

# HAM RADIO 2013

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FRIEDRICHSHAFEN

## Measurement and Application of Scattering Parameters in RF-Design

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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*

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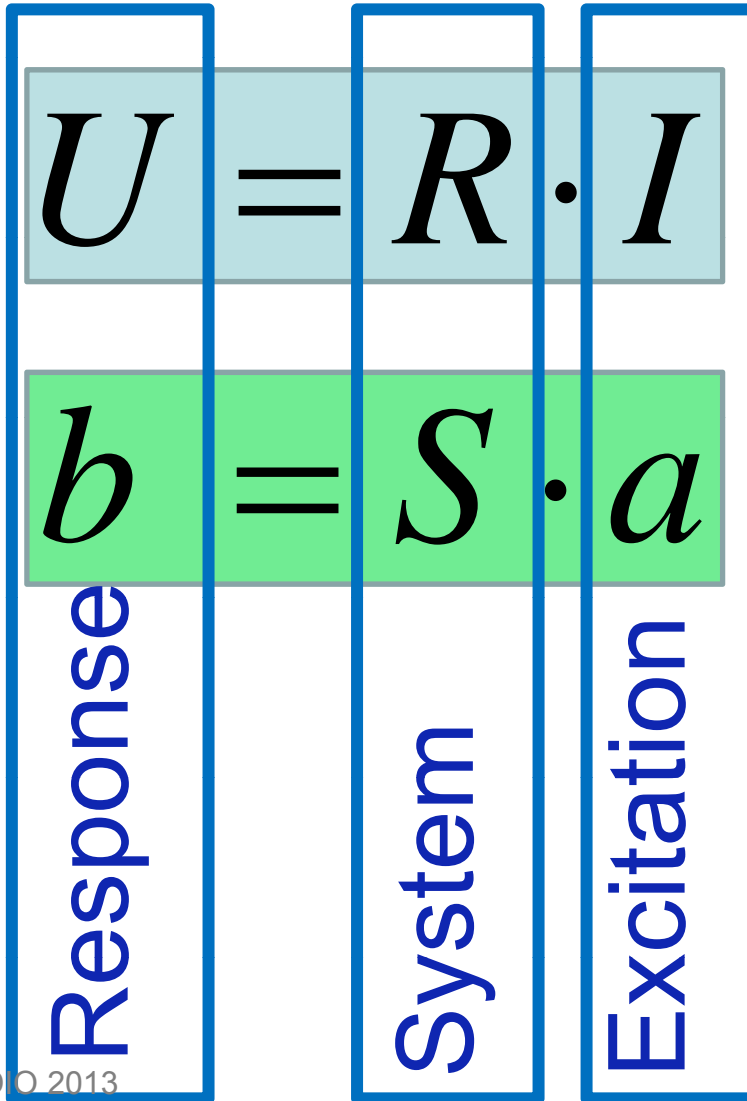


# What are Scattering Parameters?

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

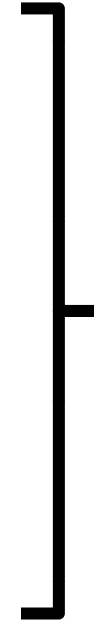


# Who is afraid of S-parameters!



Ohm

S-Par.



equivalent  
description

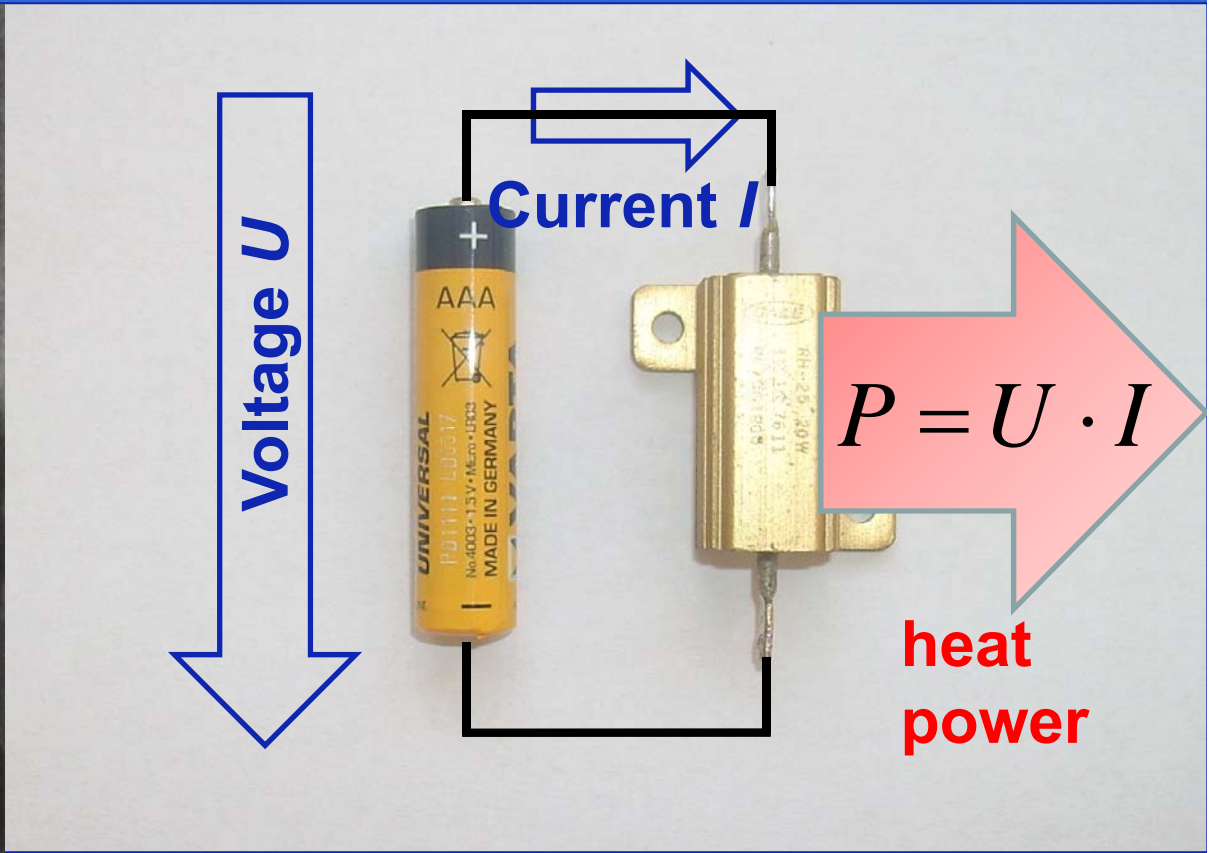




# A different angle to dc Ohms' Law (1)



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

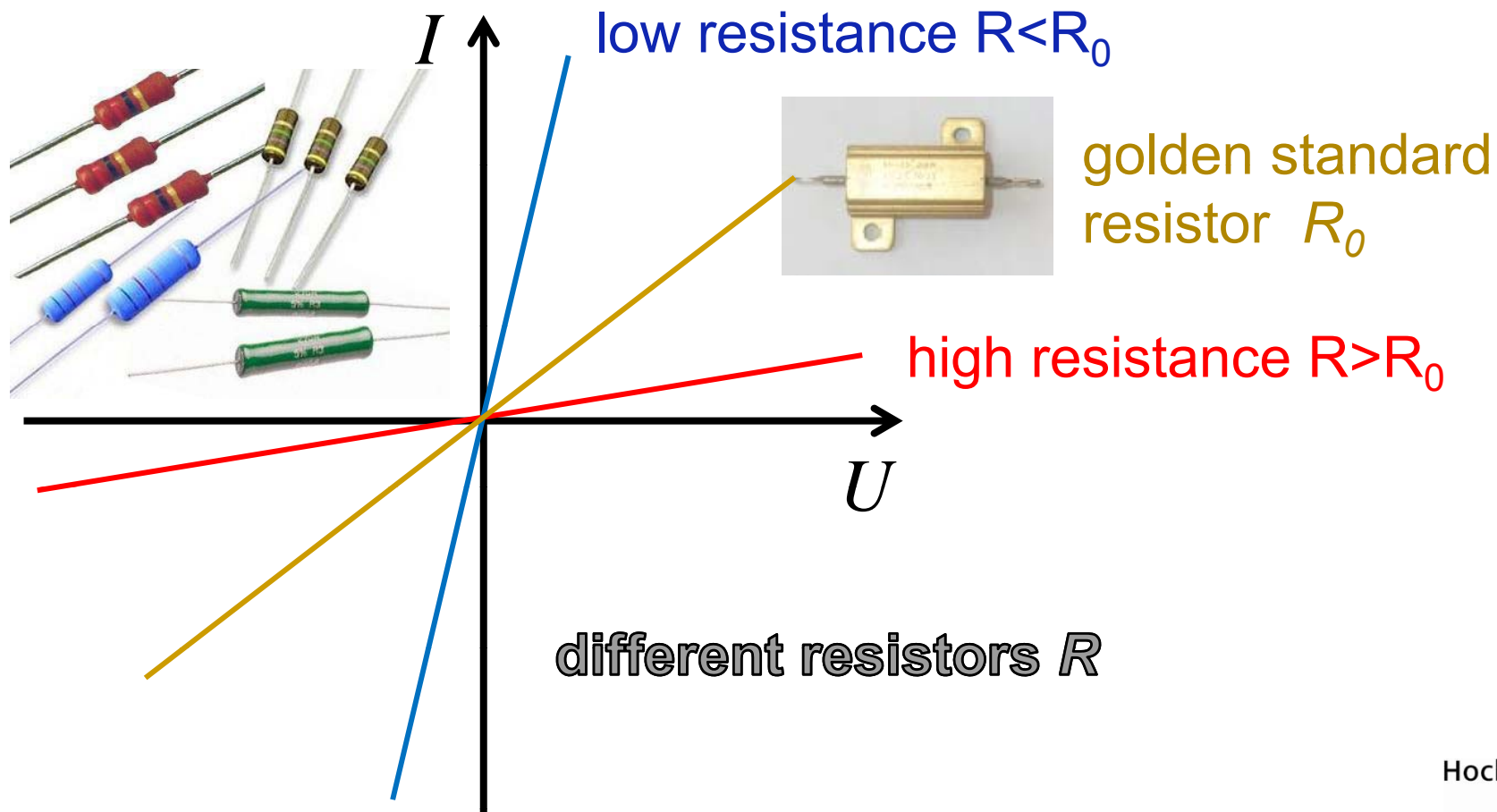


$$U = R \cdot I$$

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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  $R_0$  :

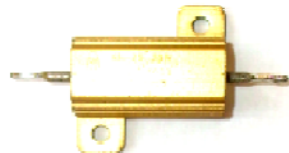
Resistor  $R$



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

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

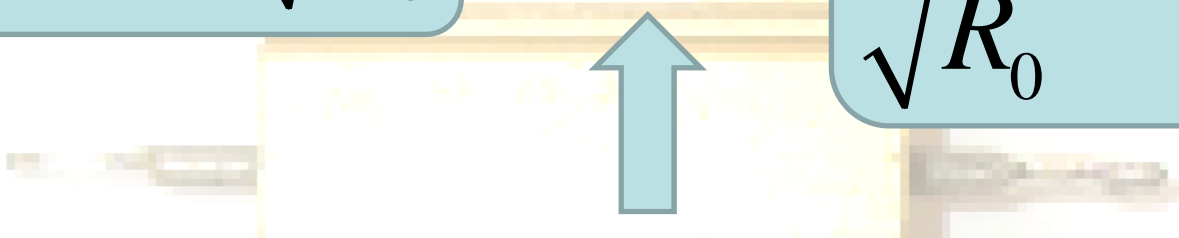


# New Units for Voltage and Current:

$$I \rightarrow i$$

$$U \rightarrow u$$

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:

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

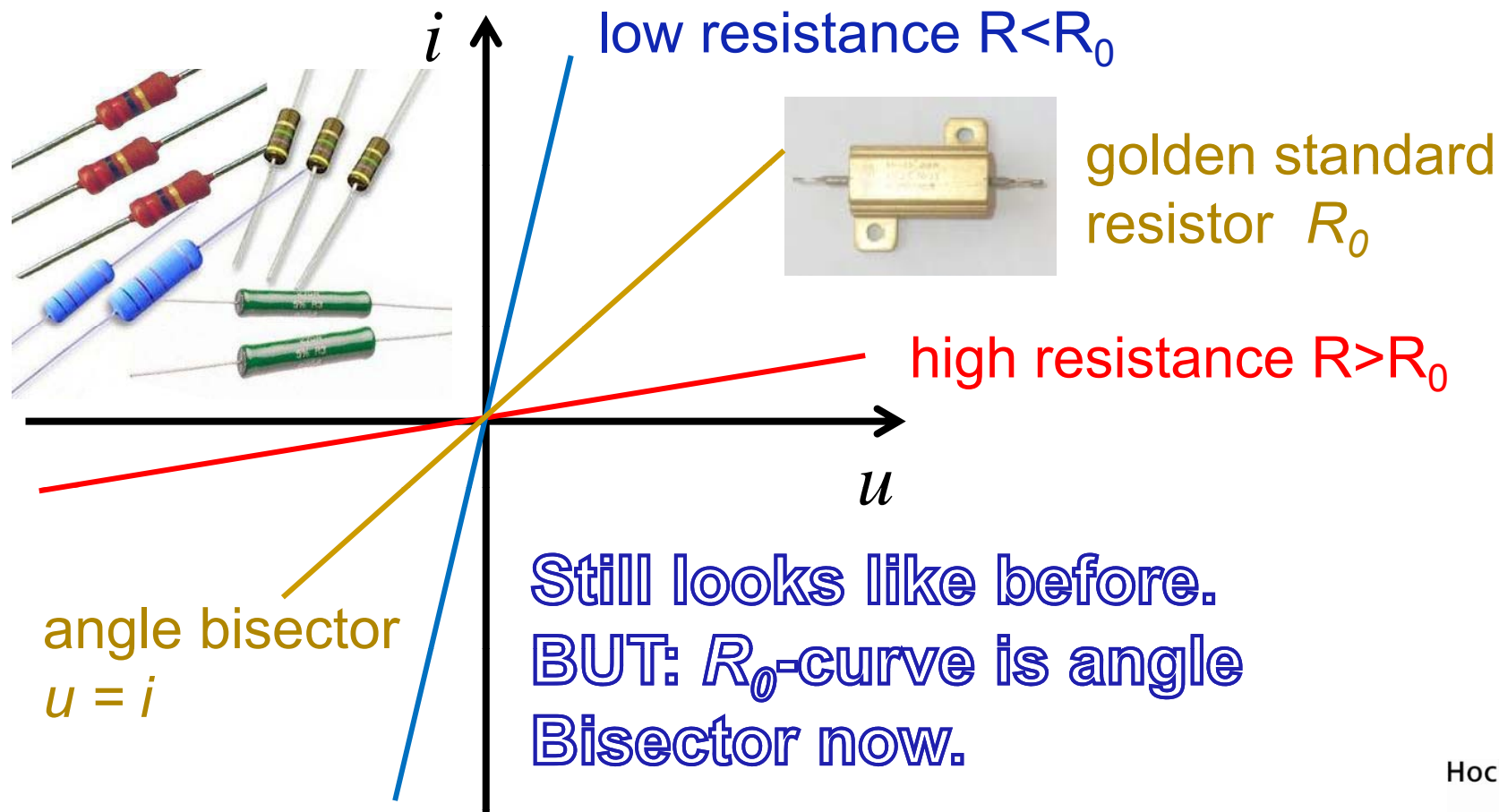
reduce!

Now arbitrary resistor  $R!!!$

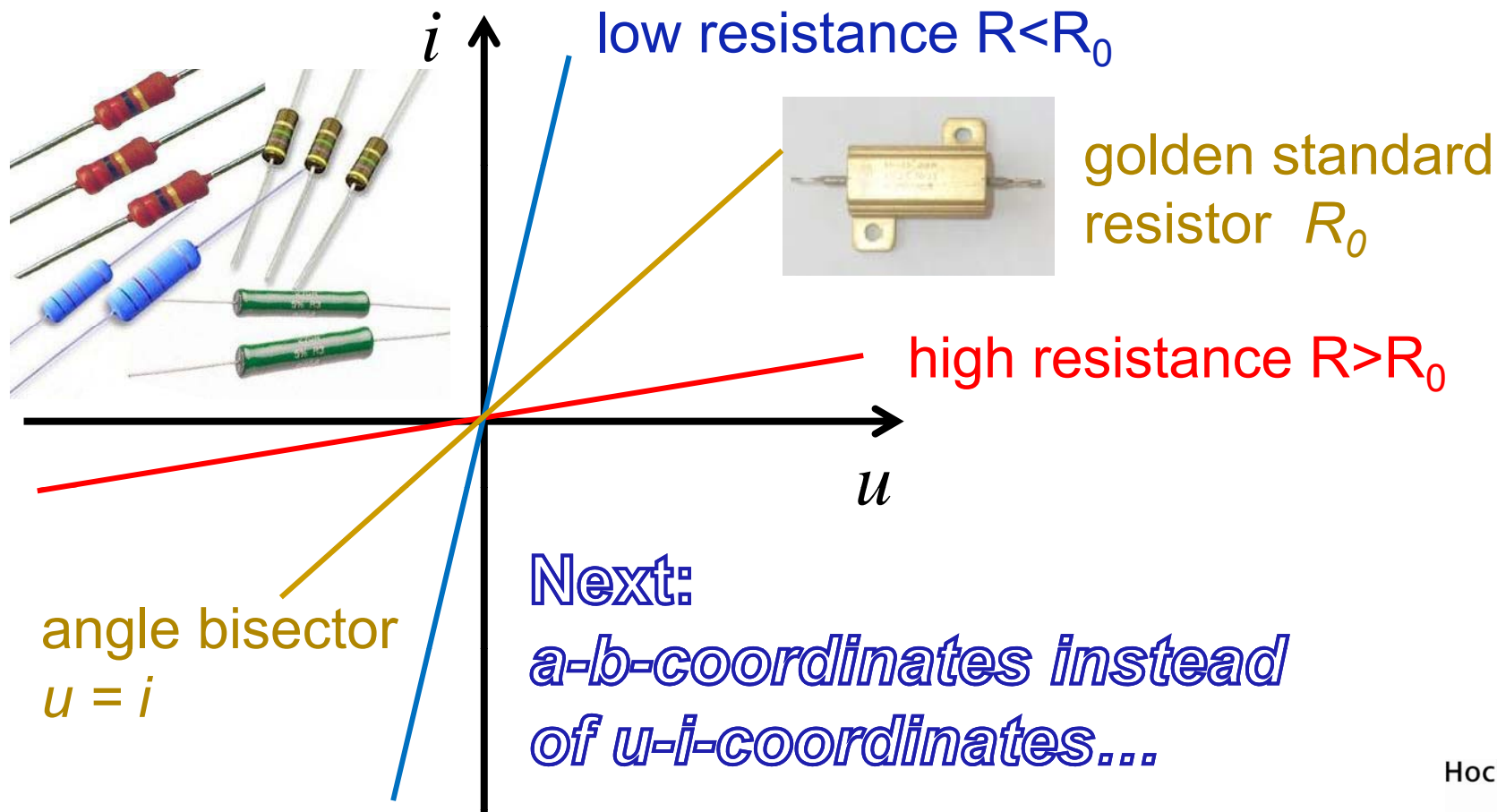




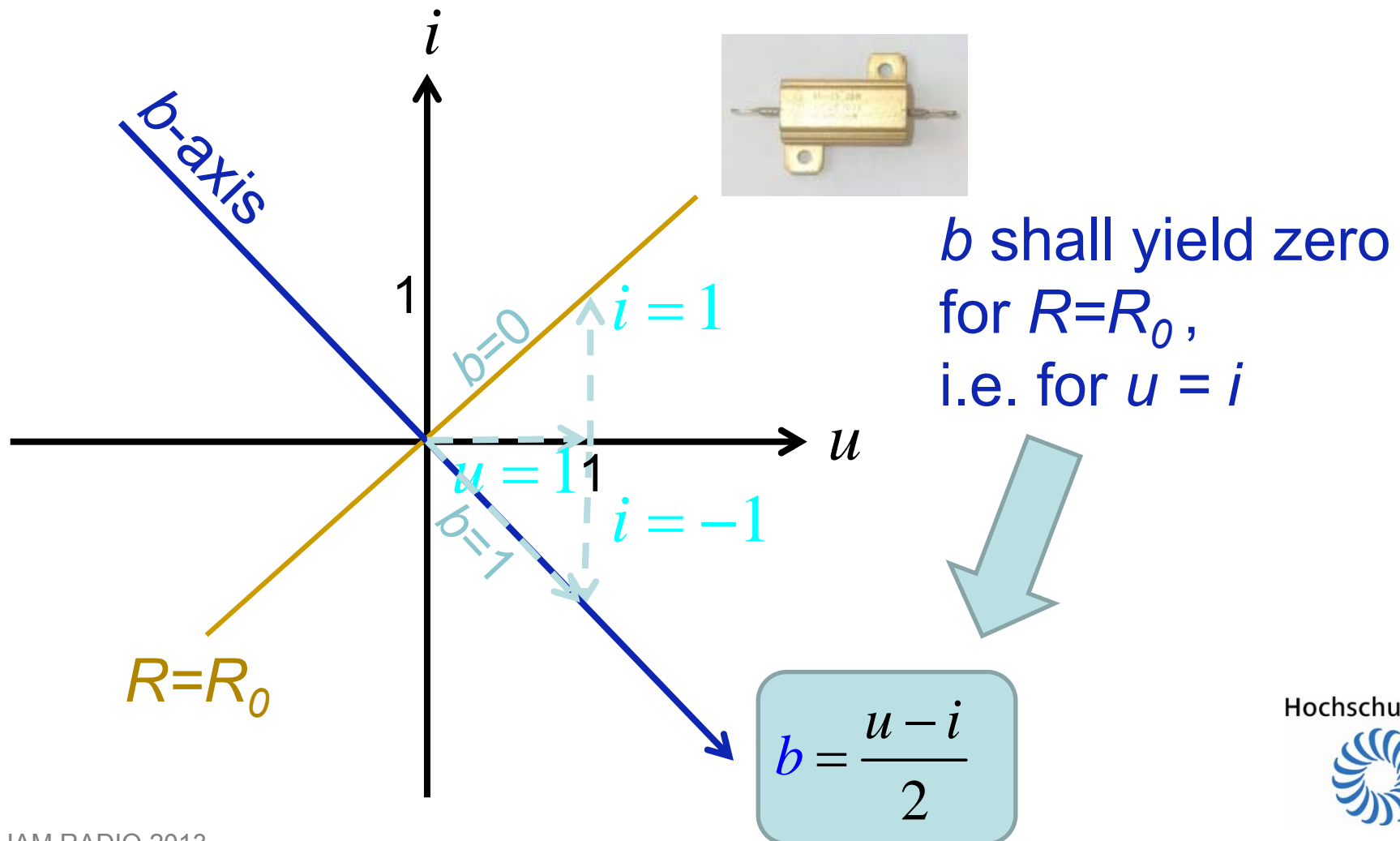
# Ohm's Law with new Voltage and Current Units



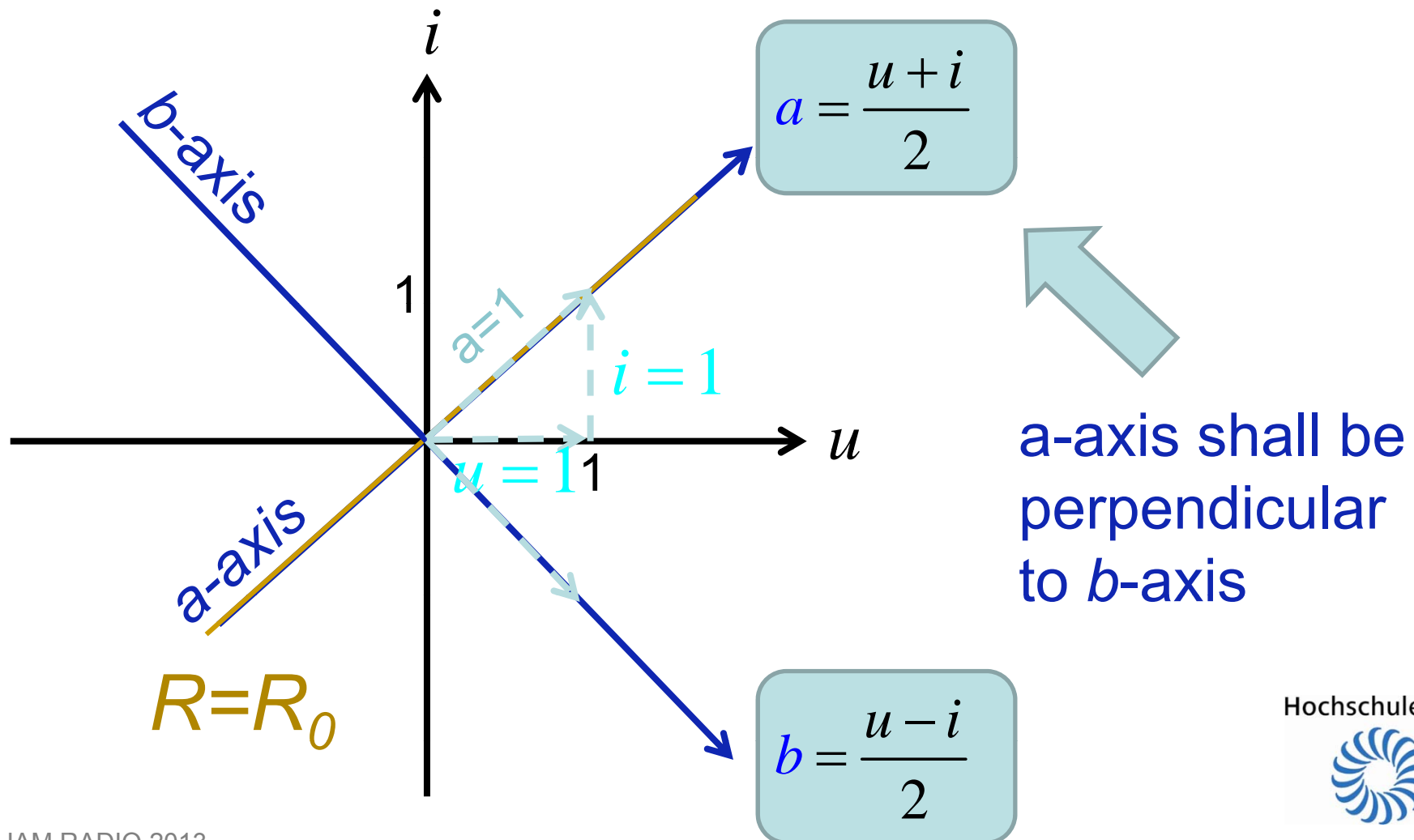
# Now we get down to business: A different angle to dc...



