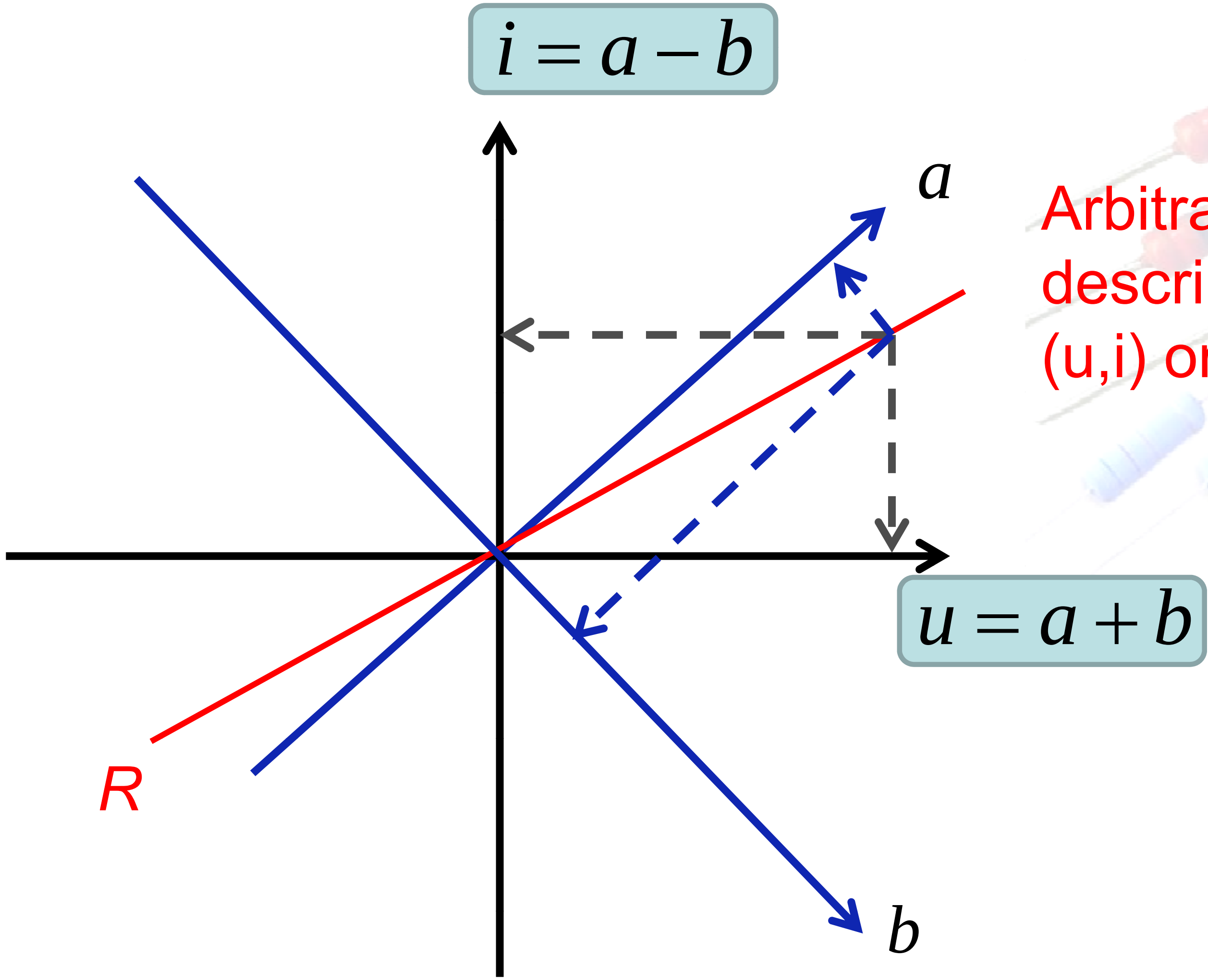
This works the other way round, too: Voltage and Current from *a* and *b*



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

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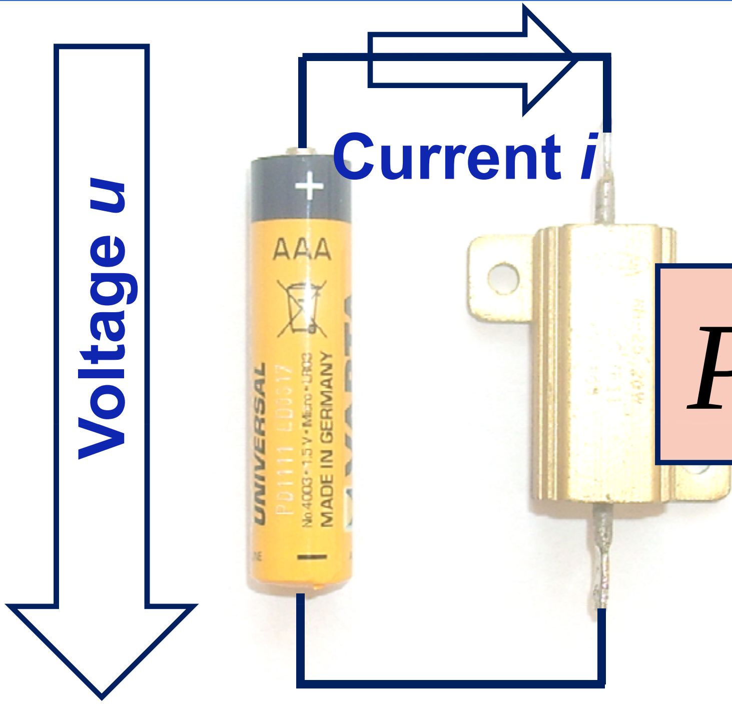
A different angle to dc: Dissipated power in resistor *R*



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

because

$$P = u \cdot i$$

$$= (a+b)\cdot(a-b)$$

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

if $R = R_0 \Rightarrow b = 0$

$$\Rightarrow P = a^2$$

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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*:

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

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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*

$$\begin{cases} P = |a|^2 - |b|^2 \\ \text{and} \quad b = 0 \\ \text{if} \quad Z = Z_0 \end{cases}$$

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

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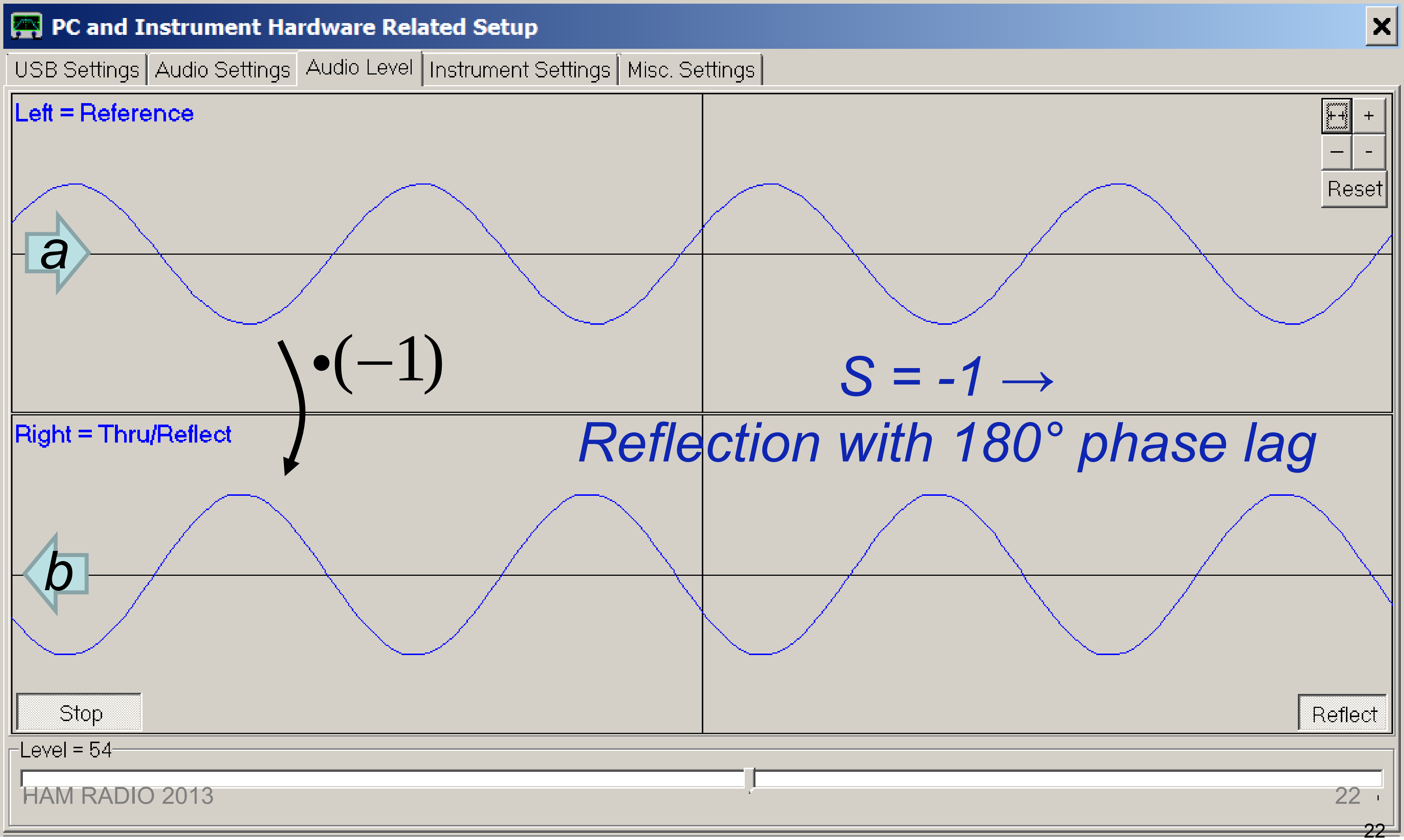
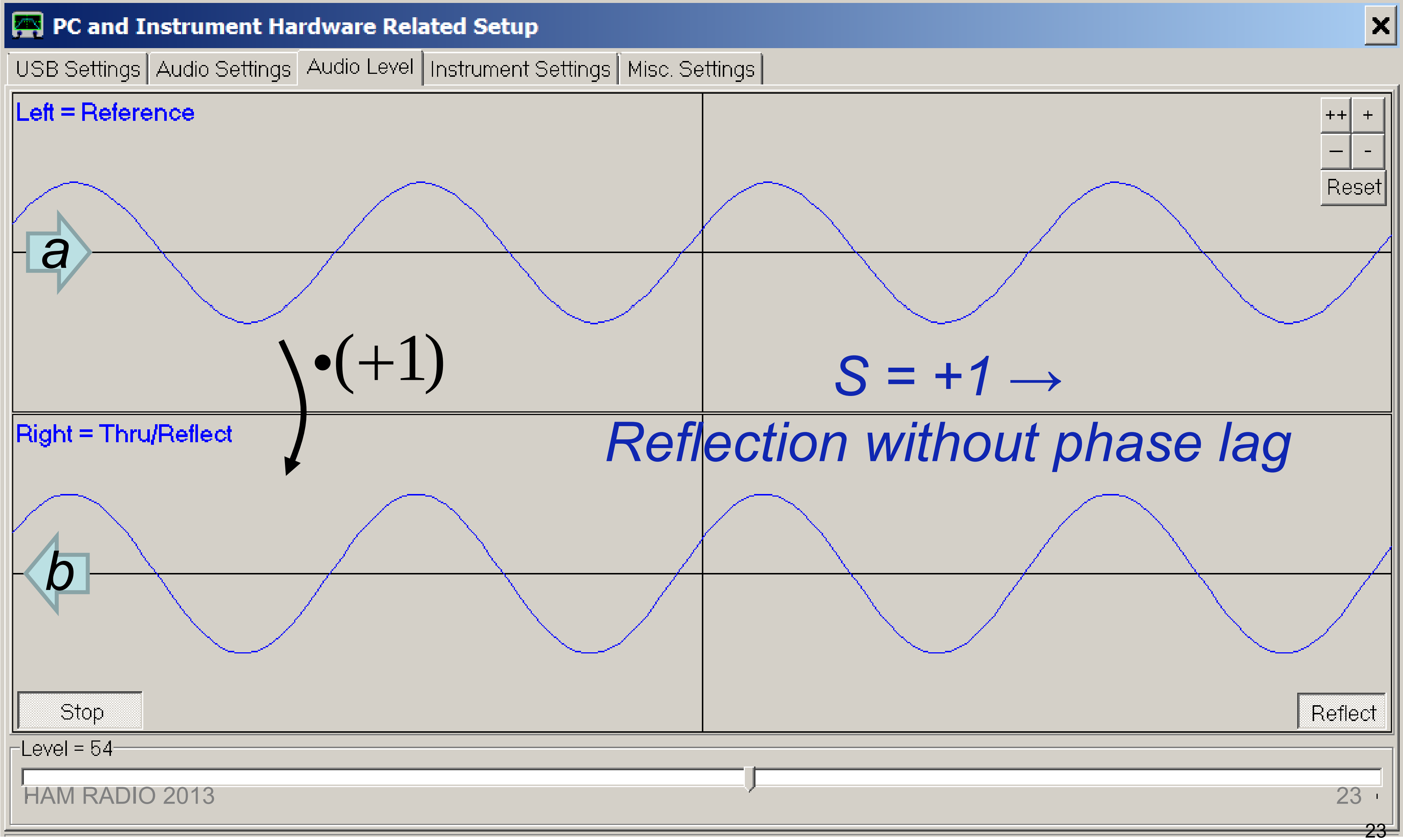
e.g. Short: $z = 0 \rightarrow S = -1$

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 $S = b/a$ …

Short

$$S = -1$$

Open

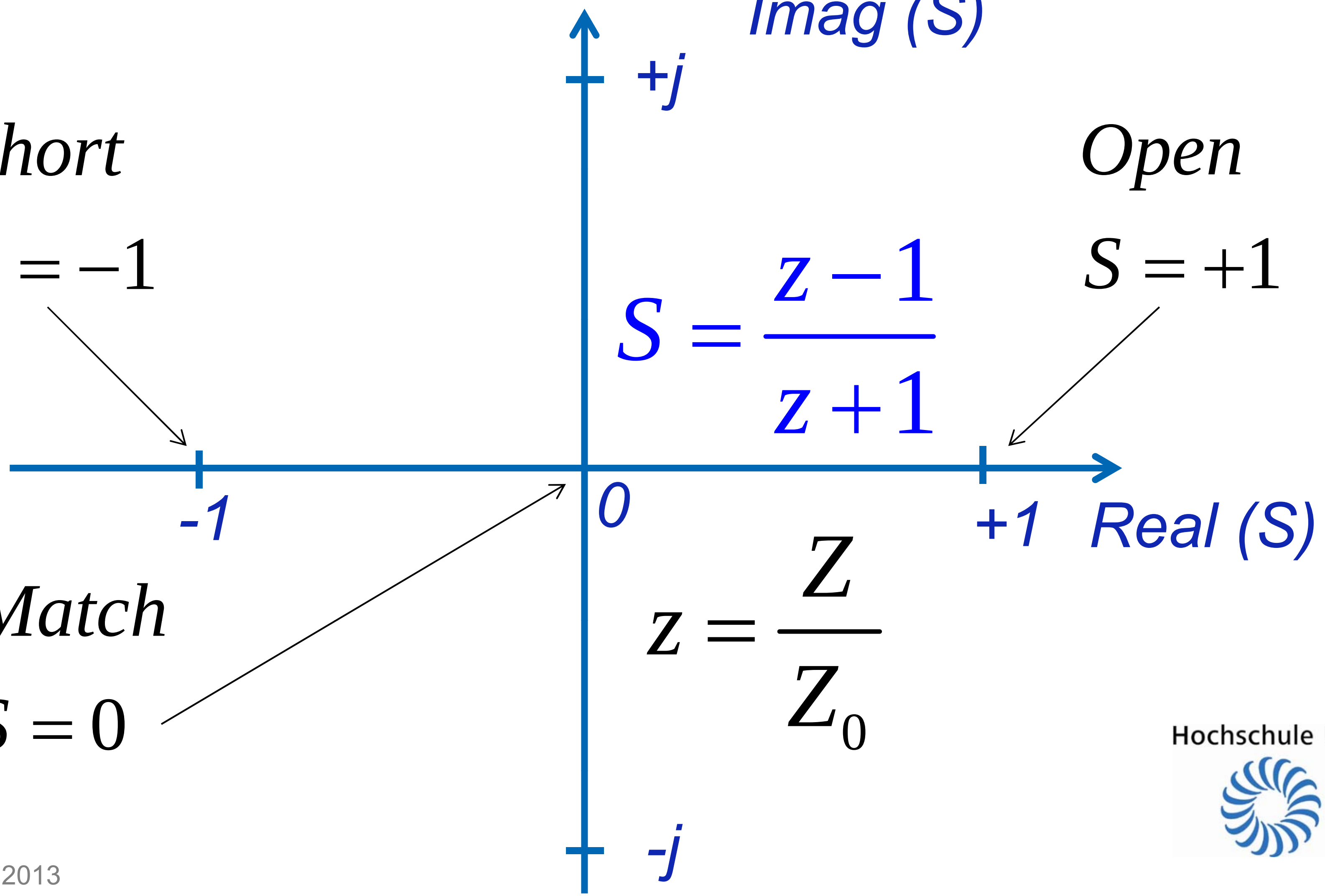
$$S = +1$$

Match

$$S = 0$$

$$S = \frac{z-1}{z+1}$$

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



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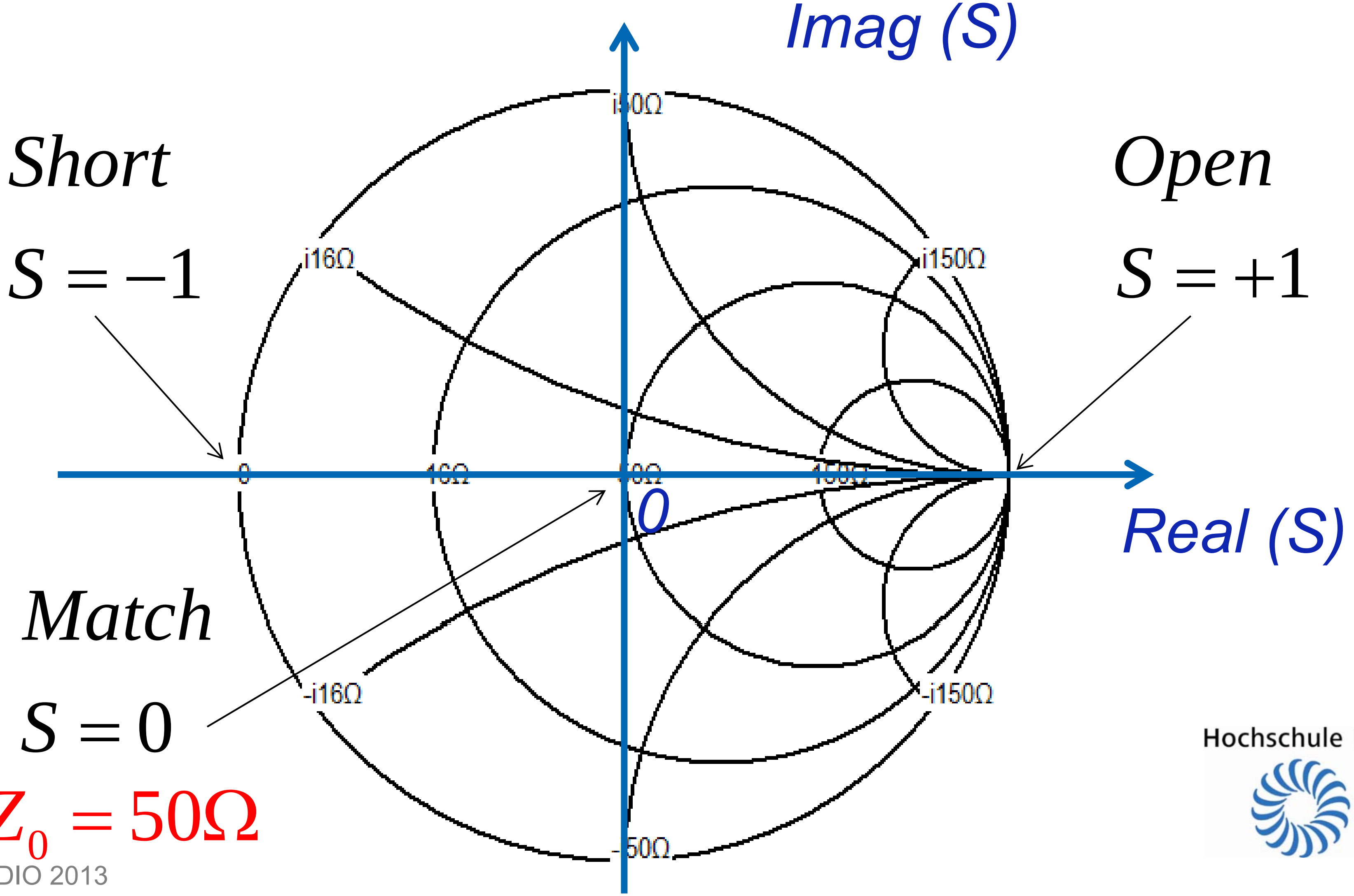
Complex Reflection Coefficient $S = b/a$ and Smith Chart



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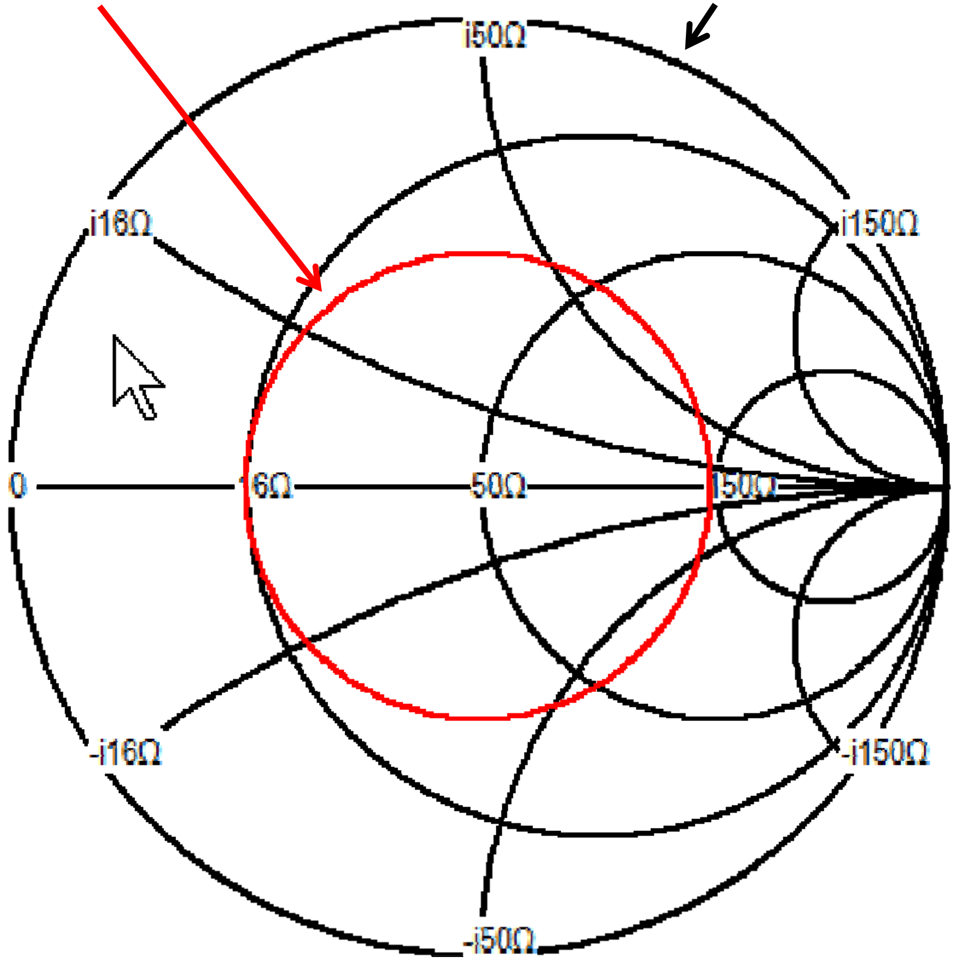
Complex Reflection Coefficient *S* = *b/a* and Voltage Standing Wave Ratio VSWR

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

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

0,5·0,5=25%
reflected power



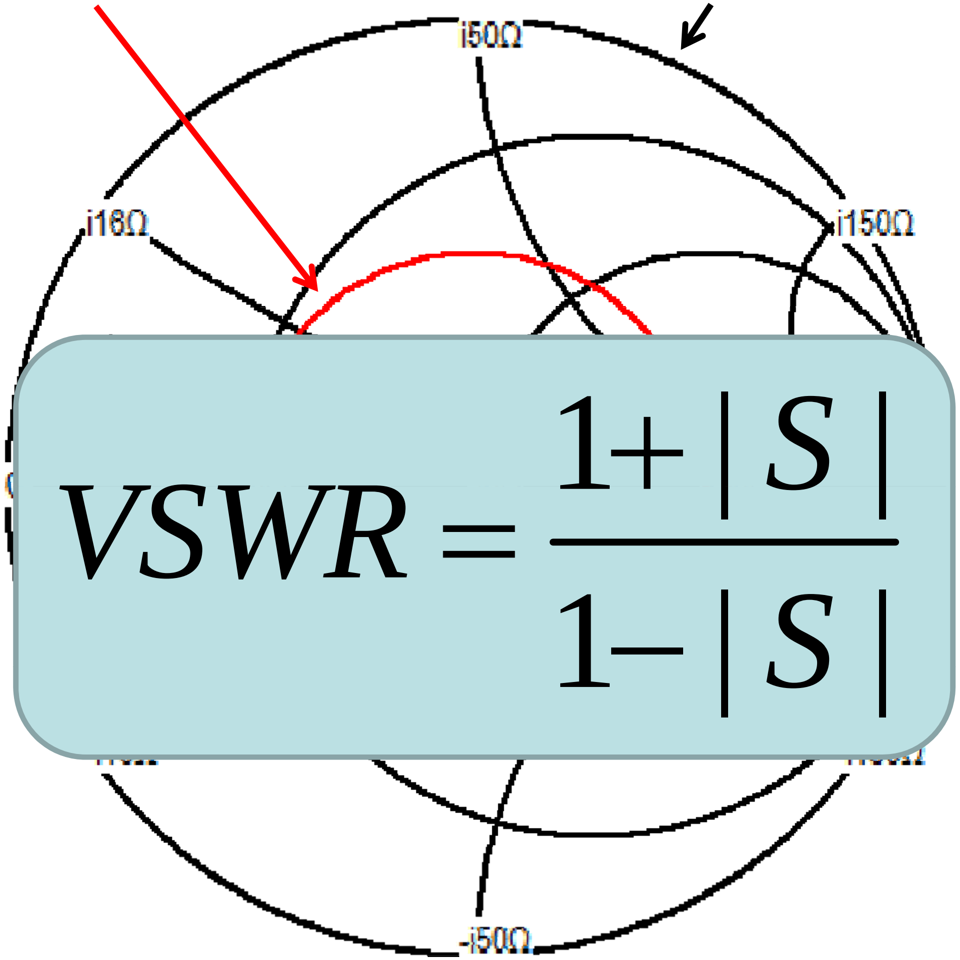
1·1=100%
reflected power

Hochschule Ulm

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

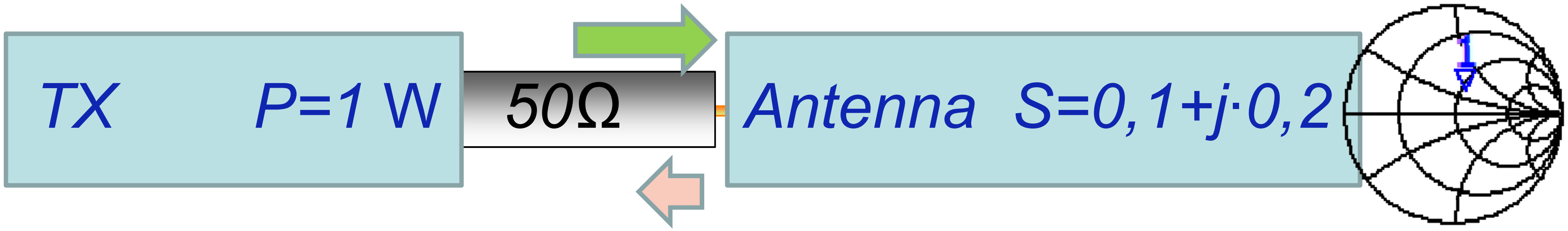
$|S| = 0,5 \quad VSWR = 3$

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



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

Complex Reflection Coefficient $S = b/a$
Calculus Example: Reflected Power



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

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

Reflected Power:

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

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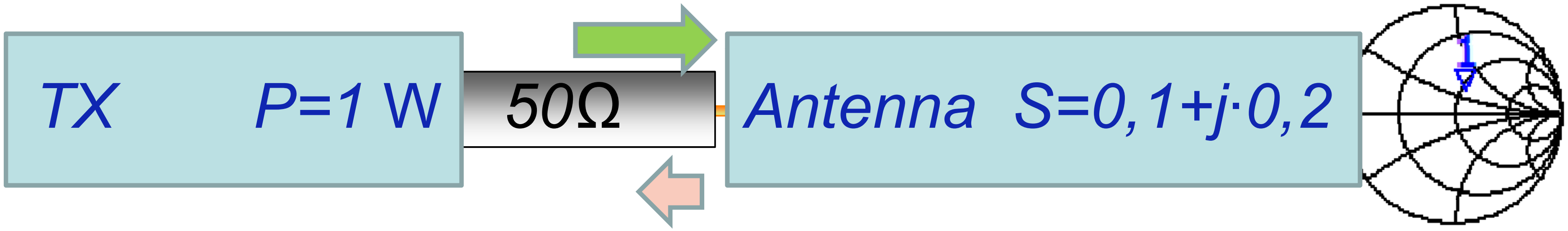
Complex Reflection Coefficient $S = b/a$
Calculus Example: VSWR



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

VSWR:

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

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

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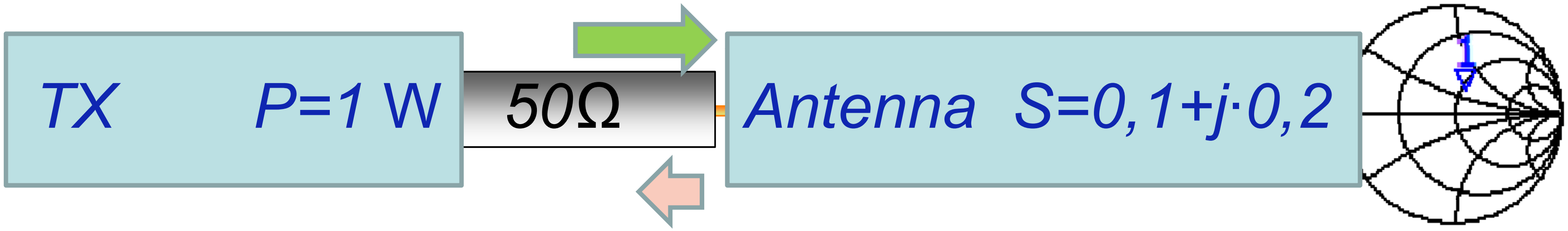
Complex Reflection Coefficient $S = b/a$ Calculus Example: Antenna Voltage



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

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

Effective Voltage at Antenna:

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

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

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

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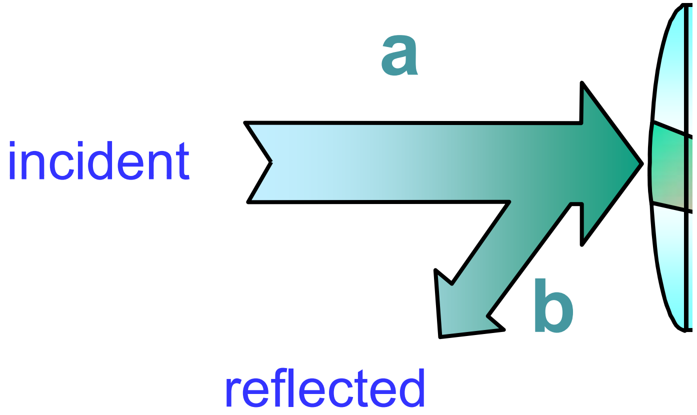
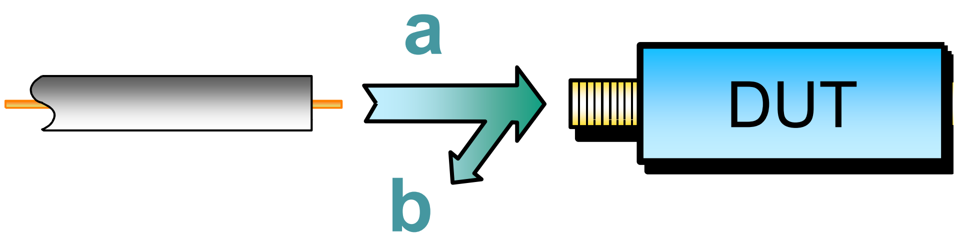
Complex Reflection Coefficient *S* = *b/a*
We call it Scattering Parameter now!