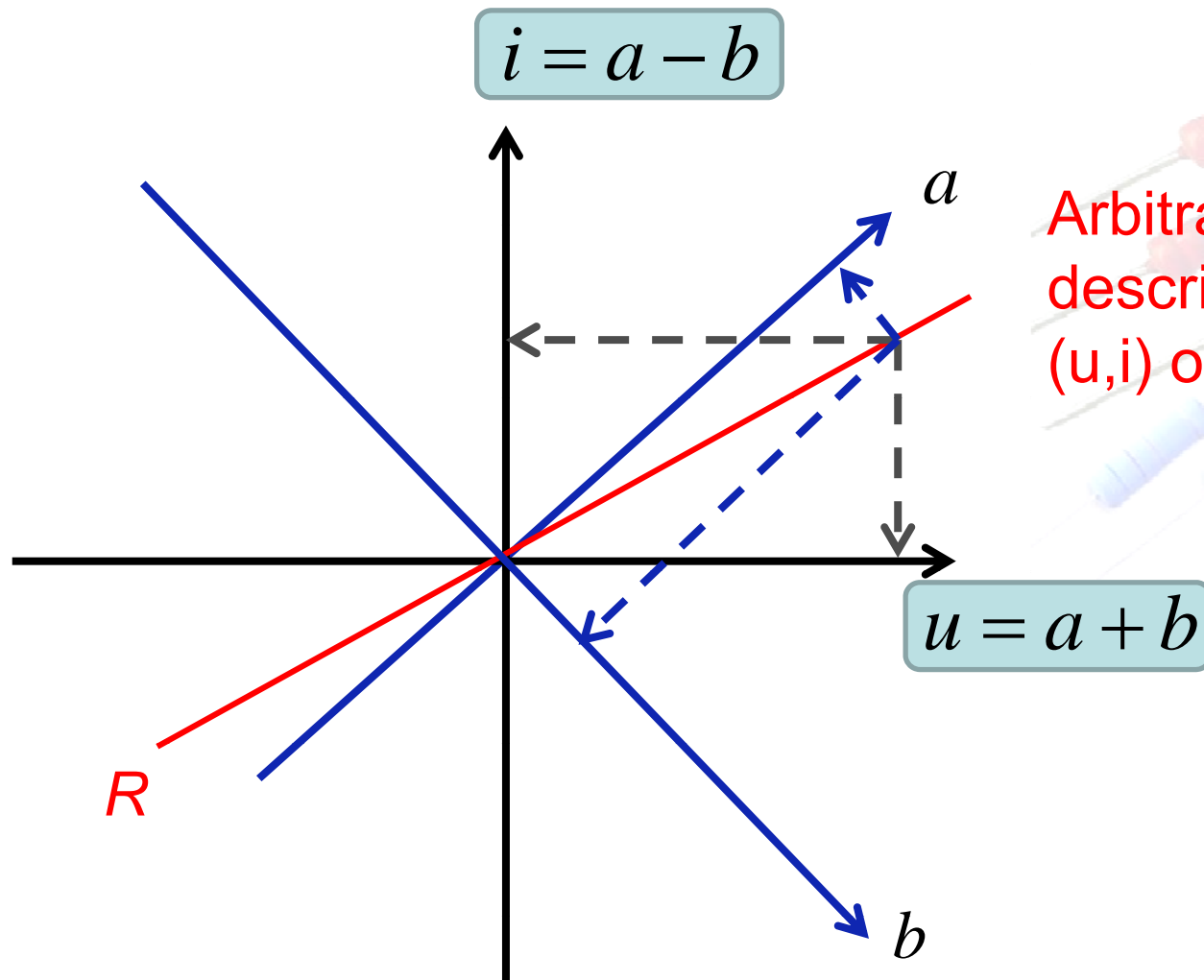
# From Voltage and Current... ...to $b$ ...



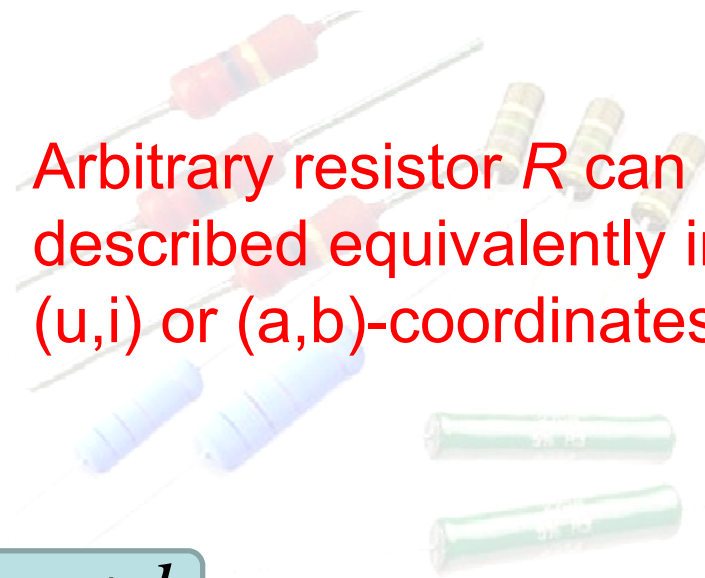
# From Voltage and Current... ...to $b$ ...and $a$ !



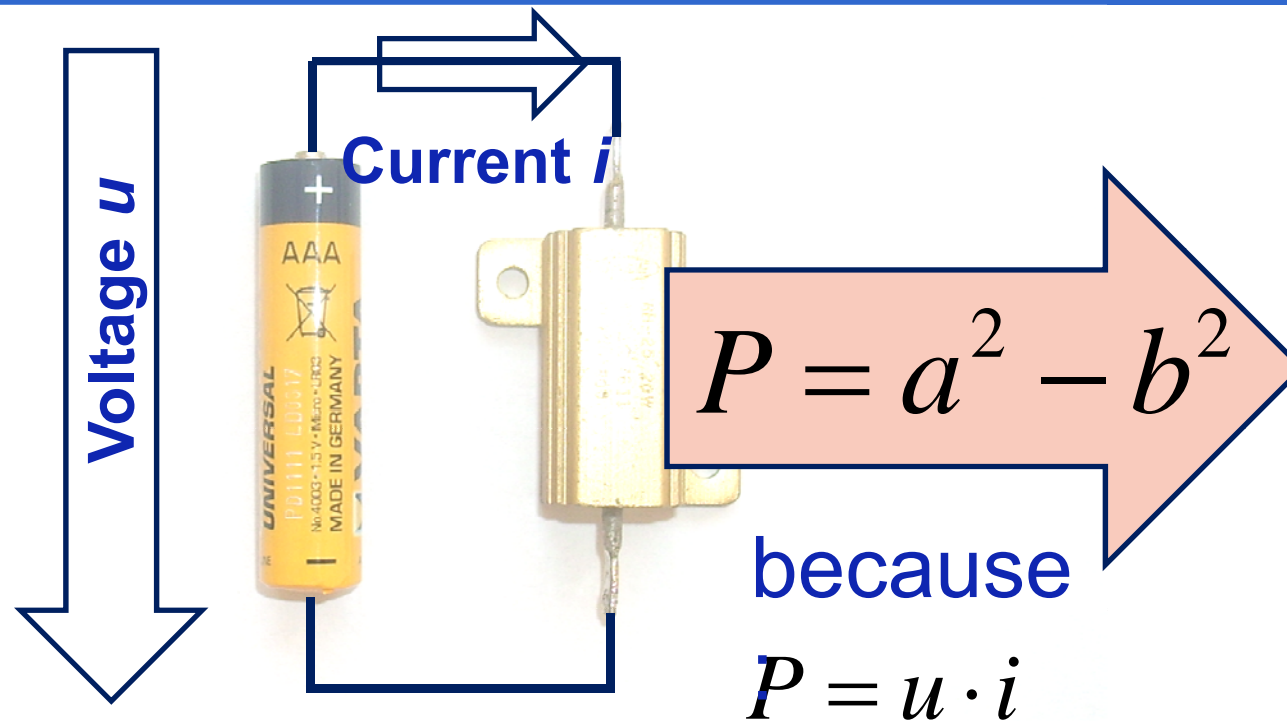
# This works the other way round, too: Voltage and Current from $a$ and $b$



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



# A different angle to dc: Dissipated power in resistor $R$



if  $R = R_0 \Rightarrow b = 0$   $= (a + b) \cdot (a - b)$

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

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.

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

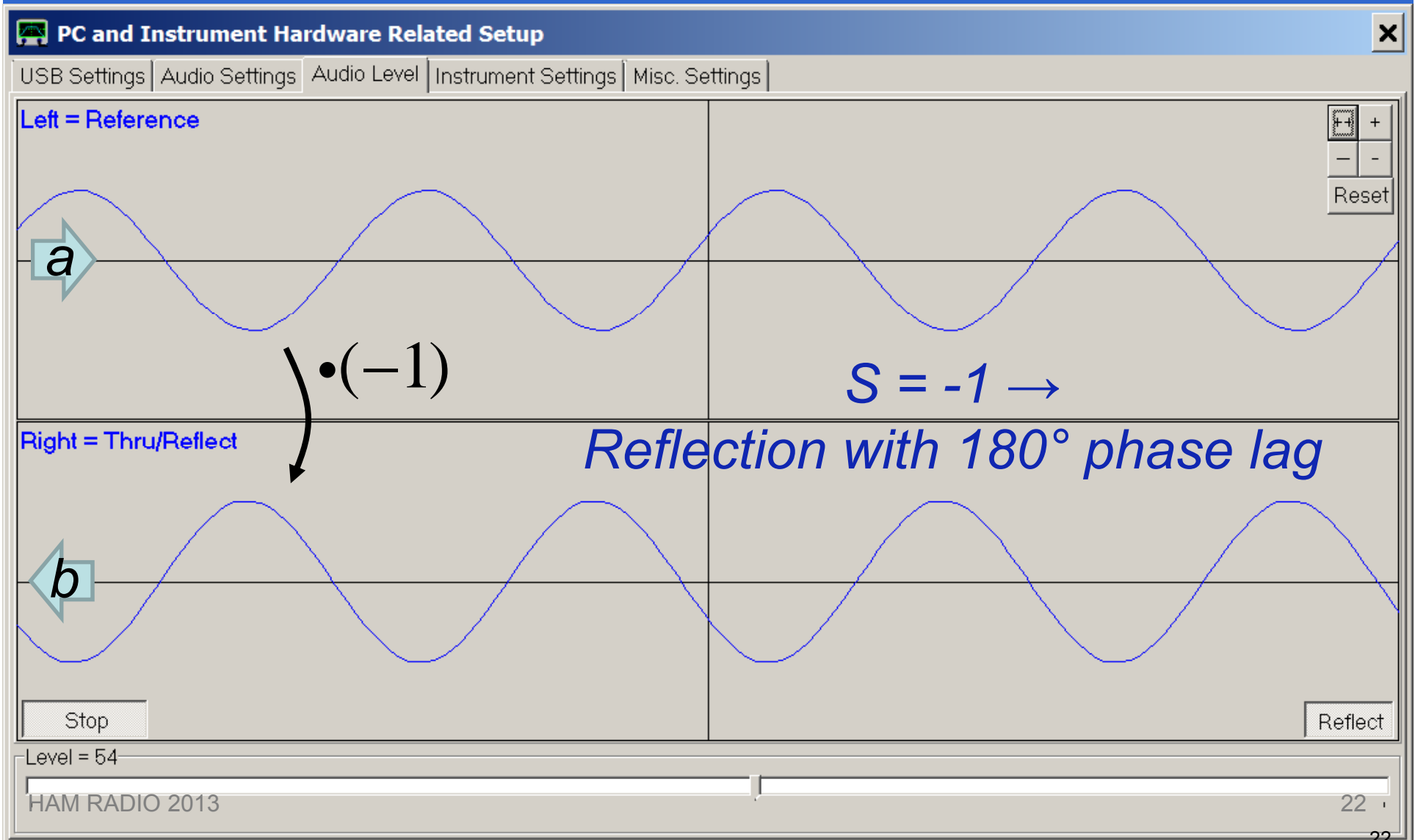
with  $z = \frac{Z}{Z_0}$

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

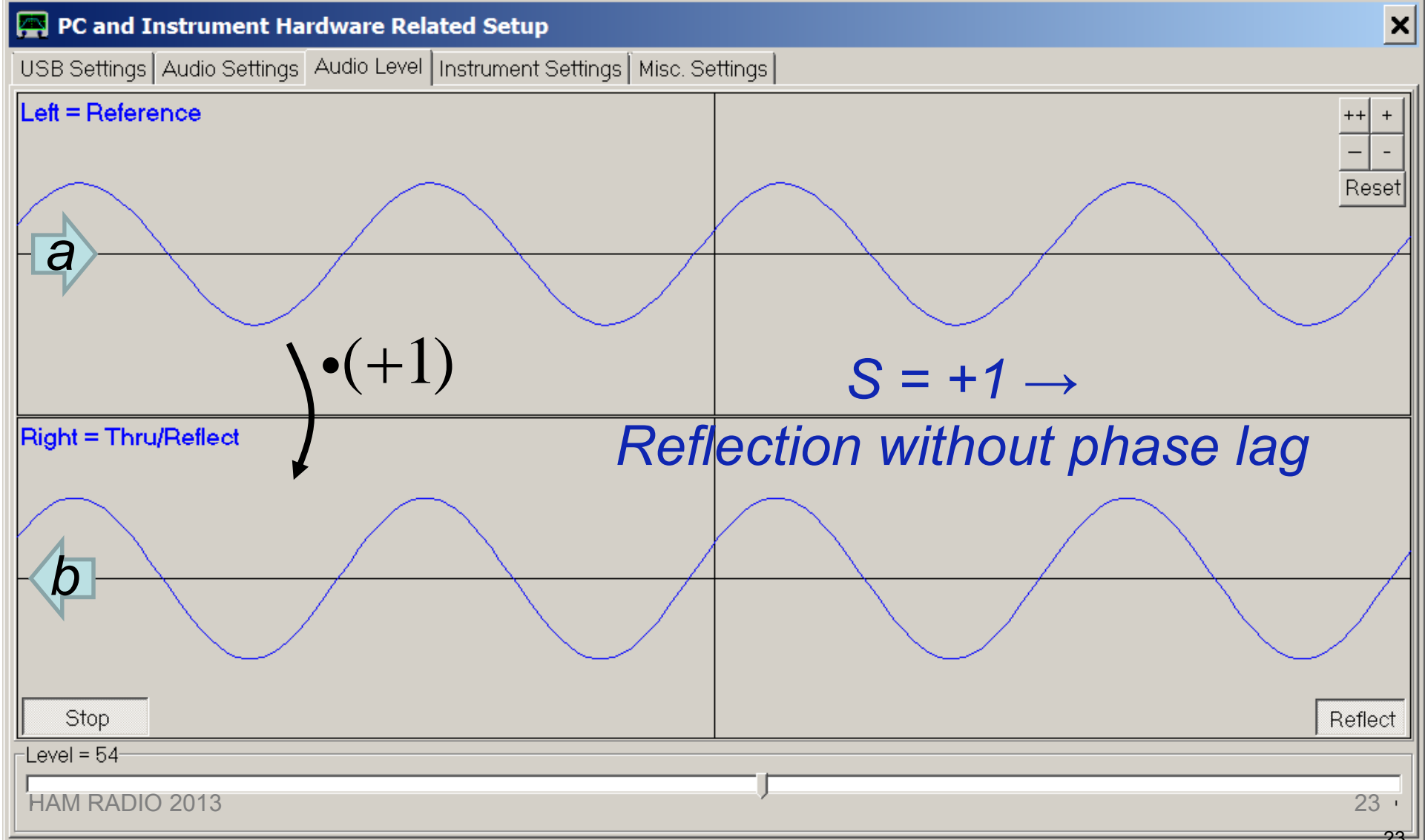


# We can see a and b using the VNWA

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

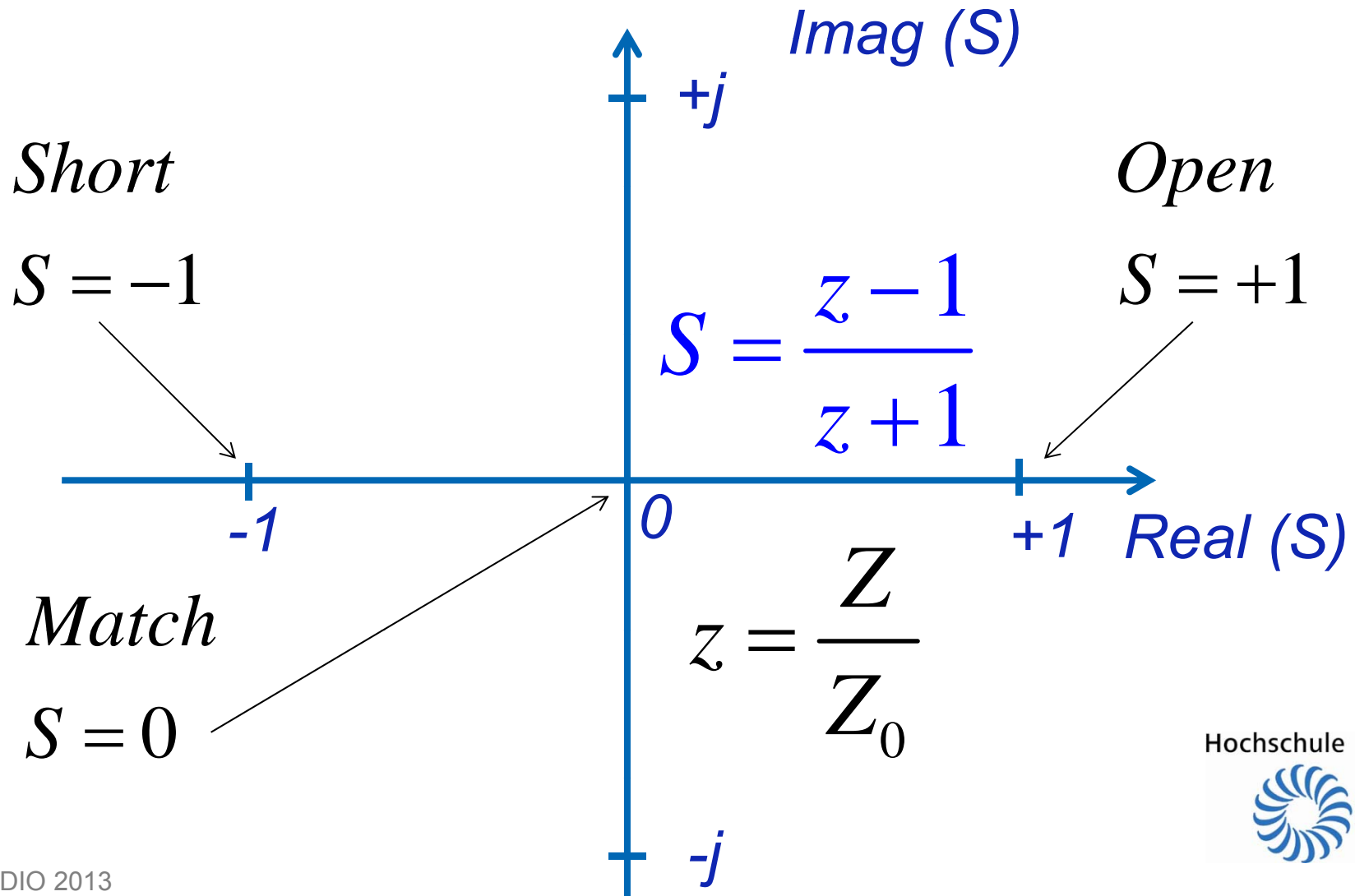


We can see a and b using the VNWA  
E.g. Open Circuit  $S=+1$ :



# Complex Reflection Coefficient $S = b/a$

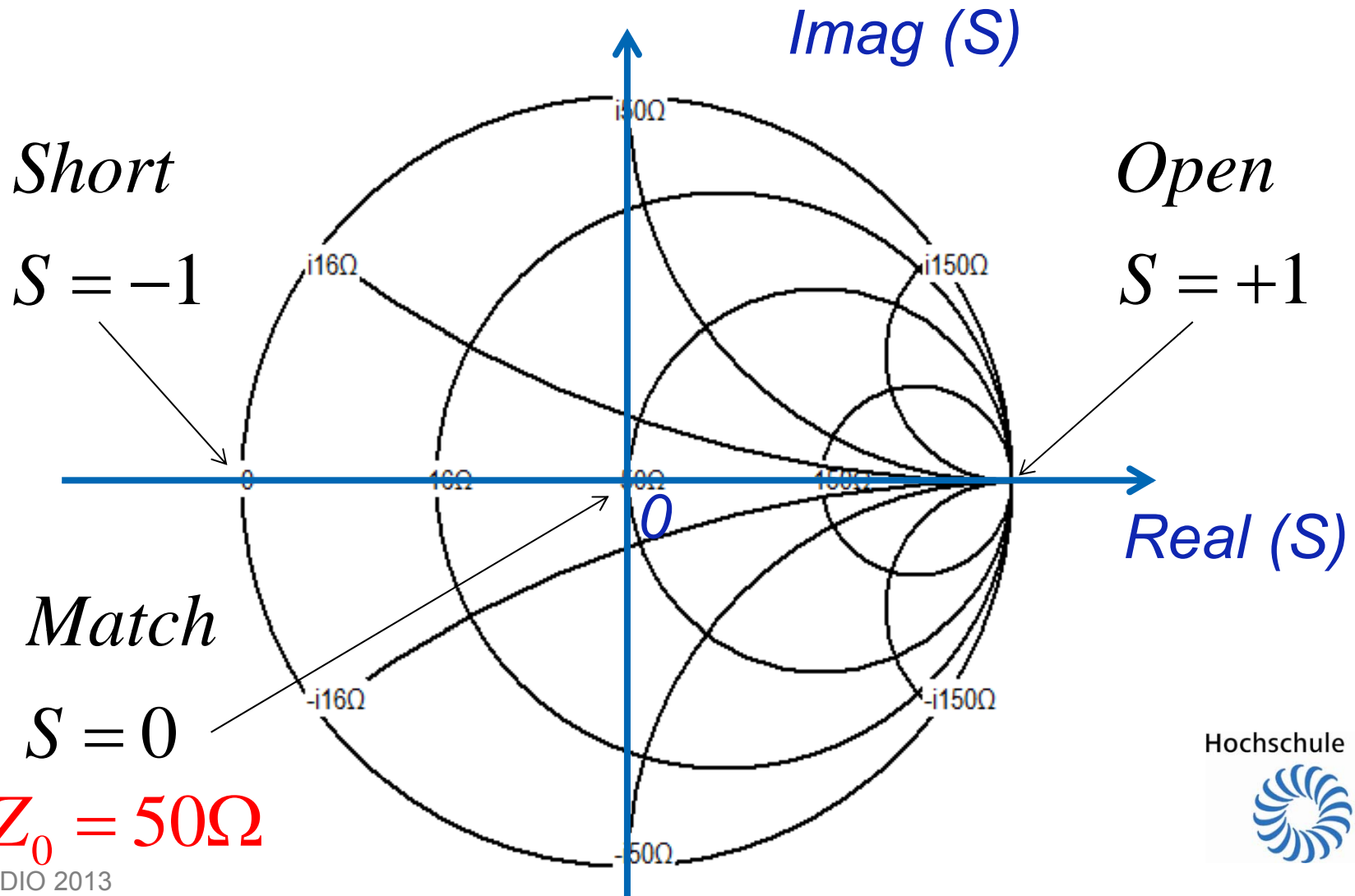
...



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

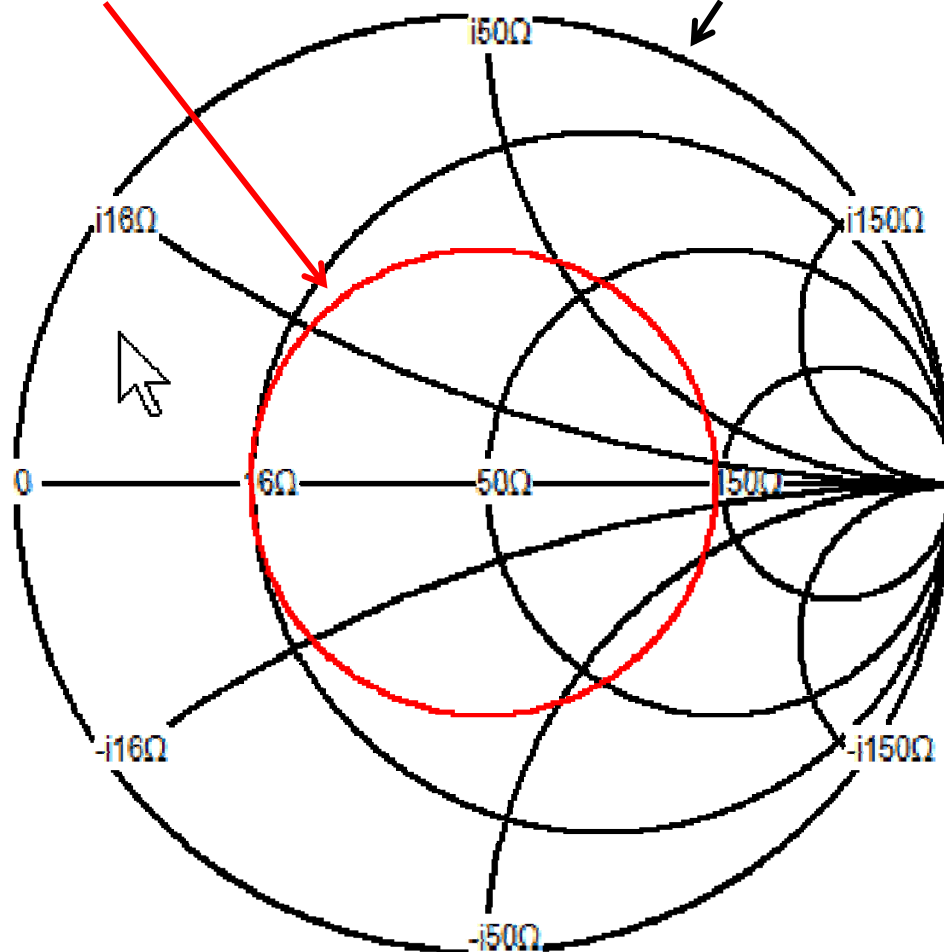


# Complex Reflection Coefficient $S = b/a$ and Voltage Standing Wave Ratio VSWR

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

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

0,5 · 0,5 = 25%  
reflected power



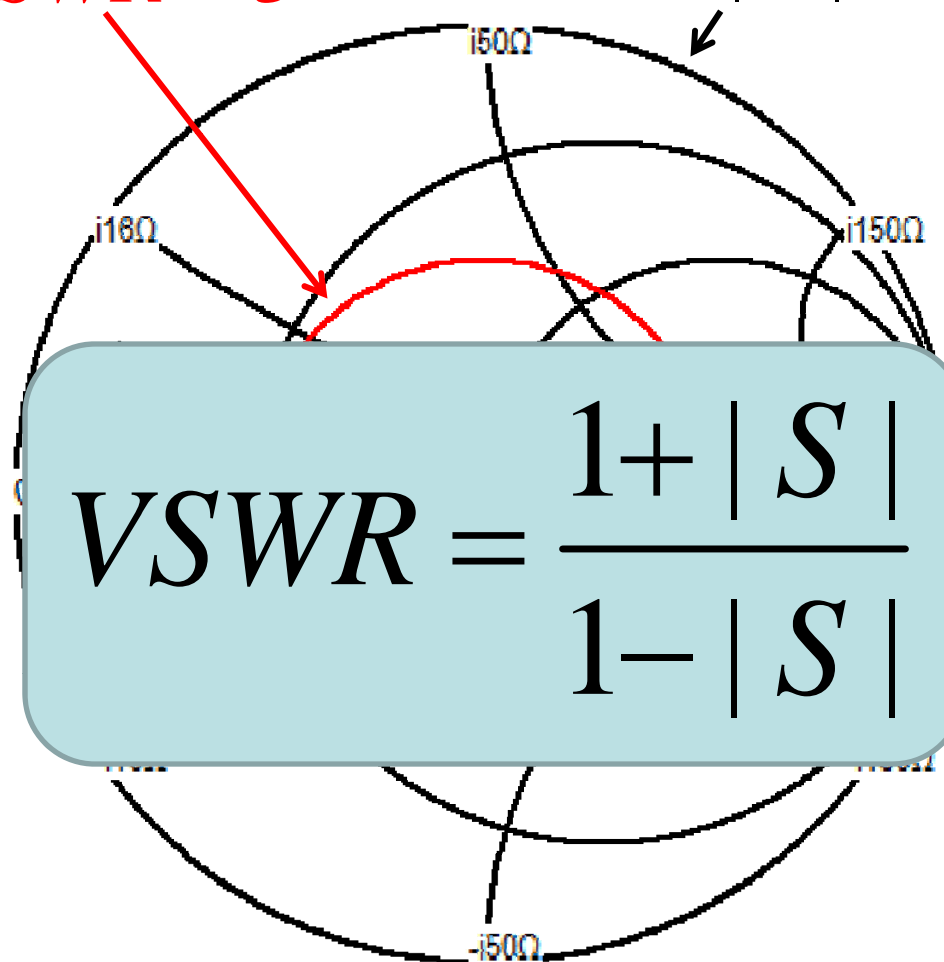
1 · 1 = 100%  
reflected power



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

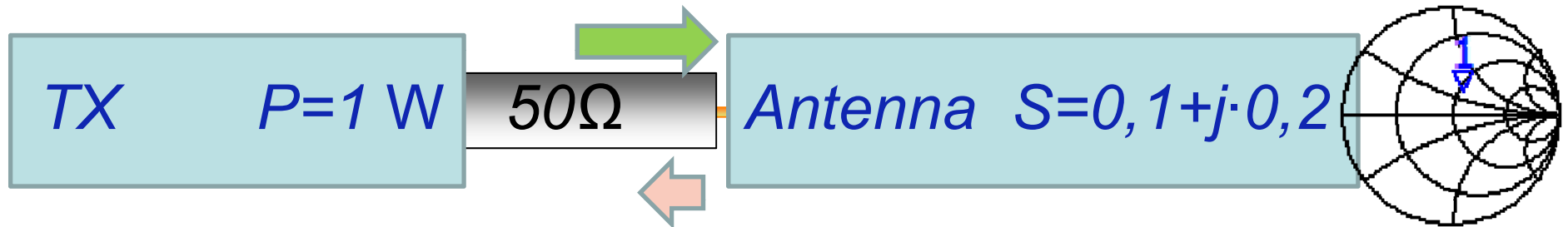
$$|S| = 0,5 \quad VSWR = 3$$

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



# 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:

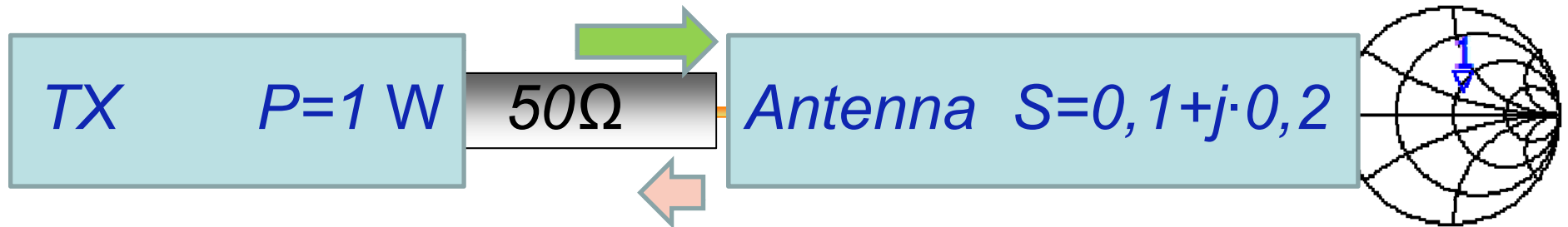
$$P_r = |b|^2 = 0,1^2 + 0,2^2 \text{ W} = 0,05 \text{ W}$$





# Complex Reflection Coefficient $S = b/a$

## Calculus Example: VSWR



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

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

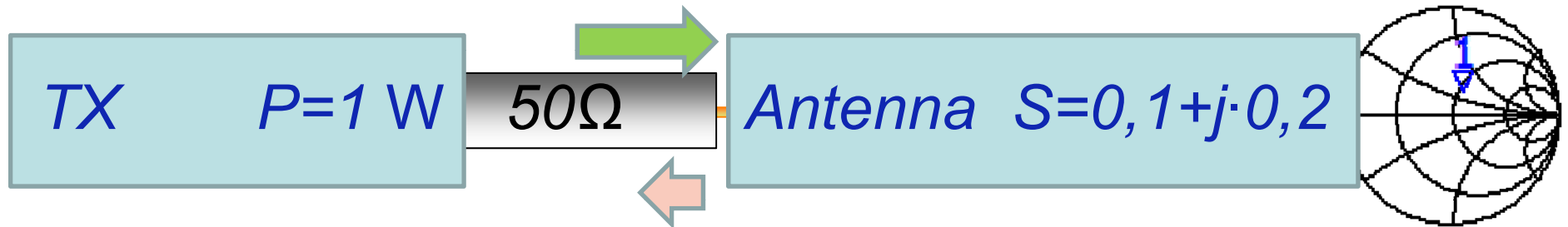
VSWR:

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

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

# 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:

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

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

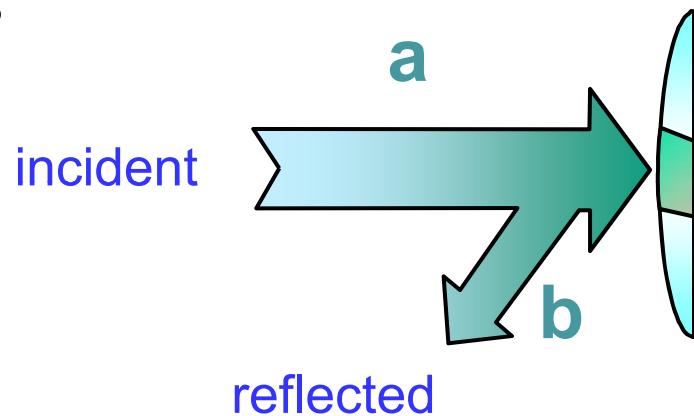
$$U_{eff} = |U| = \sqrt{7,8^2 + 1,4^2} \text{ V} \approx 7,9 \text{ V}$$



# Complex Reflection Coefficient $S = b/a$

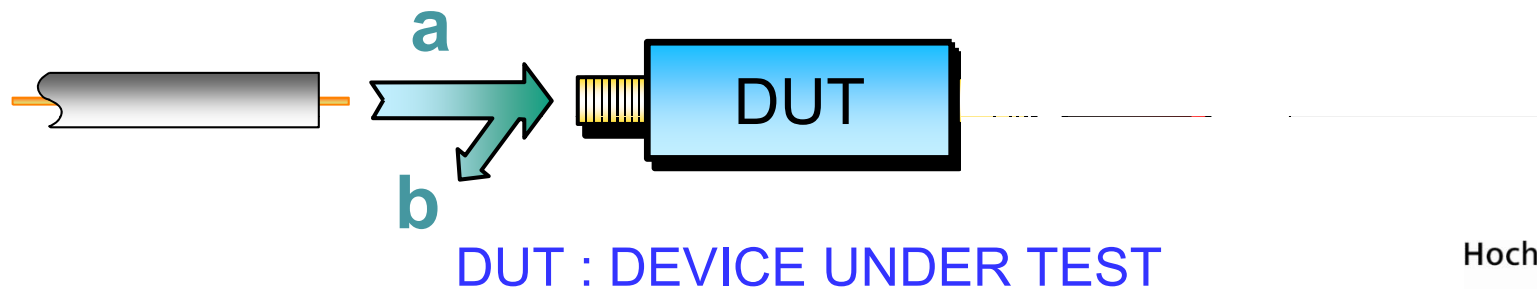
We call it Scattering Parameter now!

## Optics



Scattering and absorption of waves at one port

## Elektrical

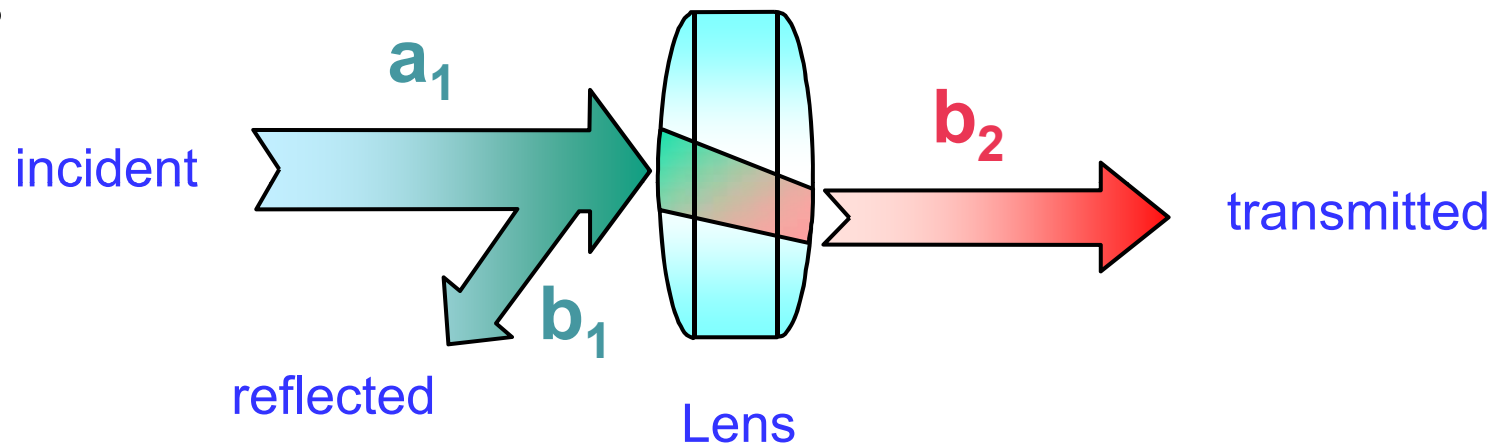


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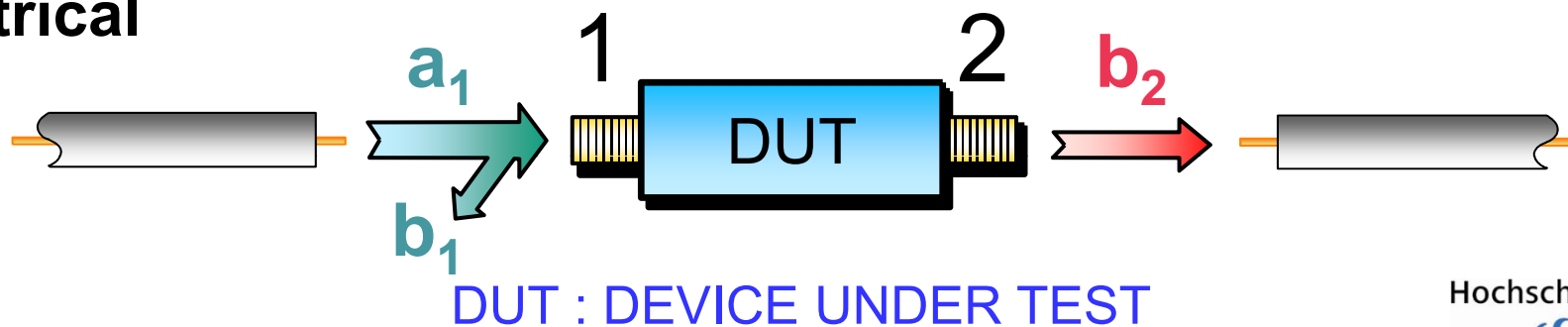


# Scattering Parameters or short S-Parameters: Now two Ports!

## Optics



## Electrical

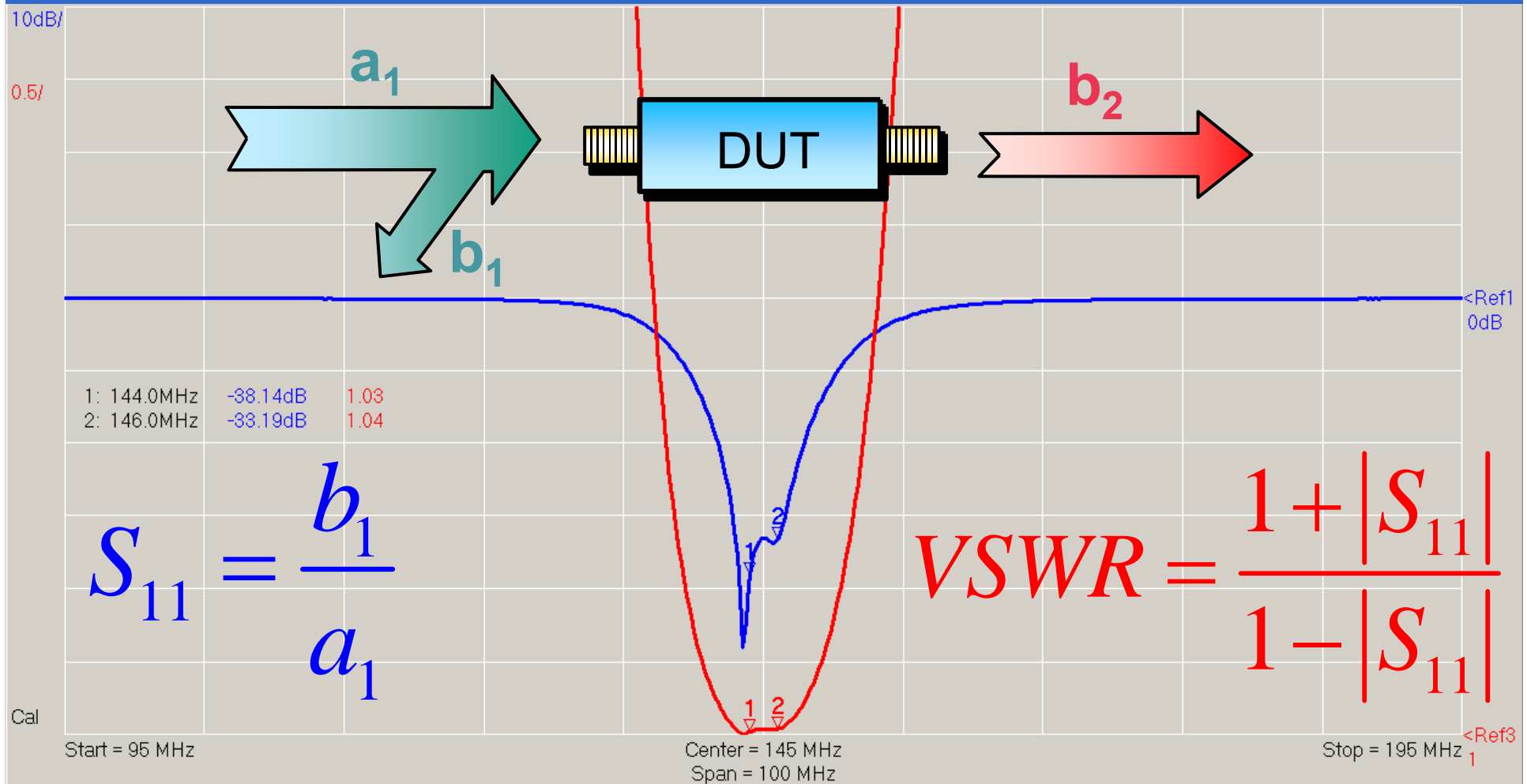


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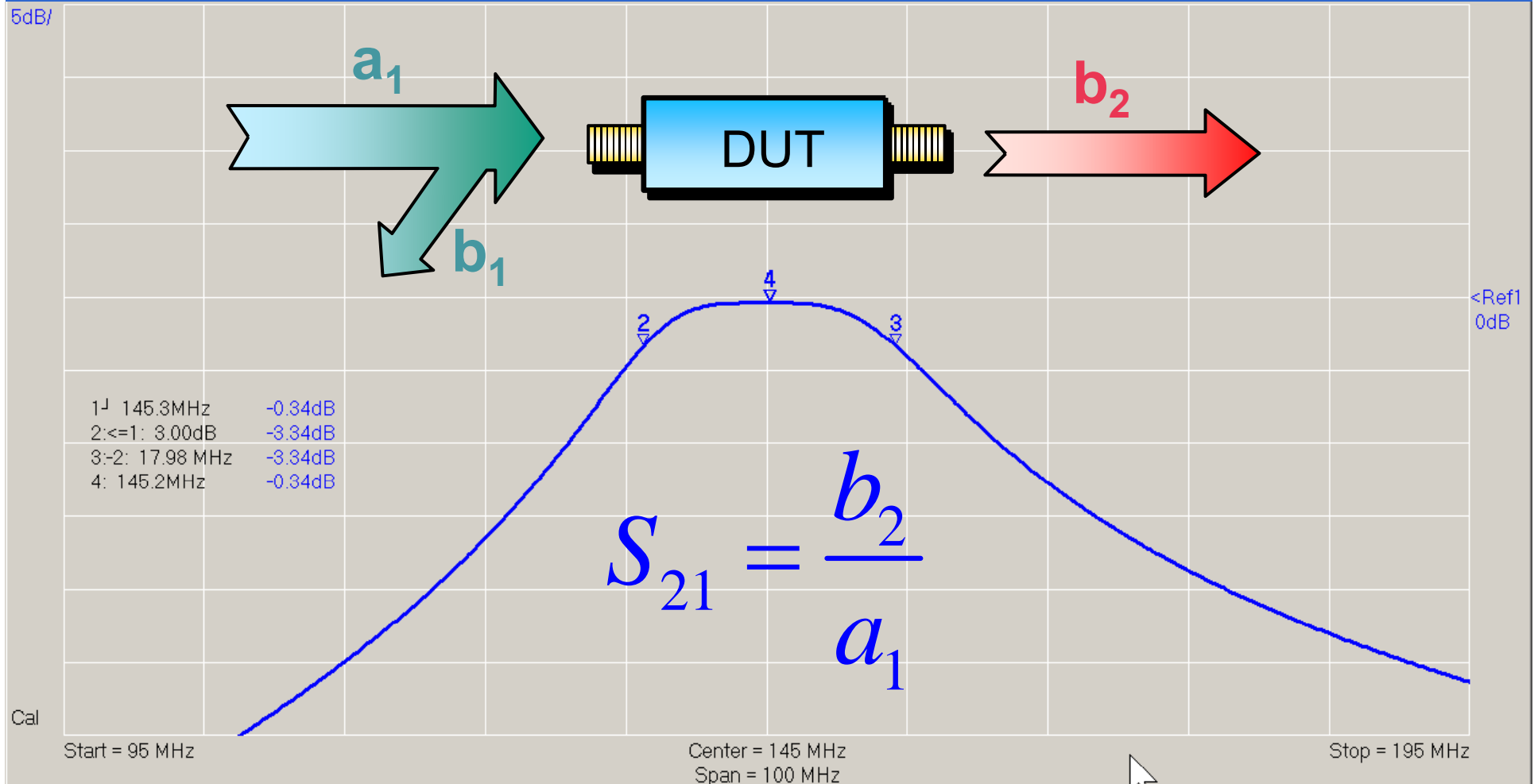
# S-Parameter $S_{11}$ (used to be $S$ )