Optics



Scattering and absorption of waves at *one* port

Elektrical

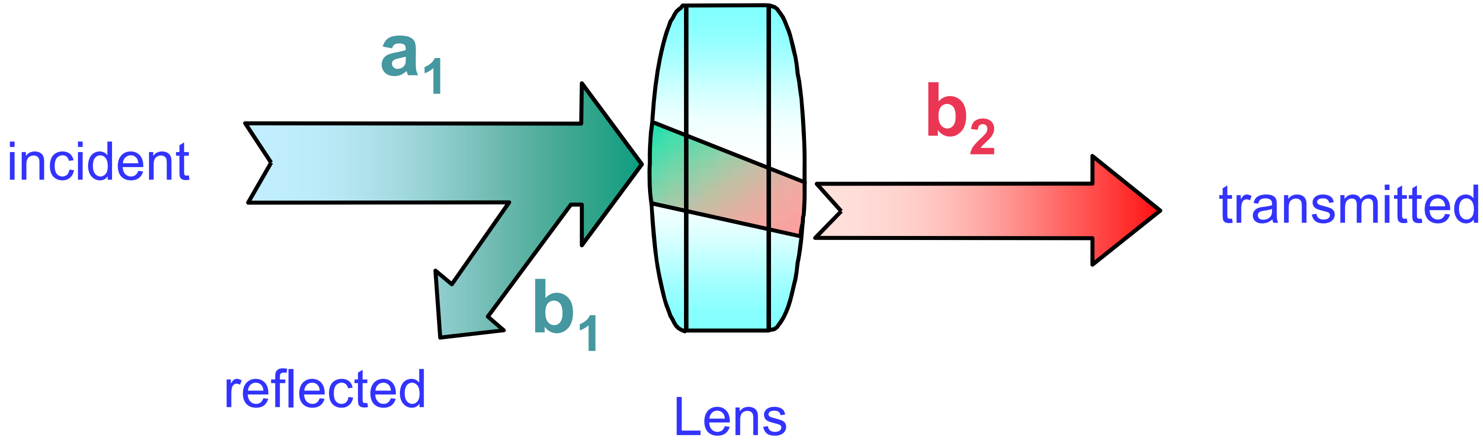


DUT : DEVICE UNDER TEST

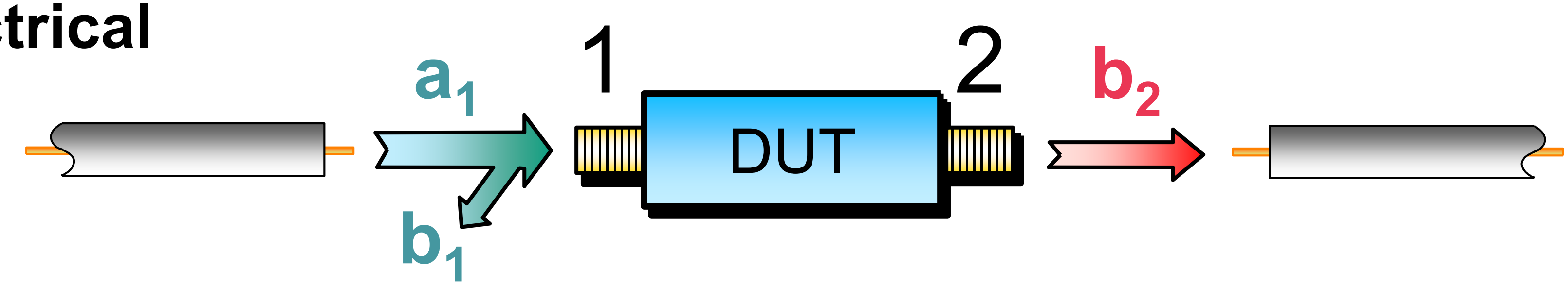
Hochschule Ulm

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

Optics



Electrical



DUT : DEVICE UNDER TEST

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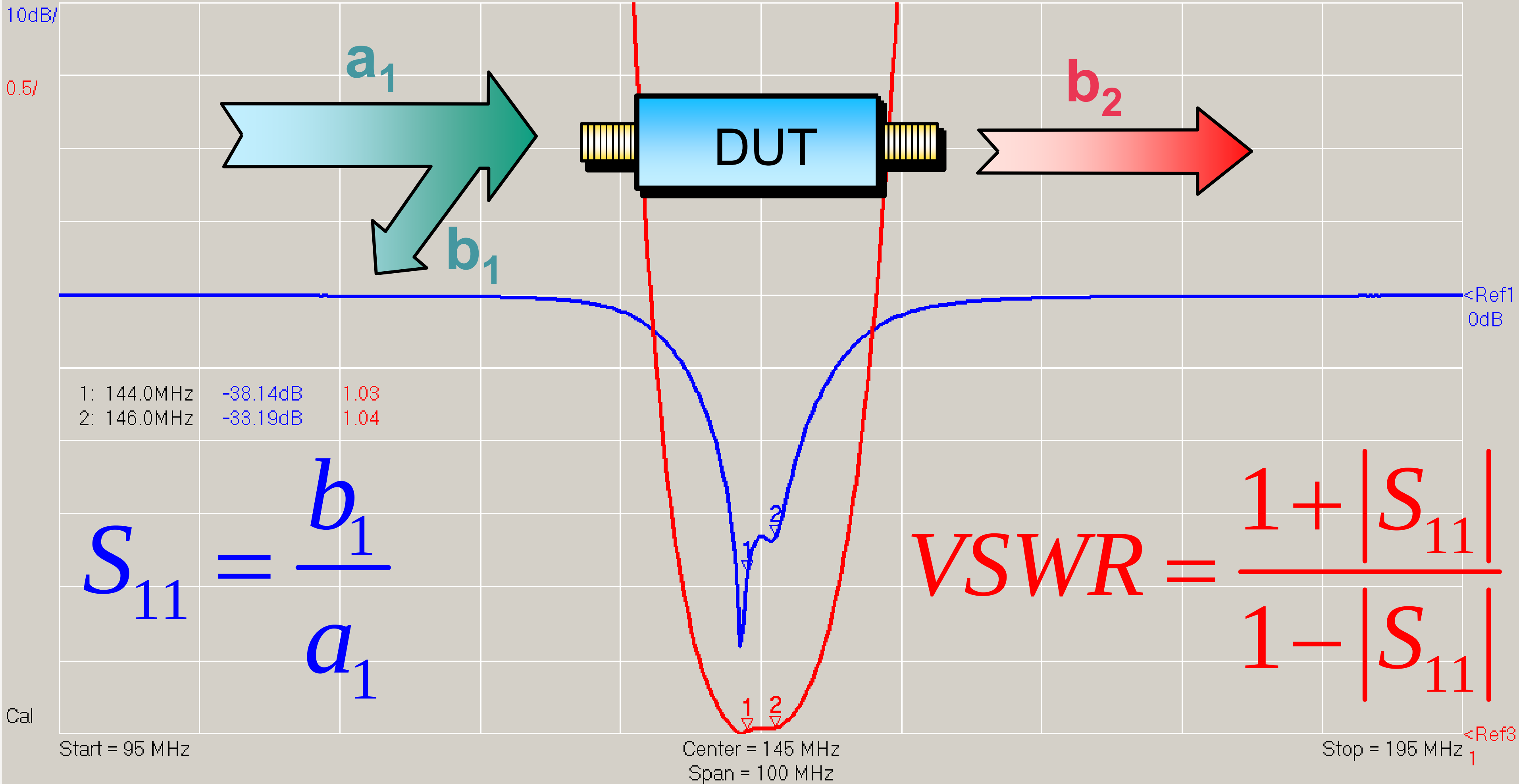
S-Parameter S_{11} (used to be S)

$|S_{11}|$ → Return Loss

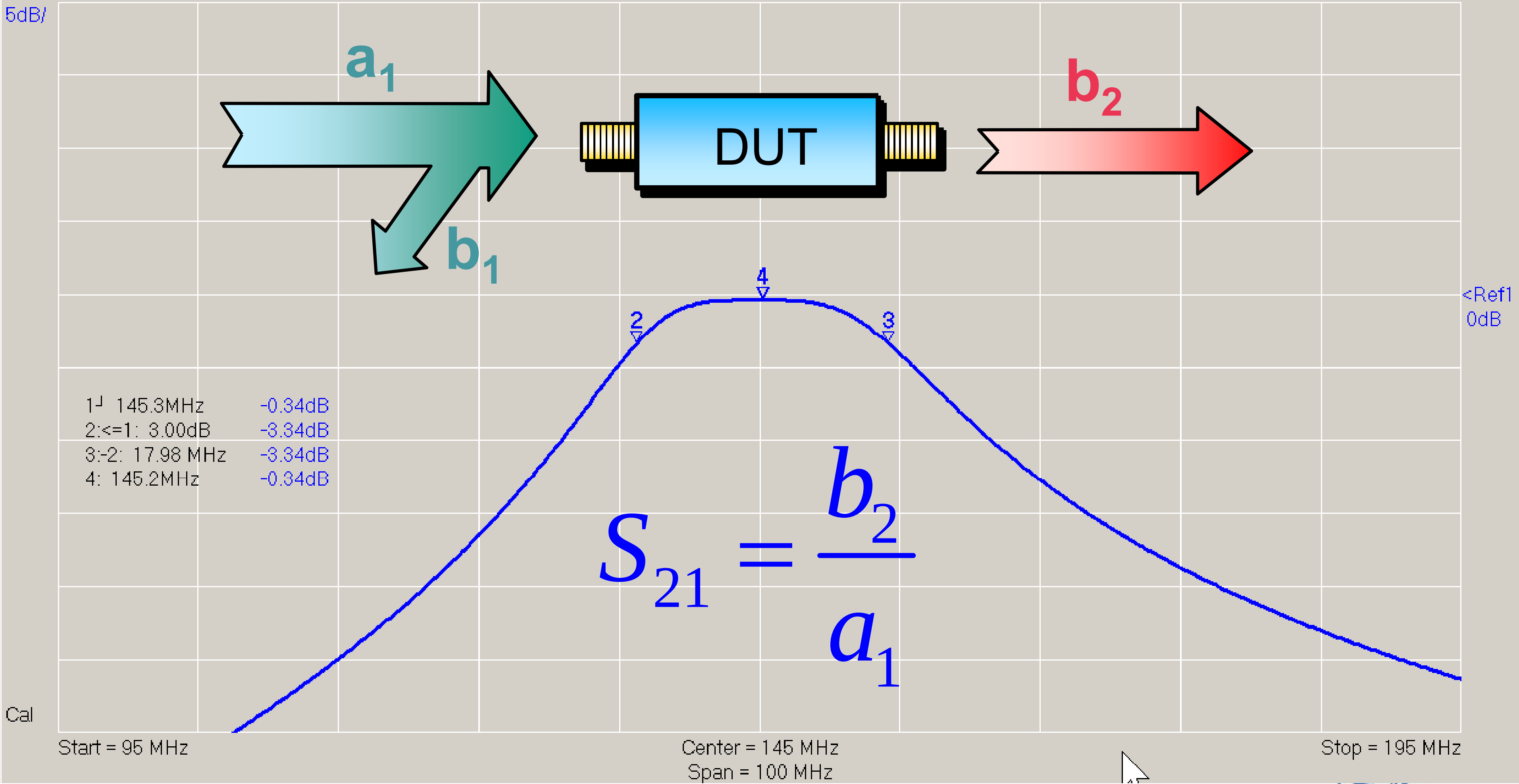


$$S_{11} = \frac{b_1}{a_1}$$

$$VSWR = \frac{1 + |S_{11}|}{1 - |S_{11}|}$$

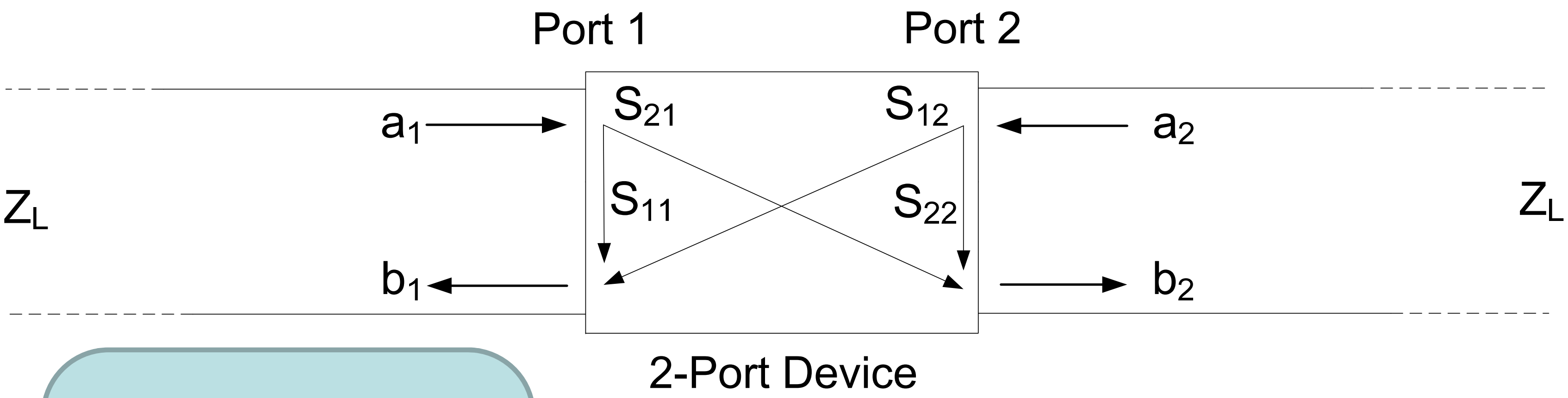
S-Parameter S_{21}

$|S_{21}|$ = Transmission Gain



$$S_{21} = \frac{b_2}{a_1}$$

General:
S-Parameters S_{ik}



$$S_{ik} = \frac{b_i}{a_k} \qquad i,k = 1 \ldots \text{ number of ports}$$

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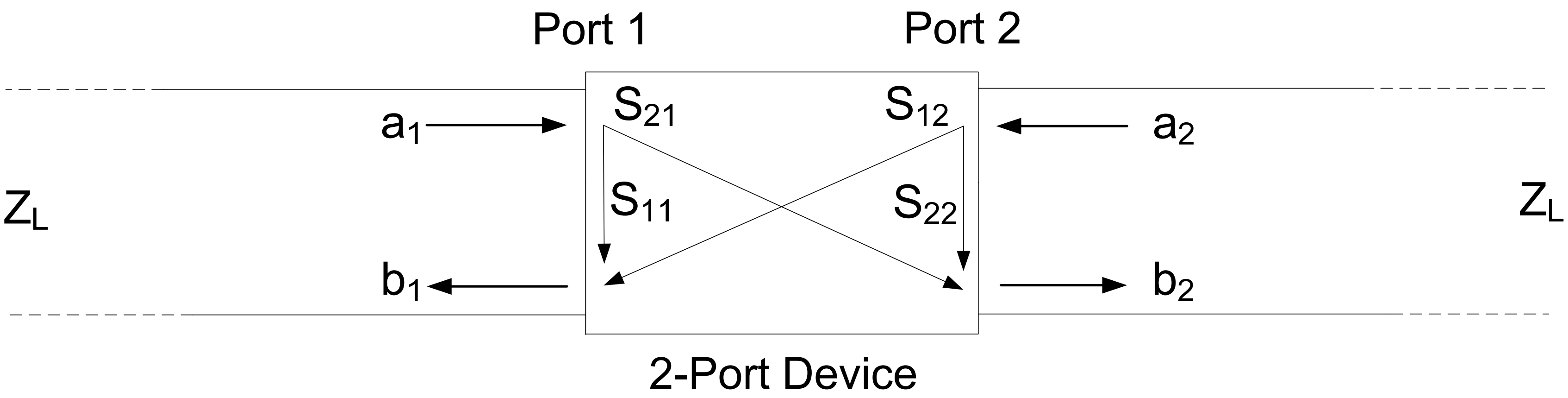
General:
S-Parameters S_{ik}



Scattering parameters S_{11}, S_{21}, S_{12}, S_{22}

completely describe linear two port device!

=> useful for simulations

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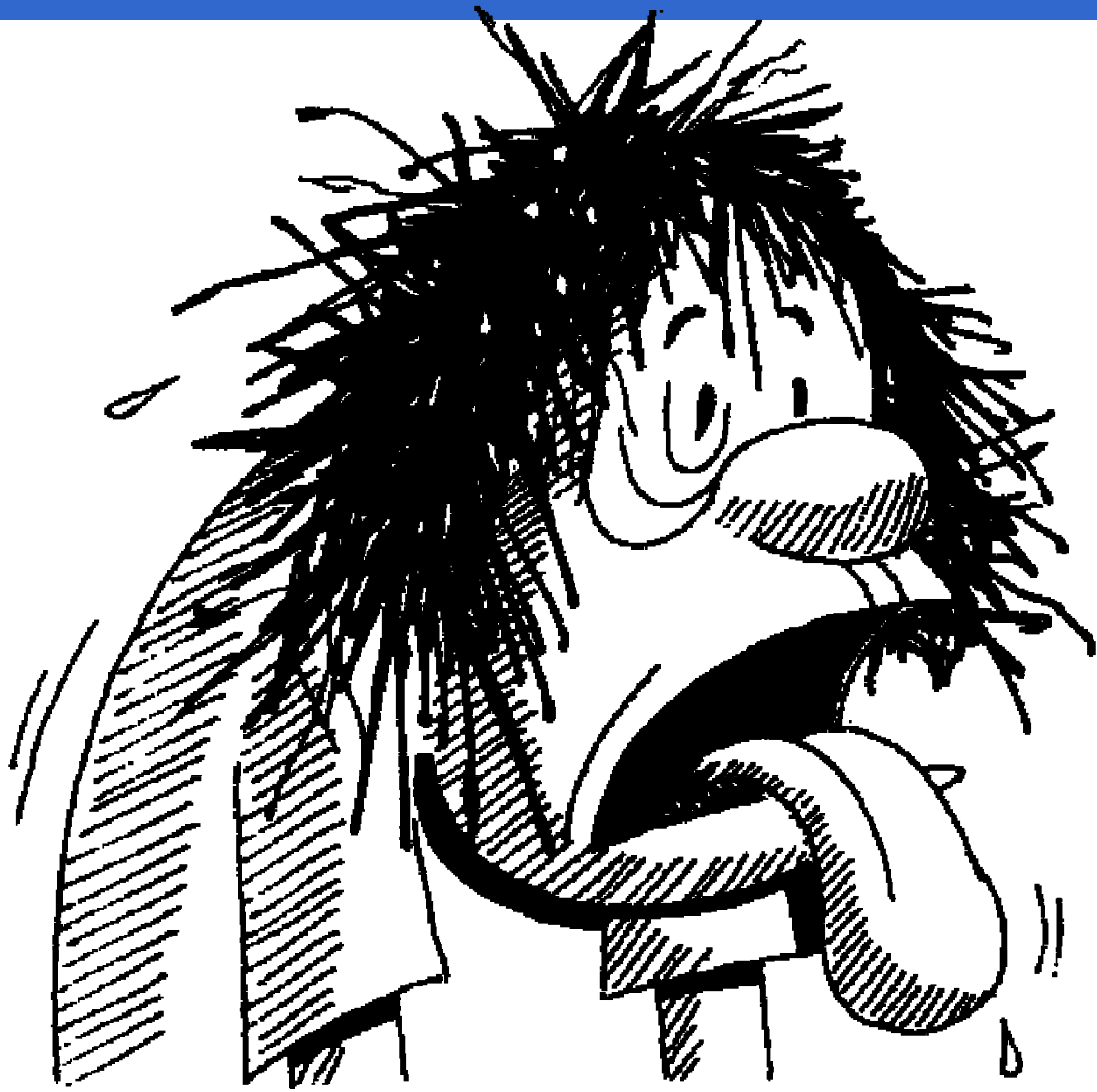
BREAK ???



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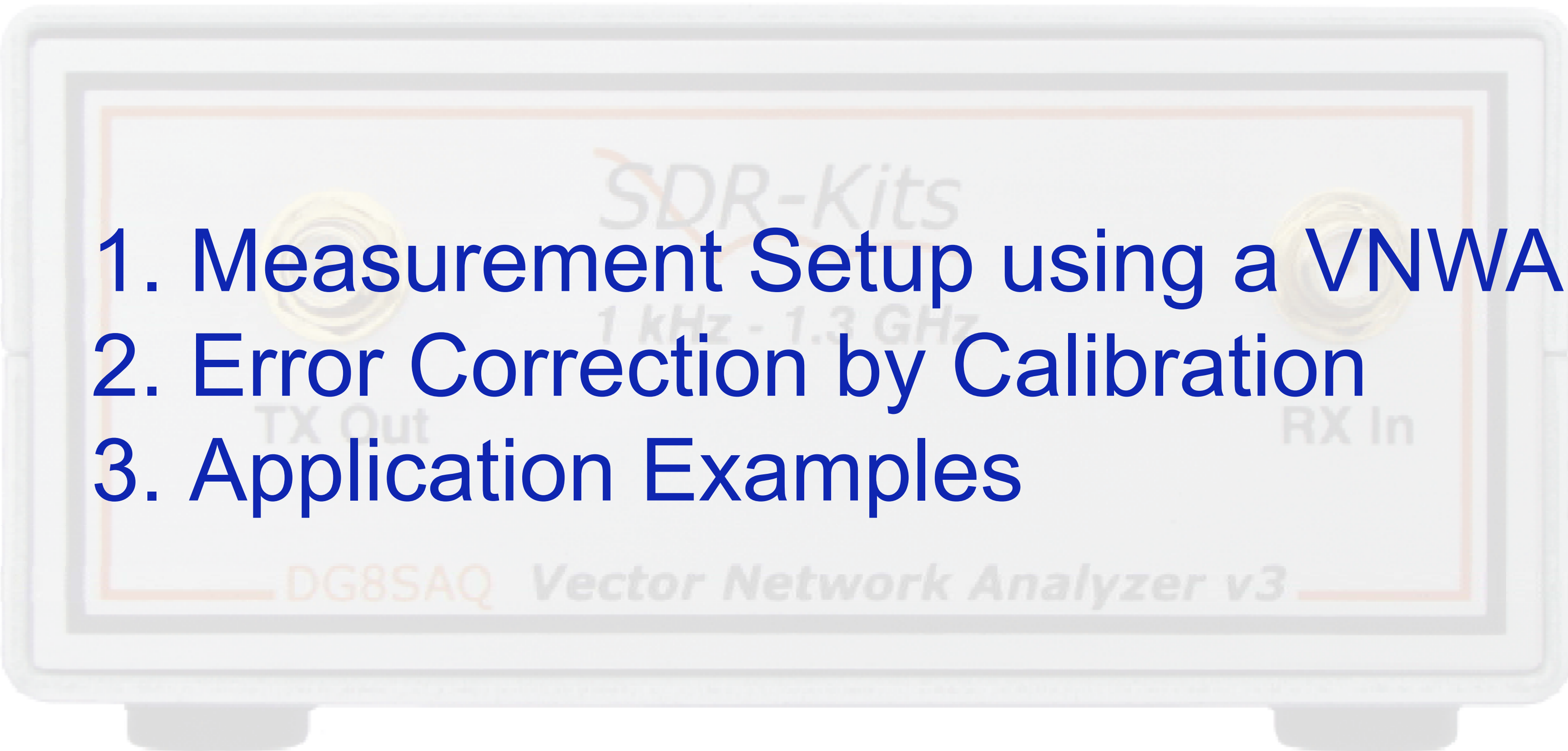
Measuring S-Parameters using a Vector-Network Analyzer



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

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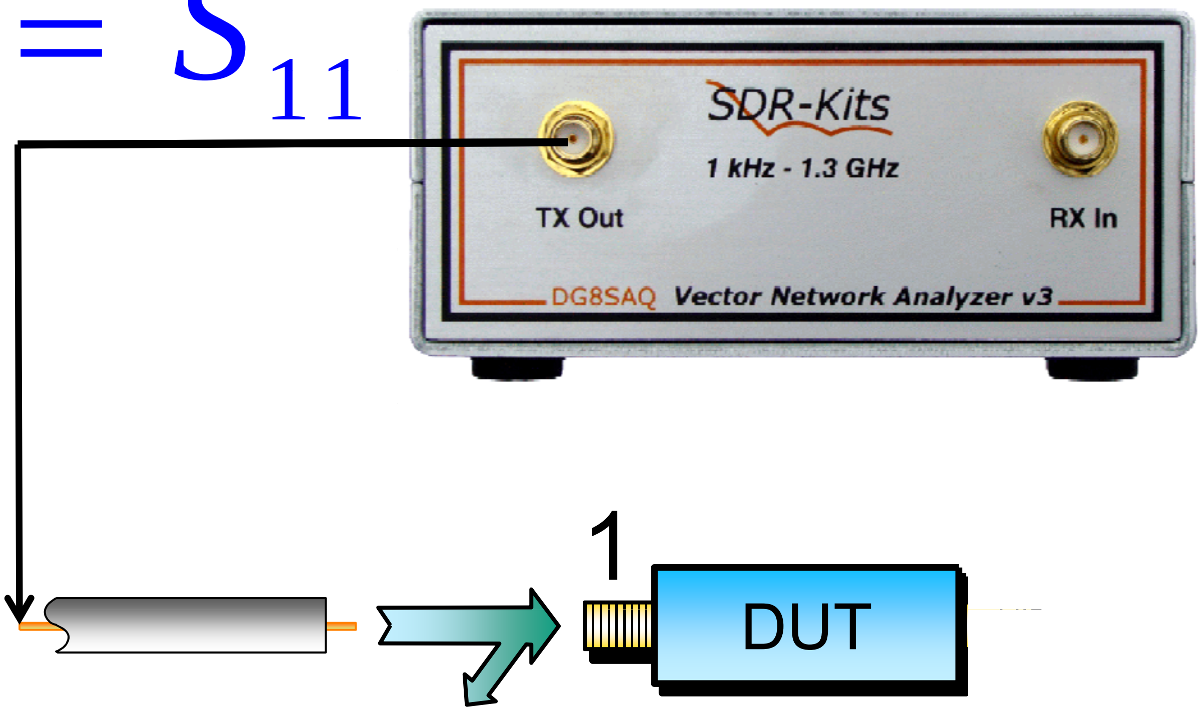
Measurement Setup using a VNWA Example 1-Port Device:

$$S = S_{11}$$



DUT : DEVICE UNDER TEST

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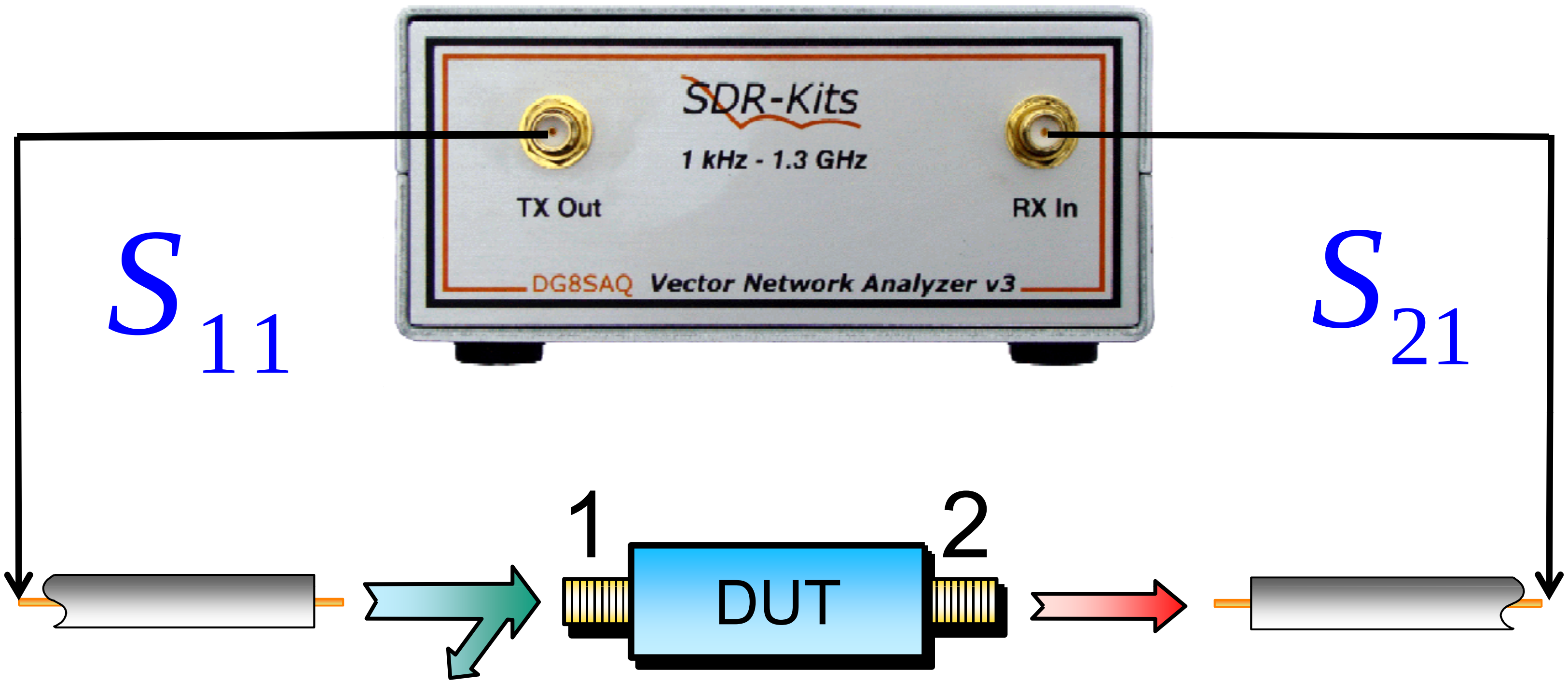
Measurement Setup using a VNWA
Example 2-Port Device forward:



DUT : DEVICE UNDER TEST

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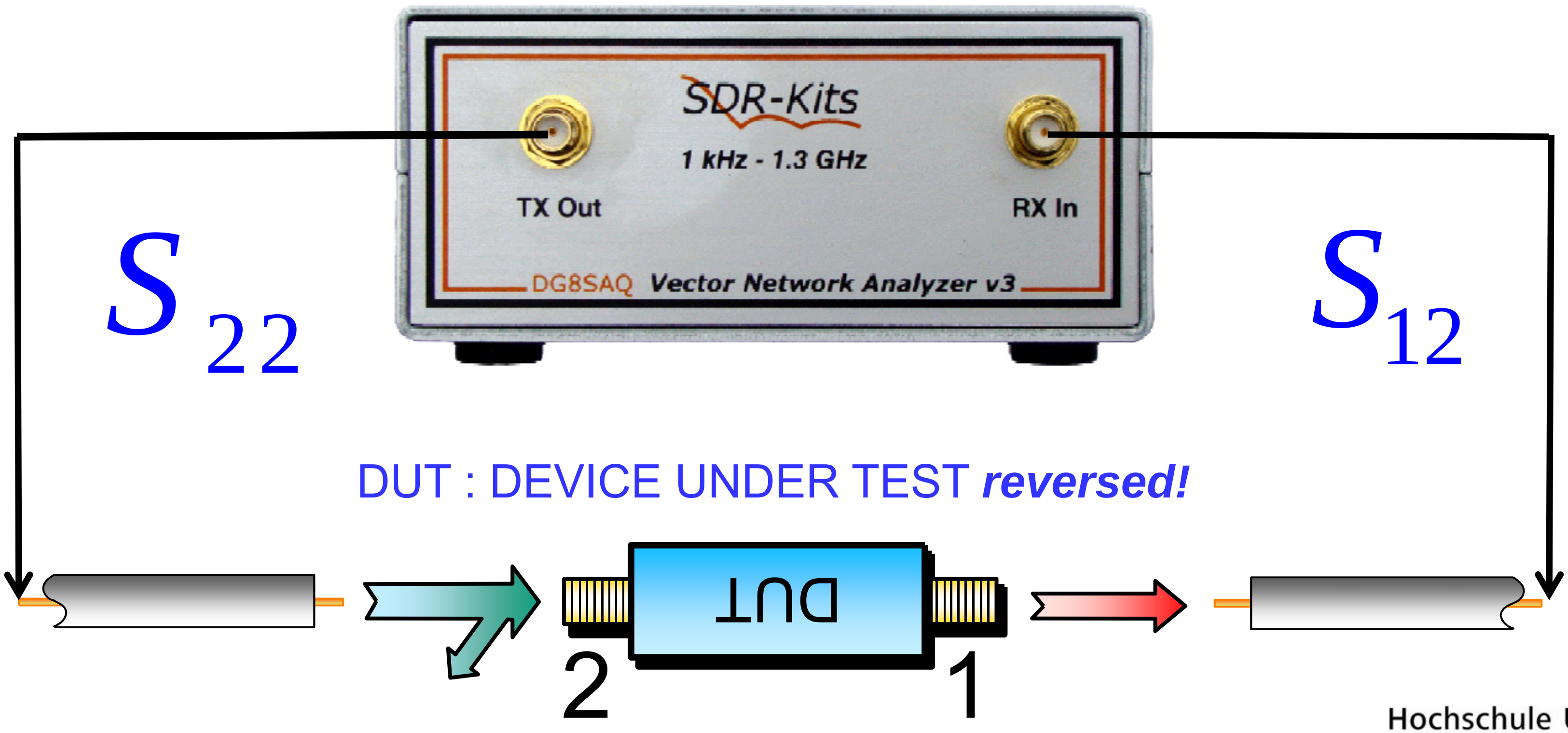
Measurement Setup using a VNWA Example 2-Port Device reverse:



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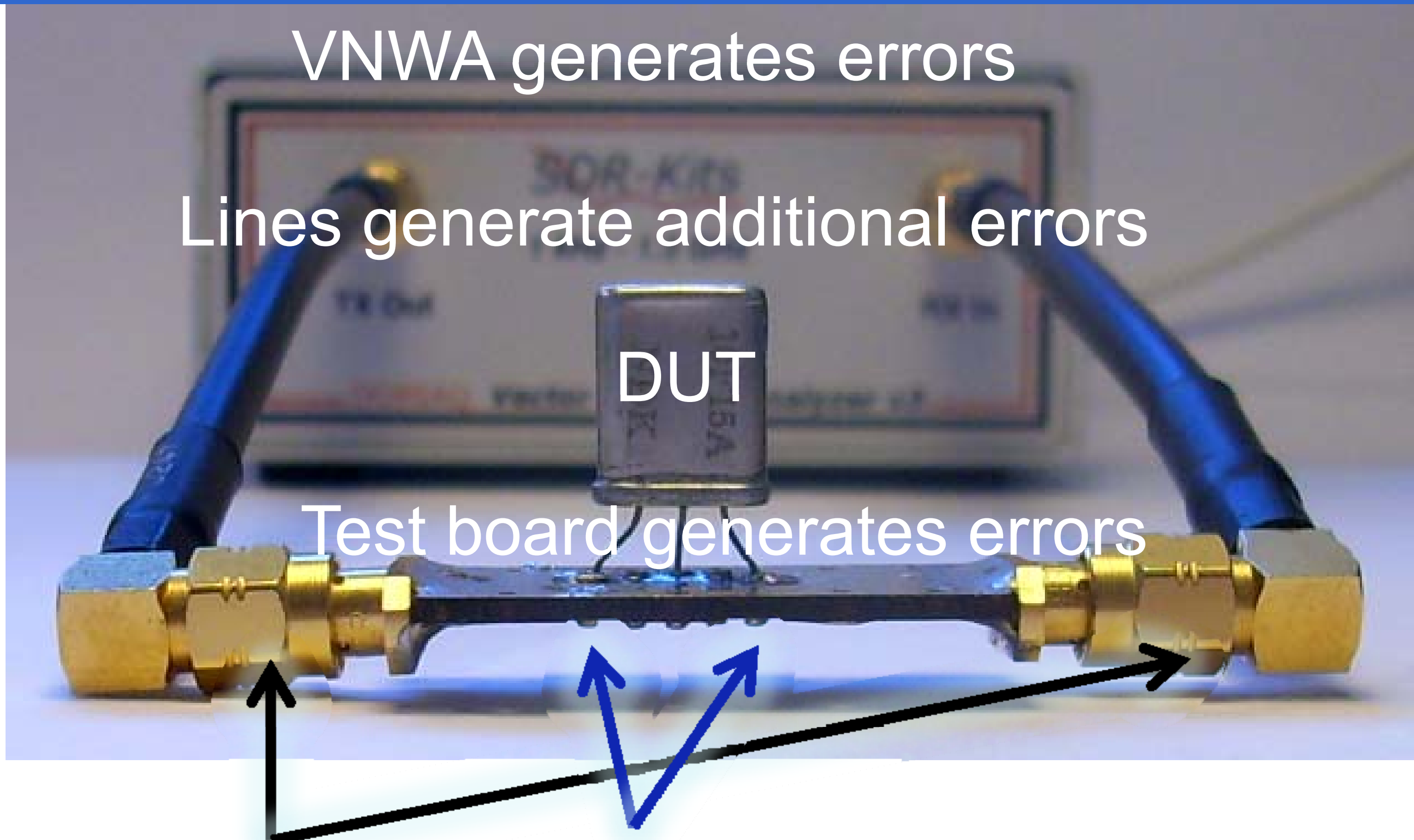
Error Correction by Calibration
Error Sources



We calibrate here!

We want to measure here!

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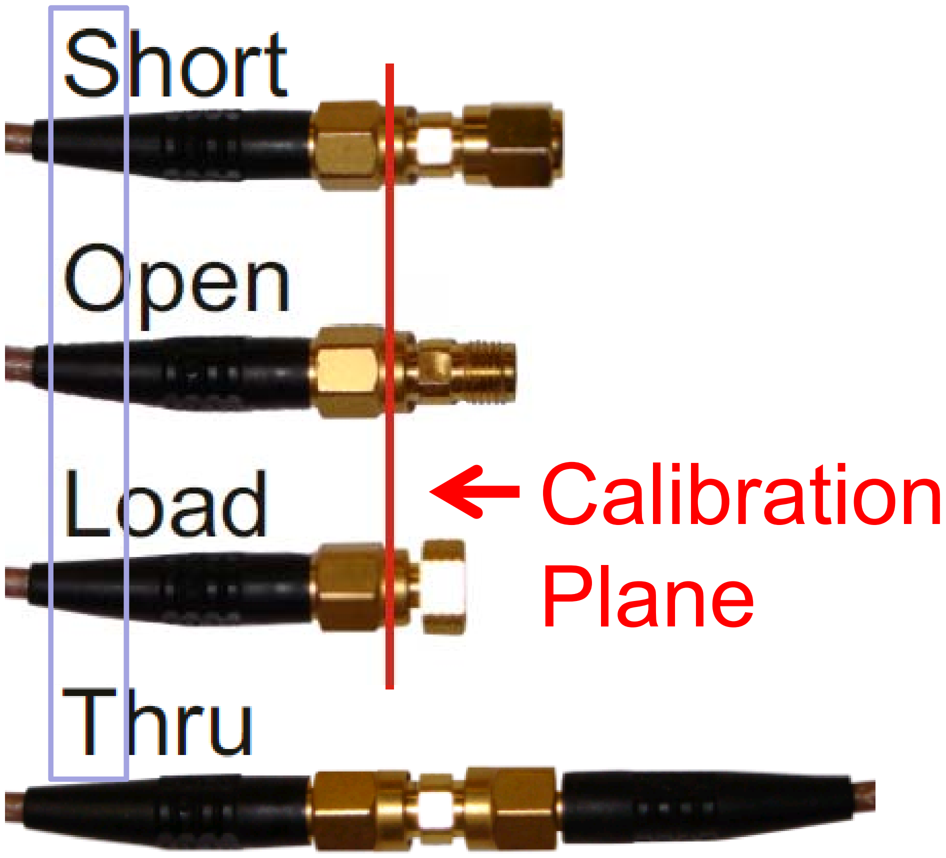
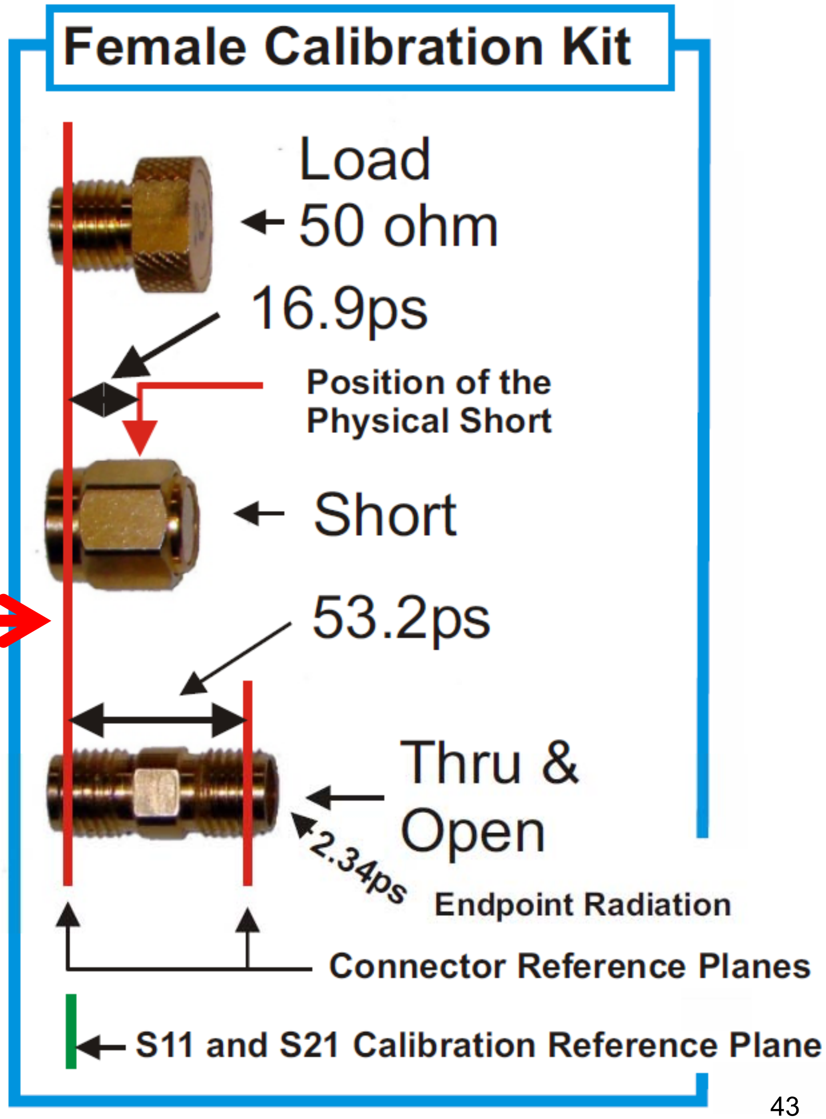
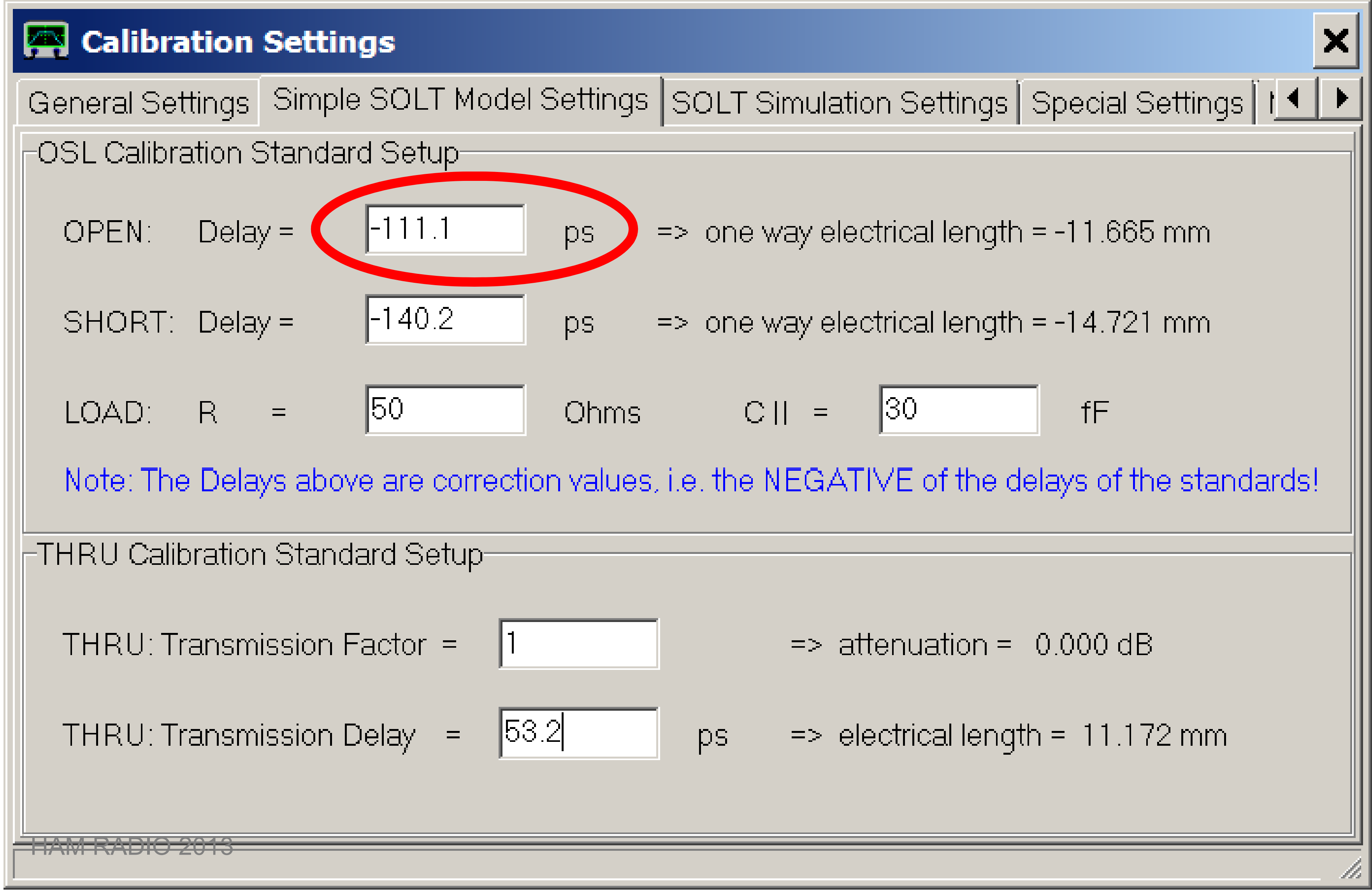
SOLT-Calibration removes Errors from VNWA and Test Cables…



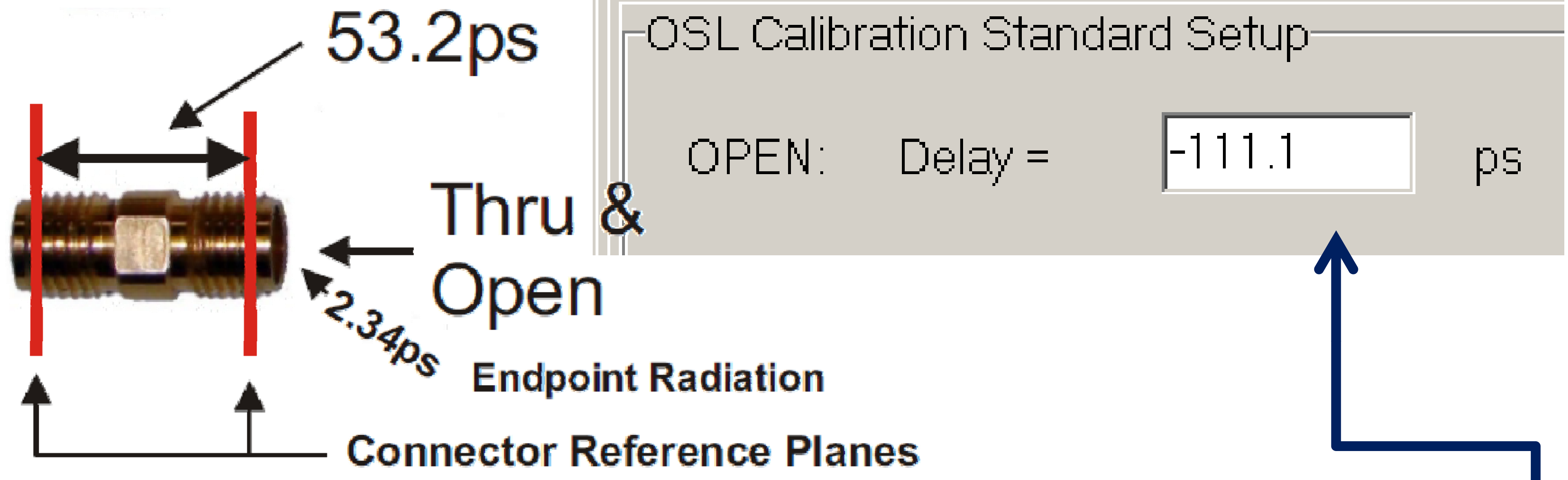


http://www.hamcom.dk/VNWA/

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



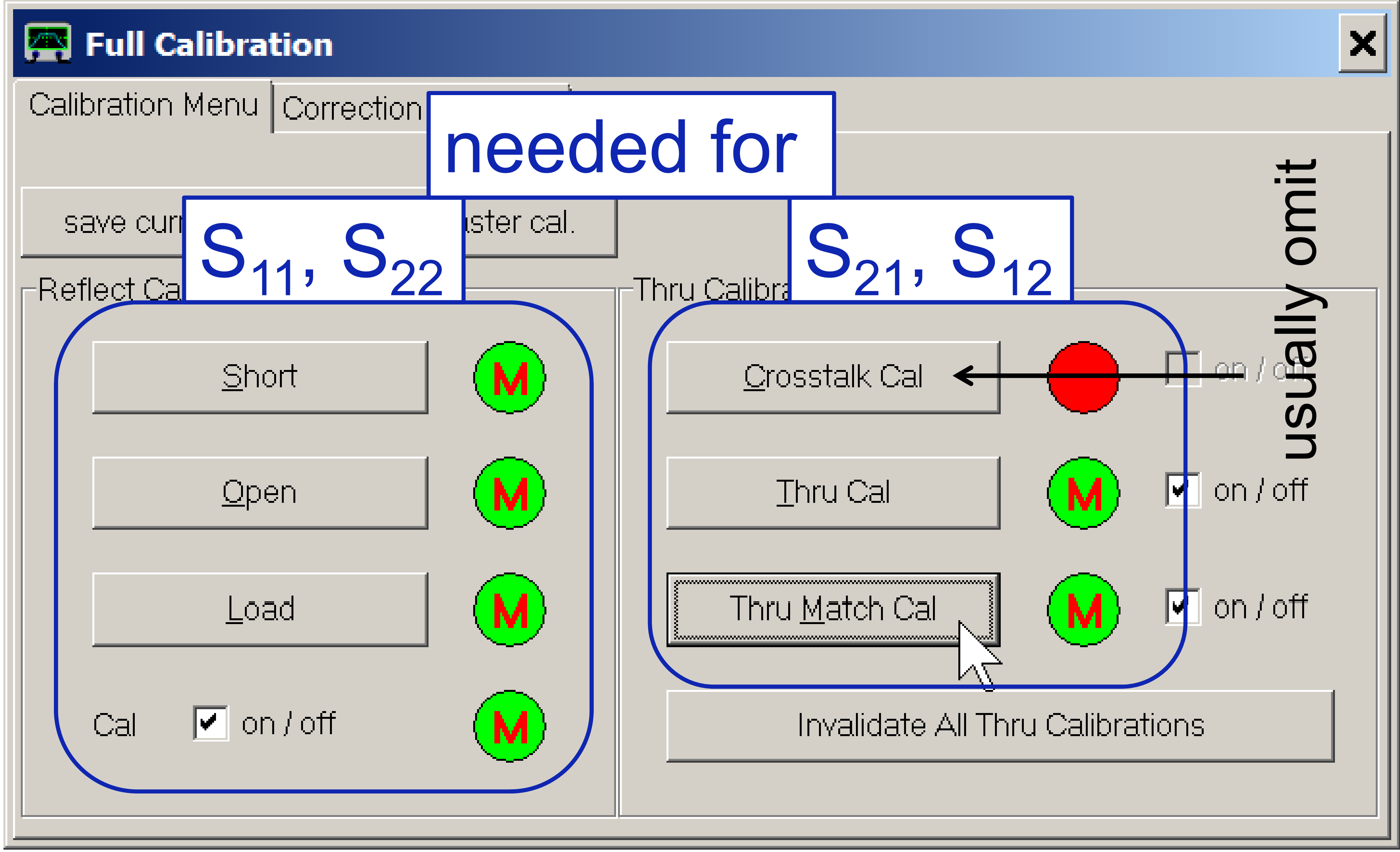
Example: Open Standard



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



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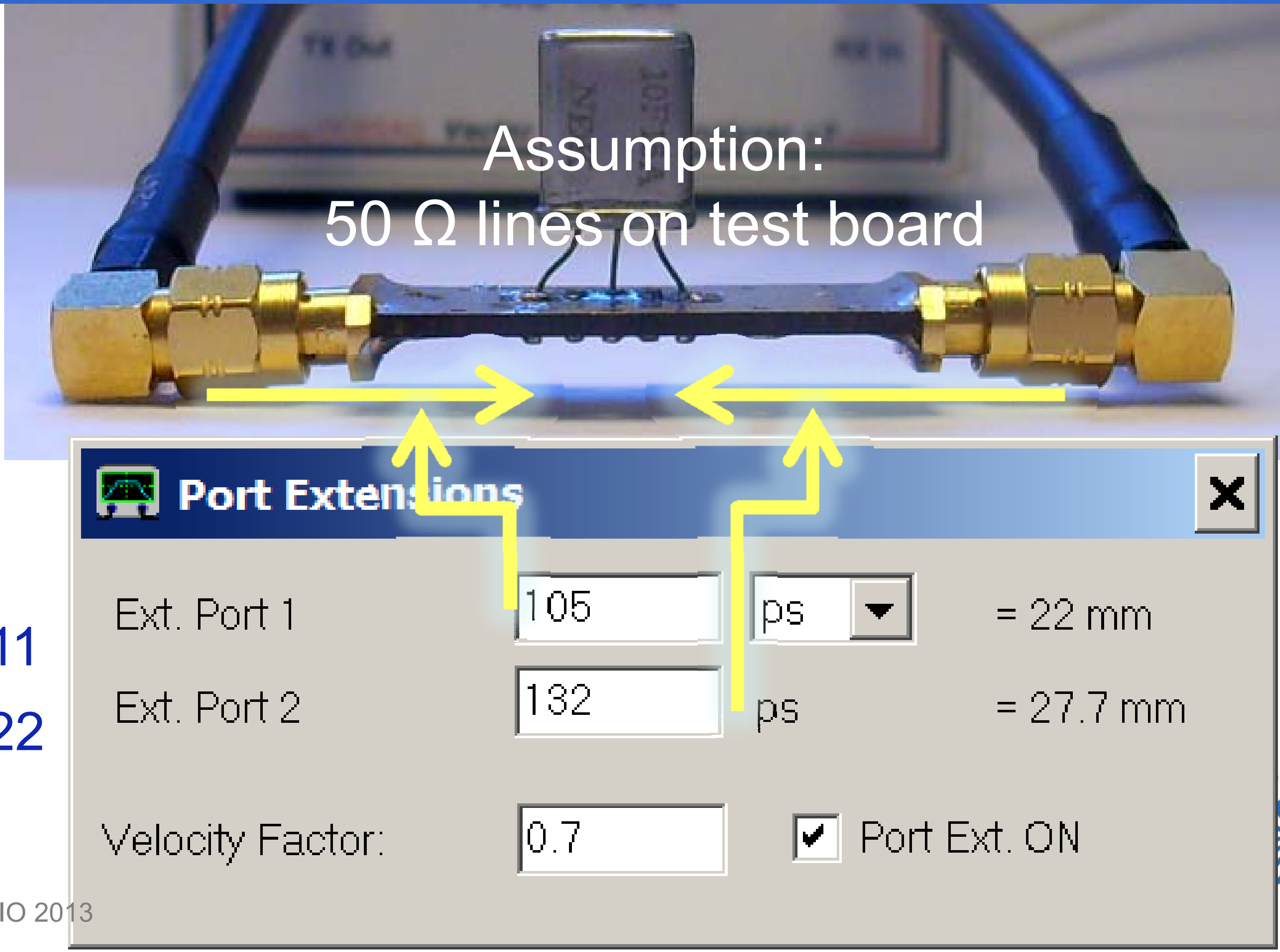
Delay Correction with Port Extensions



S_{11}
S_{22}

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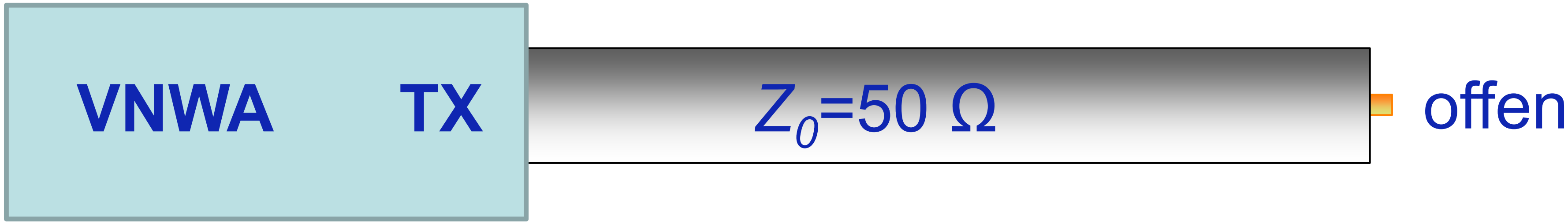
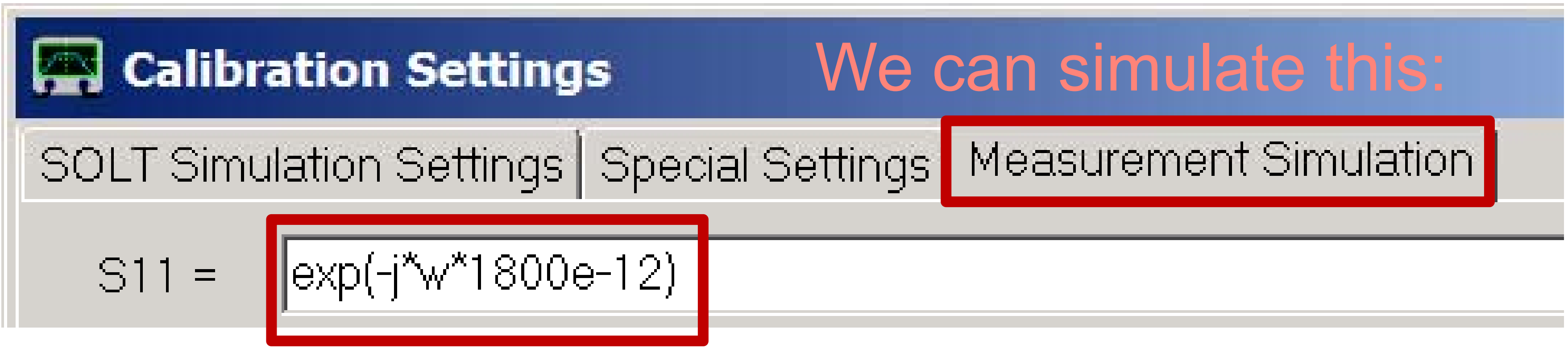
Wrong Cal Parameters cause Port Mismatch Example: open 50 Ohms – Line (1)