→  $|S_{11}|$  → Return Loss

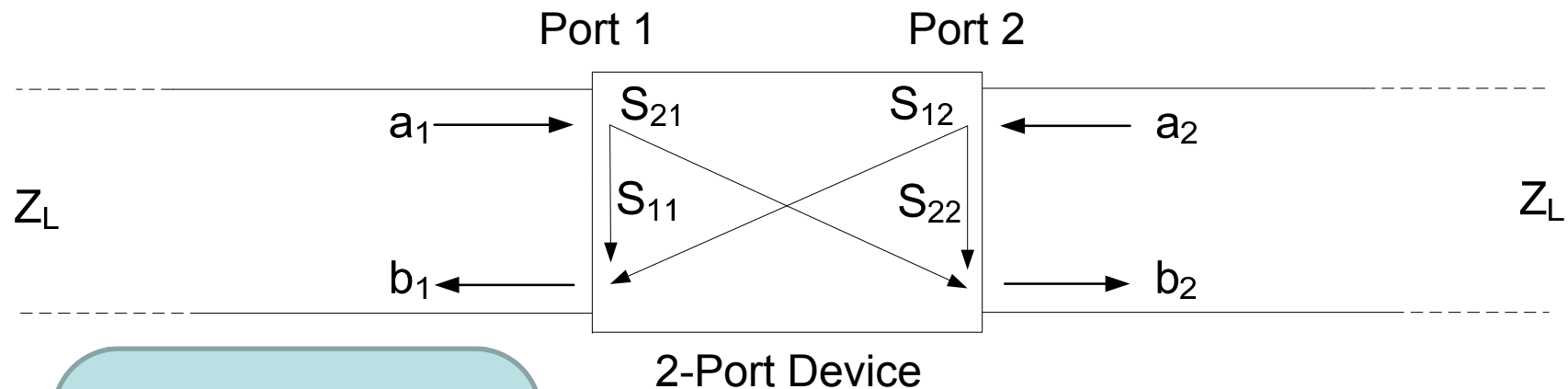


# S-Parameter $S_{21}$

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



# General: S-Parameters $S_{ik}$

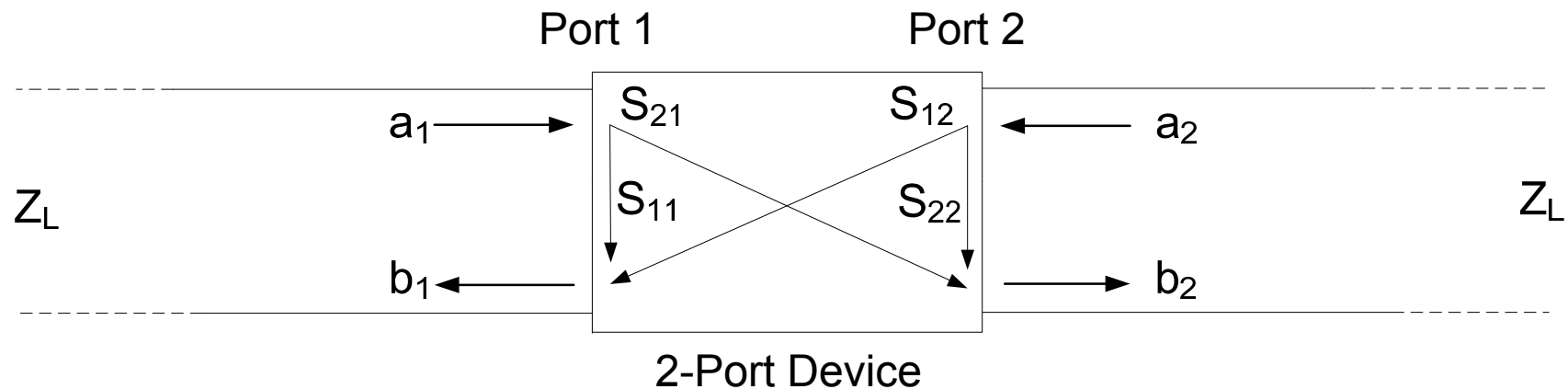


$$S_{ik} = \frac{b_i}{a_k}$$

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



# General: S-Parameters $S_{ik}$

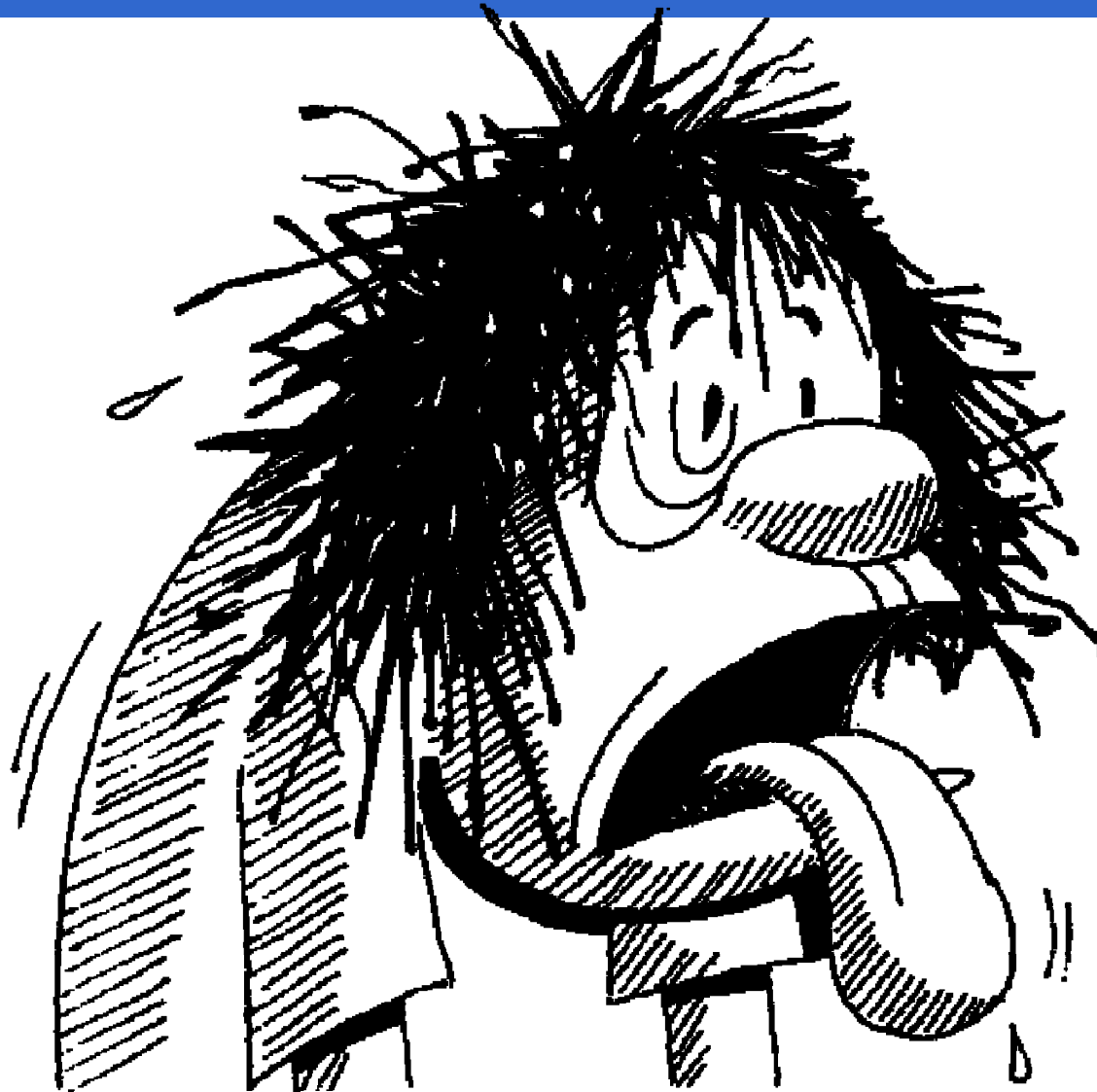


Scattering parameters  $S_{11}$ ,  $S_{21}$ ,  $S_{12}$ ,  $S_{22}$   
completely describe linear two port device!  
=> useful for simulations





# BREAK ???



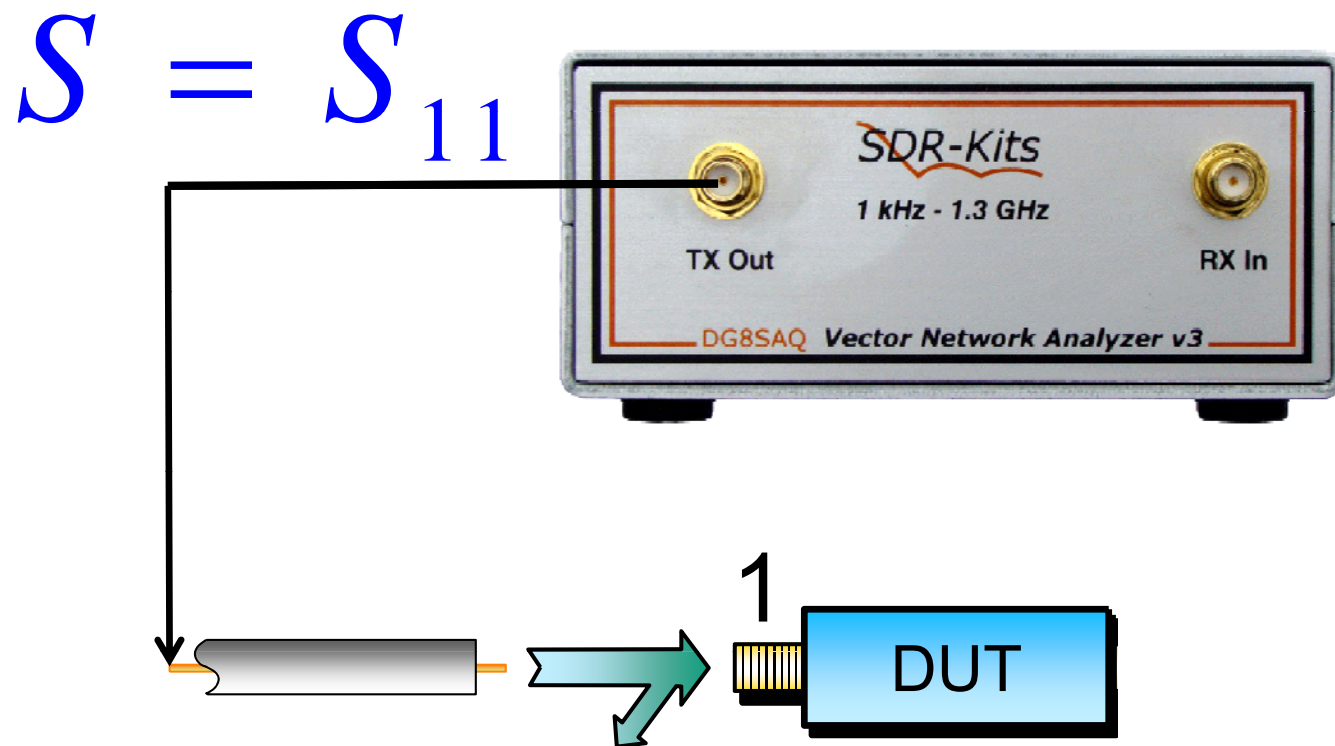
# Measuring S-Parameters using a Vector-Network Analyzer

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



# Measurement Setup using a VNWA

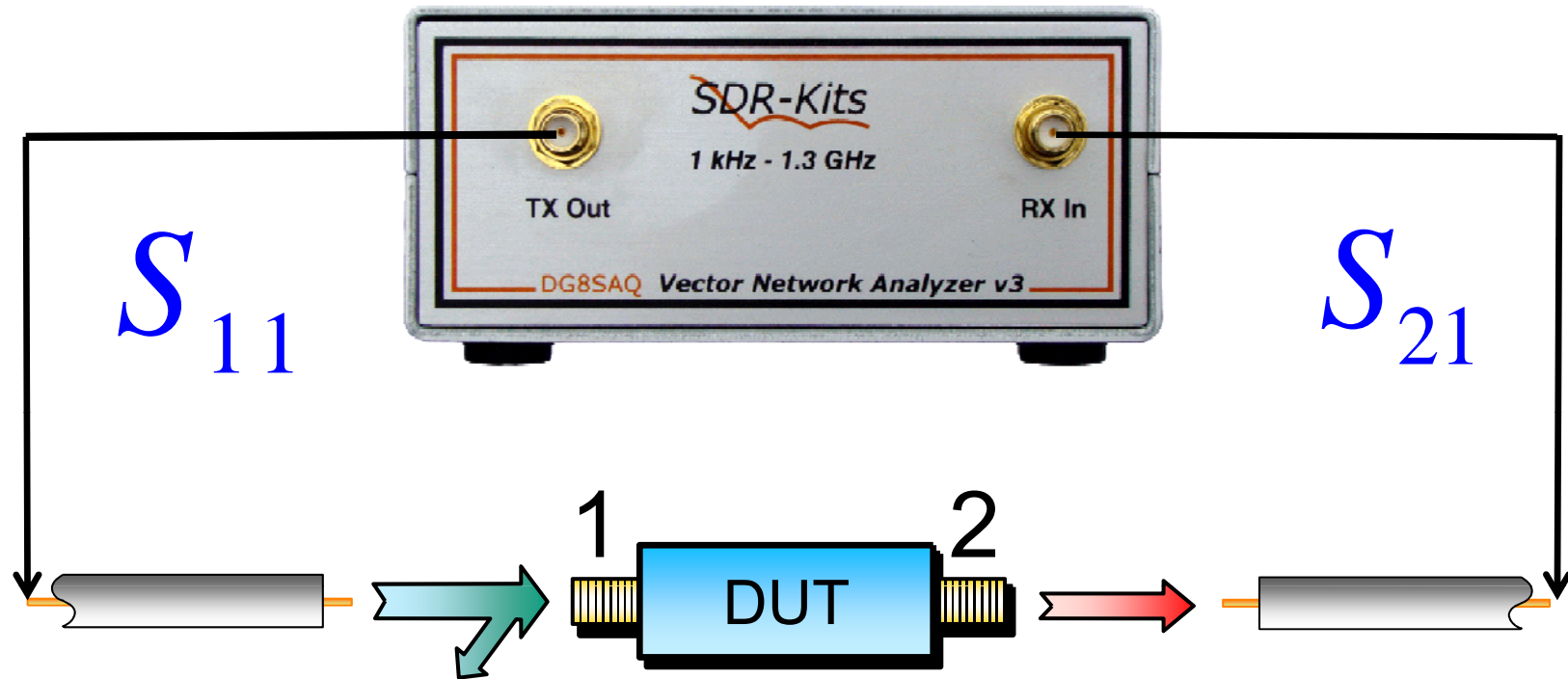
## Example 1-Port Device:



DUT : DEVICE UNDER TEST

# Measurement Setup using a VNWA

## Example 2-Port Device forward:



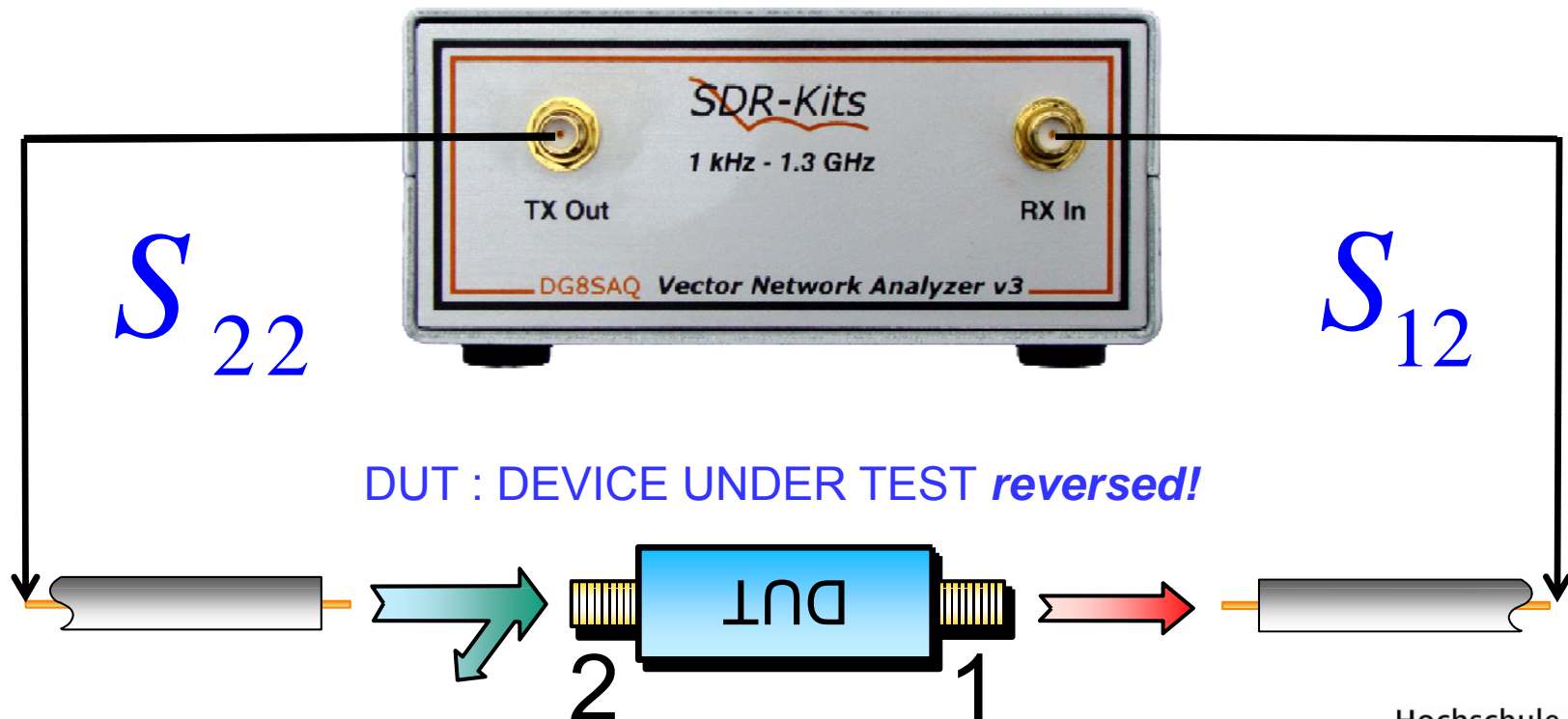
DUT : DEVICE UNDER TEST

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# Measurement Setup using a VNWA

## Example 2-Port Device reverse:

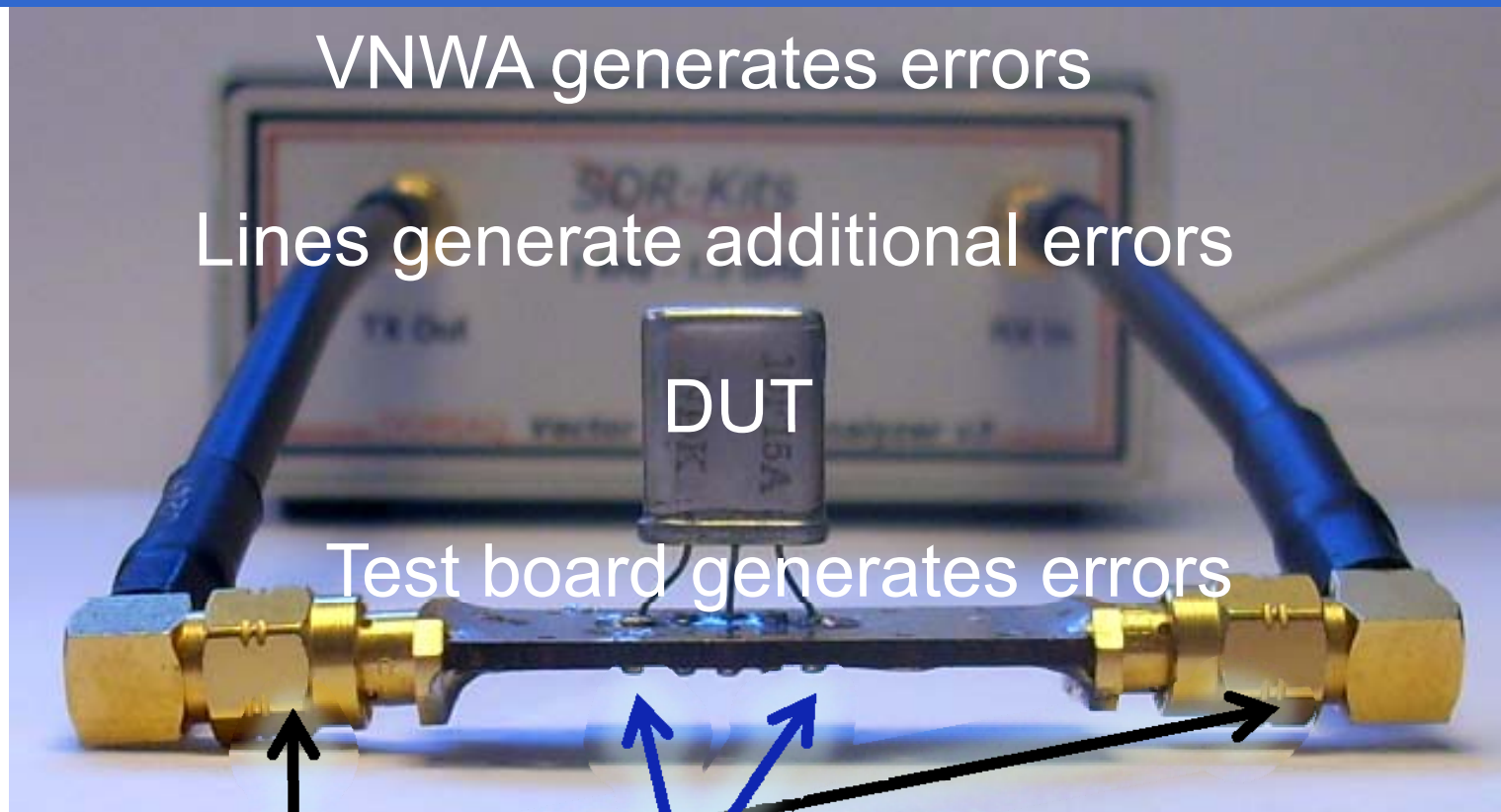


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# Error Correction by Calibration

## Error Sources



We calibrate here!