$\tau = 1800\ \mathrm{ps}$

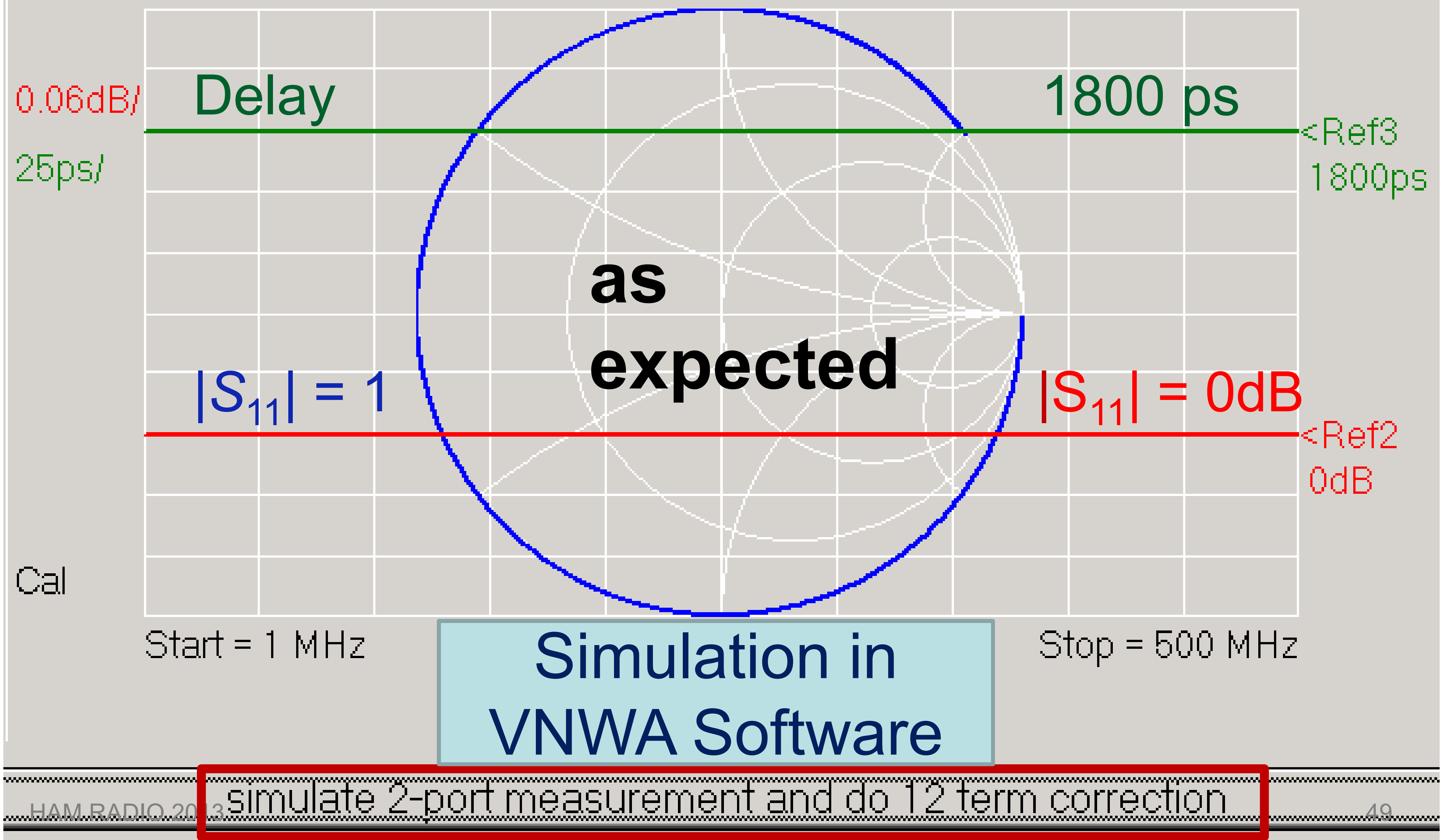


i.e. $|S_{11}| = 1$ total power reflected

Phase(S_{11})=$-\omega \cdot 1800$ ps

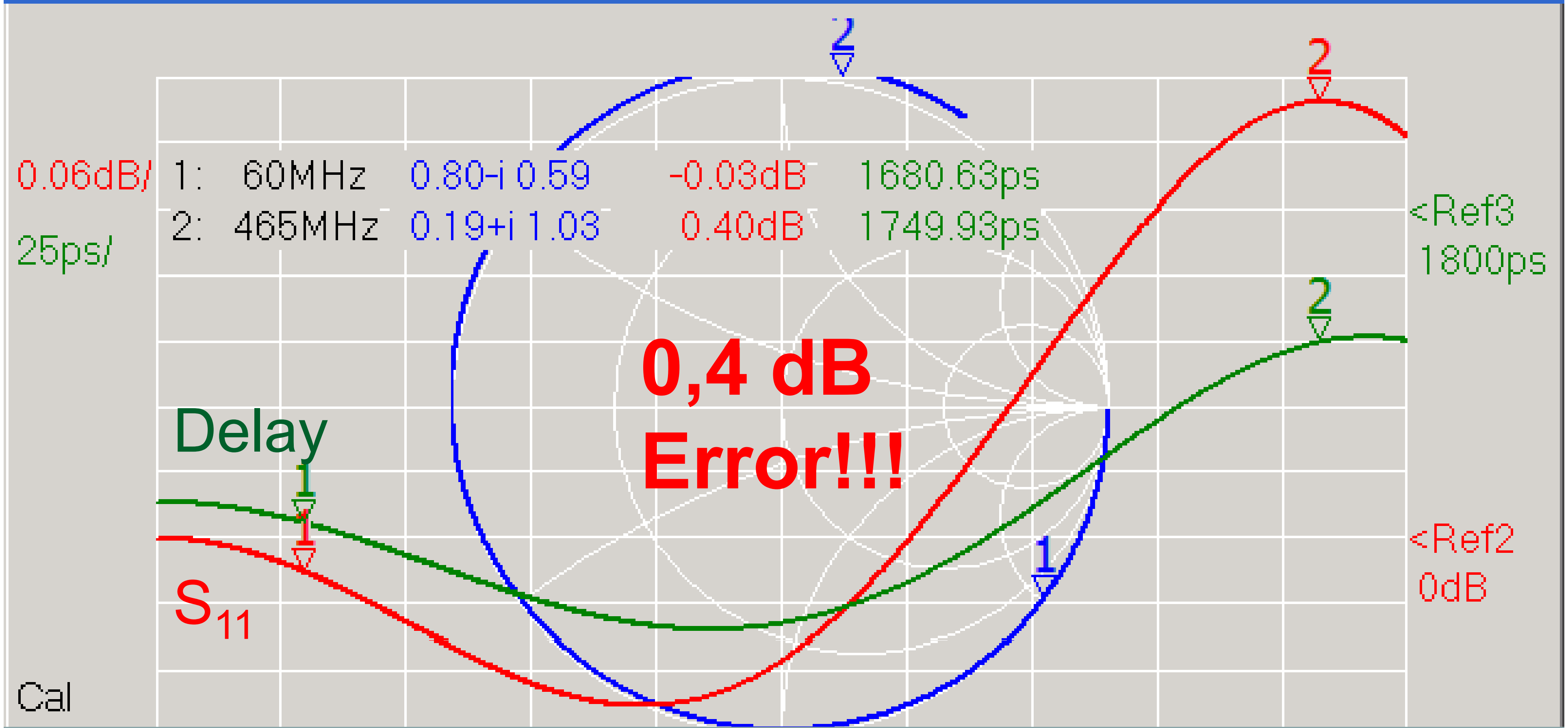
Hochschule Ulm

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



Simulation in VNWA Software

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

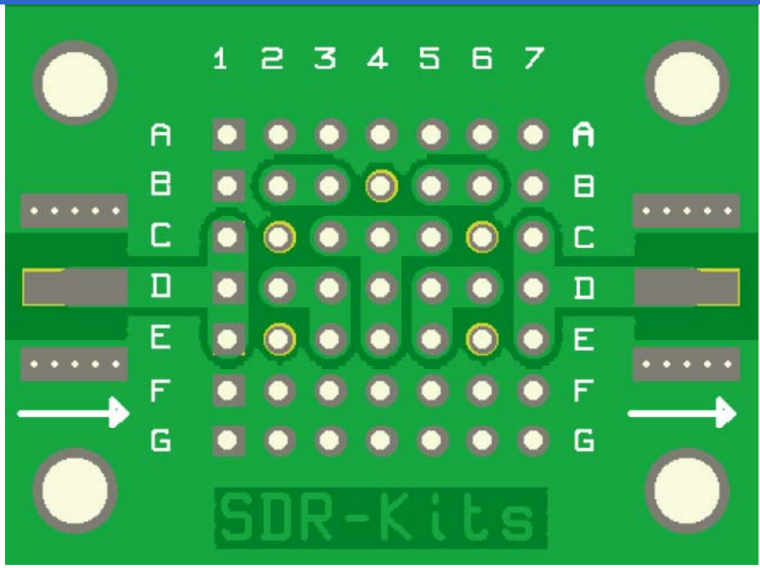


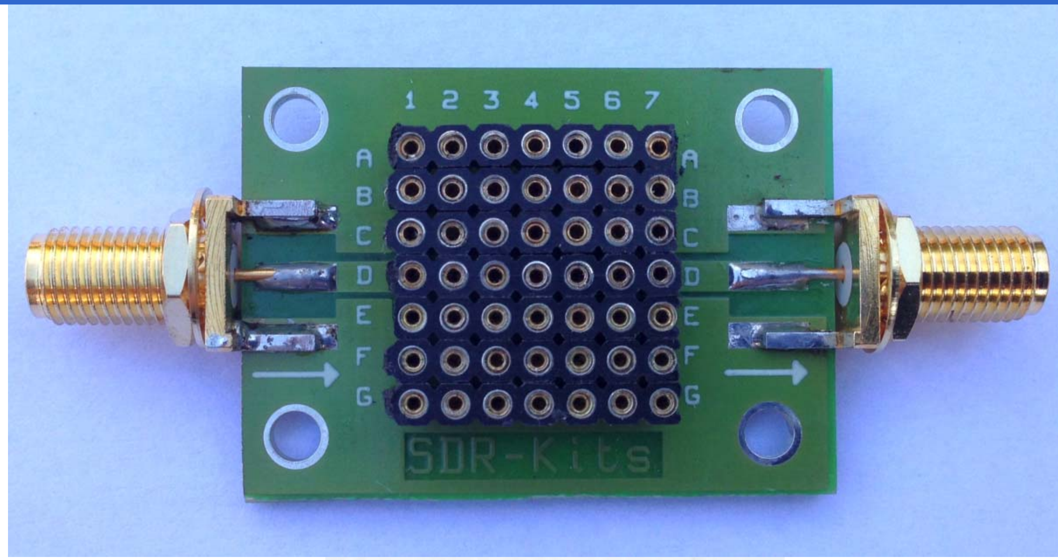
Previously simulated measurement data corrected again using ideal cal parameters

Applications …

Hochschule Ulm

Test Board for HF Experiments





Calibration Standards:

Short:

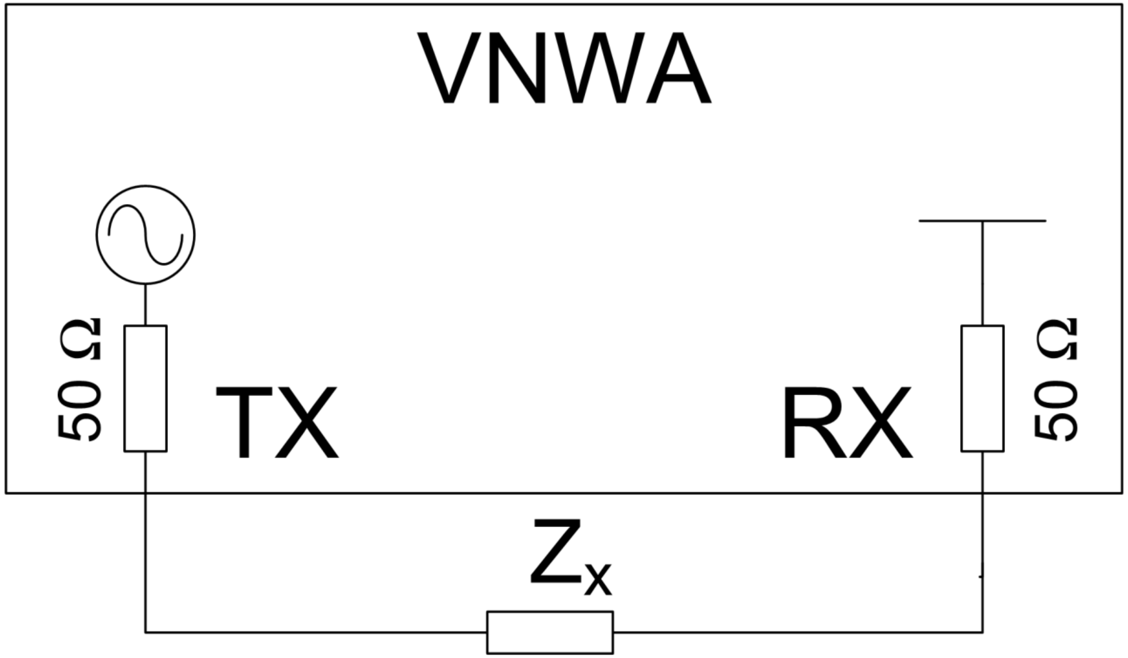
Load = 47Ω:

Open = n.c.

Thru:

Hochschule Ulm

Measuring „Load"-Resistor without SOL-Calibration?



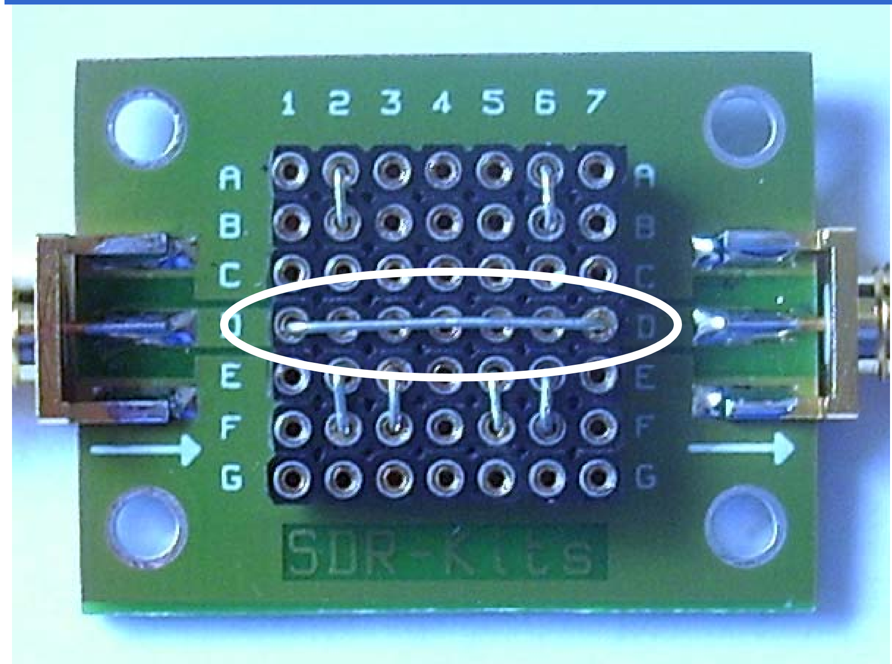
Z_x = 47 Ω yield ≈3,4 dB insertion loss.

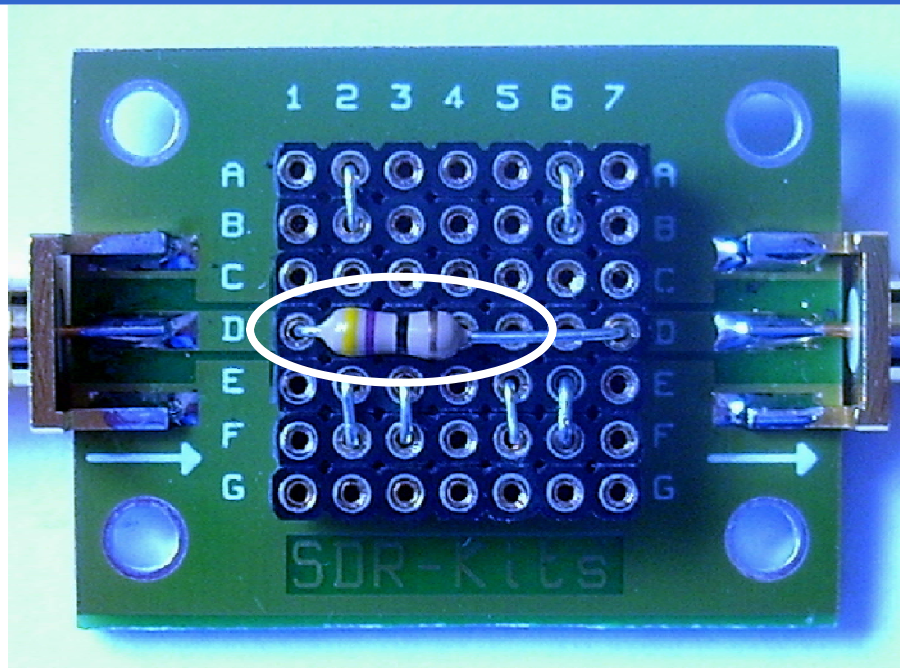
Works, because VNWA TX and RX port impedances are exactly 50 Ω.

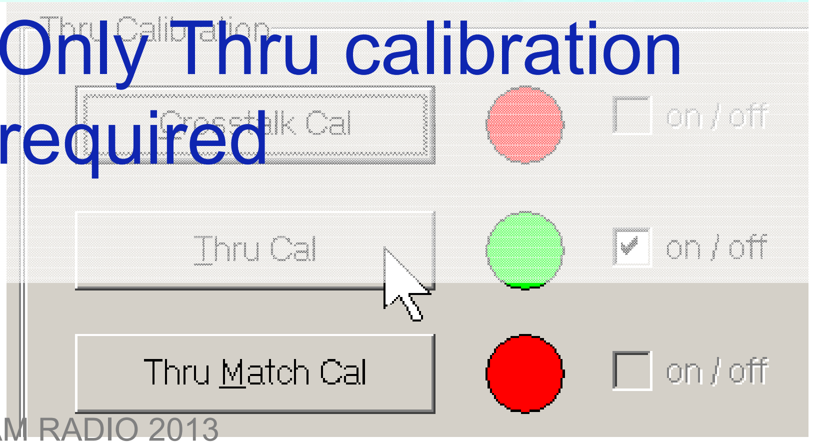
- only Thru calibration required!

Hochschule Ulm

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





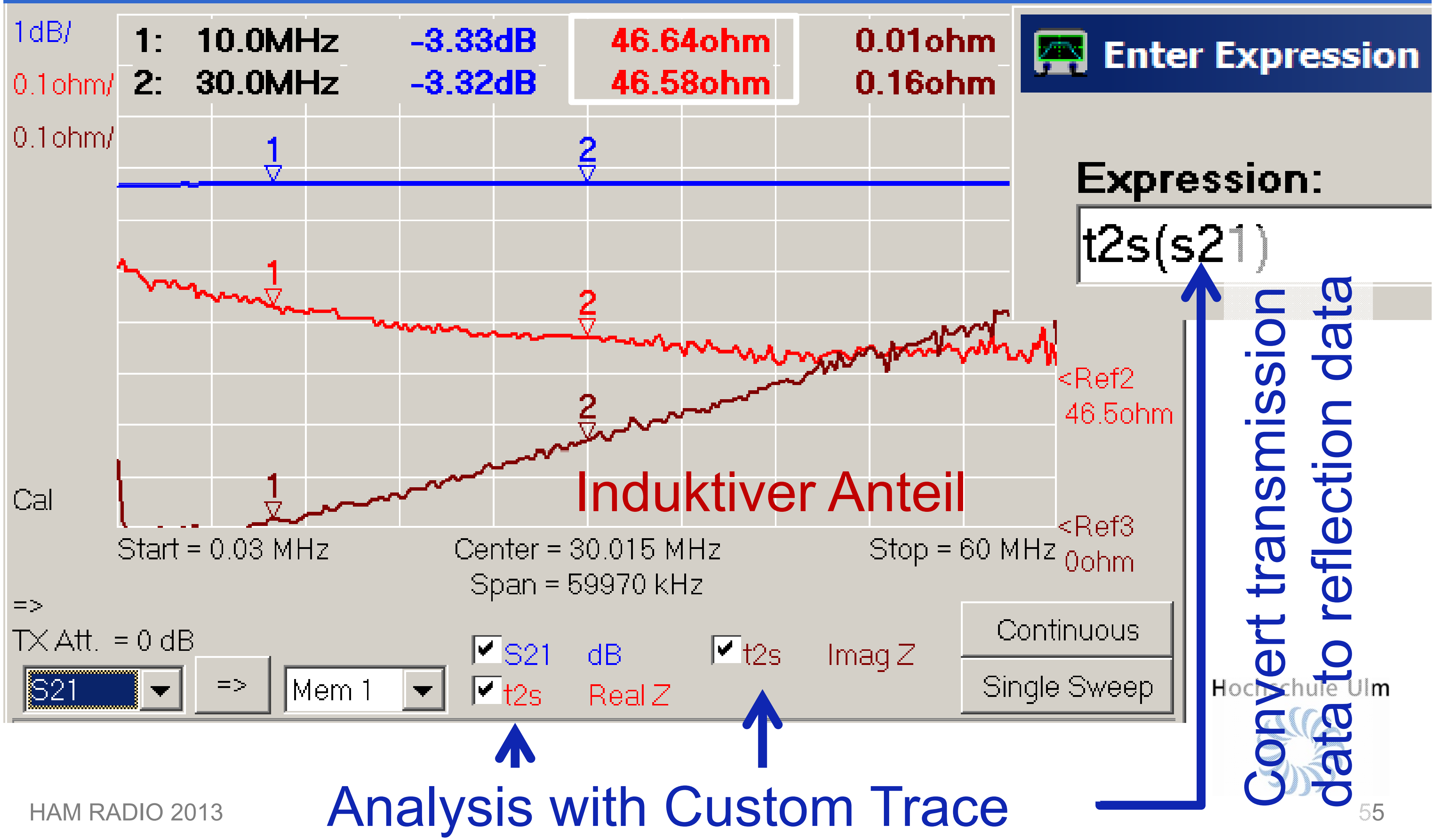


Only Thru calibration required

Measurement:
Resistor between TX and RX

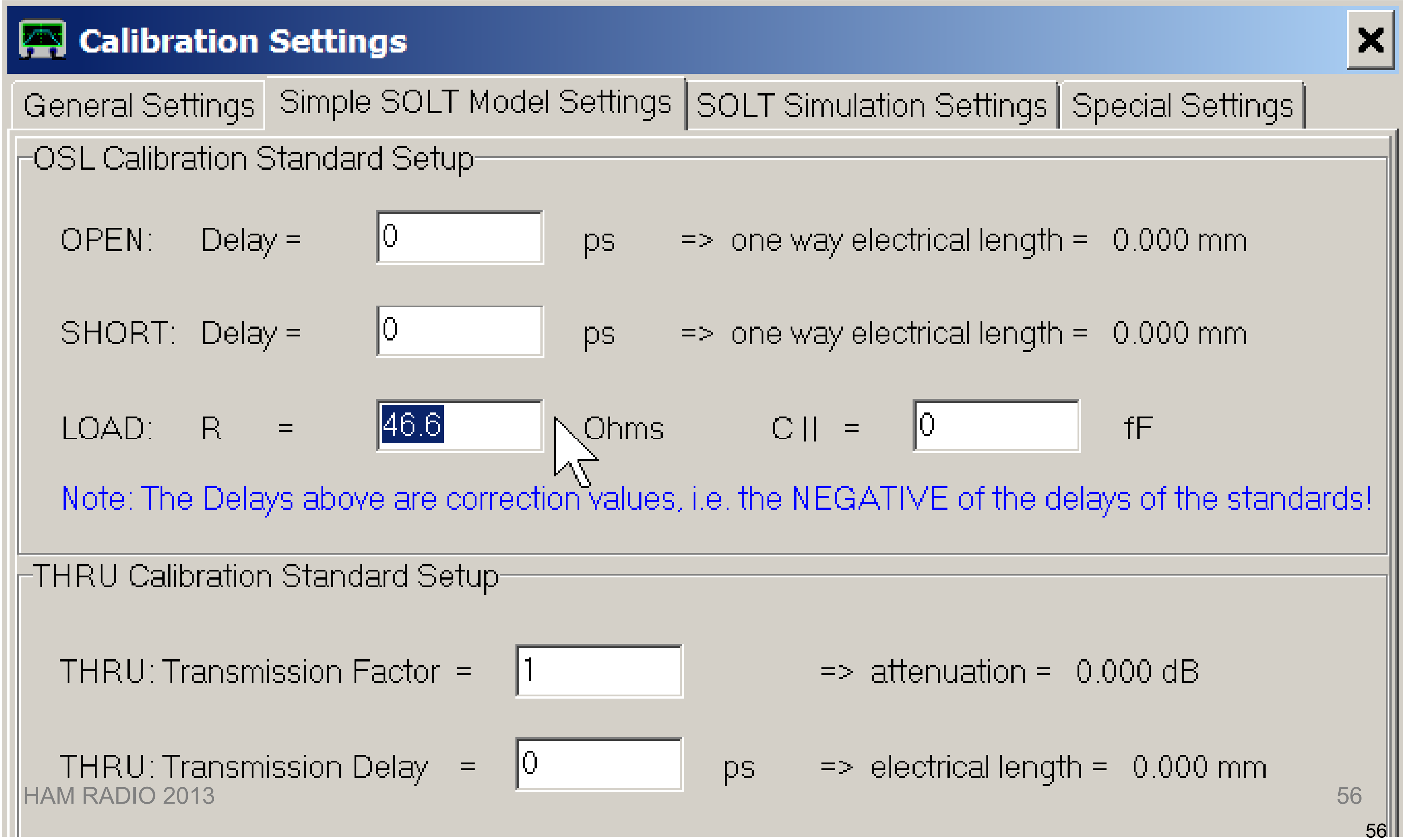
Hochschule Ulm

Measuring „Load"-Resistor
Result = 46,6 Ω

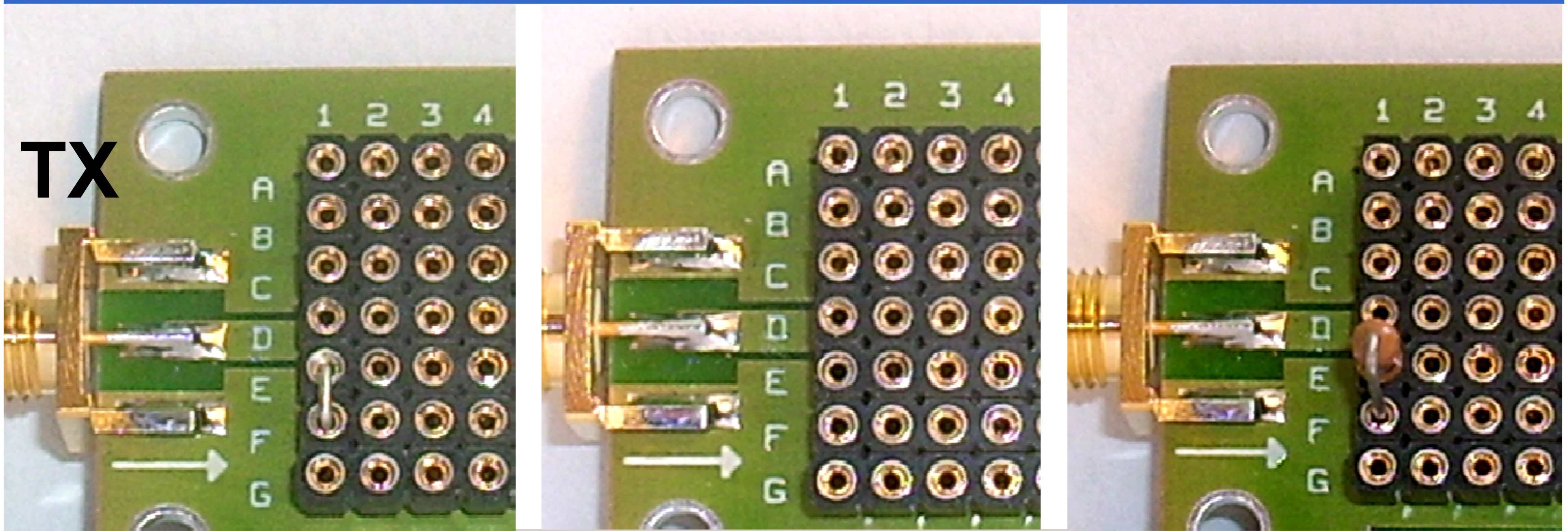


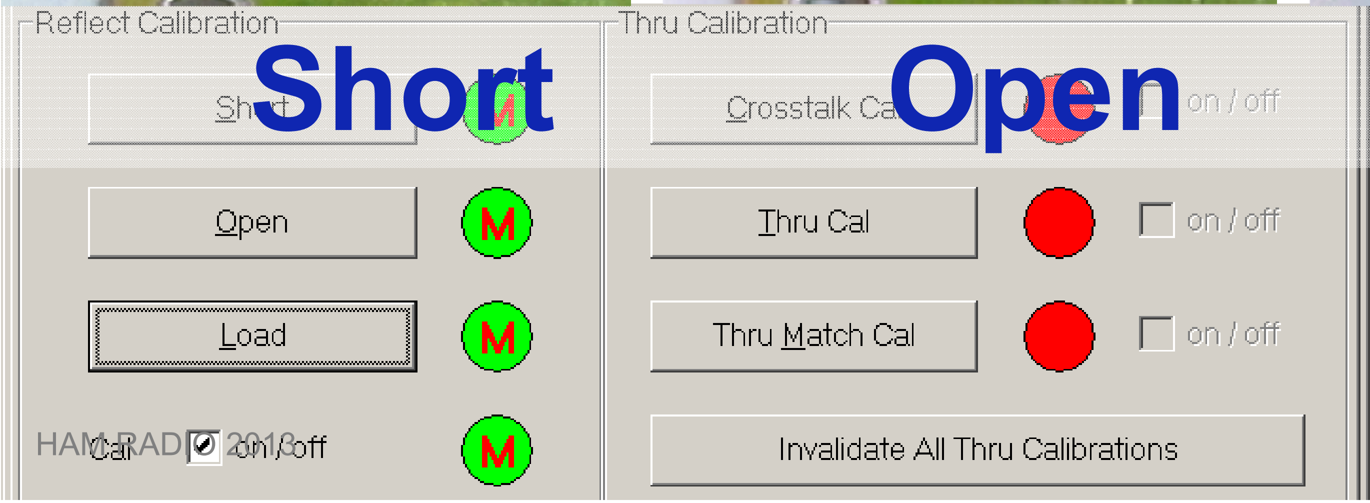
Hochschule Ulm

Simple Calibration Standard Model: Only measured Load-Resistance



SOL-Calibration for S_{11}-Measurement





Short **Open** **Load**

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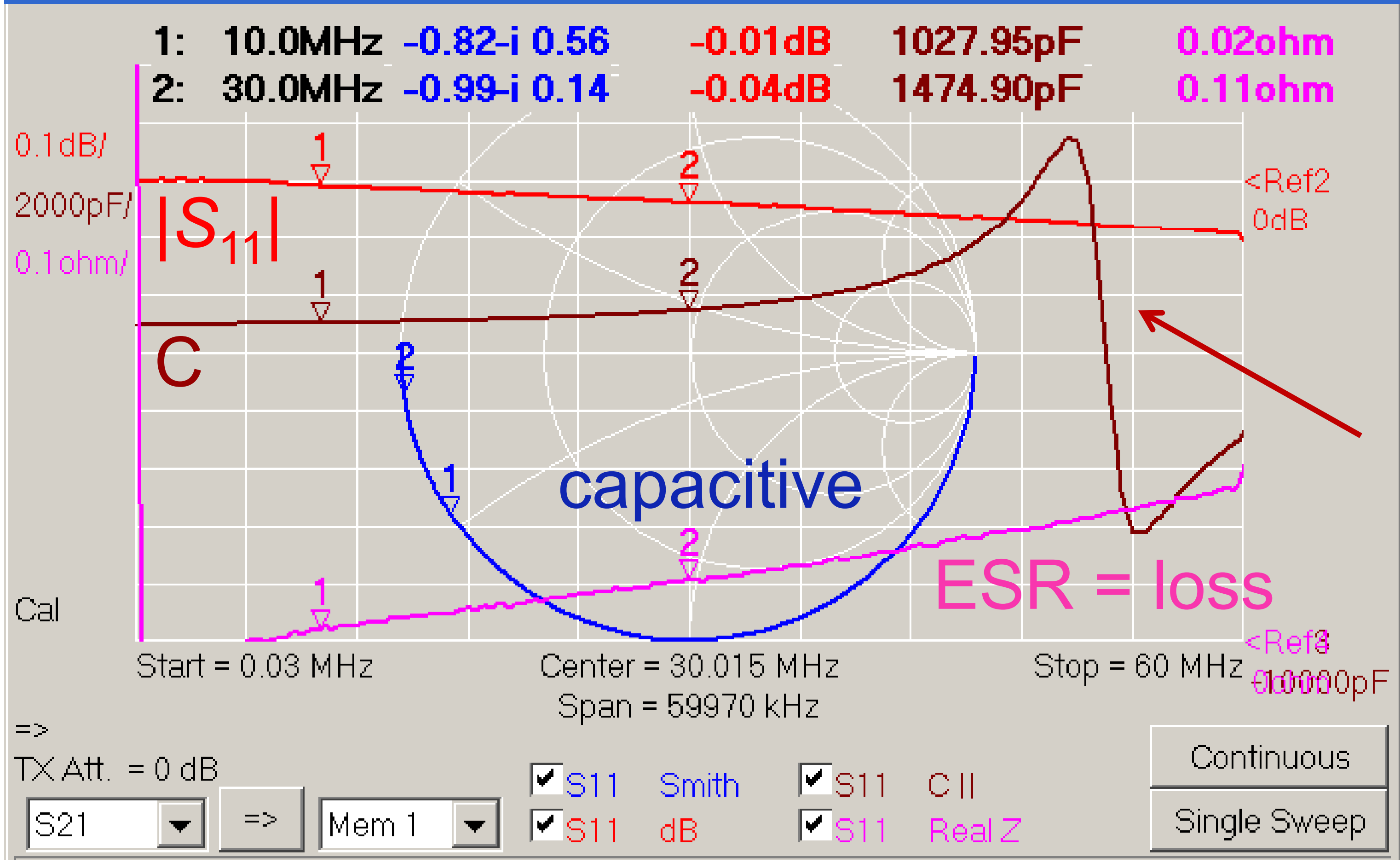
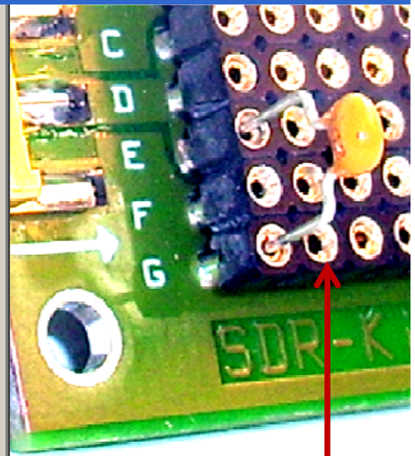
Reflexion Measurement (S_{11}) of a 1 nF Capacitor