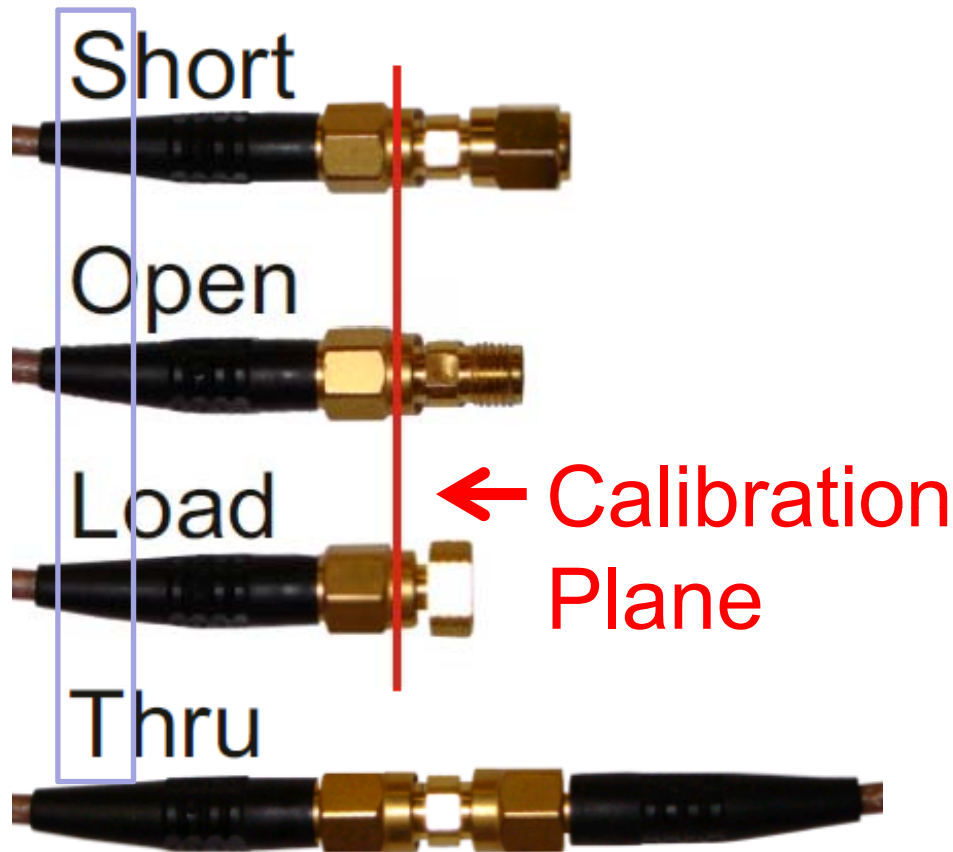
We want to measure here!

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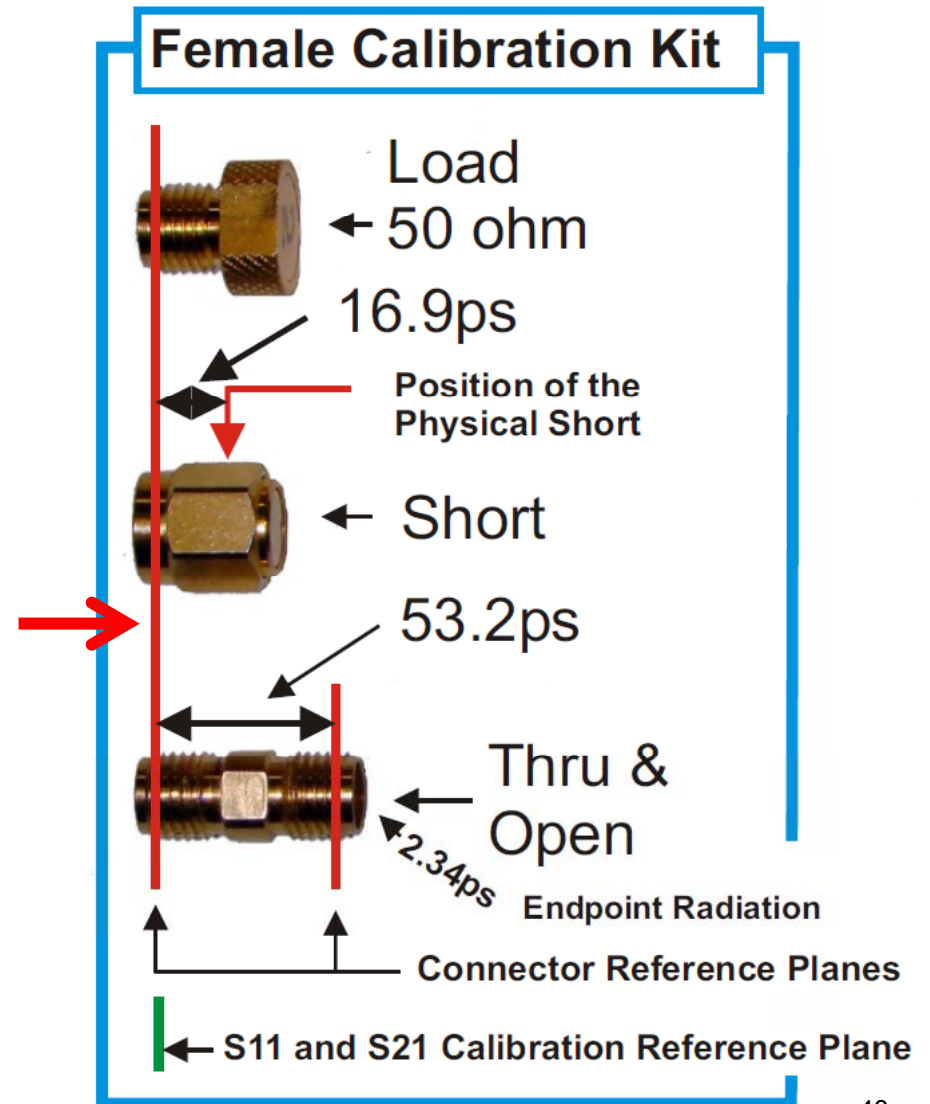


# SOLT-Calibration removes Errors from VNWA and Test Cables...



<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

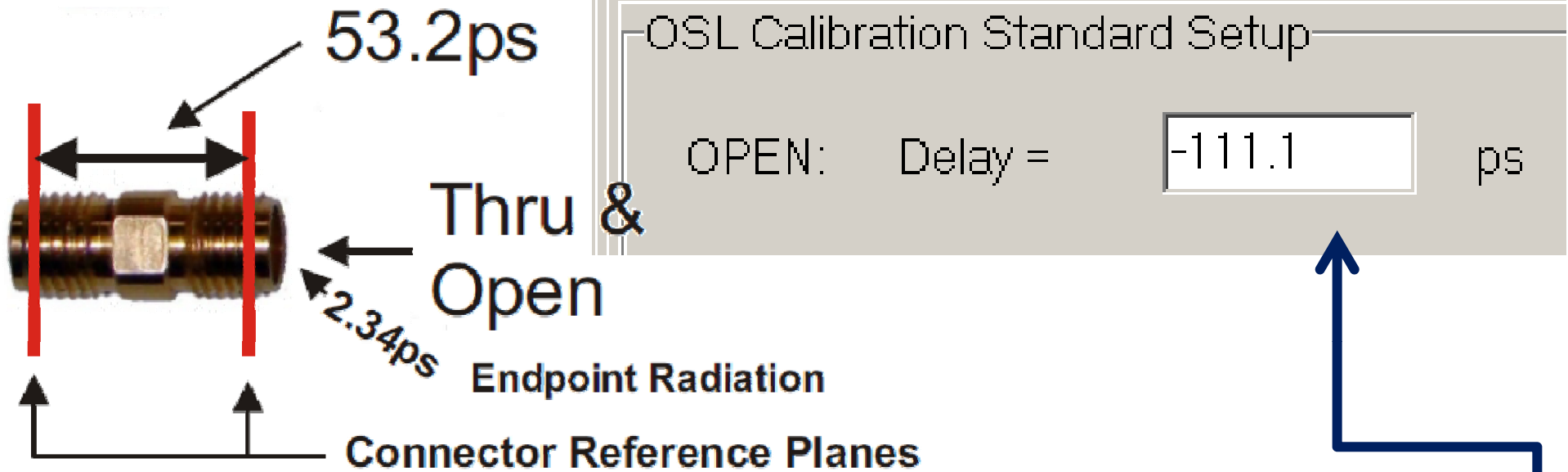
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# Example: Open Standard



Signal travels standard twice, namely forth and back:

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



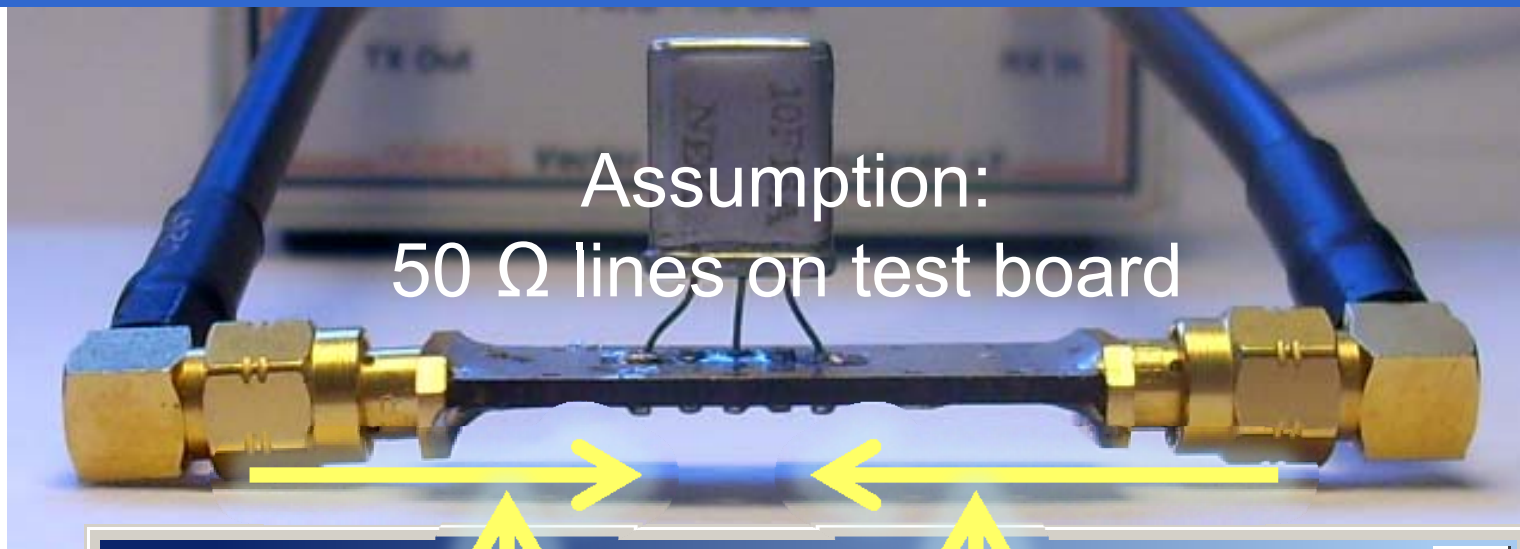
# Now, connect standards to VNWA and calibrate

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

- Window Title:** Full Calibration
- Menu:** Calibration Menu | Correction
- Buttons:** save cur..., aster cal., Reflect Cal, Thru Calibra, Cal  on / off, Invalidate All Thru Calibrations
- Annotations:**
  - A box labeled "needed for" points to the "Correction" menu.
  - A box labeled  $S_{11}, S_{22}$  is positioned over the Reflect Cal section.
  - A box labeled  $S_{21}, S_{12}$  is positioned over the Thru Calibra section.
  - A red circle with an arrow points to the "Crosstalk Cal" button, with the text "usually omit" written vertically to its right.
  - A mouse cursor is pointing at the "Thru Match Cal" button.
- Calibration Options:**
  - Short (M)
  - Open (M)
  - Load (M)
  - Cal  on / off (M)
  - Crosstalk Cal (Red circle)  on / off
  - Thru Cal (M)  on / off
  - Thru Match Cal (M)  on / off

UIm

# Delay Correction with Port Extensions



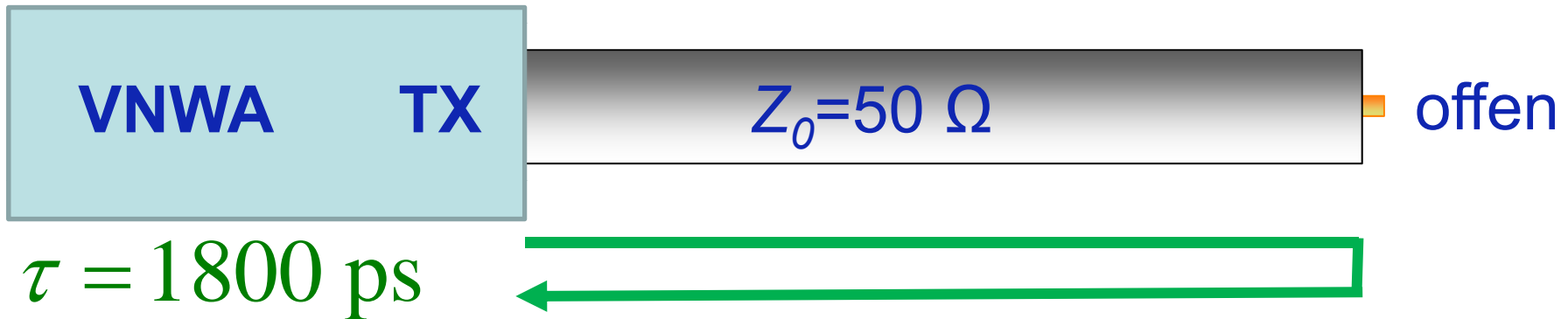
$S_{11}$   
 $S_{22}$

**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)



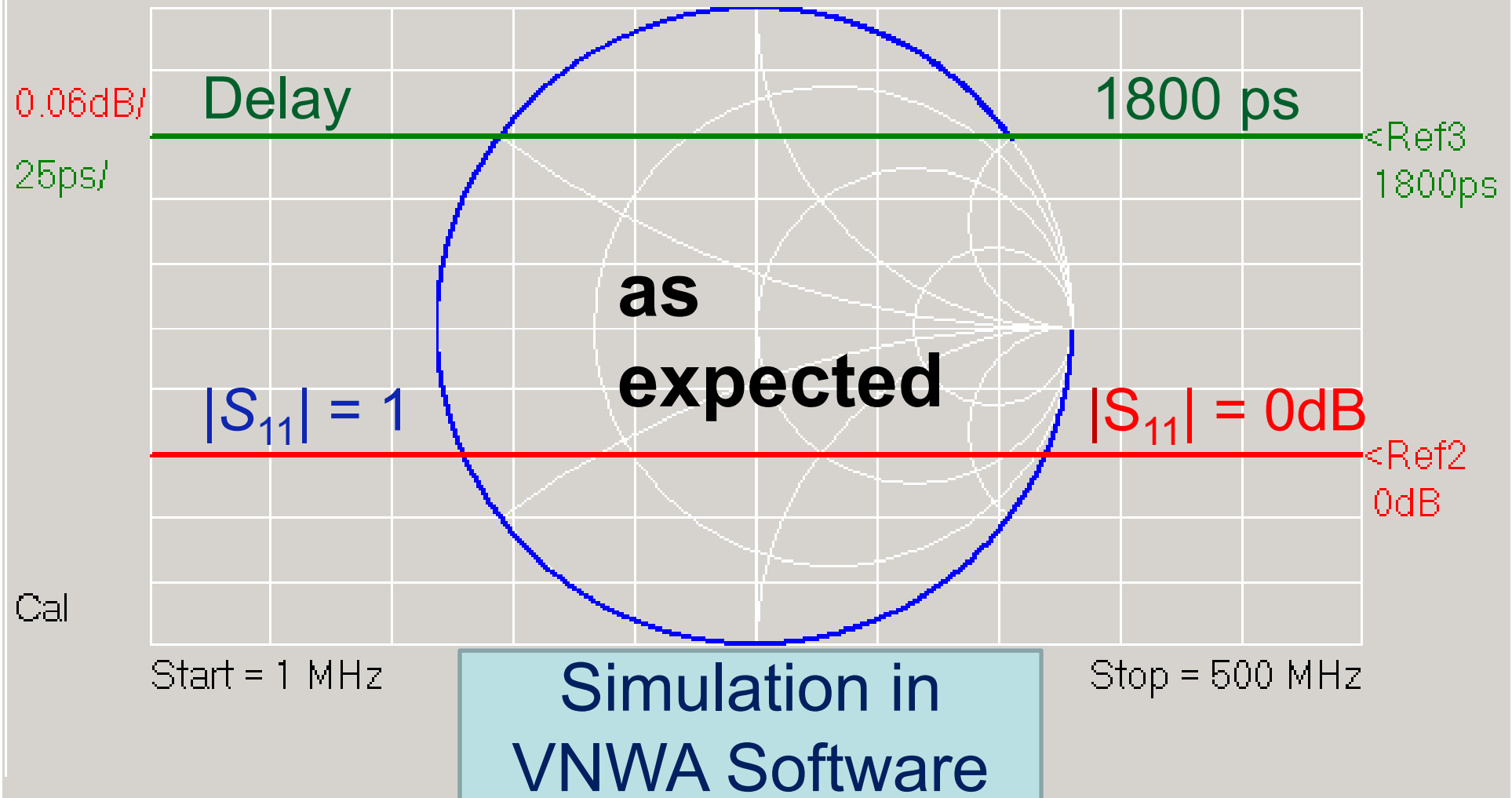
**Calibration Settings** We can simulate this:

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

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

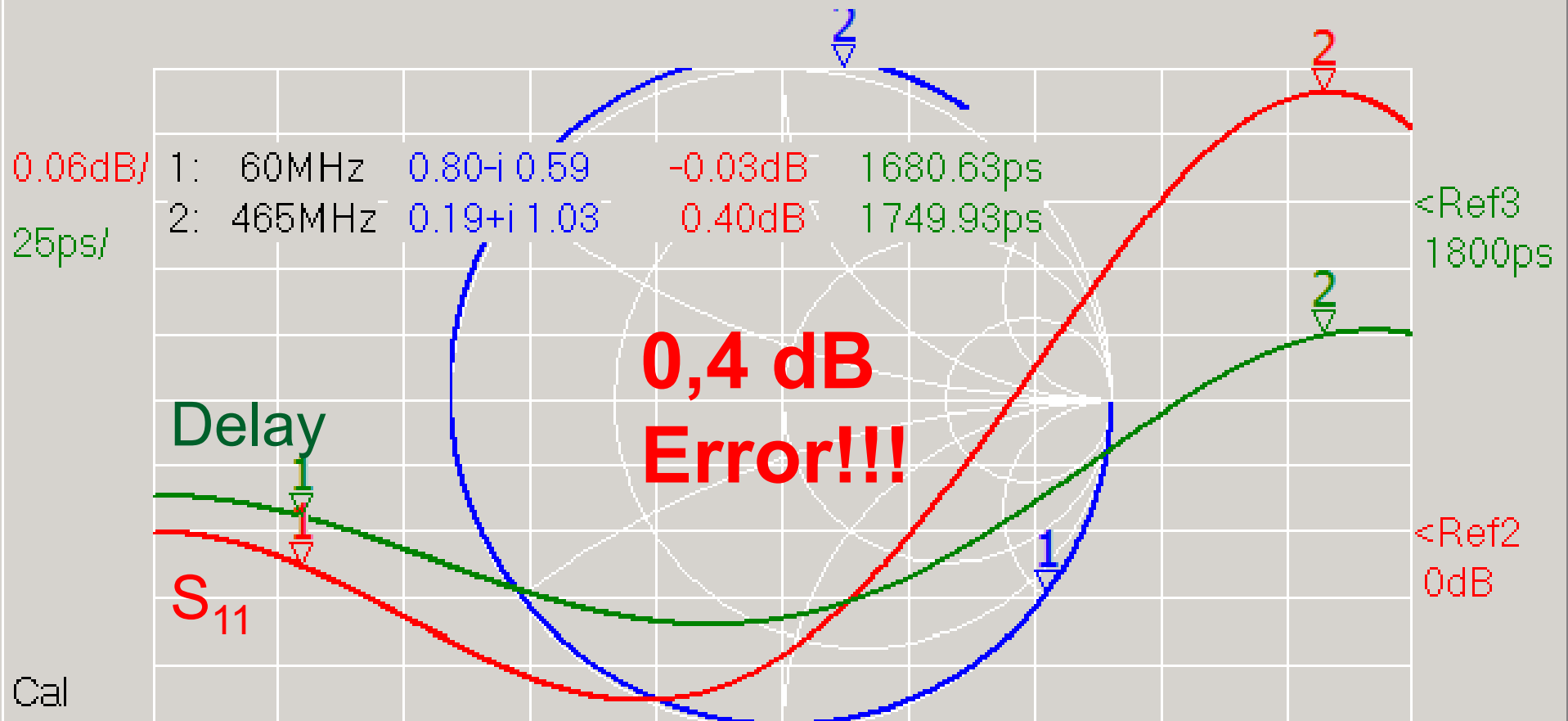
i.e.  $|S_{11}| = 1$  total power reflected  
 $\text{Phase}(S_{11}) = -\omega \cdot 1800 \text{ ps}$

# 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:



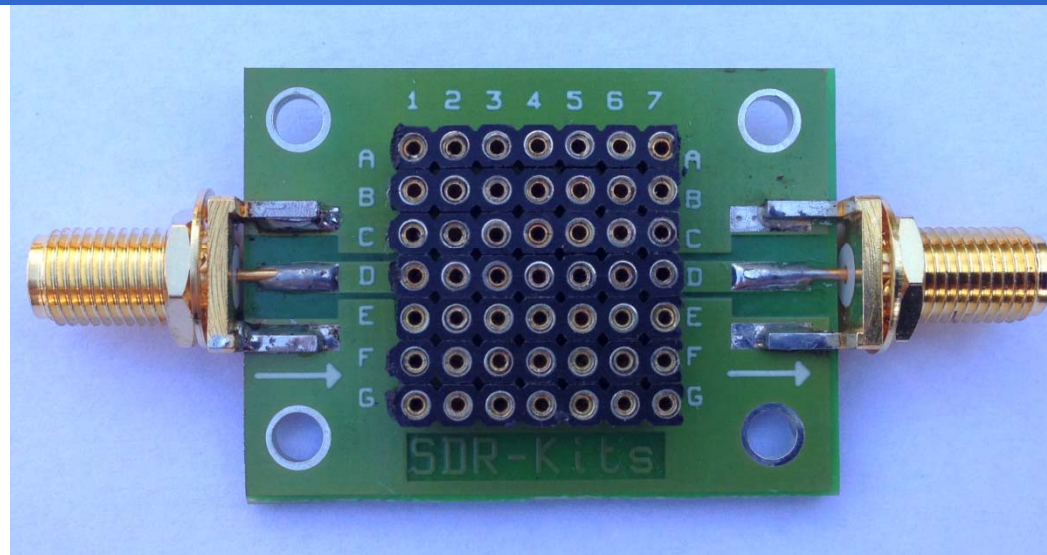
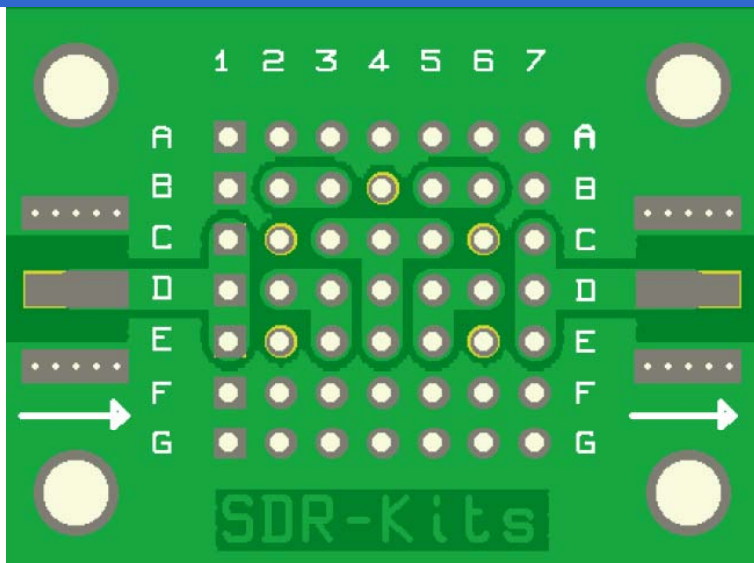
Previously simulated measurement data corrected again using ideal cal parameters

# Applications ...





# Test Board for HF Experiments



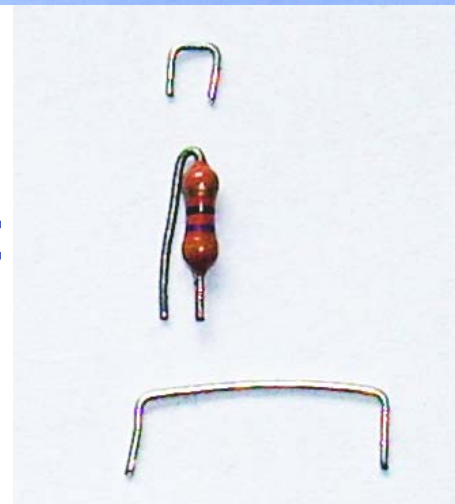
**Calibration  
Standards:**

Open = n.c.