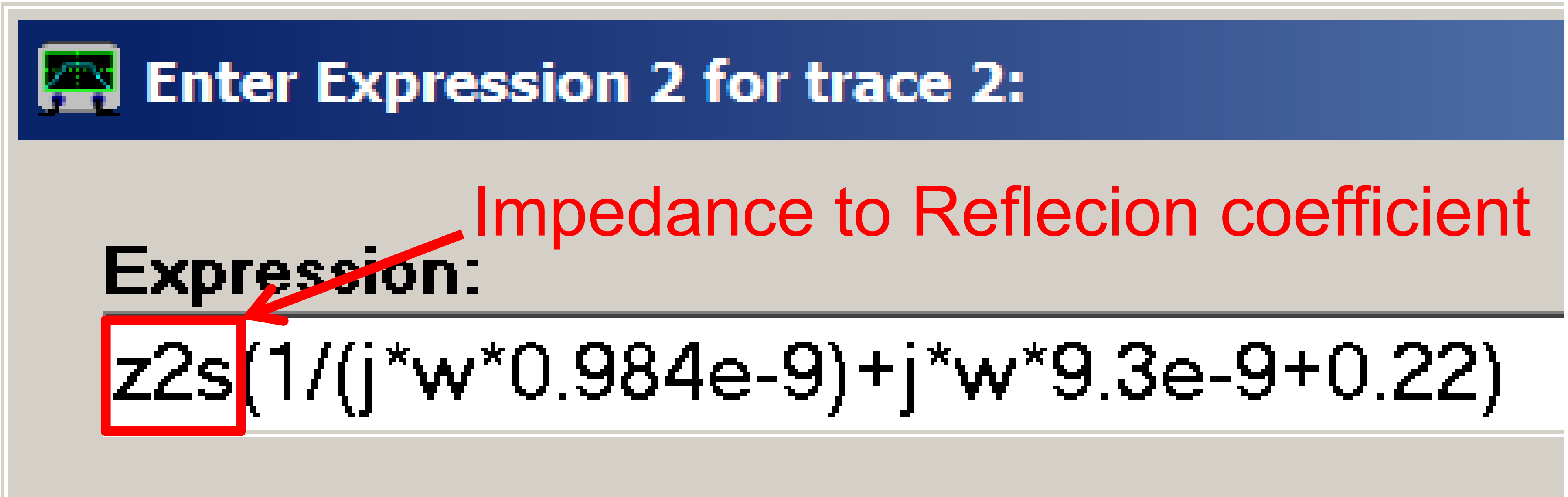


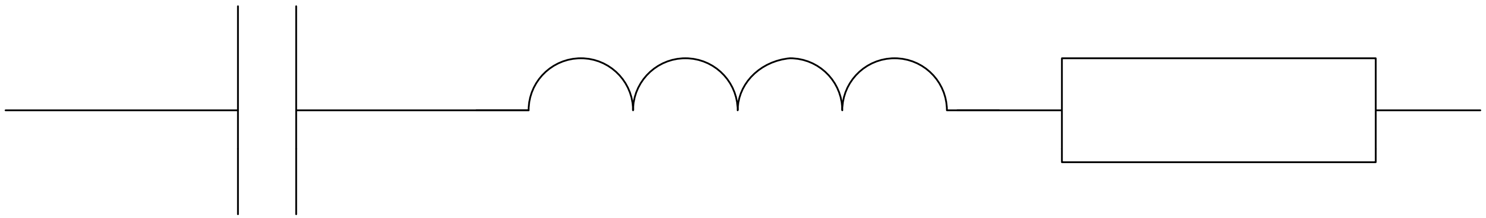
Resonance due to component wires

Hochschule Ulm

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

Modelling of Measurement Result in VNWA using Custom-Trace



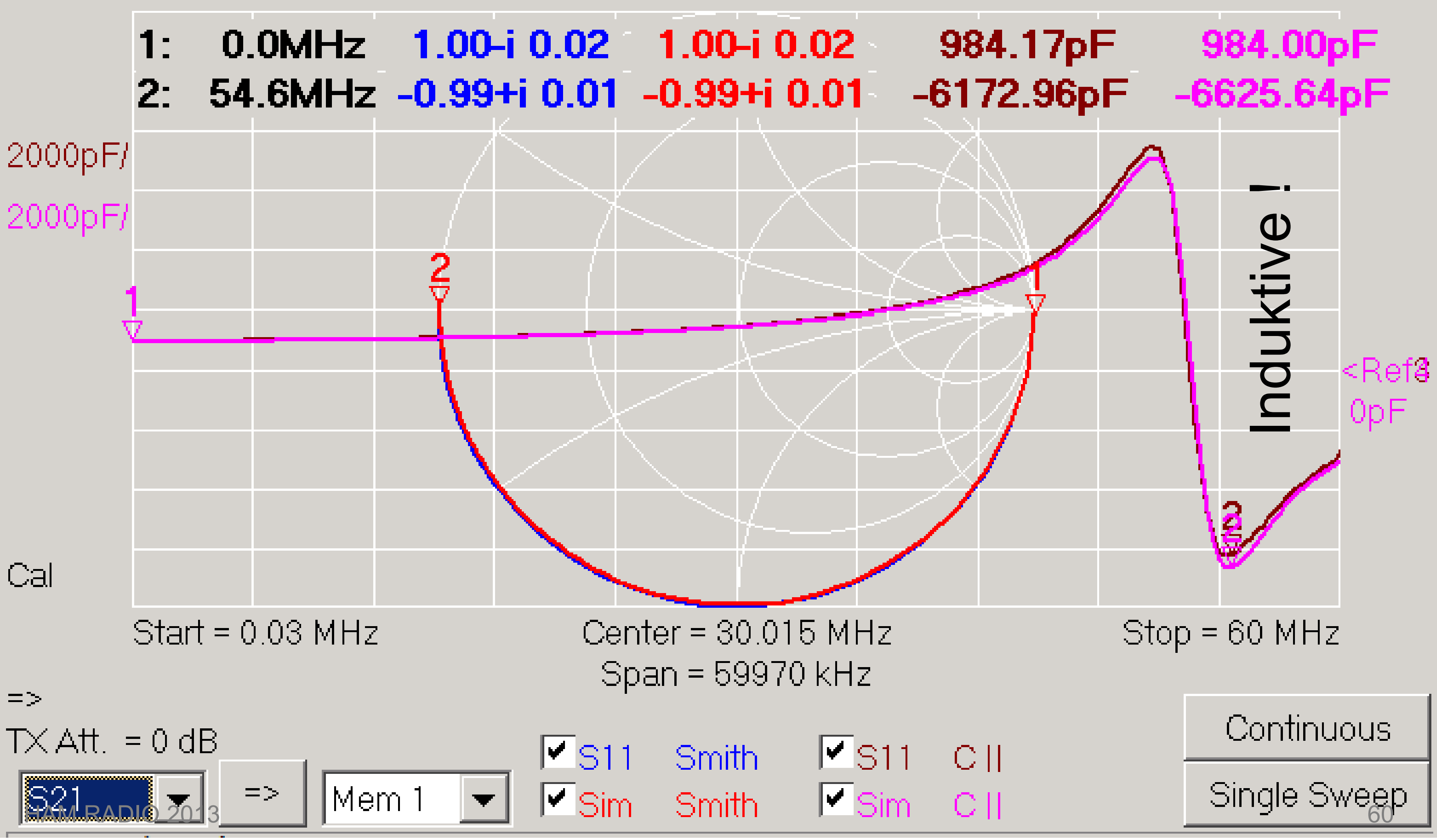


0,984 nF 9,3 nH 0,22 Ω

einfaches Modell

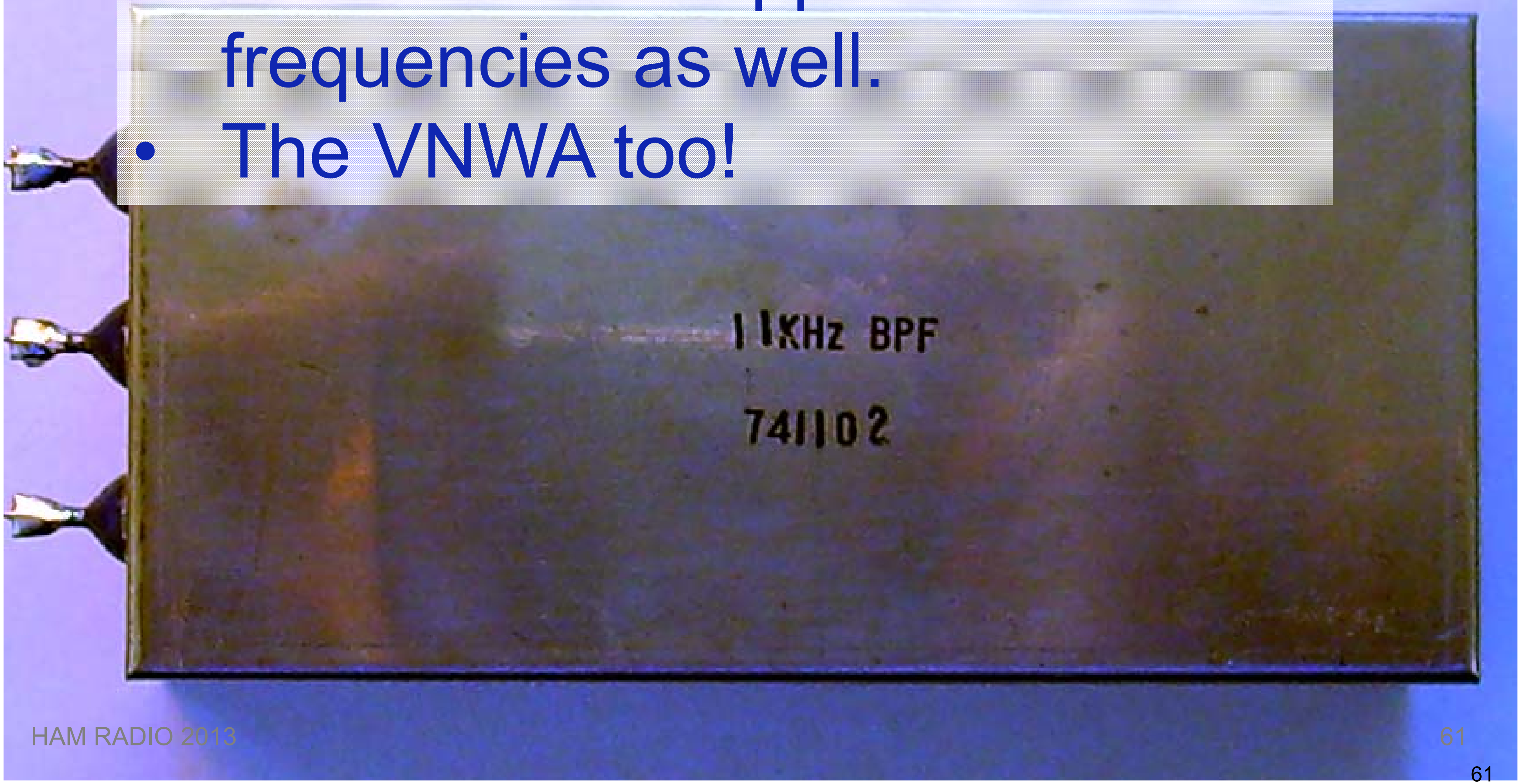
Hochschule Ulm

The Model is quite accurate!

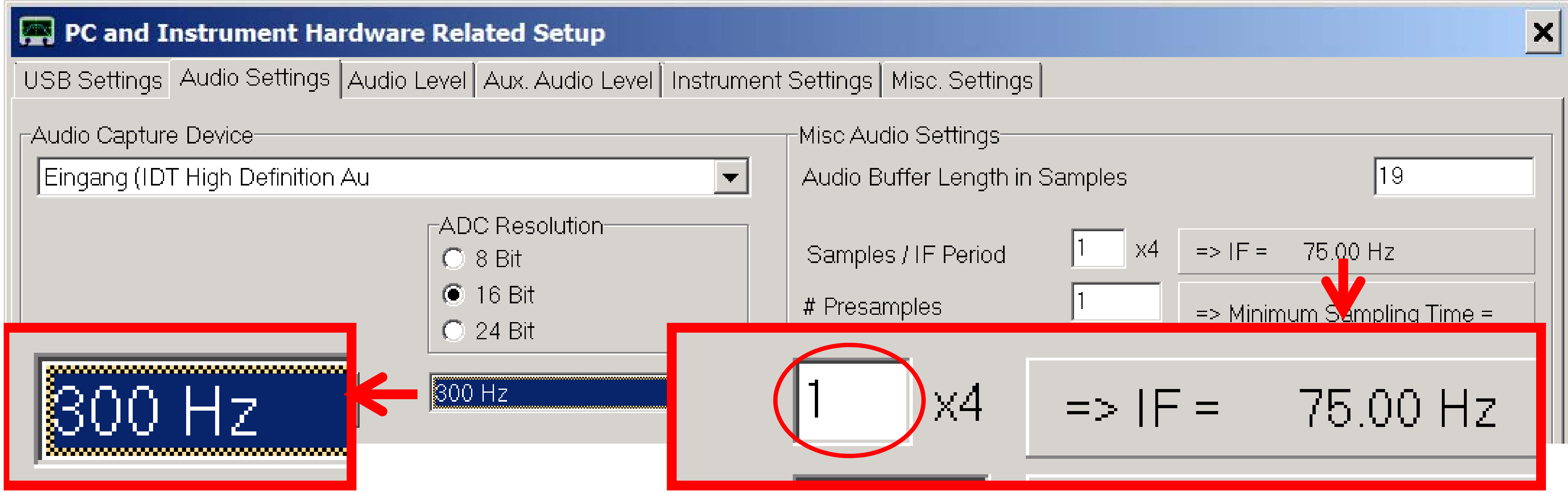


Two Port Measurement of a 12 kHz Band Pass Filter

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



Special VNWA Settings for low Frequencies

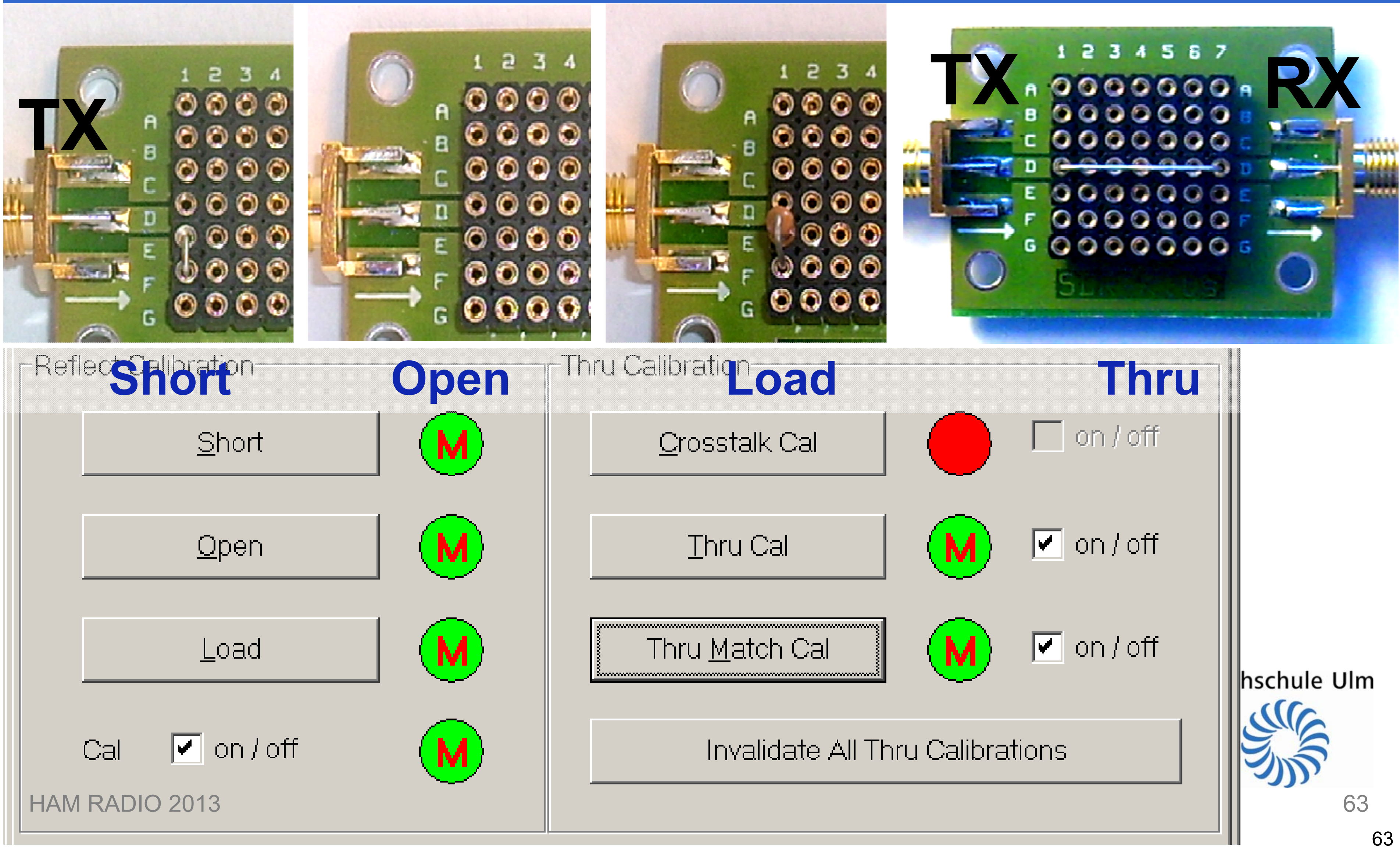


Lowest sample rate 300 Hz
→ Nyquist limit 150 Hz
→ Measurements down to ≈150 Hz possible

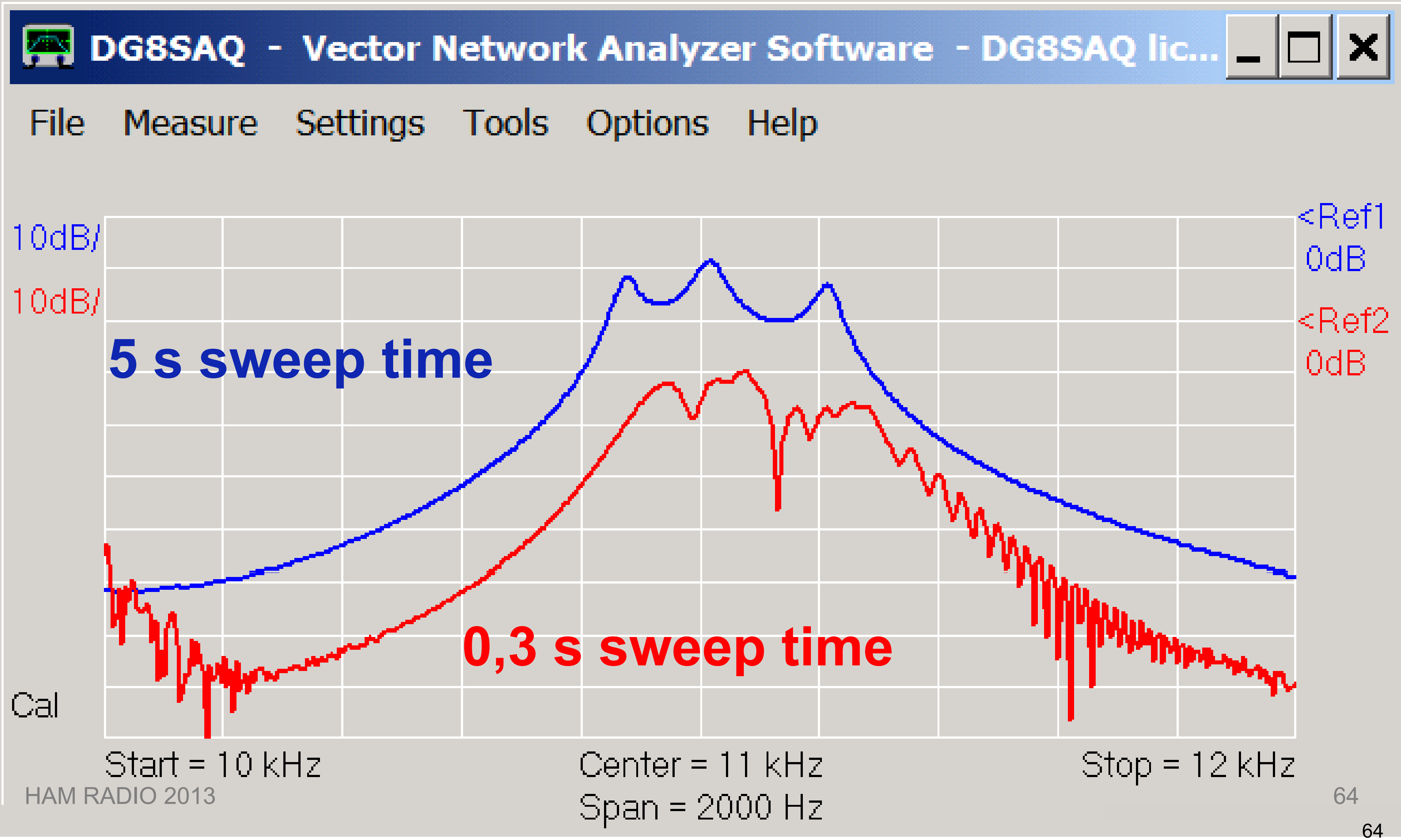
IF must be within Codec frequency range (20 Hz…16kHz)

Hochschule Ulm

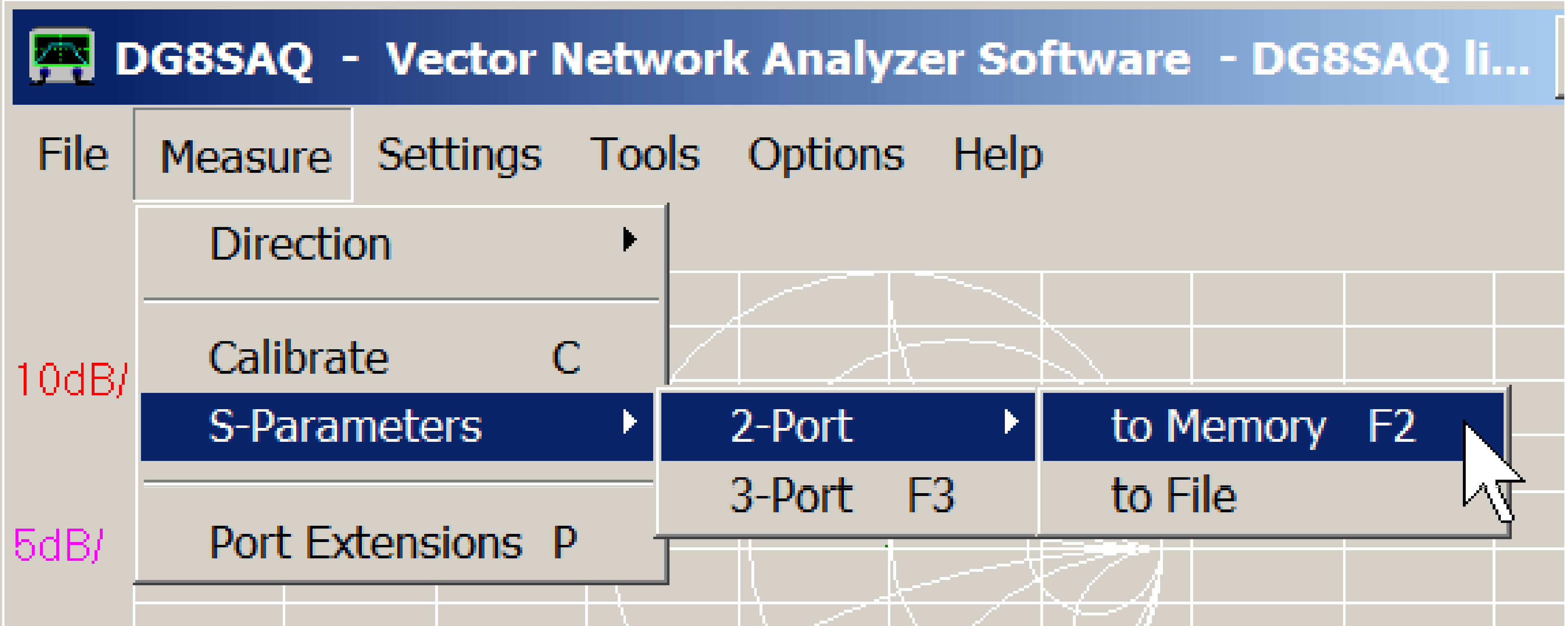
SOLT-Calibration for 2-Port Measurements



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



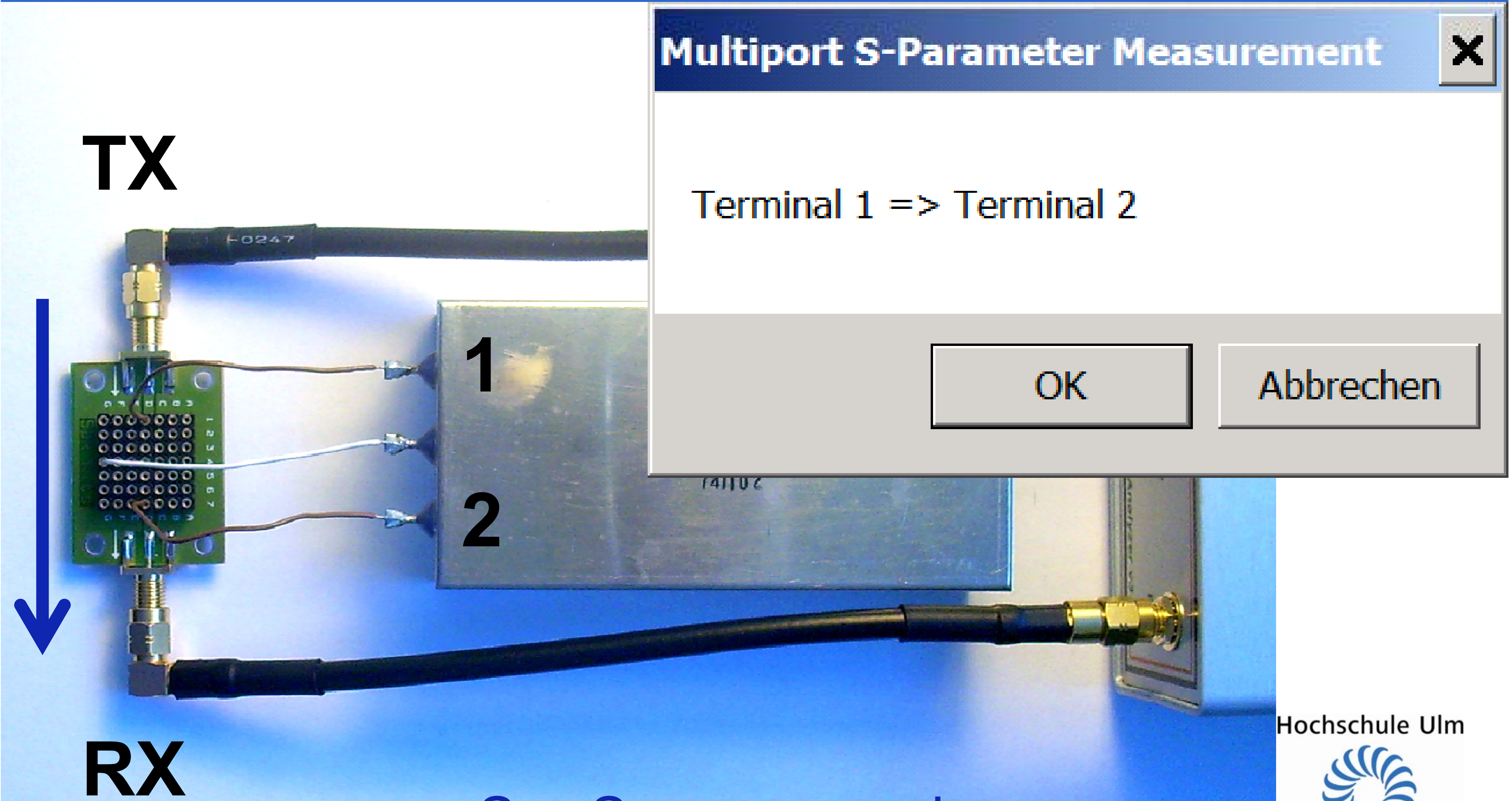
Two Port Measurement of a 12 kHz Band Pass Filter



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

Hochschule Ulm

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



S_{11}, S_{21} measured

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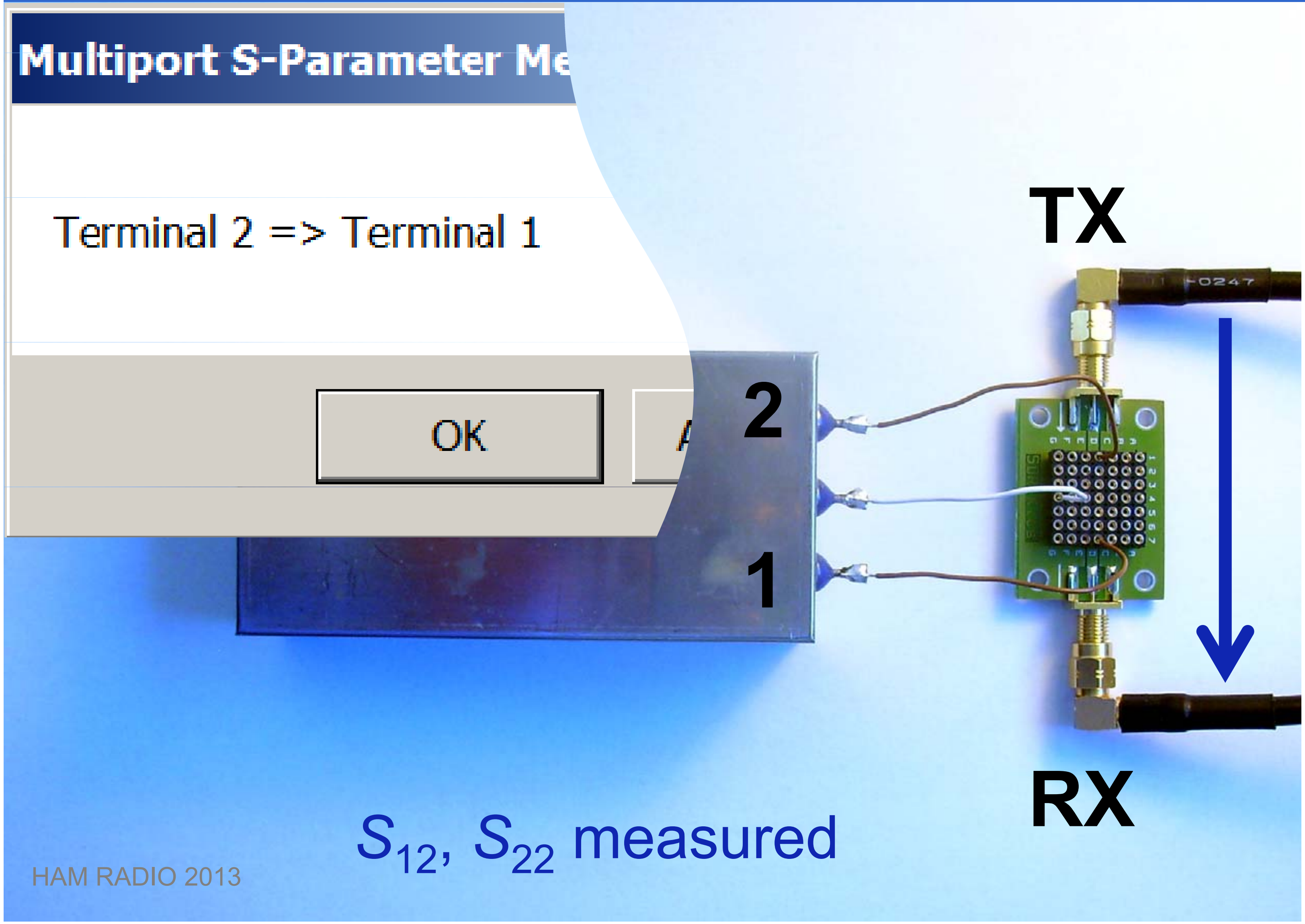
Two Port Measurement of a 12 kHz Band Pass Filter: Reverse Measurement



S_{12}, S_{22} measured

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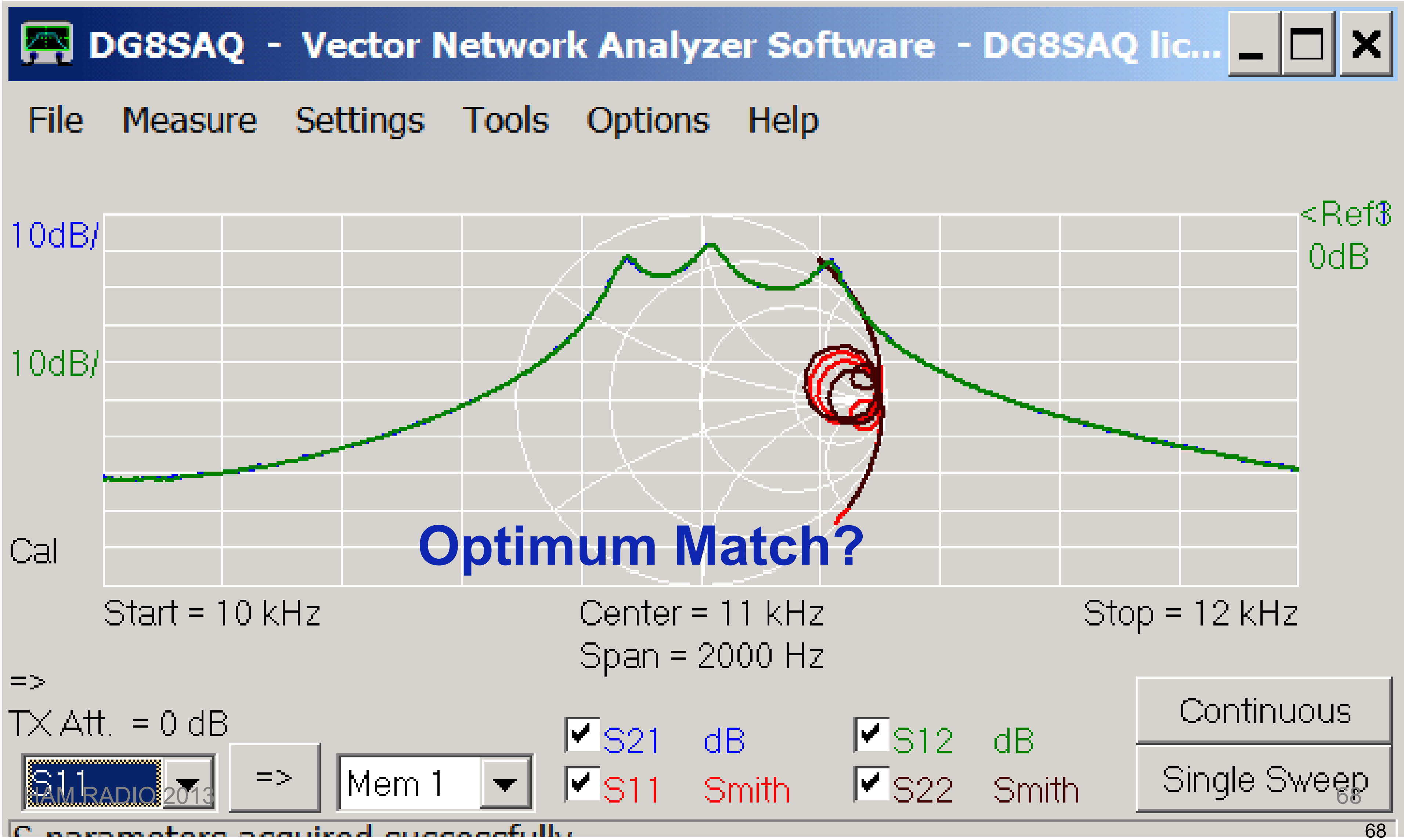
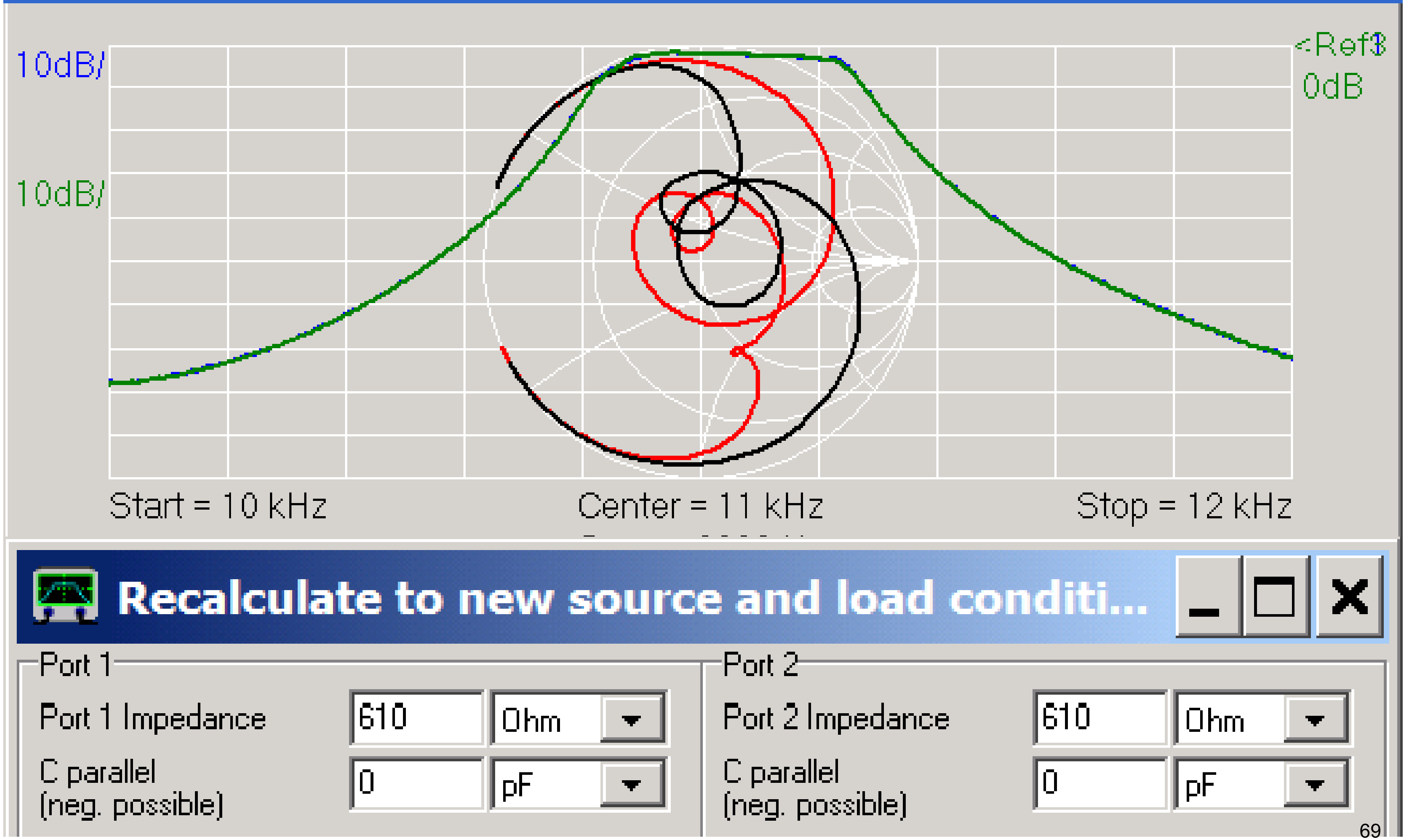
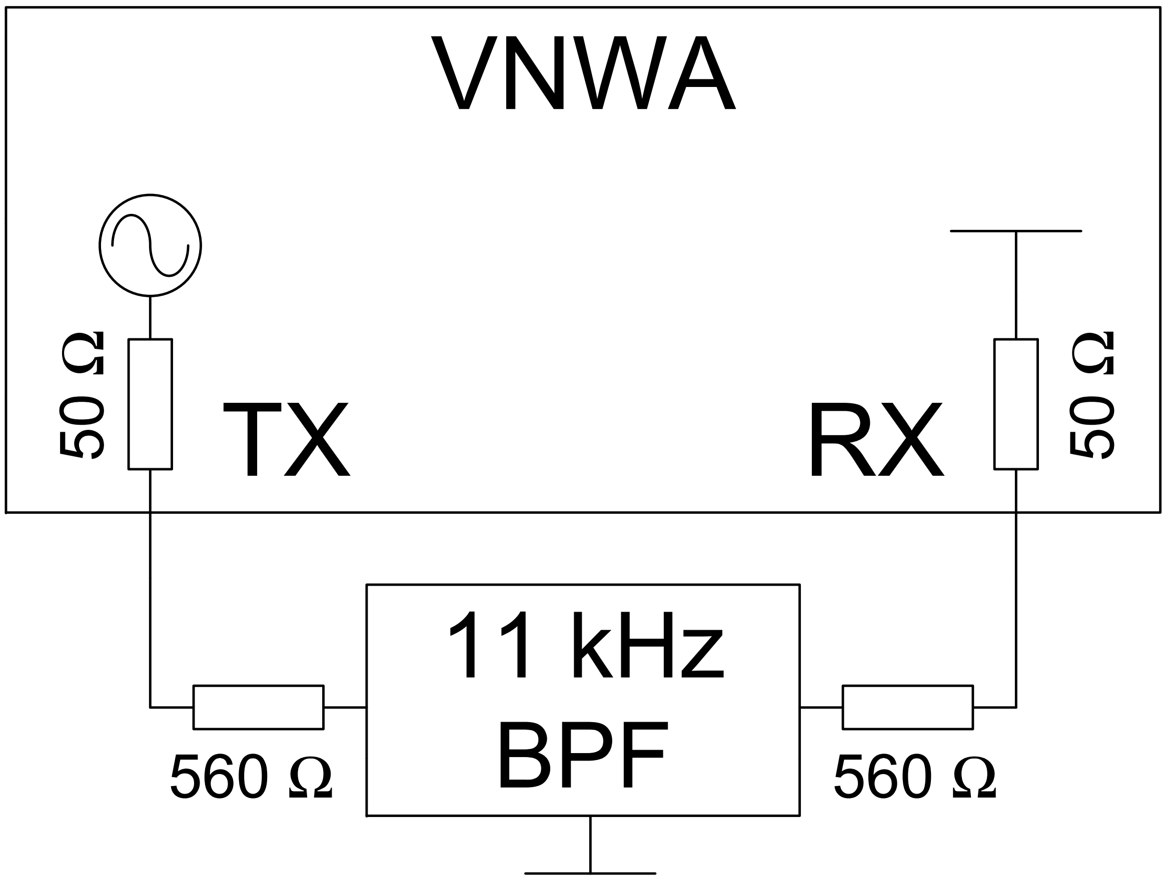
What are measured 2-Port S-Parameters good for?



Matching Analysis: VNWA Matching Tool
Optimum: $Z_{in} = Z_{out} = 610\ \Omega$



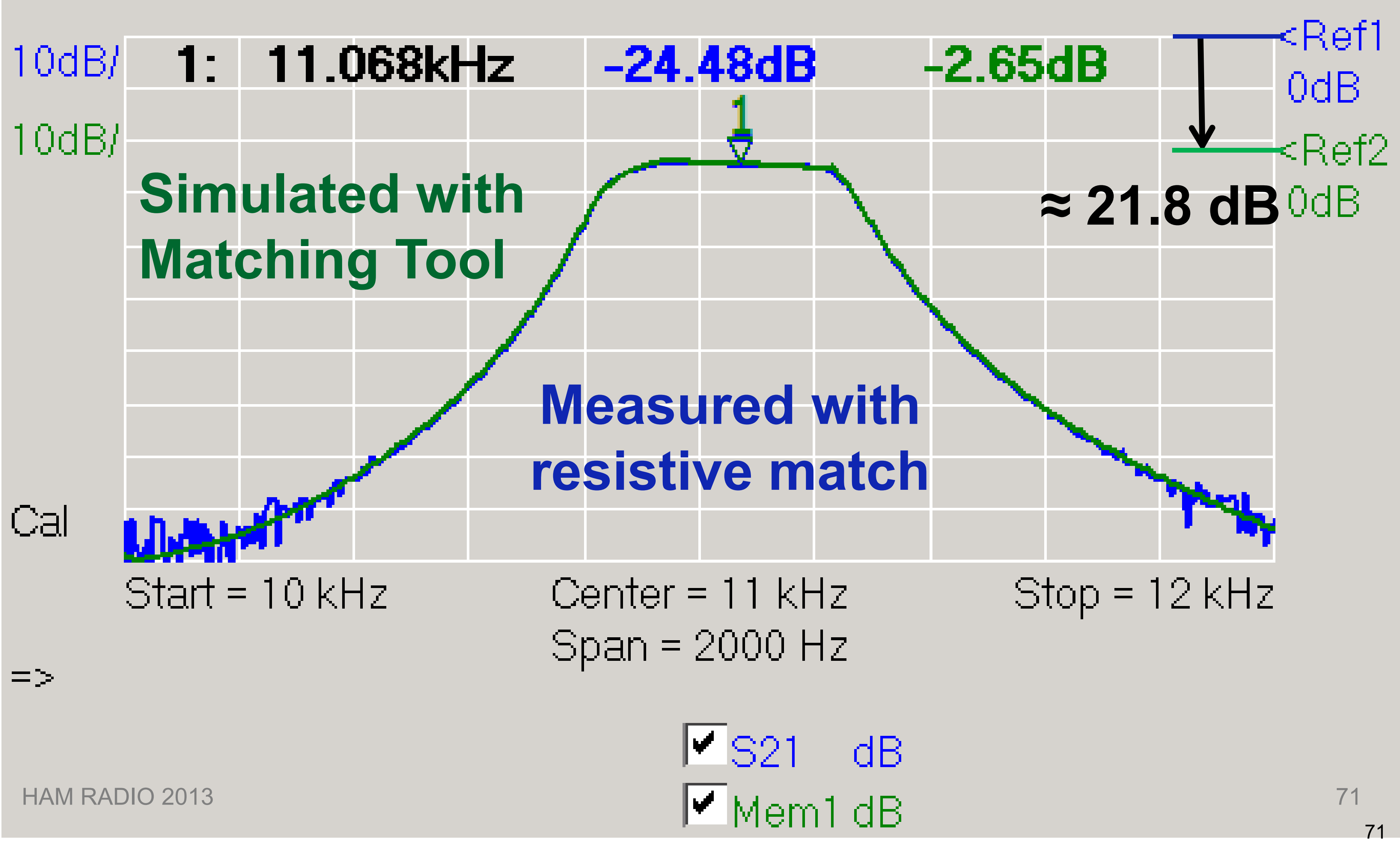
Forced Impedance Match using Resistors



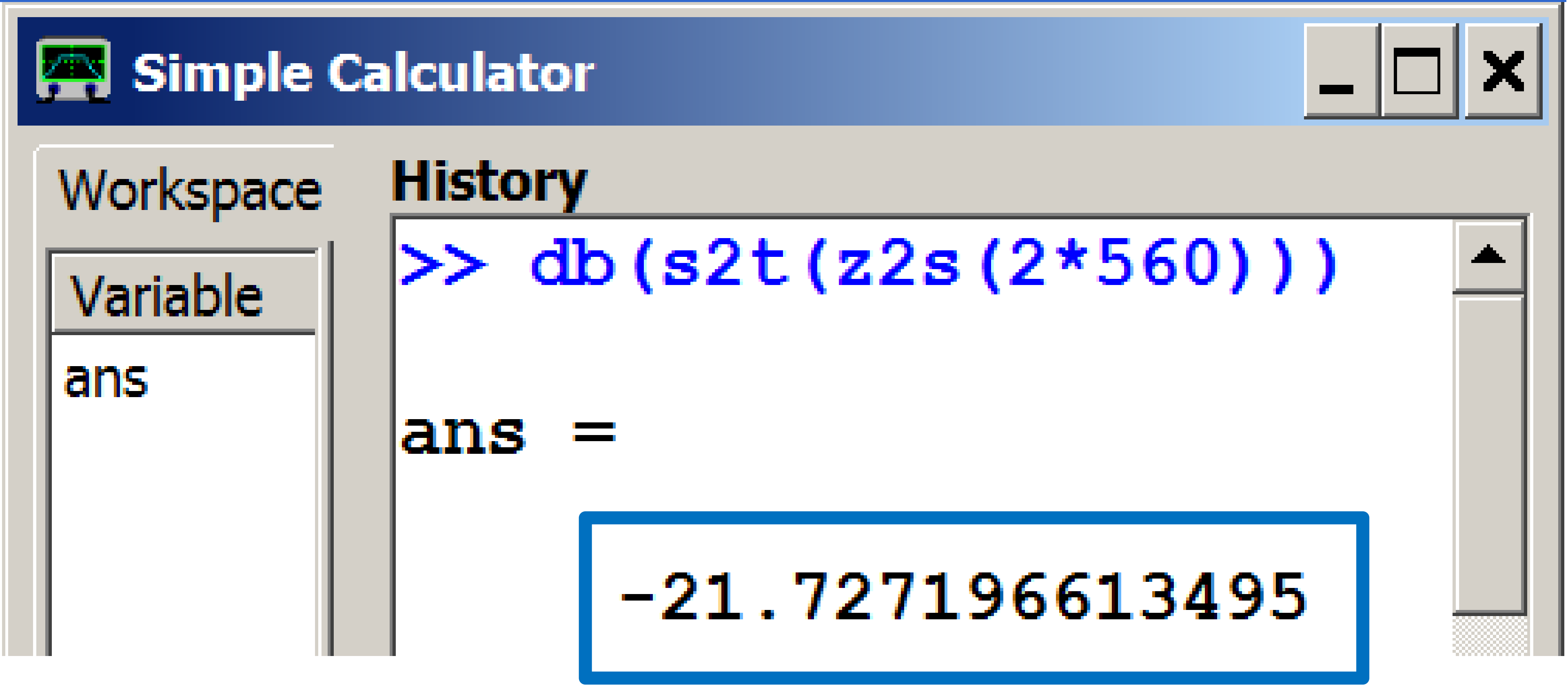
$50\ \Omega + 560\ \Omega = 610\ \Omega$

Hochschule Ulm

Match works except for increased Loss



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

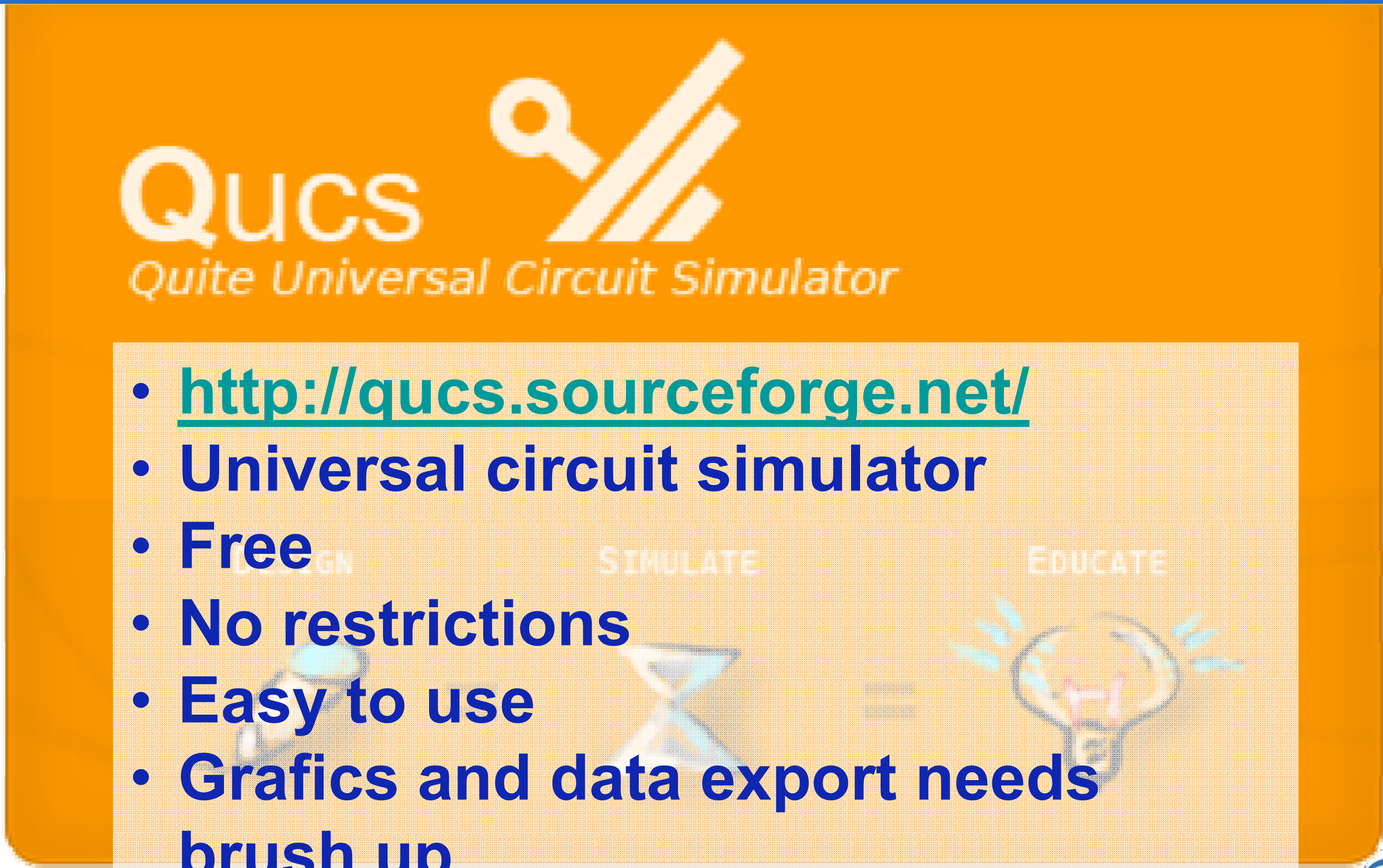


21,7 dB additional attenuation ✓

Hochschule Ulm

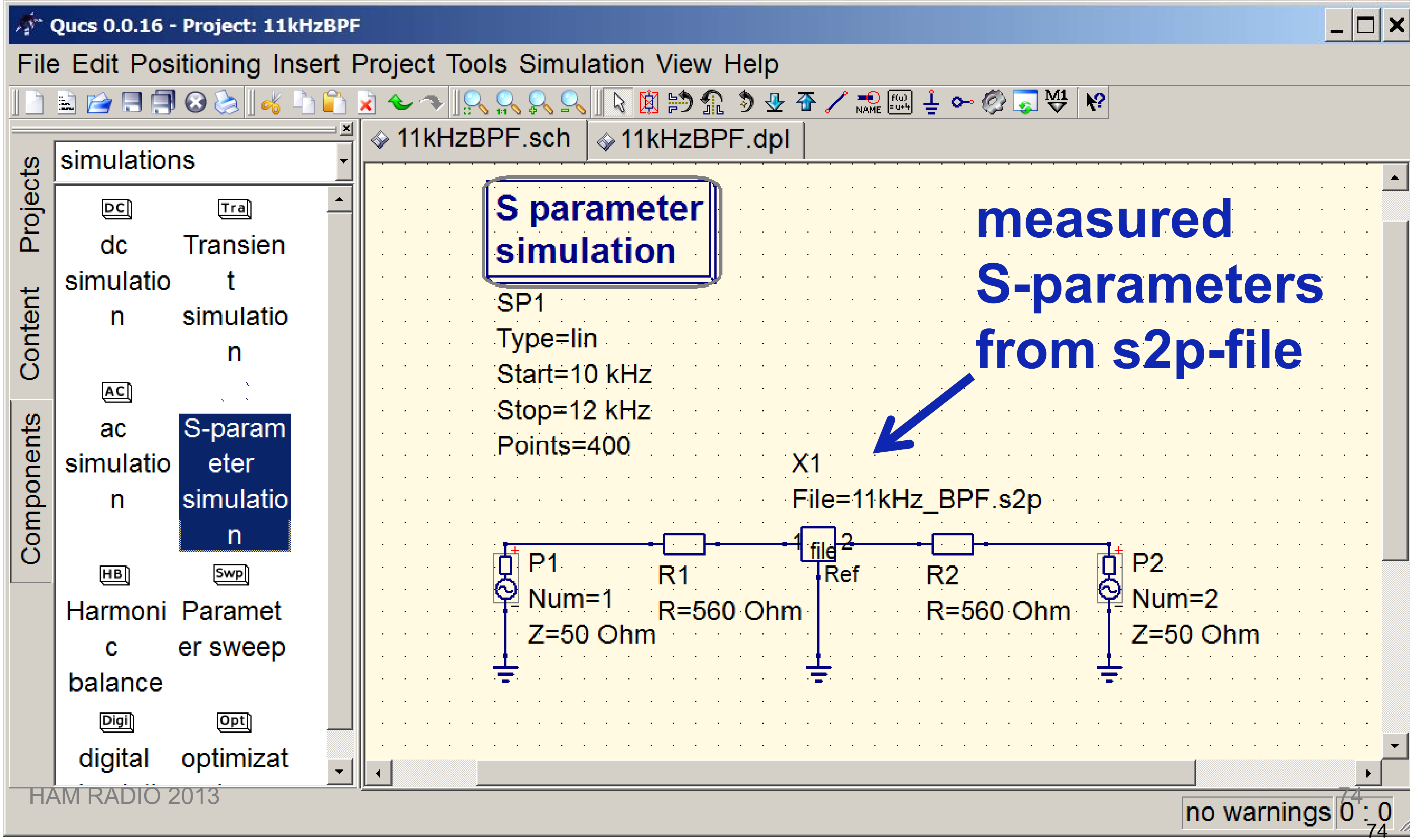
72

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

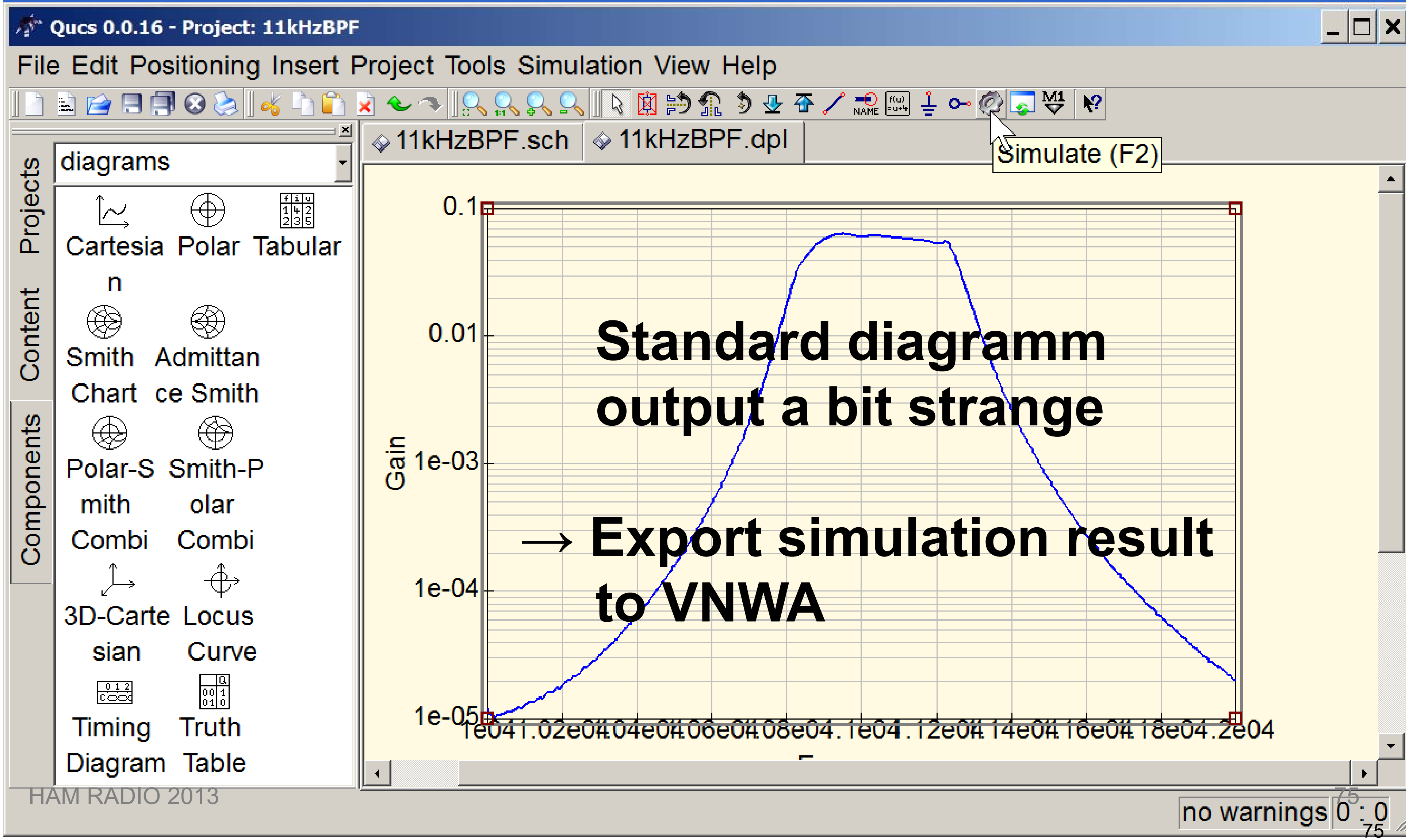


- http://qucs.sourceforge.net/
- **Universal circuit simulator**
- **Free**
- **No restrictions**
- **Easy to use**
- **Grafics and data export needs brush up**