Short:

Load =  $47\Omega$ :

Thru:

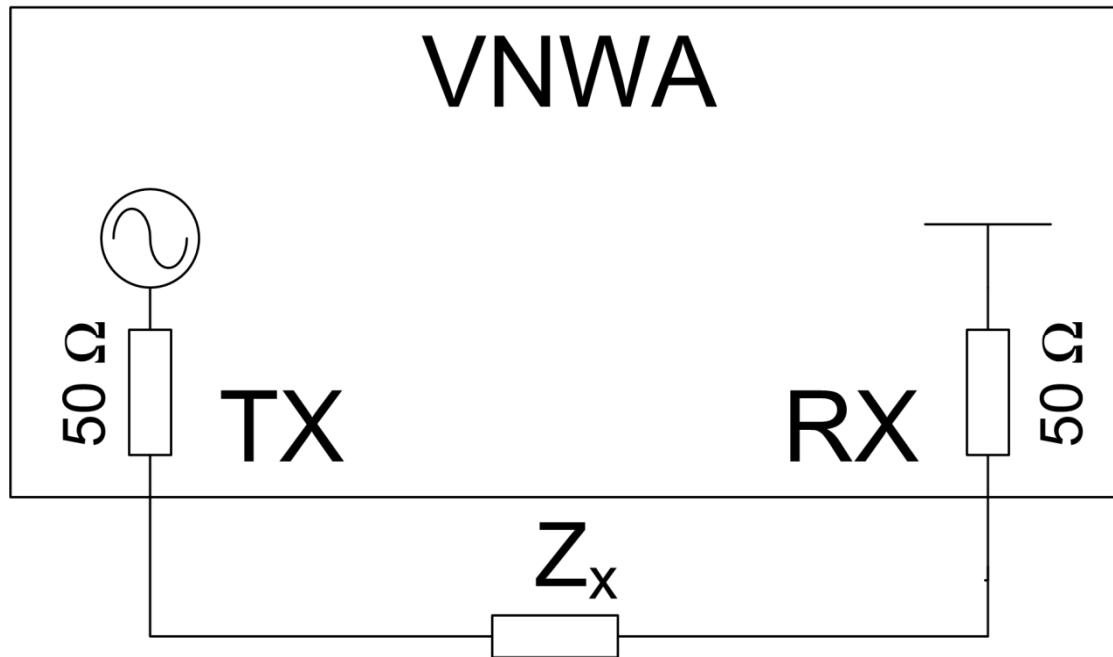


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# Measuring „Load“-Resistor without SOL-Calibration?

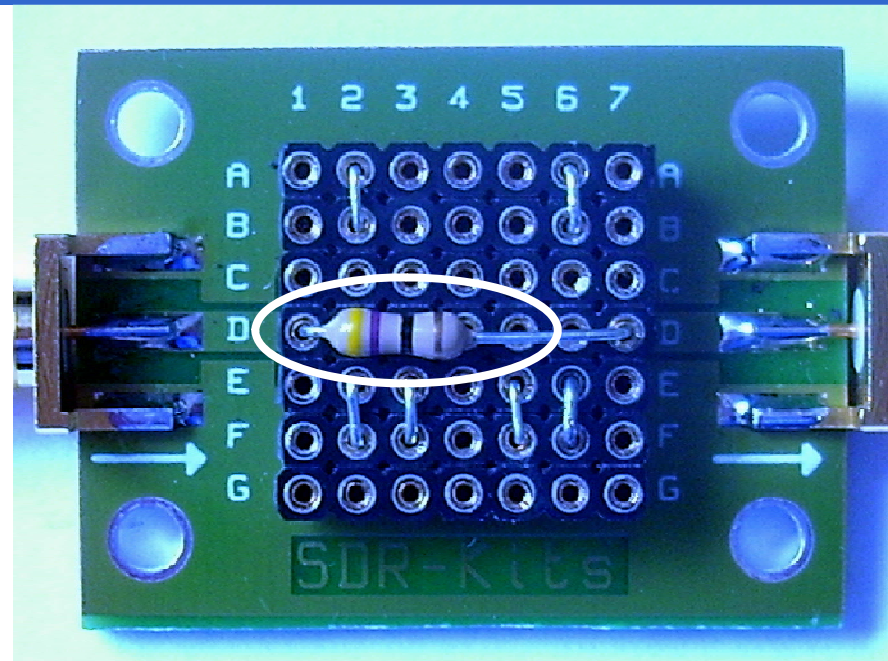
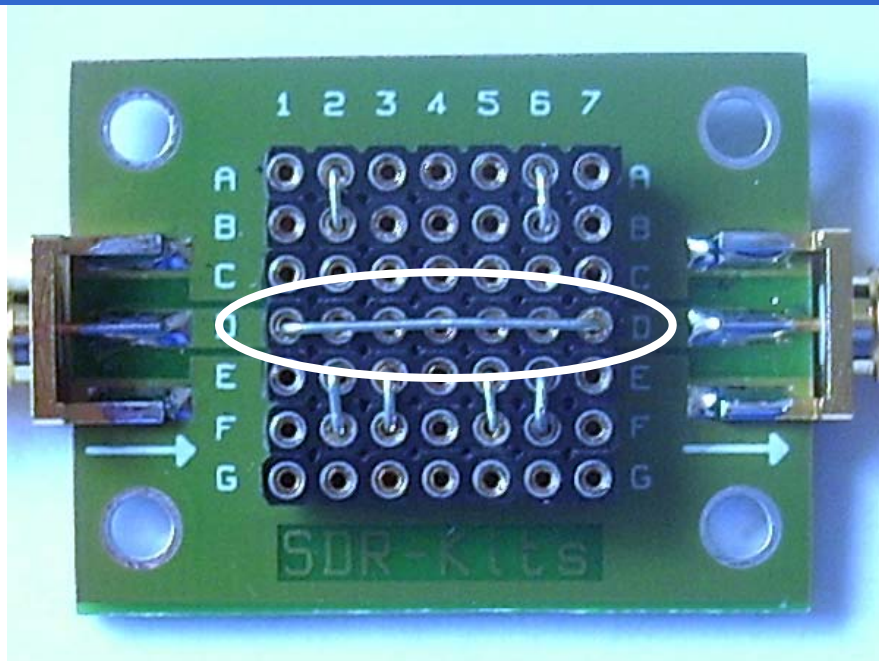


$Z_x = 47 \Omega$  yield  $\approx 3,4$  dB insertion loss.

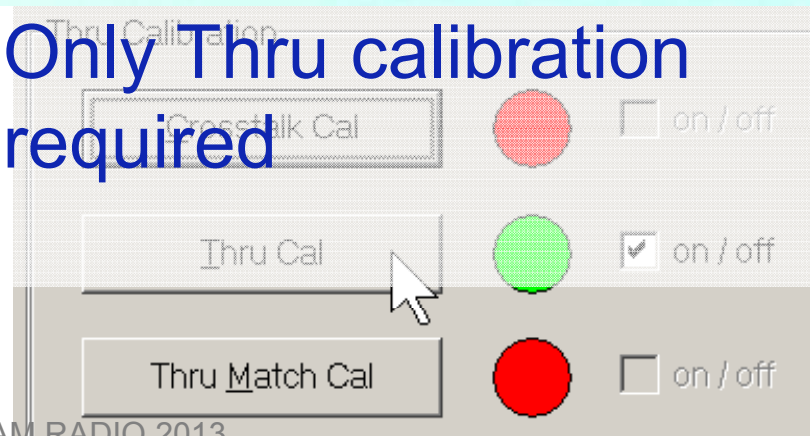
Works, because VNWA TX and RX port impedances are exactly 50  $\Omega$ .

➤ only Thru calibration required!

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



Only Thru calibration  
required



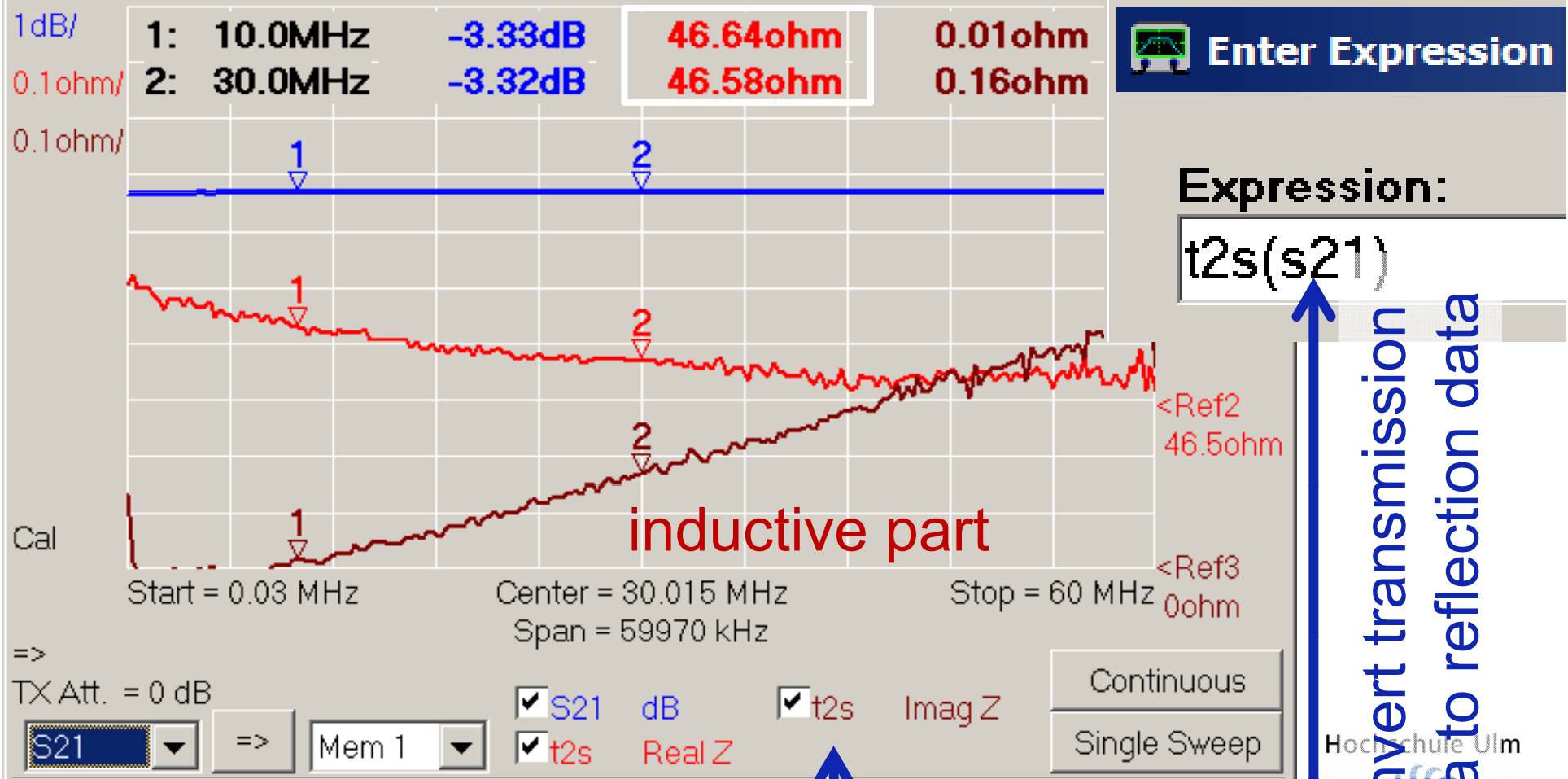
**Measurement:**  
Resistor between  
TX and RX

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# Measuring „Load“-Resistor

## Result = 46,6 $\Omega$



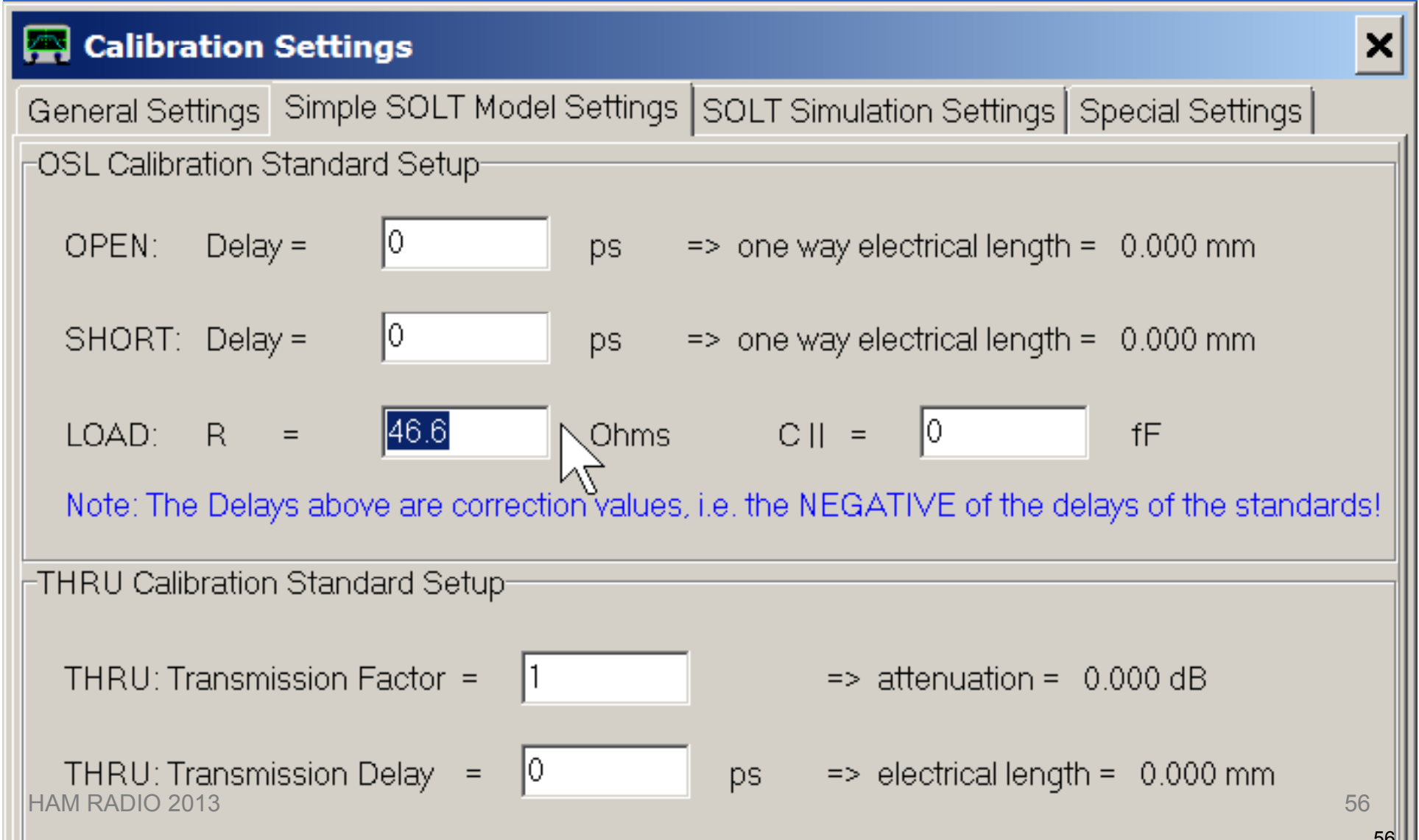
inductive part

<Ref2  
46.5ohm  
<Ref3  
0ohm

Convert transmission data to reflection data

Analysis with Custom Trace

# Simple Calibration Standard Model: Only measured Load-Resistance



The screenshot shows a software window titled "Calibration Settings" with a close button (X) in the top right corner. The window has four tabs: "General Settings", "Simple SOLT Model Settings", "SOLT Simulation Settings", and "Special Settings". The "Simple SOLT Model Settings" tab is active. The window is divided into two main sections: "OSL Calibration Standard Setup" and "THRU Calibration Standard Setup".

**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**

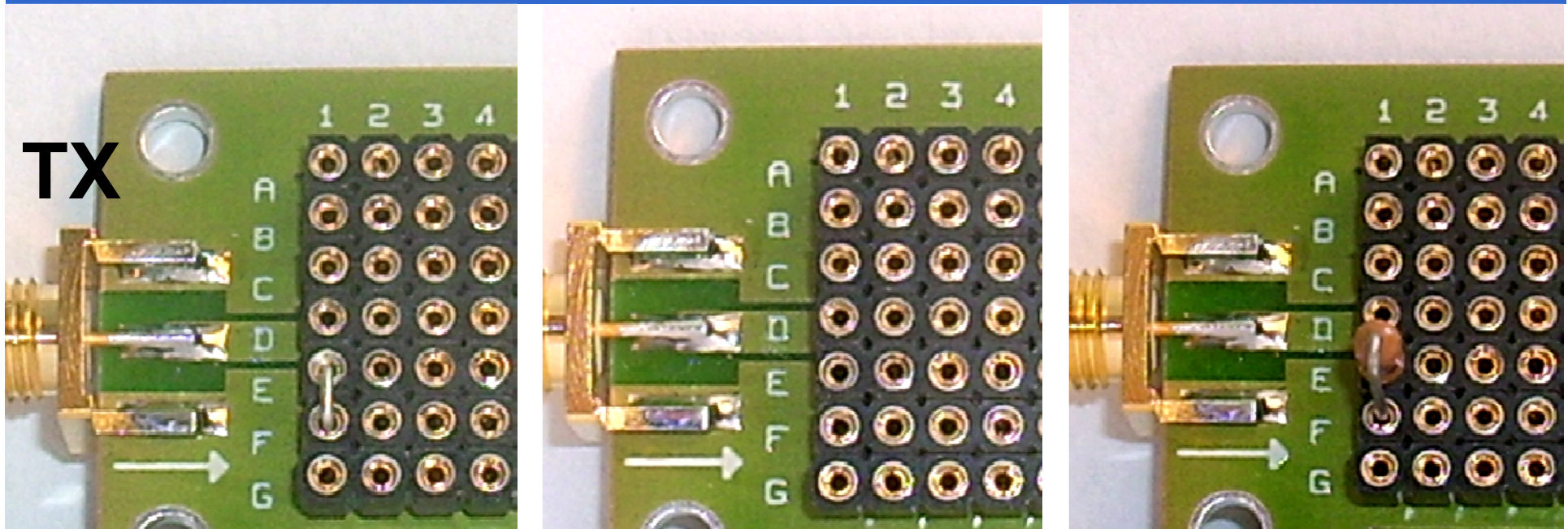
THRU: Transmission Factor =  => attenuation = 0.000 dB

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

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# SOL-Calibration for $S_{11}$ -Measurement



Reflect Calibration

**Short**

Short

Open

Load

HAMRAD  on/off

Thru Calibration

**Open**

Crosstalk Cal on/off

Thru Cal on/off

Thru Match Cal on/off

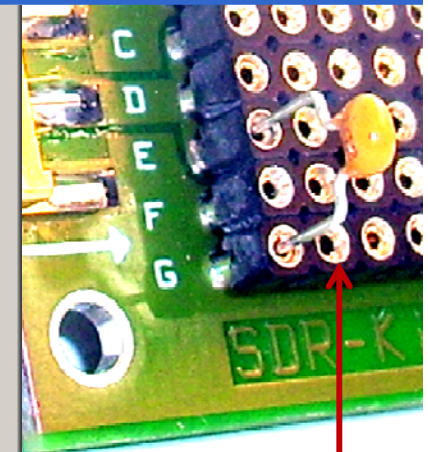
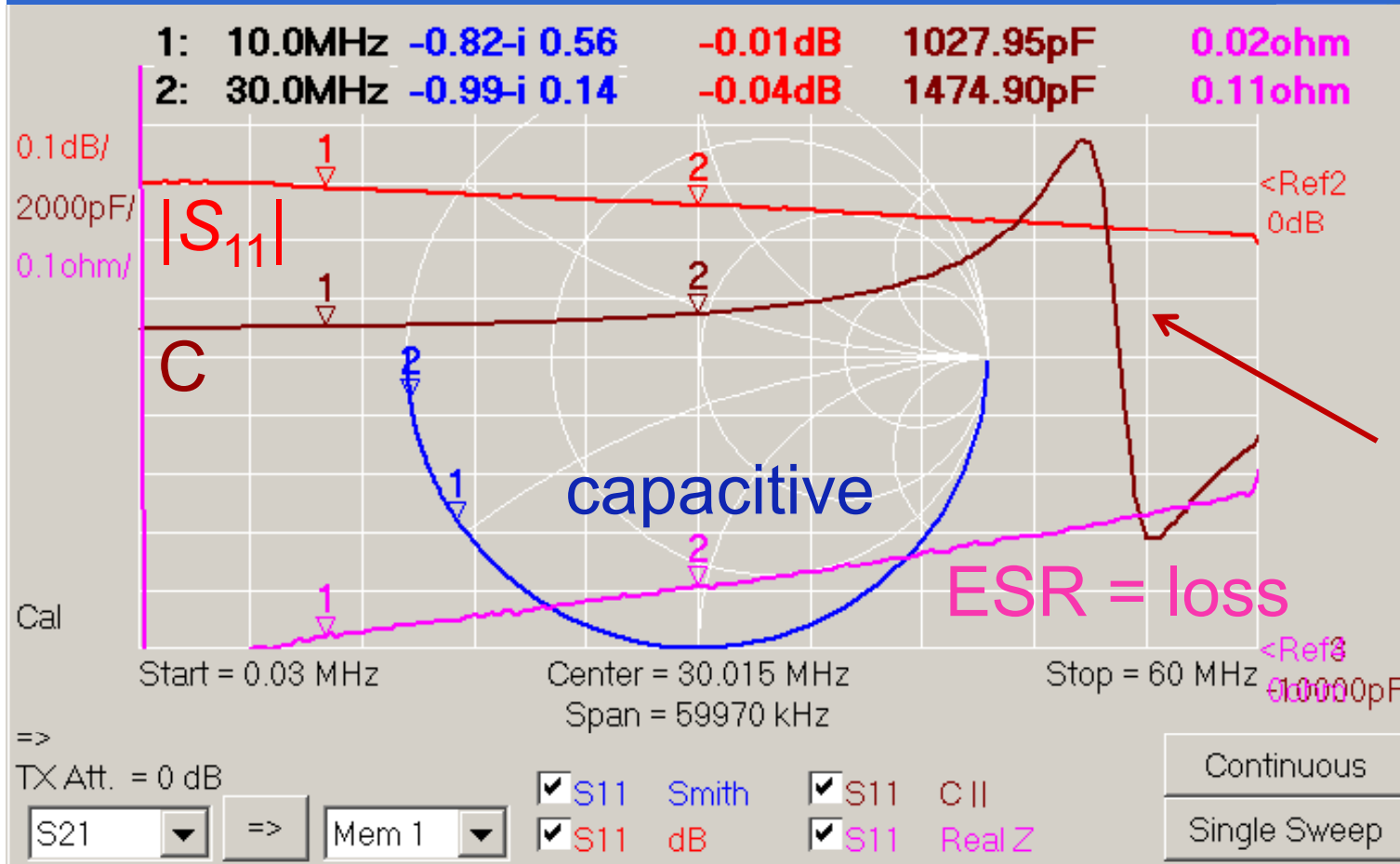
Invalidate All Thru Calibrations