Measured S-Parameters in QUCS



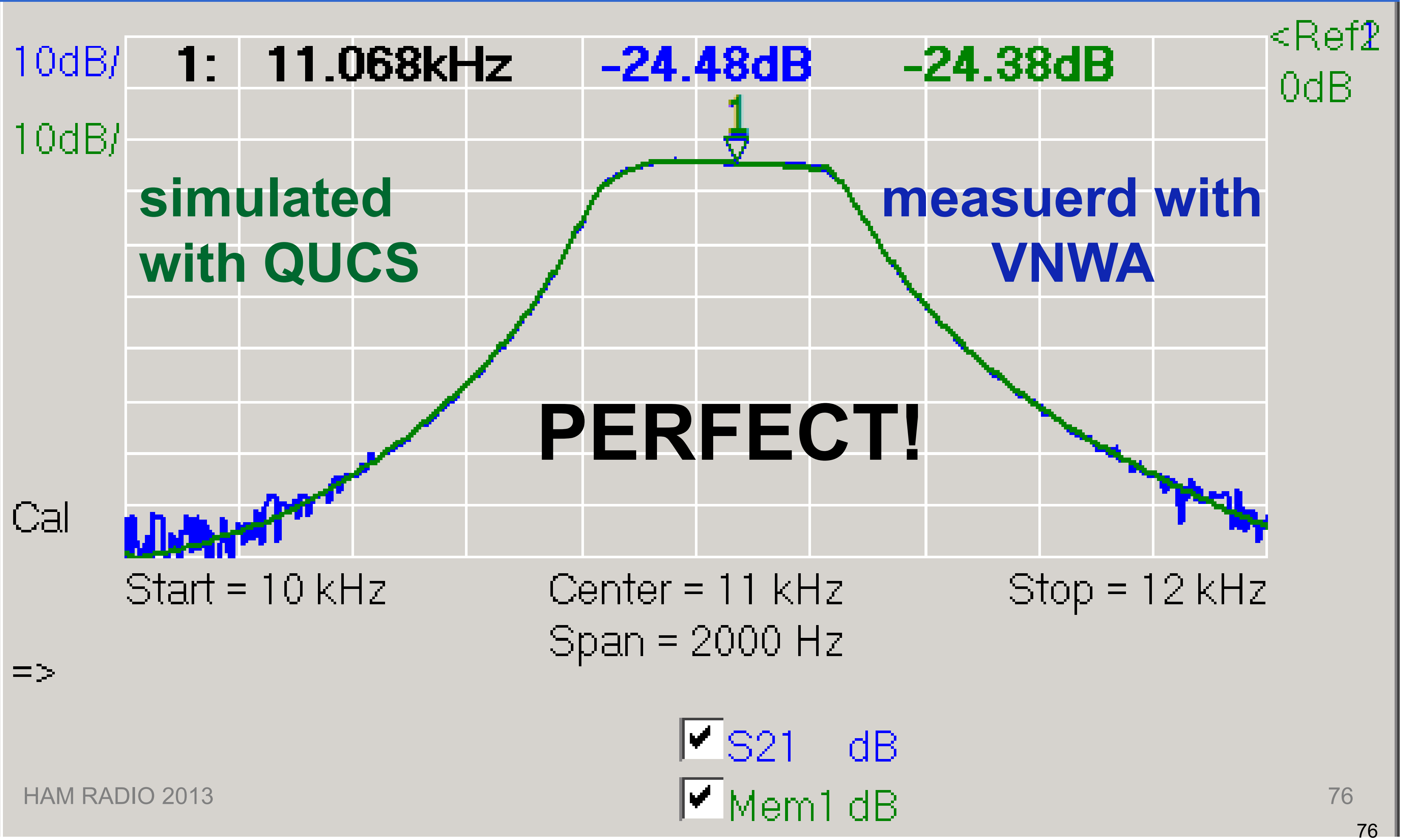
Matching Simulation in QUCS



Standard diagramm output a bit strange

→ Export simulation result to VNWA

Comparison QUCS-Simulation vs. Measurement

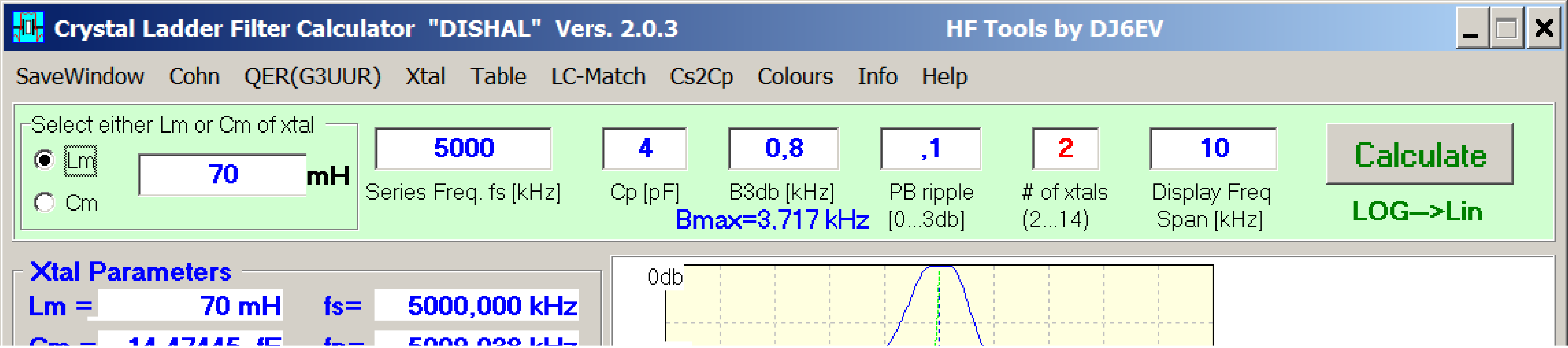


Free Filter Design Software (1): Elsie – for LC-Filters

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

Hochschule Ulm

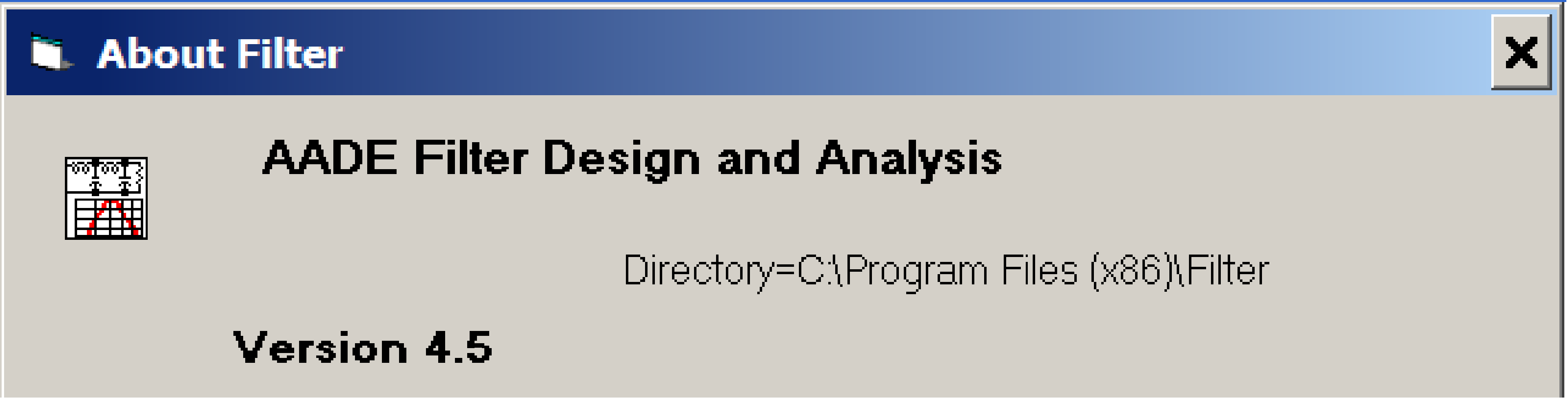
Free Filter Design Software (2): Dishal – for Crystal Filters



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

Hochschule Ulm

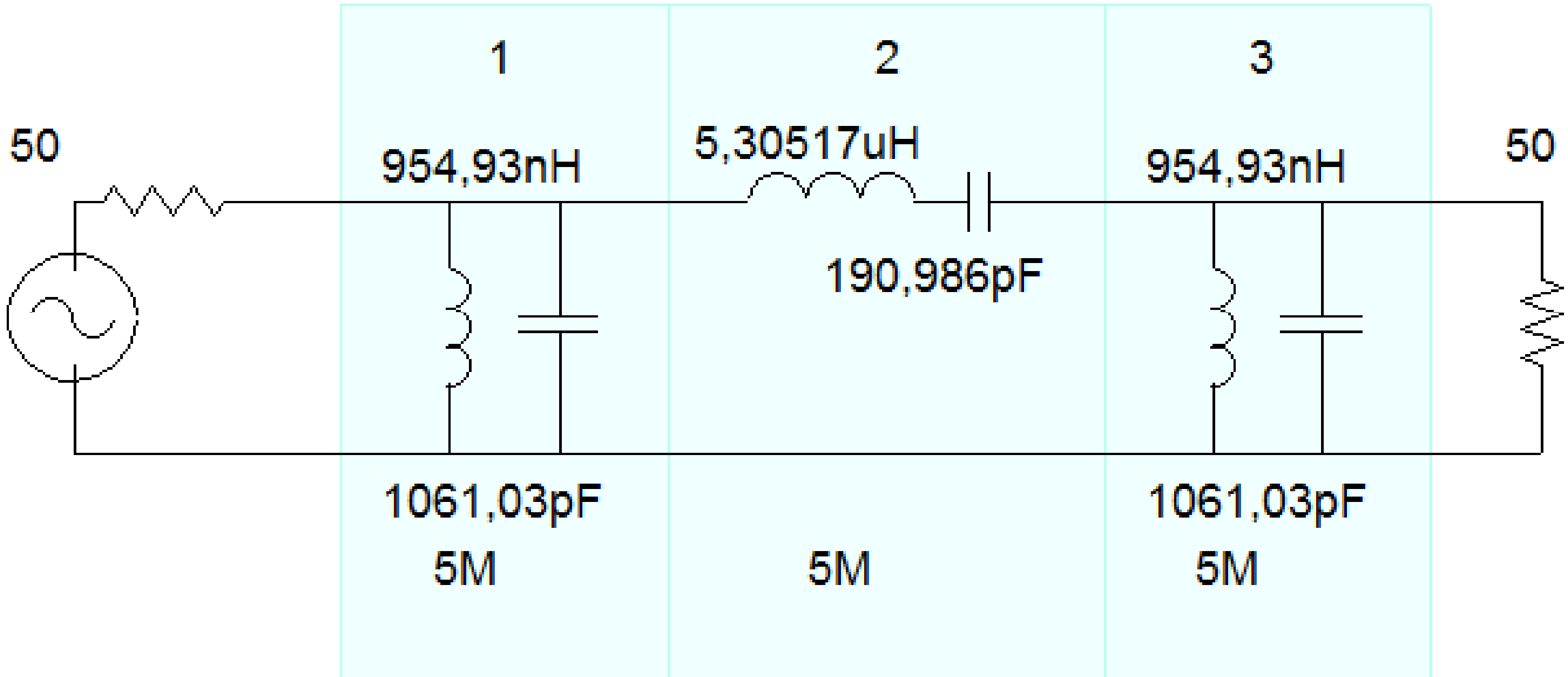
Free Filter Design Software (3): AADE Filter Design - for all filters



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

Hochschule Ulm

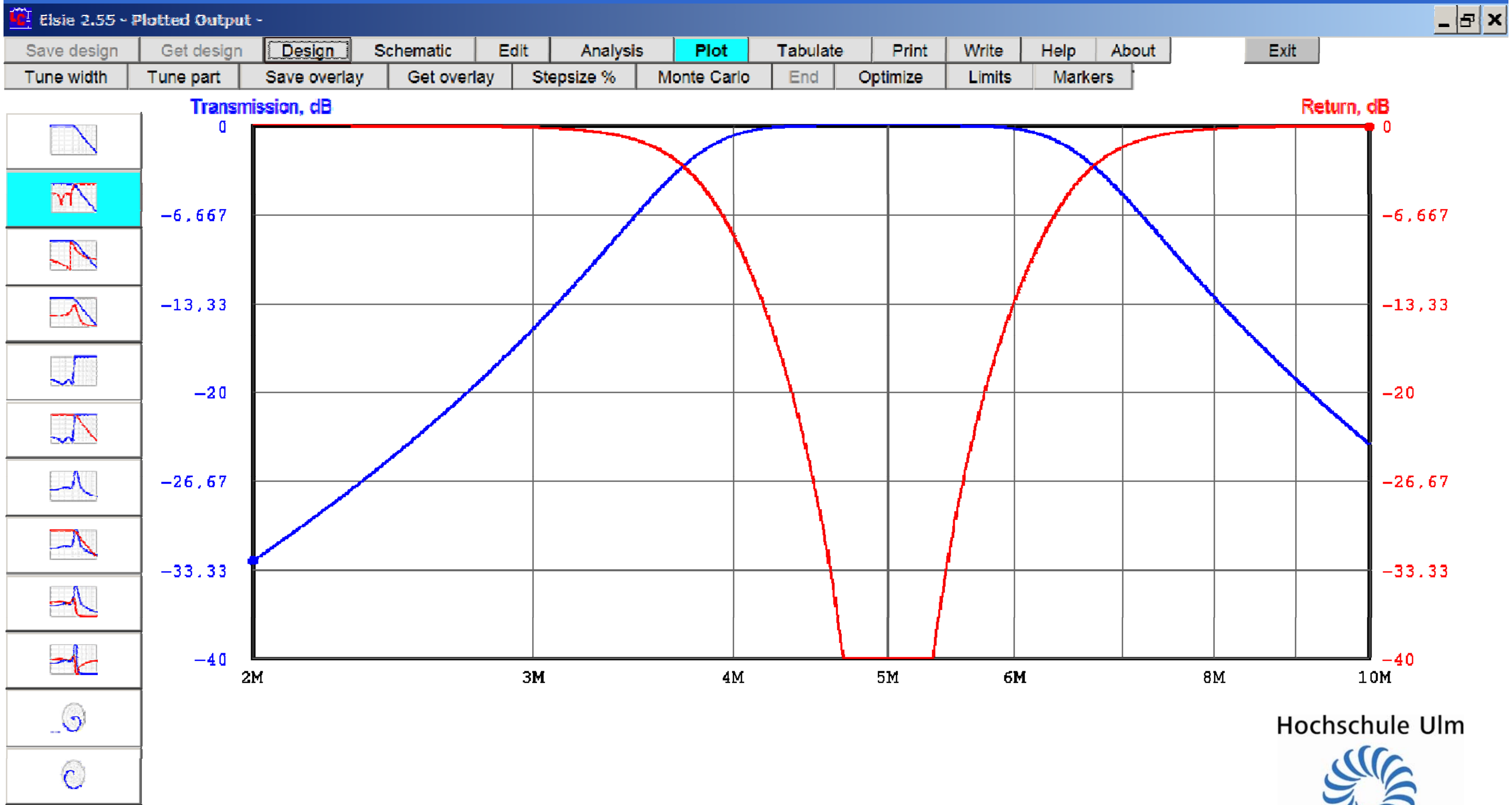
Design 3 Pole Butterworth π-Band Pass for 5 MHz with 3 MHz Bandwidth at 50 Ω