**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

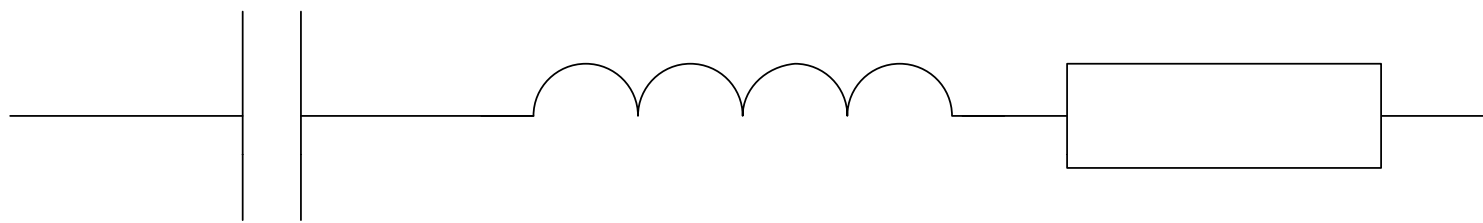


Enter Expression 2 for trace 2:

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

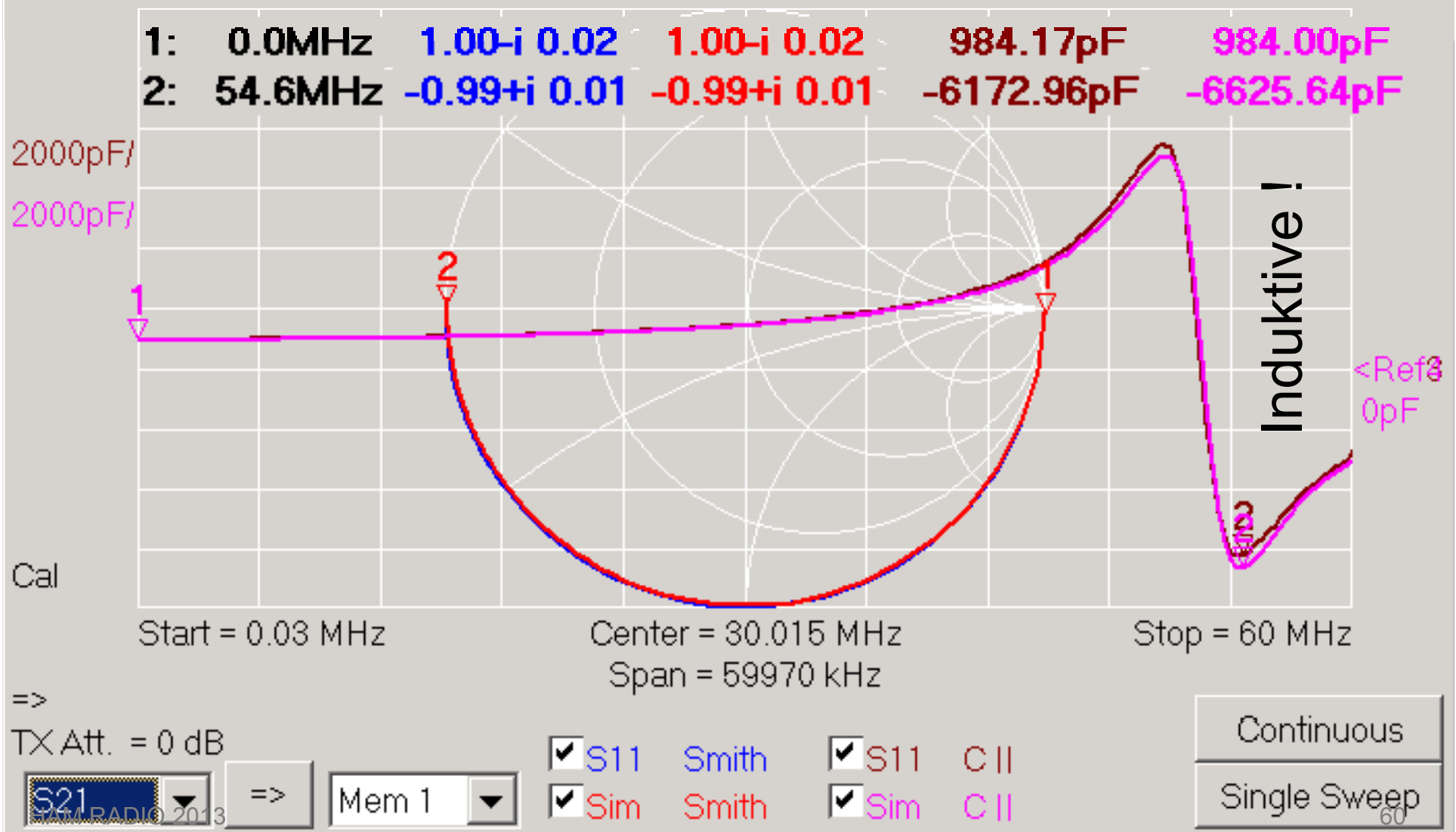
0,22 Ω

einfaches Modell

Hochschule Ulm



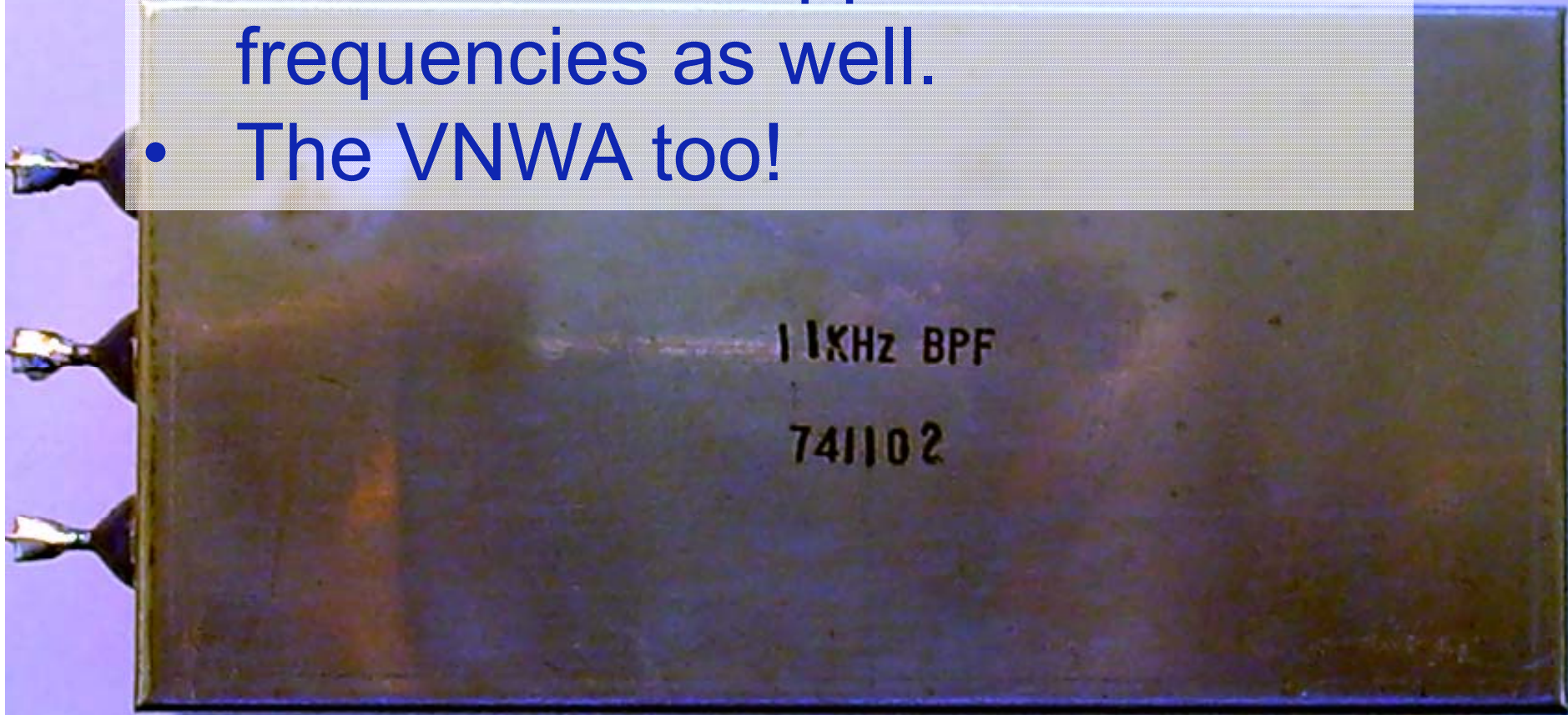
# The Model is quite accurate!



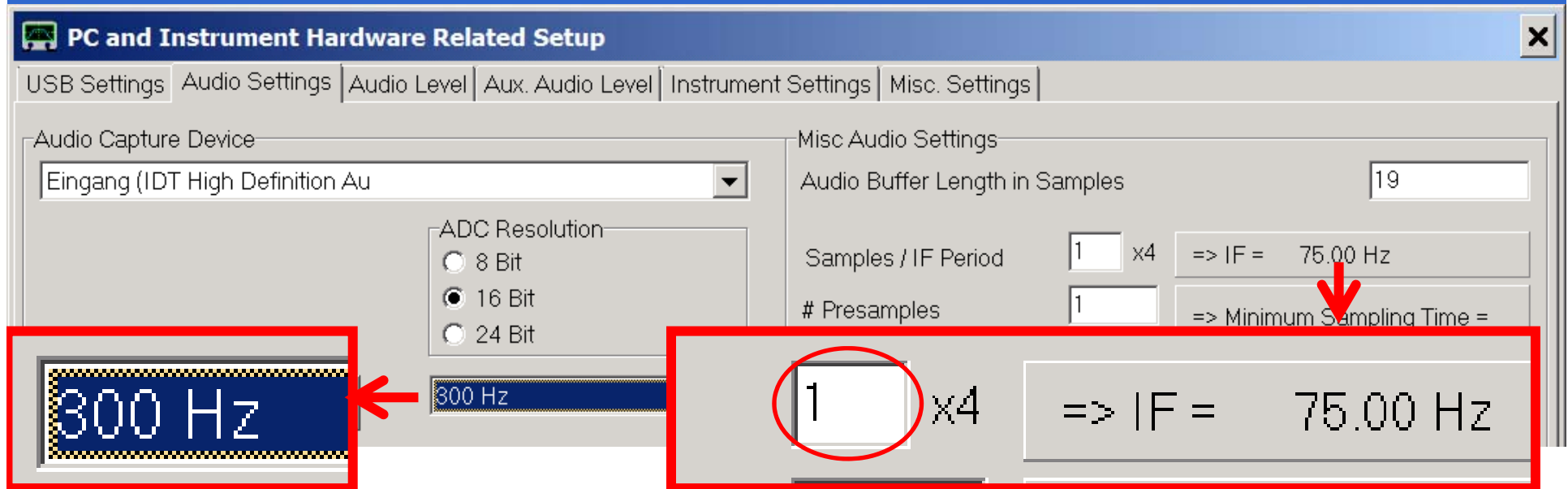


# Two Port Measurement of a 12 kHz Band Pass Filter

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



# Special VNWA Settings for low Frequencies



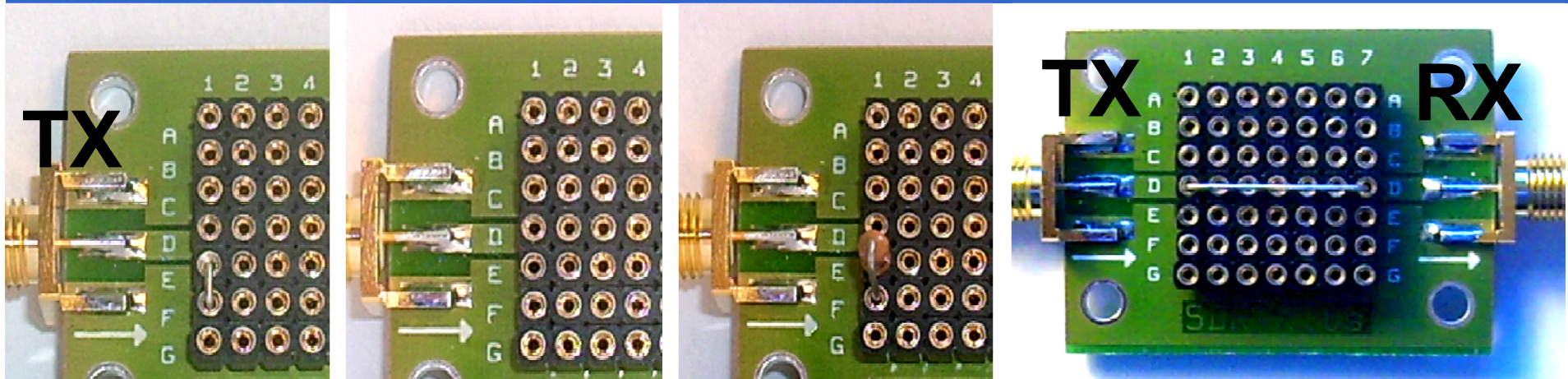
**Lowest sample rate 300 Hz** → Nyquist limit 150 Hz  
→ Measurements down to  $\approx 150$  Hz possible








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

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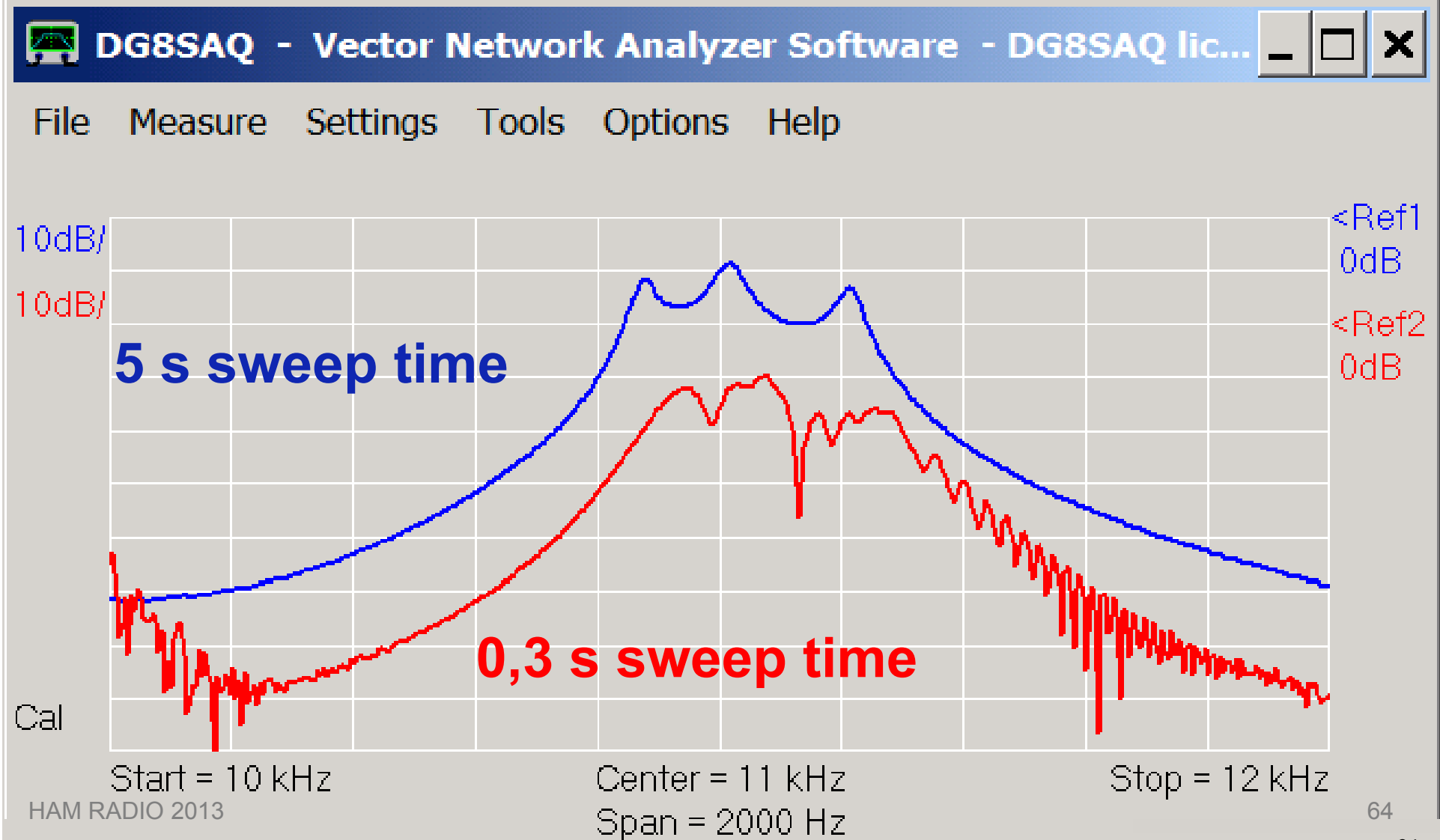
# SOLT-Calibration for 2-Port Measurements



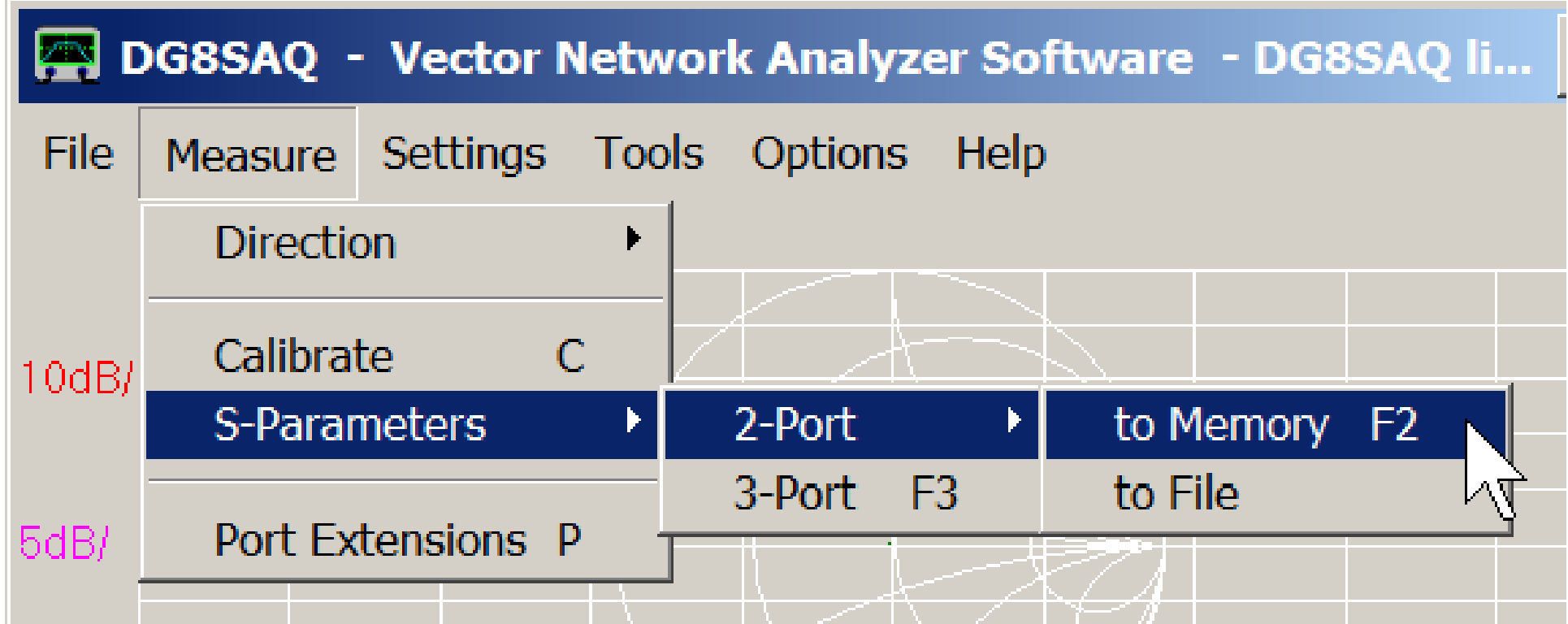
Reflect Calibration		Thru Calibration	
Short	Open	Load	Thru
Short		Crosstalk Cal	 <input type="checkbox"/> on / off
Open		Thru Cal	 <input checked="" type="checkbox"/> on / off
Load		Thru Match Cal	 <input checked="" type="checkbox"/> on / off
Cal <input checked="" type="checkbox"/> on / off		Invalidate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