Filter Design with Elsie

Hochschule Ulm

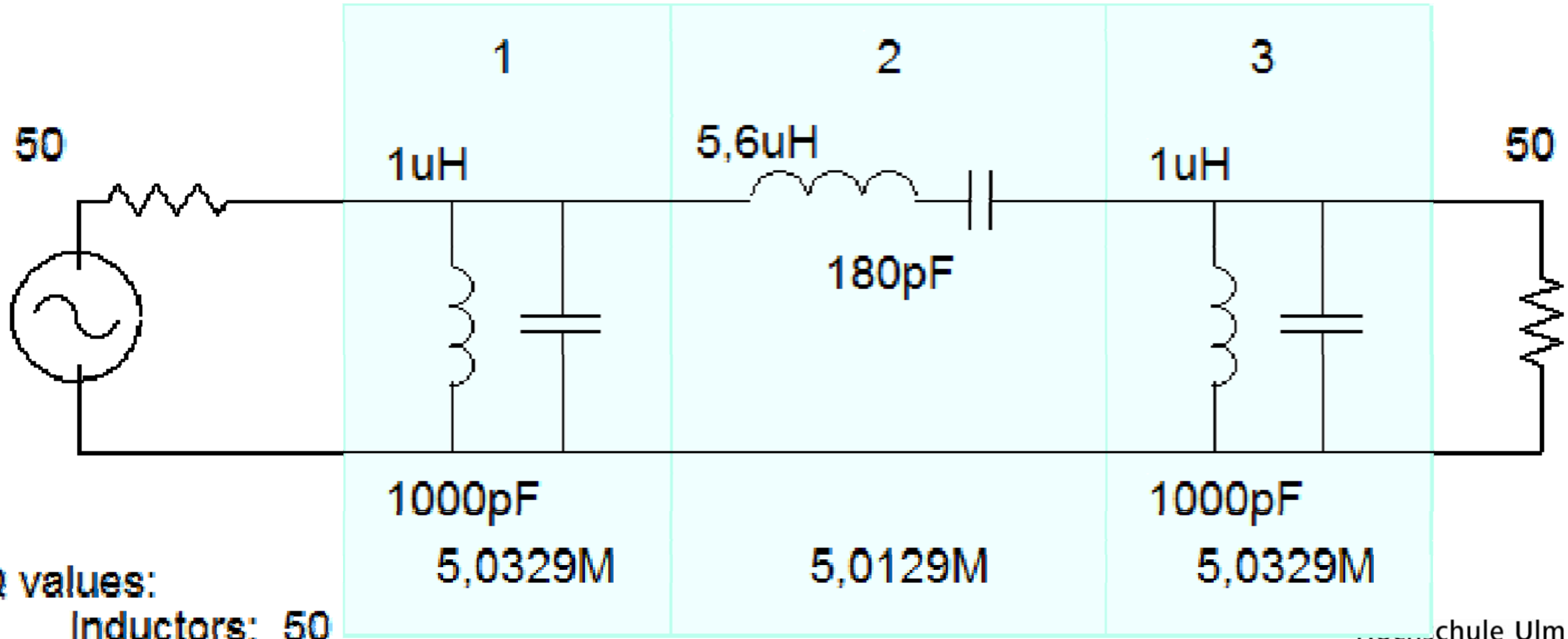
Elsie Simulation Result



Hochschule Ulm

Modify Components to standard Values and finite Q …

Schematic | **Edit** | Analysis | Plot | Tabulate | Print

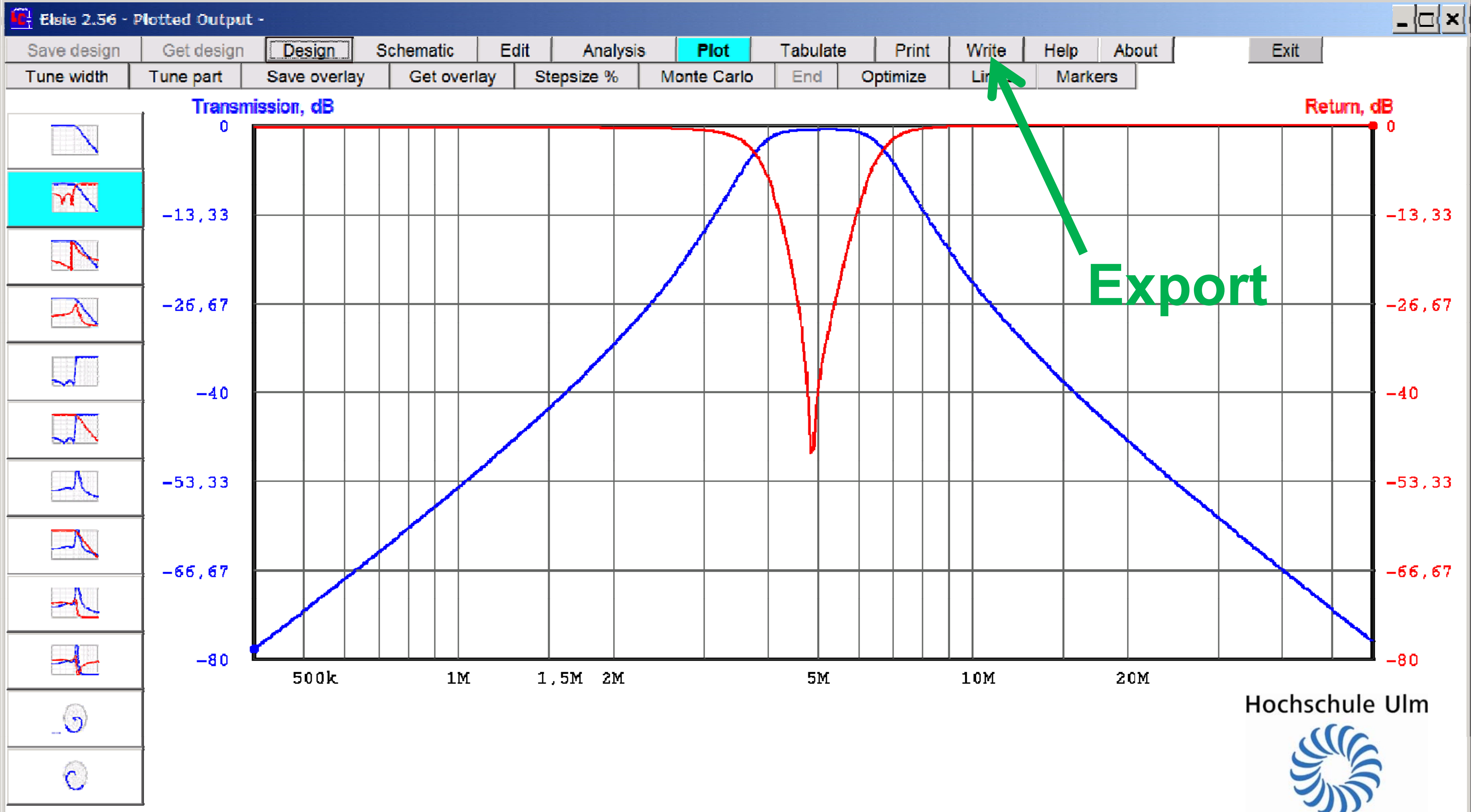


Q values:
Inductors: 50
Capacitors: 1E+07

simulation with finite Q

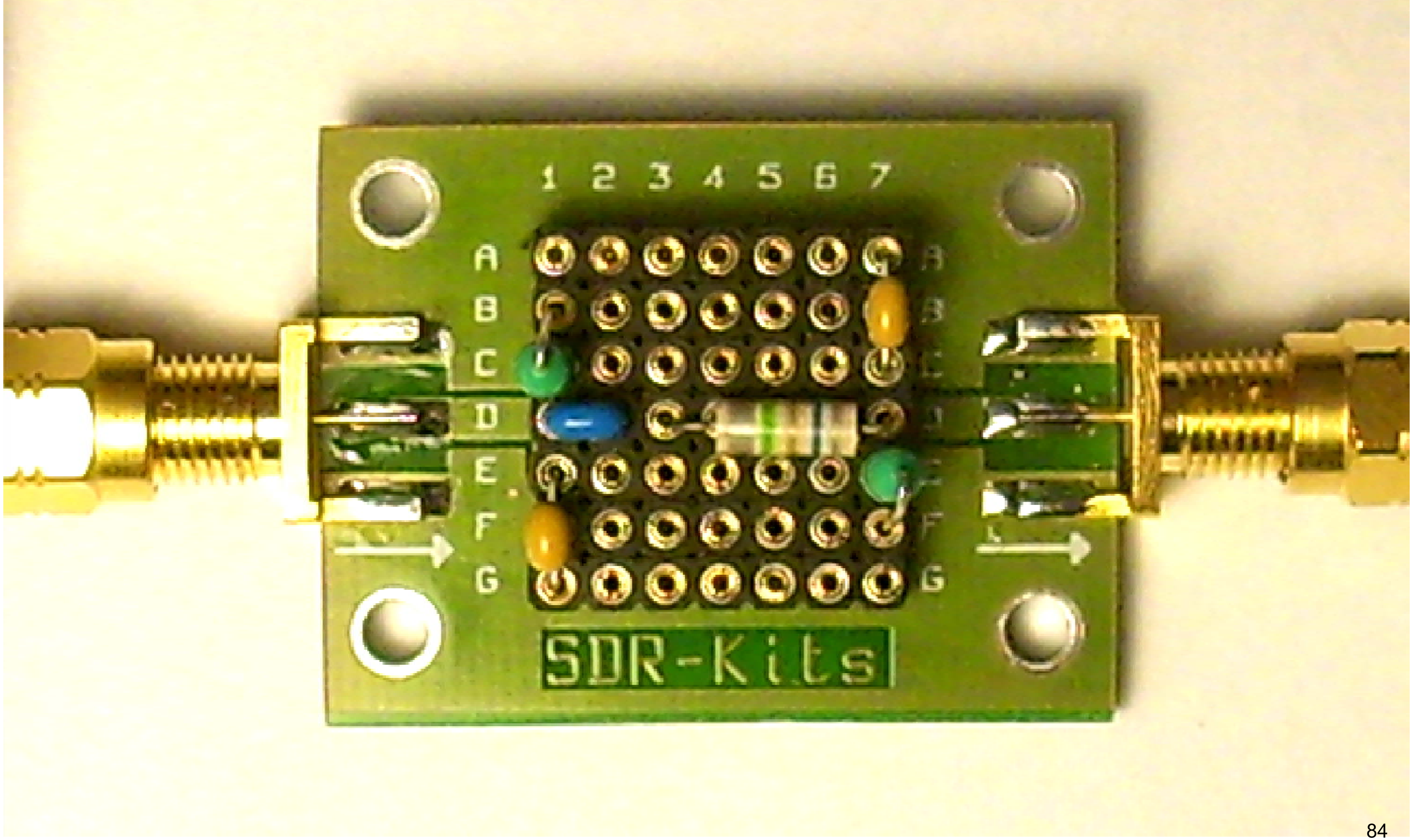
Hochschule Ulm

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



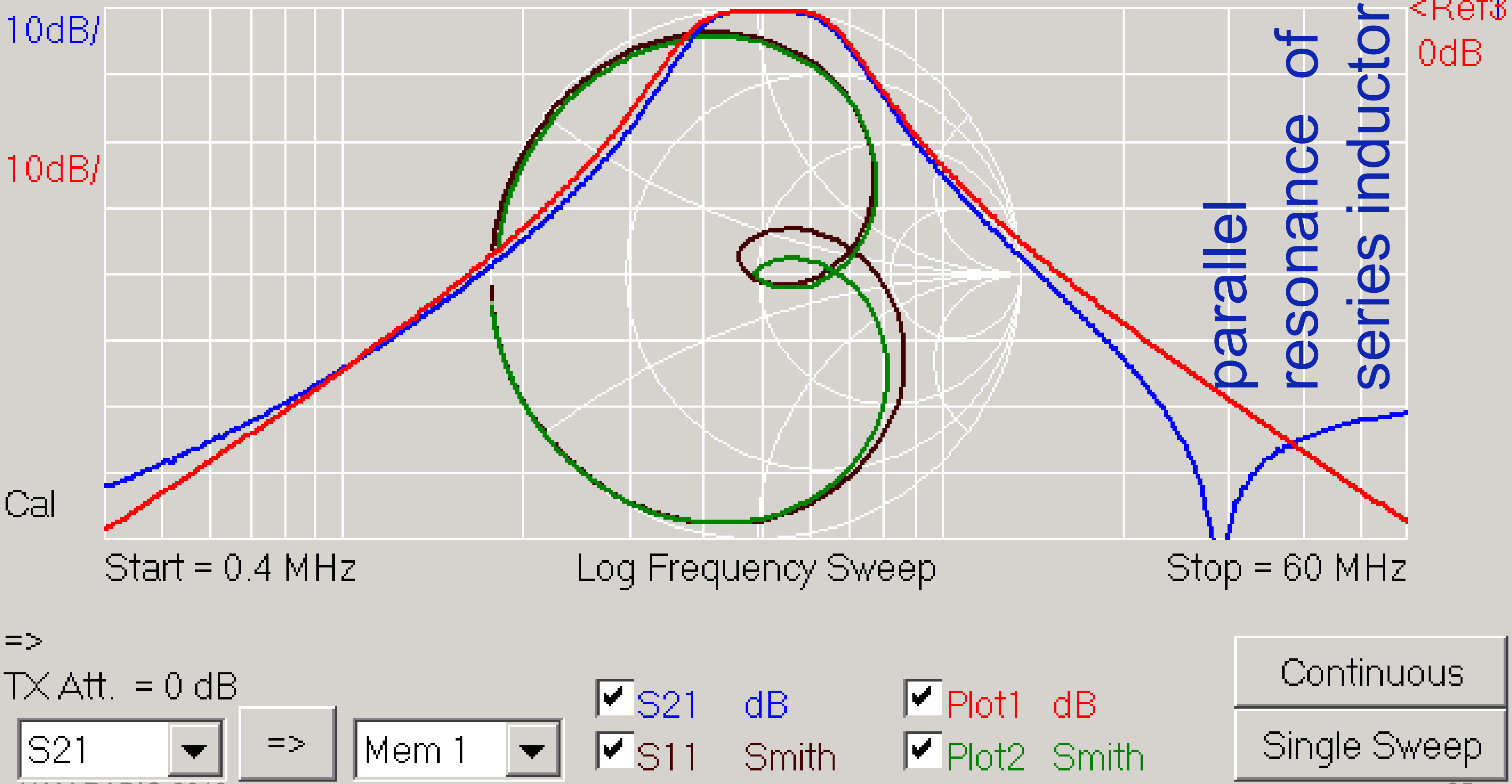
Hochschule Ulm

Filter Hardware

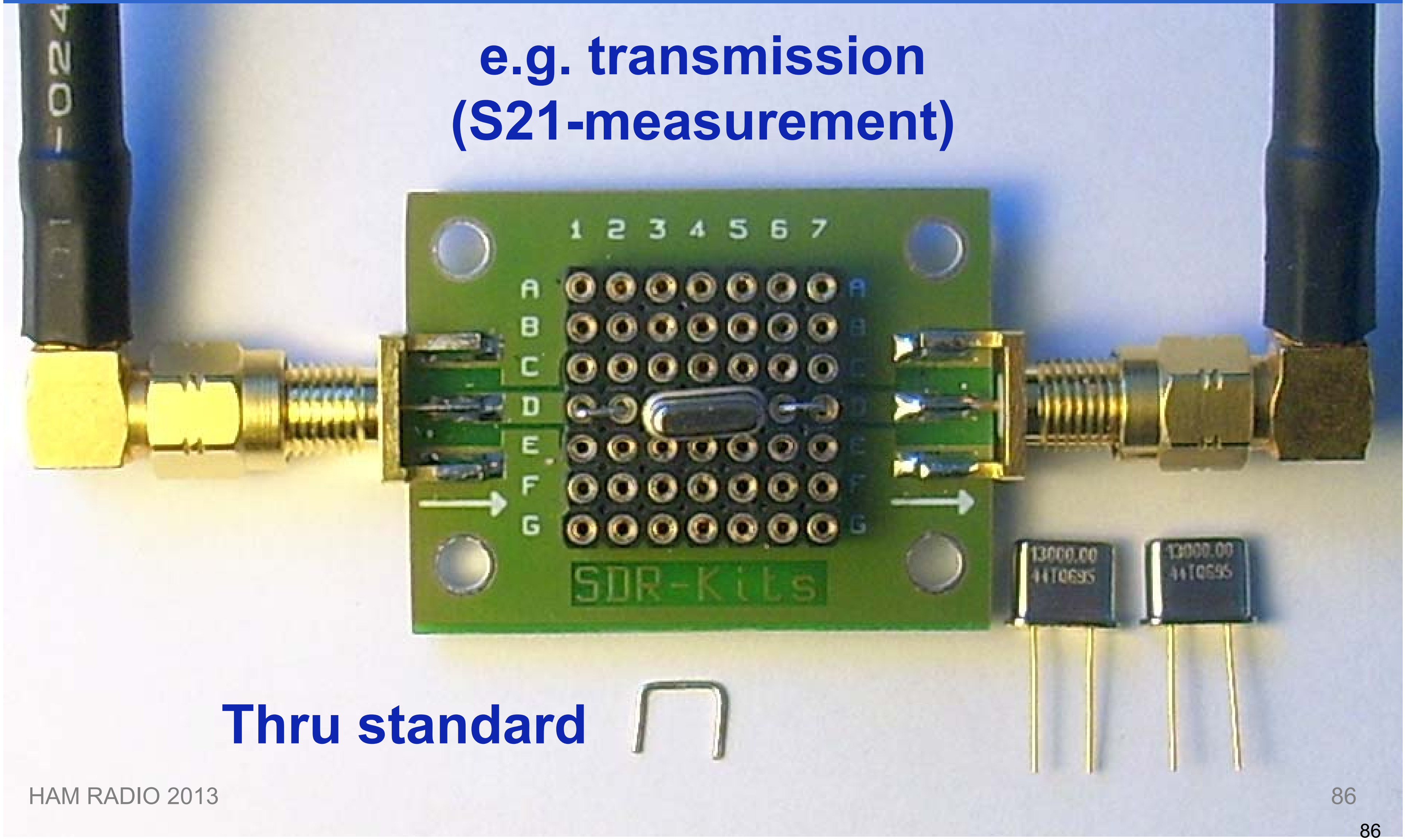


Comparison
Measurement vs. Elsie Simulation

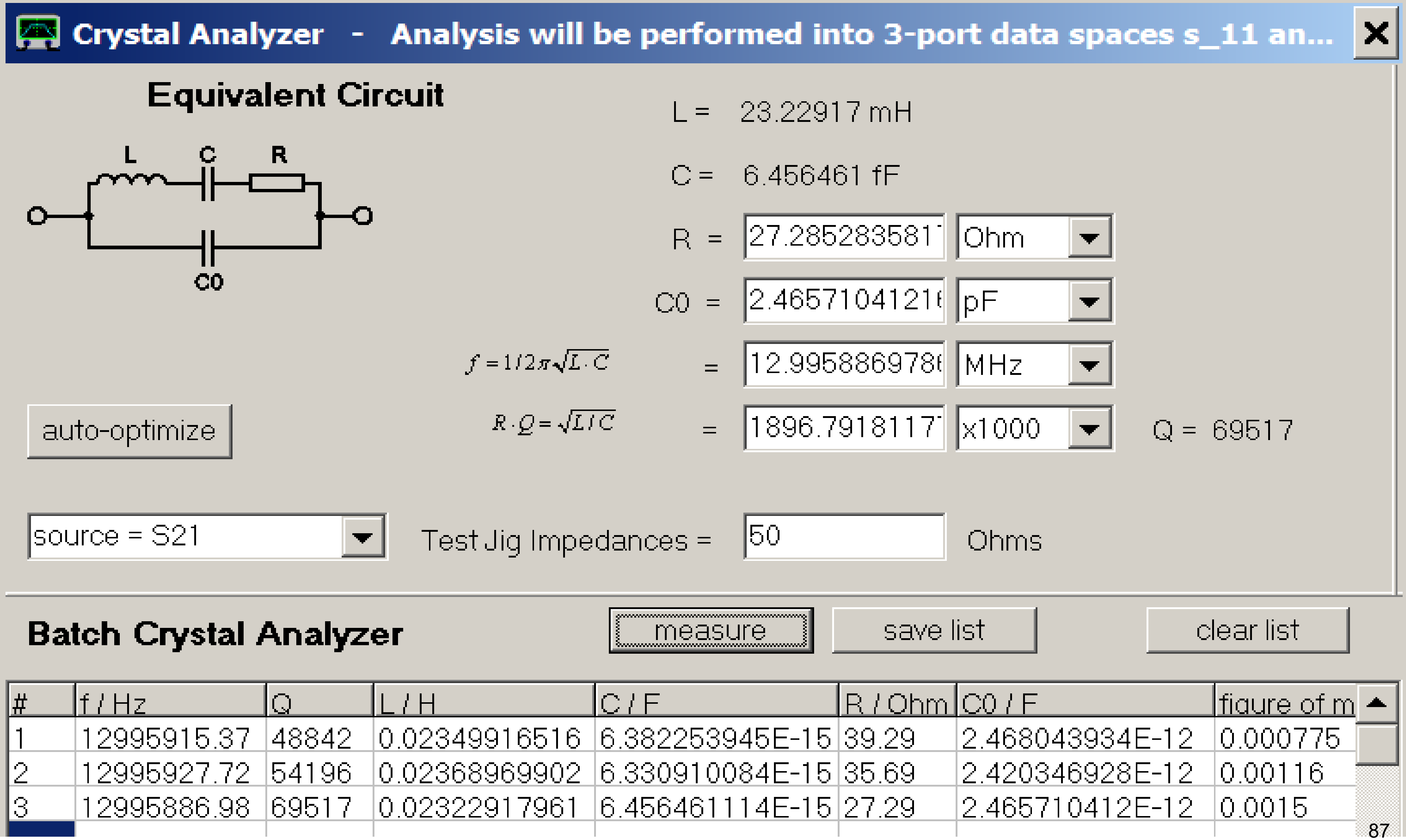
S_{21}, S_{11} measured - Plot1, Plot2 Elsie simulation



Measuring / Selecting Crystals: VNWA Crystal Analyzer

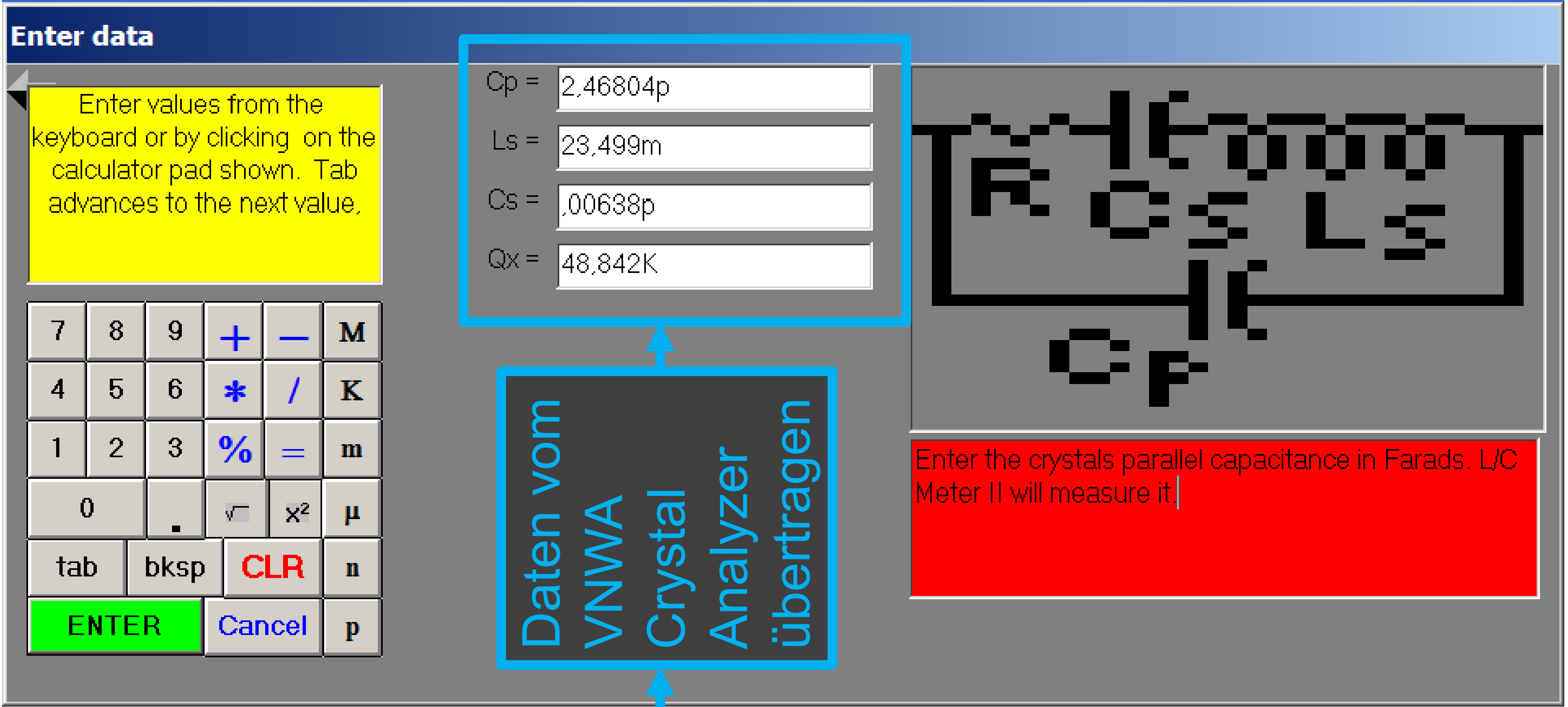


The VNWA Crystal Analyzer Tool: Find 3 similar Crystals…



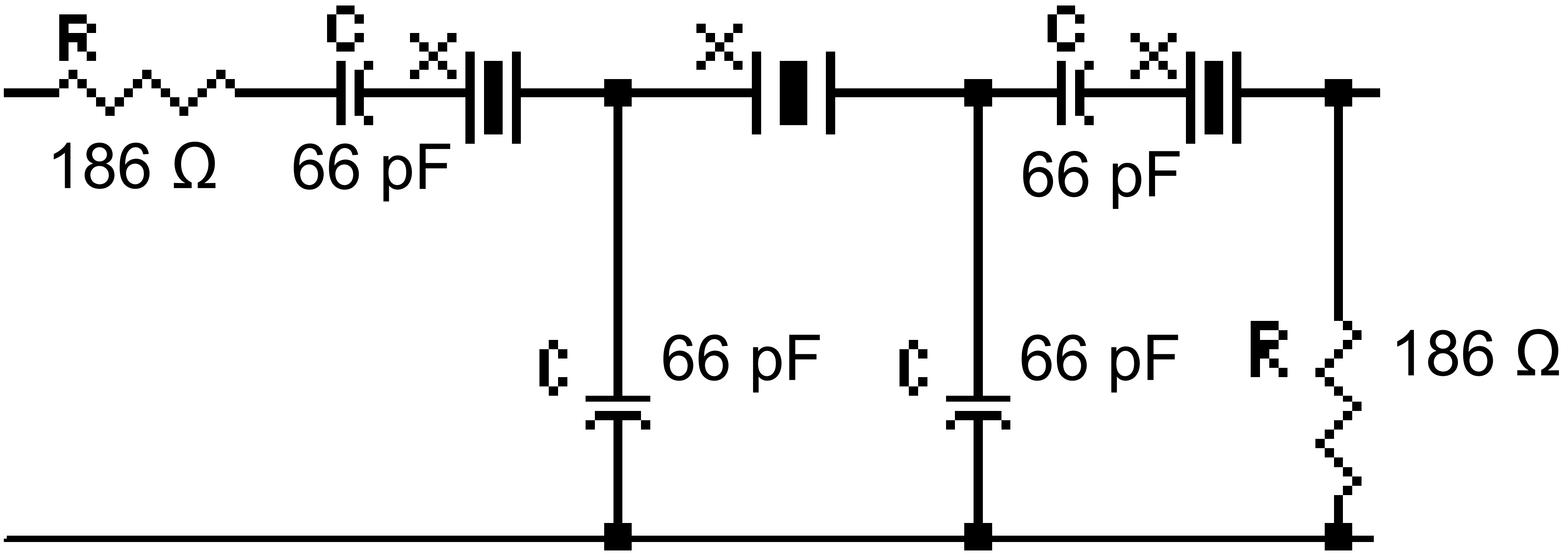
#	f / Hz	Q	L / H	C / F	R / Ohm	C0 / F	figure of m
1	12995915.37	48842	0.02349916516	6.382253945E-15	39.29	2.468043934E-12	0.000775
2	12995927.72	54196	0.02368969902	6.330910084E-15	35.69	2.420346928E-12	0.00116
3	12995886.98	69517	0.02322917961	6.456461114E-15	27.29	2.465710412E-12	0.0015

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



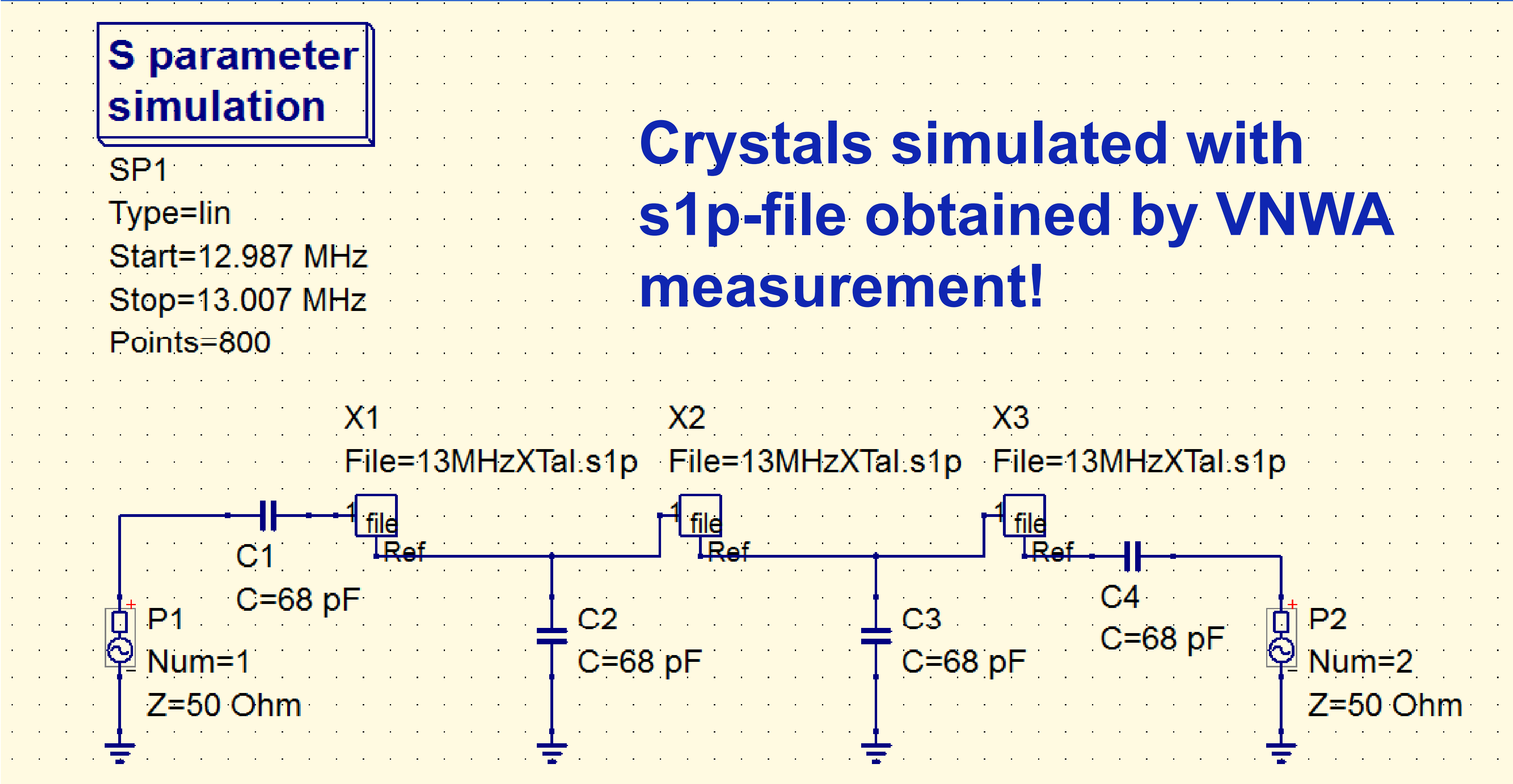
#	f / Hz	Q	L / H	C / F	R / Ohm	C0 / F	figure of m
1	12995915.37	48842	0.02349916516	6.382253945E-15	39.29	2.468043934E-12	0.000775

AADE Minimum Loss (Cohn) Design

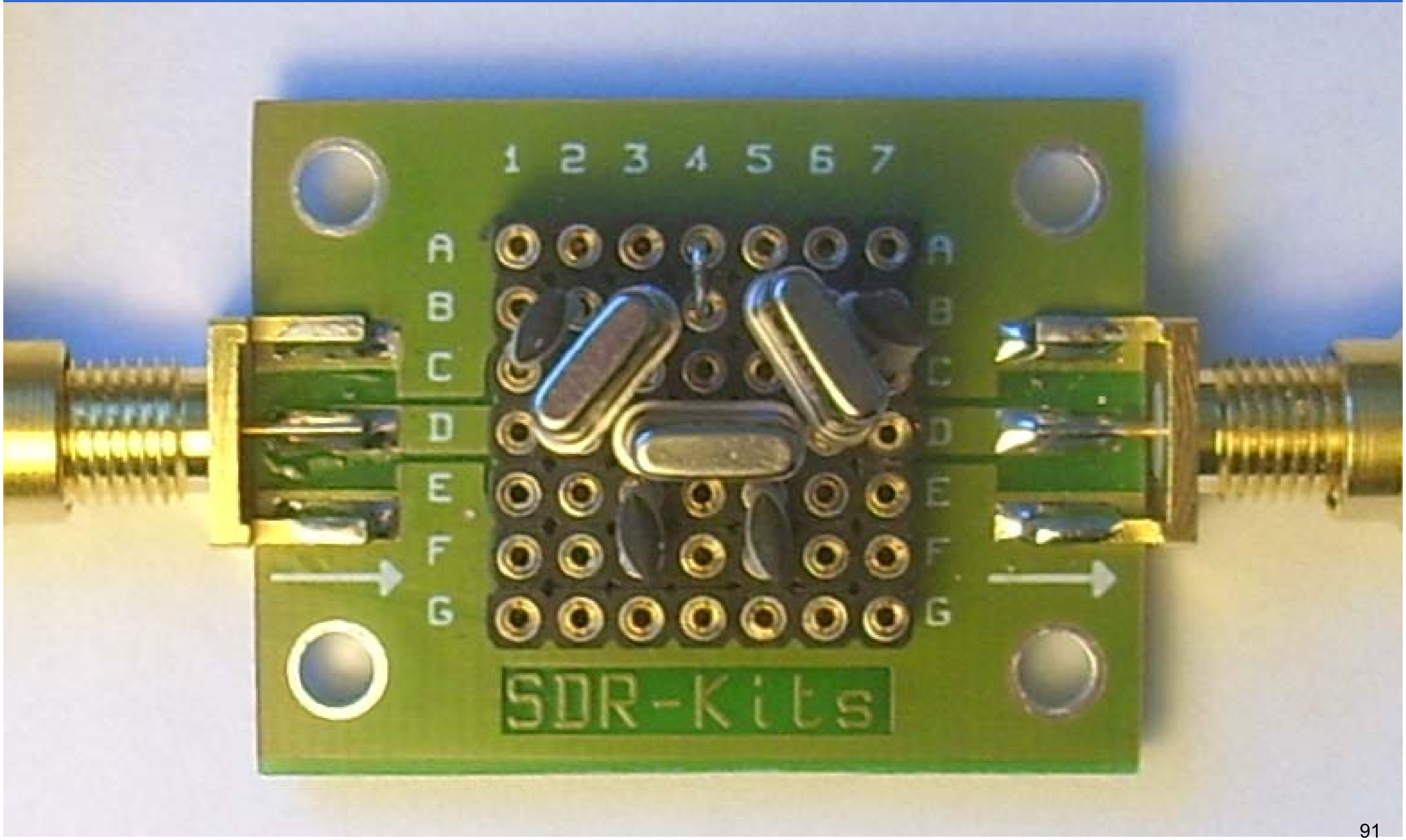


Hochschule Ulm

Simulation in QUCS at 50 Ω using standard Component Values

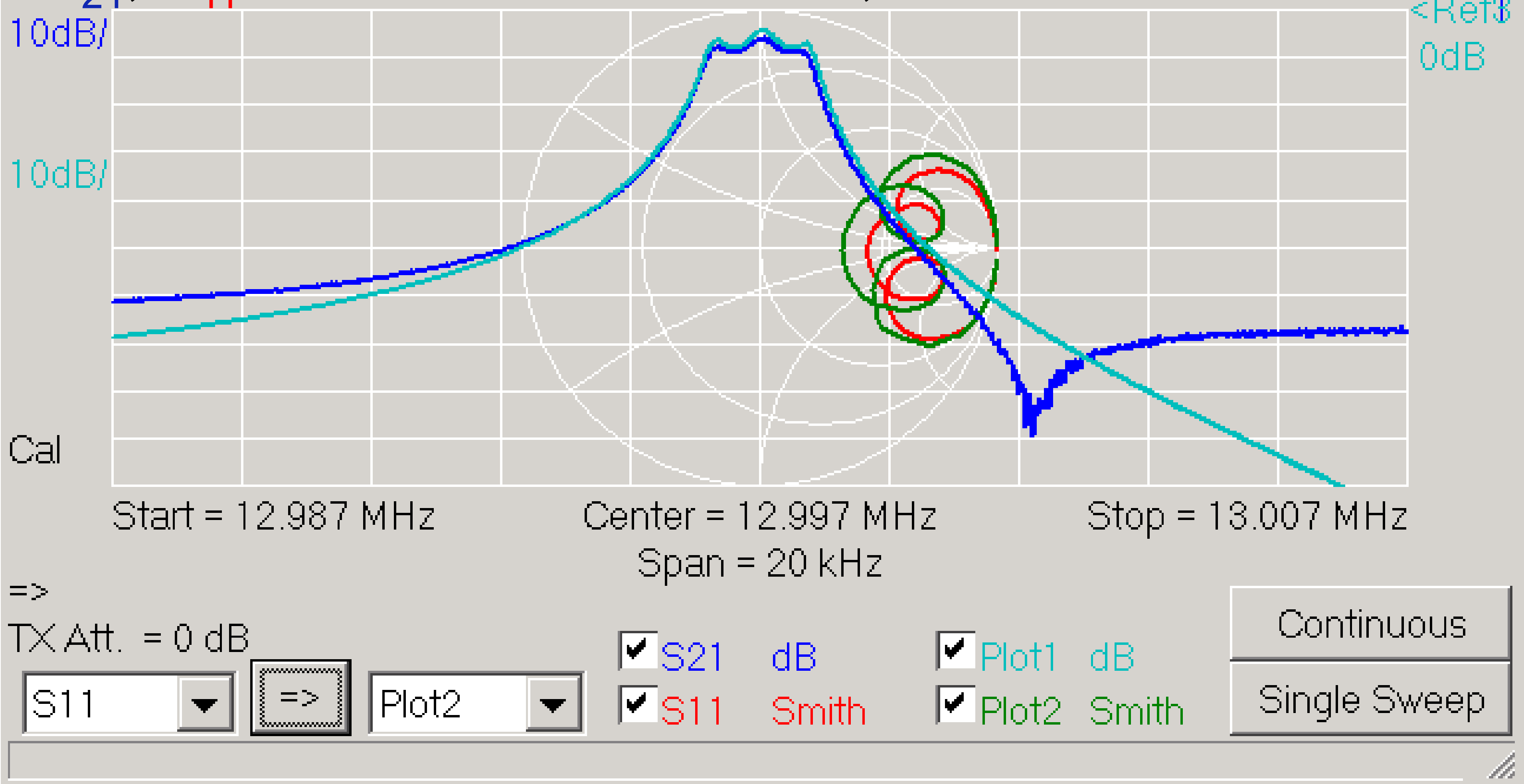


Crystal Filter Hardware



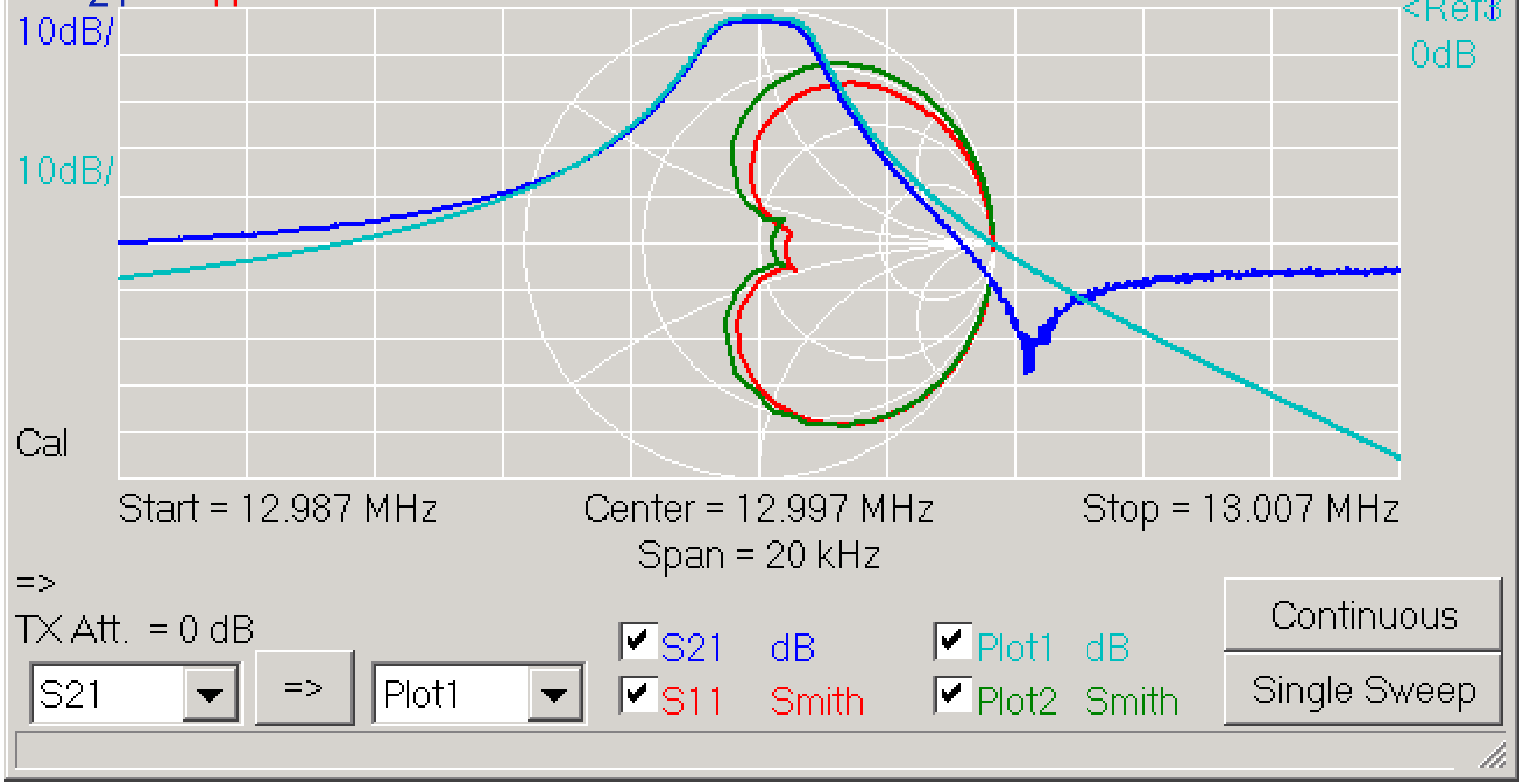
Crystal Filter: Measurement vs. Simulation at 50 Ω

S_{21}, S_{11} measurement - Plot1, Plot2 QUCS simulation



Crystal Filter:
Measurement vs. Simulation at 186 Ω

S_{21}, S_{11} measurement - Plot1, Plot2 QUCS simulation



Now, we are able to…

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

Have fun at the workshop!

Hochschule Ulm

Many thanks for your attention!