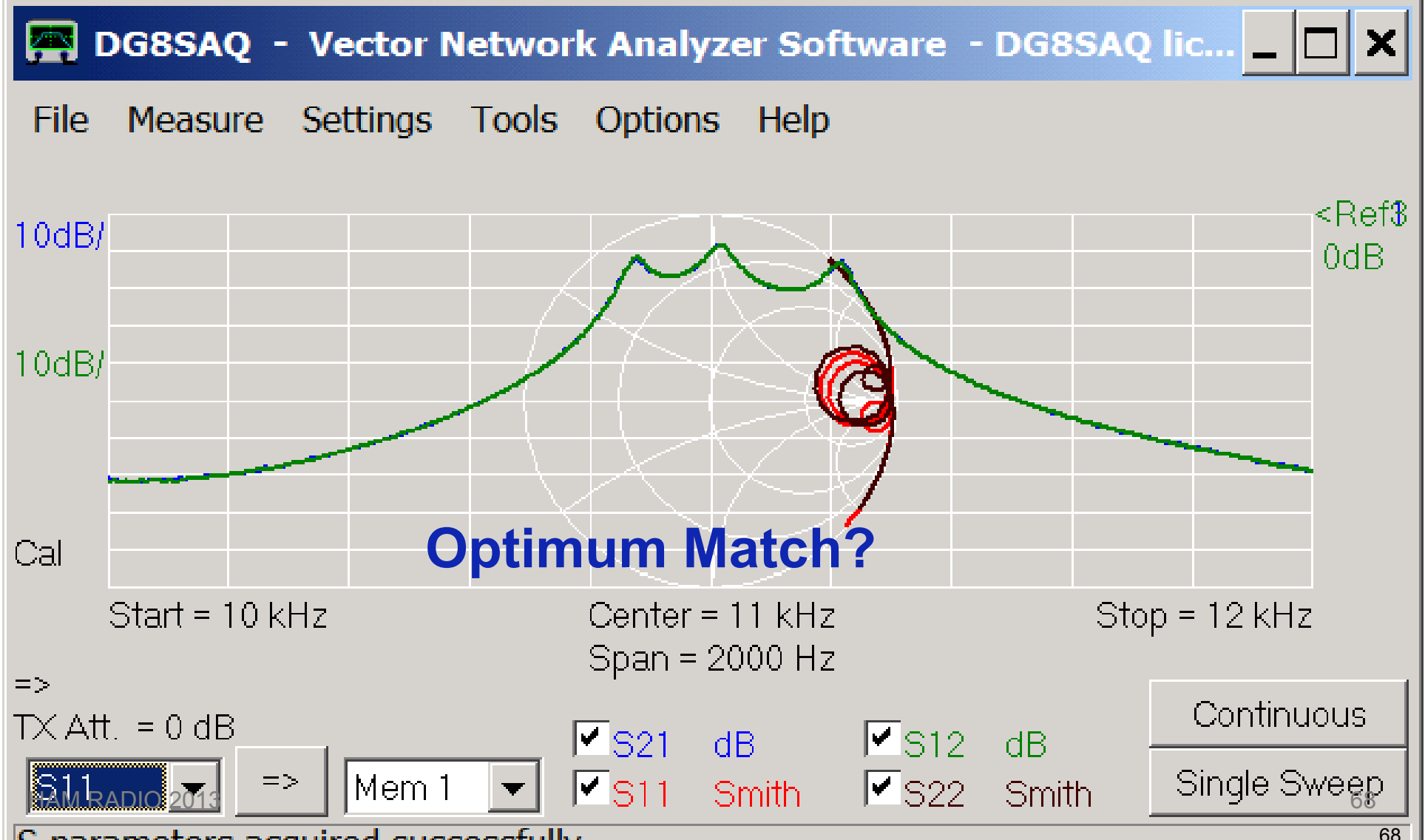
1

TX

RX

$S_{12}$ ,  $S_{22}$  measured

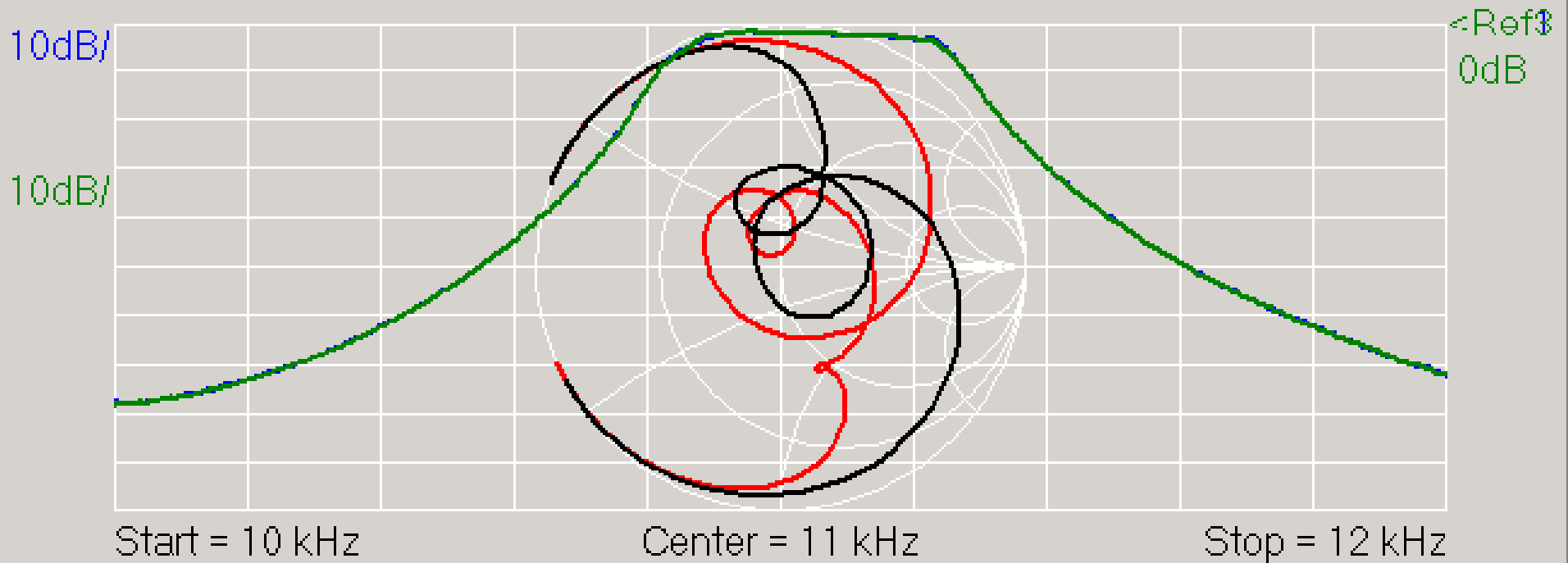
# What are measured 2-Port S-Parameters good for?



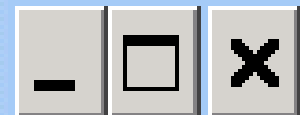


# Matching Analysis: VNWA Matching Tool

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



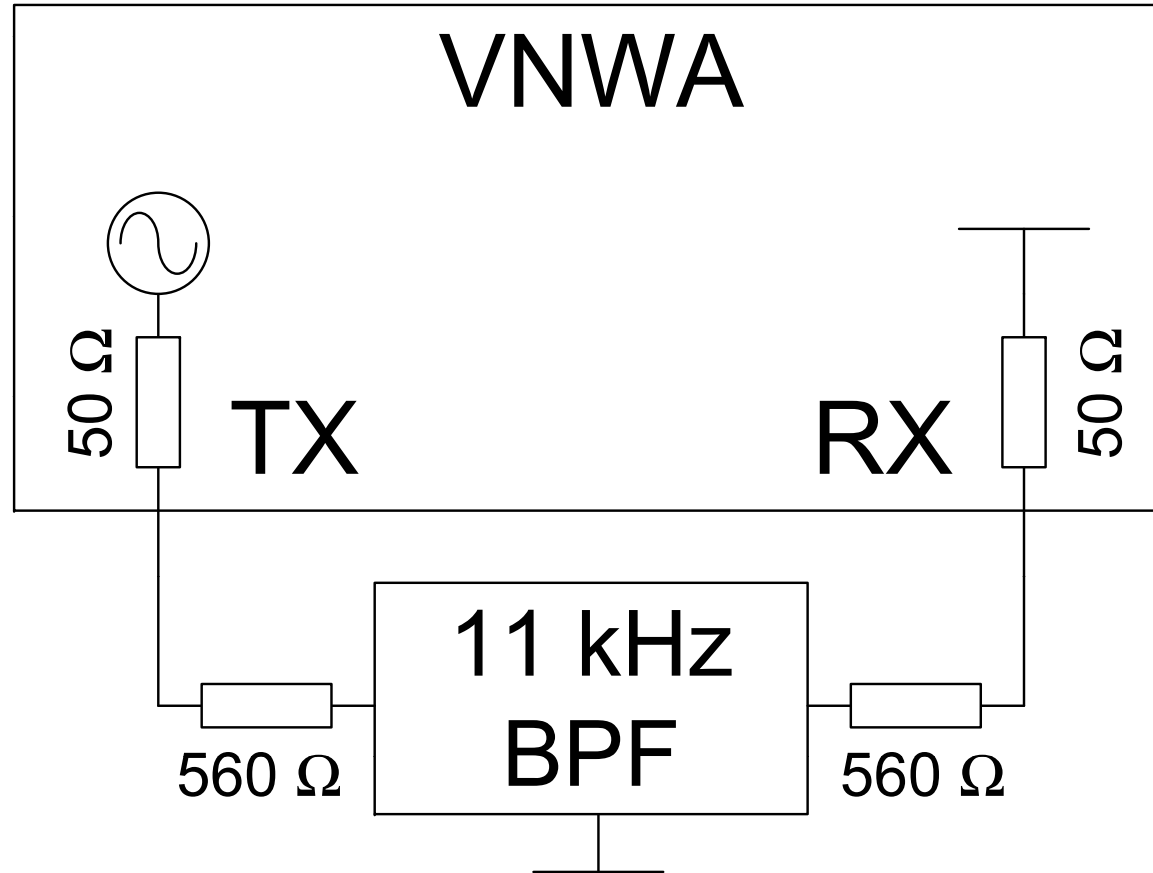
C parallel  
(neg. possible)

0

pF



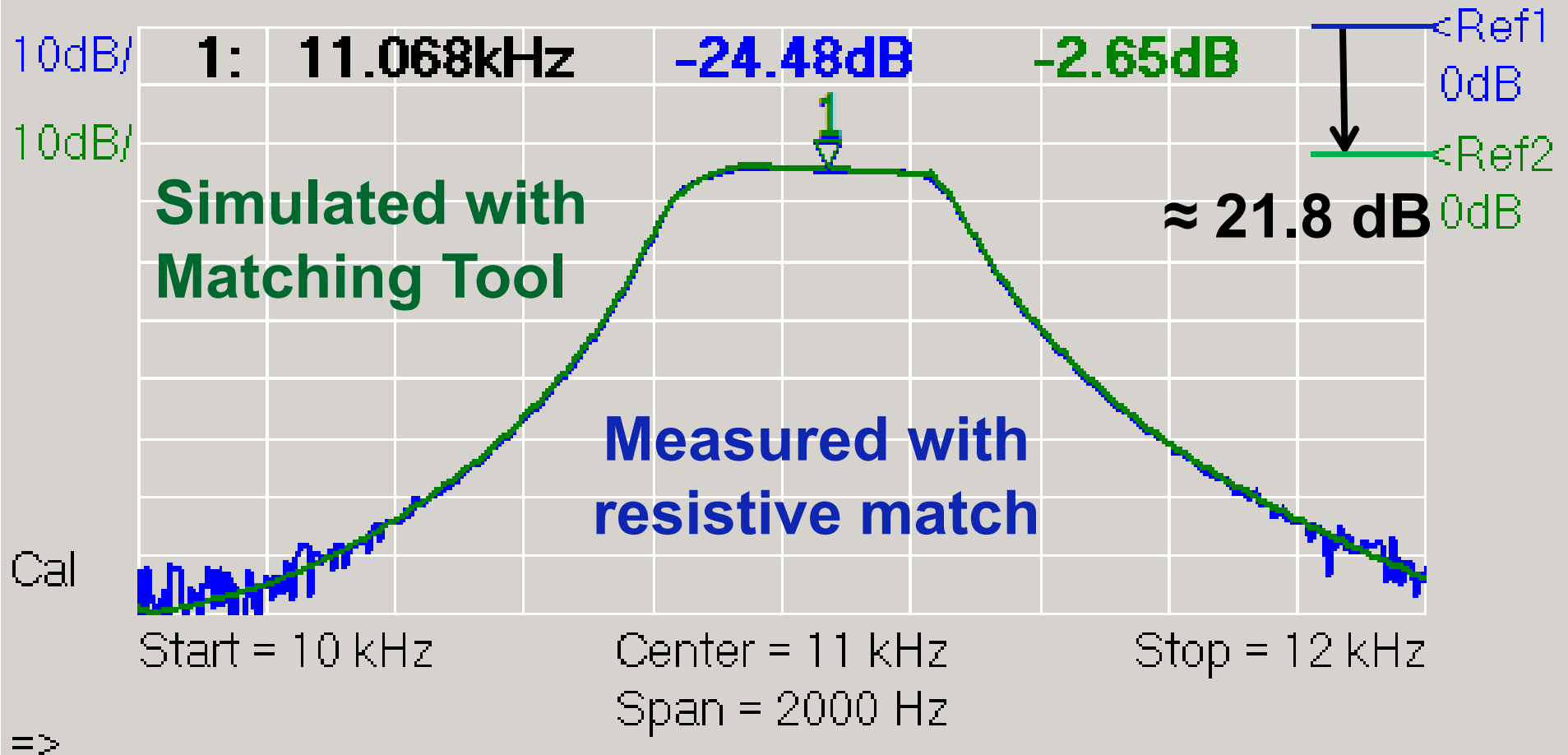
# Forced Impedance Match using Resistors



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



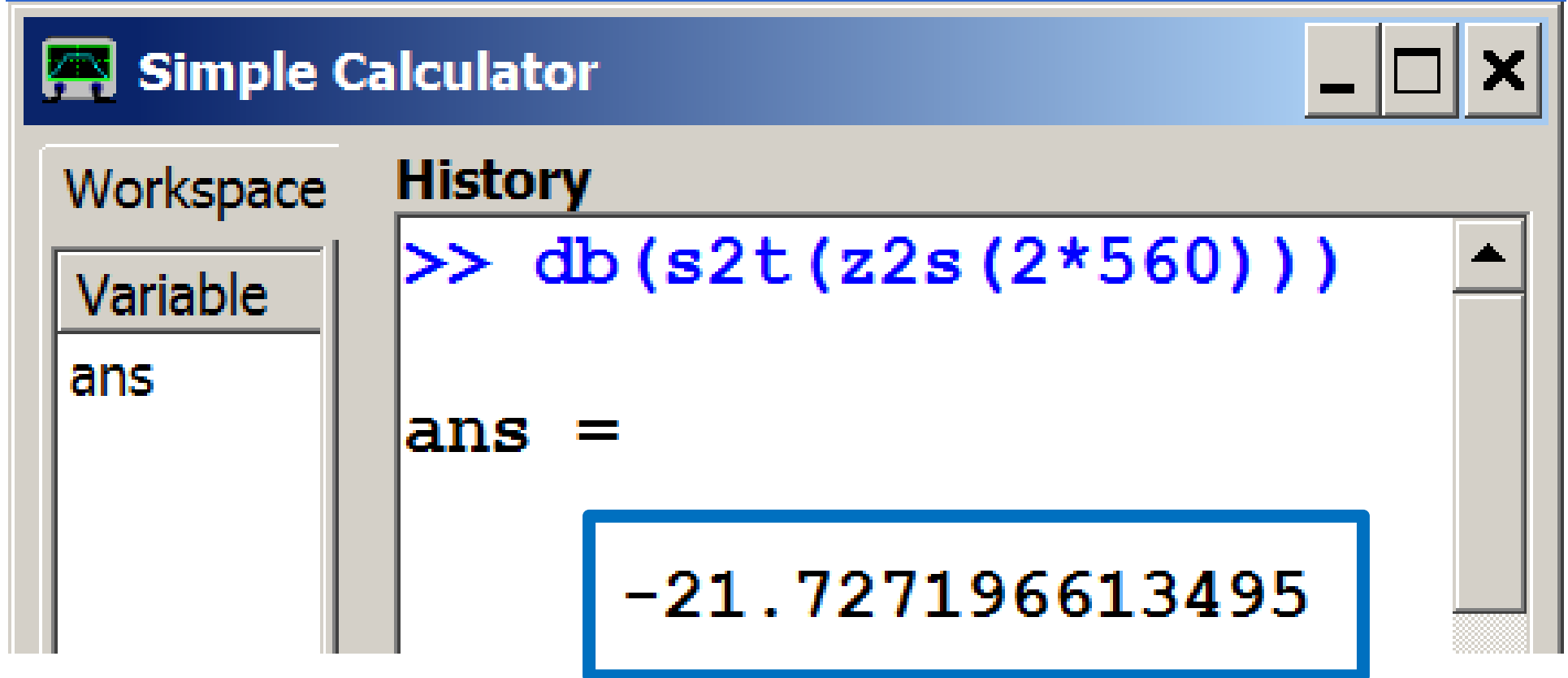
# Match works except for increased Loss



S21 dB

Mem1 dB

# Effect of two 560 $\Omega$ 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 displays the command `>> db (s2t (z2s (2*560)))` and the result `ans =` followed by the value `-21.727196613495`, which is highlighted with a blue rectangular box.

**21,7 dB additional attenuation ✓**

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72

72

# 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 the components list. The main workspace displays a circuit diagram for an S-parameter simulation. The simulation is named "SP1" and is configured with "Type=lin", "Start=10 kHz", "Stop=12 kHz", and "Points=400". The circuit diagram shows 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) which is the source of the measured S-parameters, another resistor "R2" (R=560 Ohm), and a port "P2" (Num=2, Z=50 Ohm). A reference ground "Ref" is connected to the bottom terminal of the X1 component. A blue arrow points from the text "measured S-parameters from s2p-file" to the X1 component.

**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

Ref

# 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**

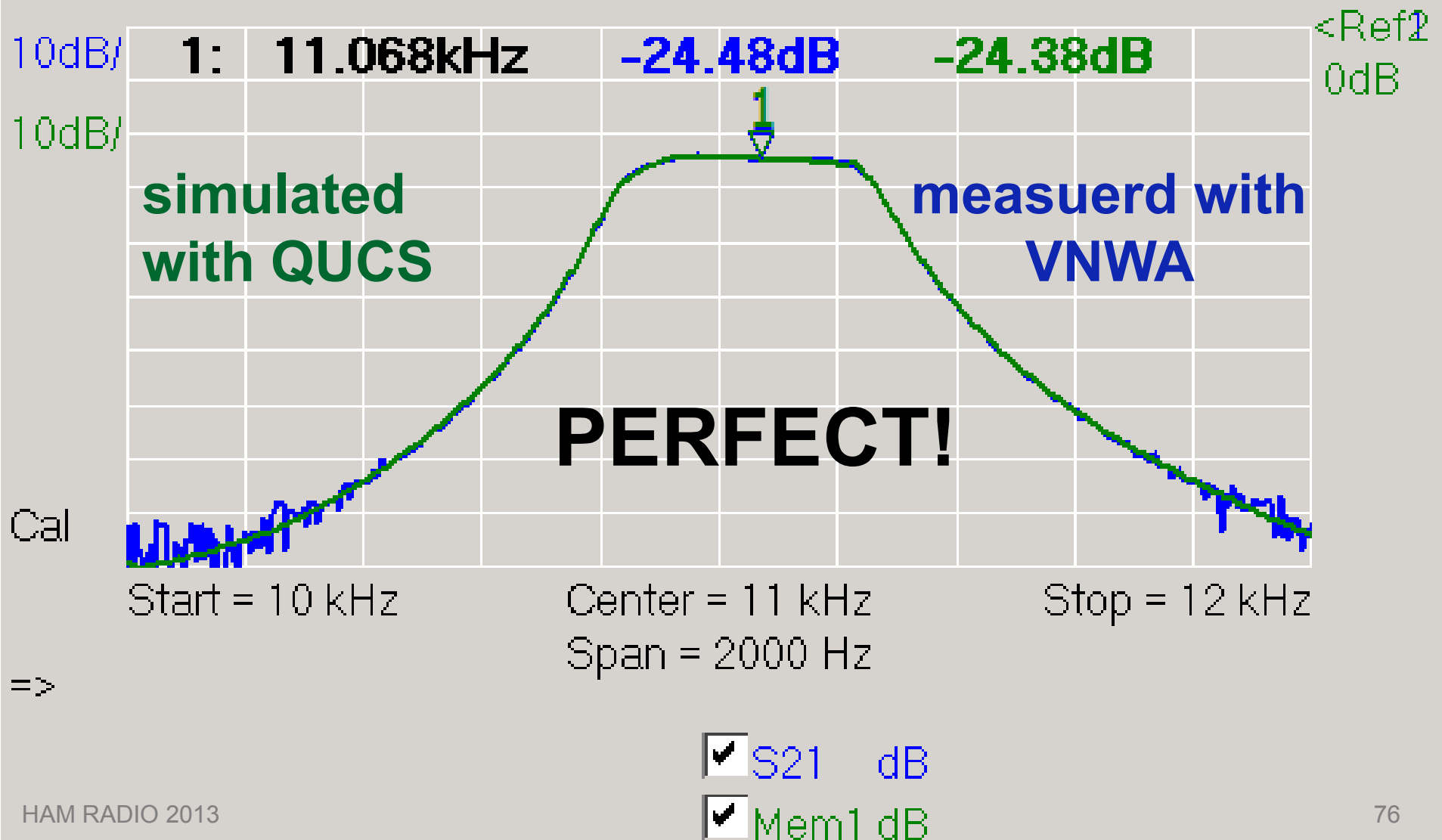
→ **Export simulation result  
to VNWA**

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no warnings 0 : 0


75

# Comparison QUCS-Simulation vs. Measurement





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

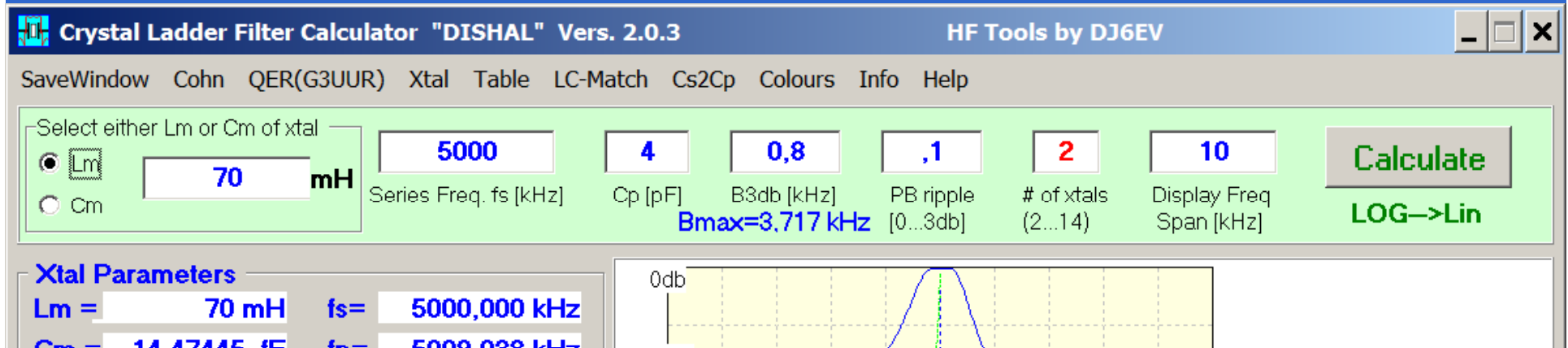
 Elsie Student Edition - Welcome !

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



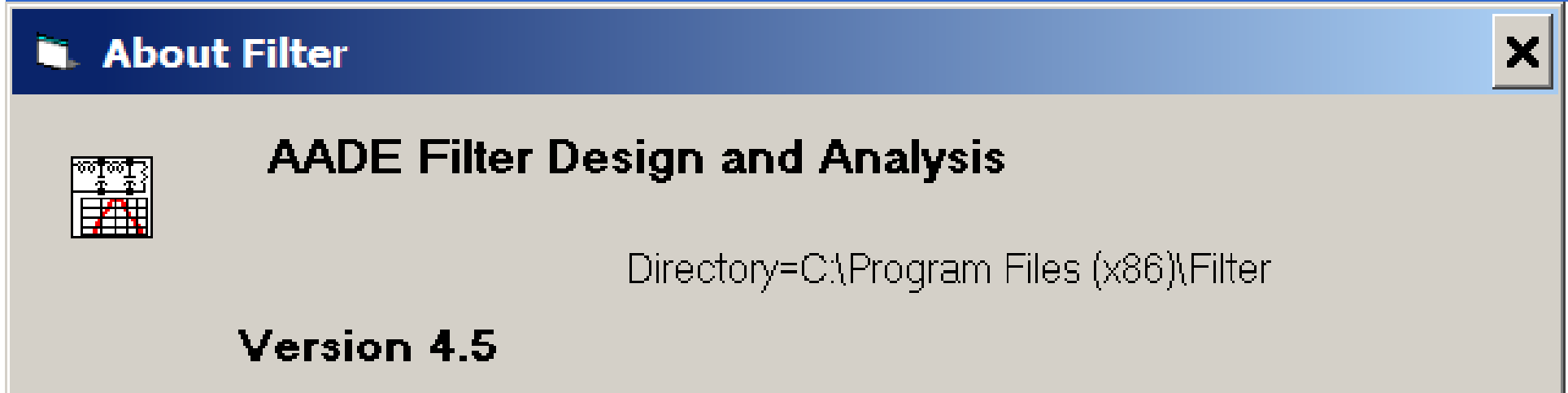
- <http://www.bartelsos.de/dk7jb.php/quarzfilter-horst-dj6ev>
- **Crystal filter designer and analyzer**
- **Simulates without crystal losses**
- **$S_{21}$ -simulation results can be exported**

Hochschule Ulm



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



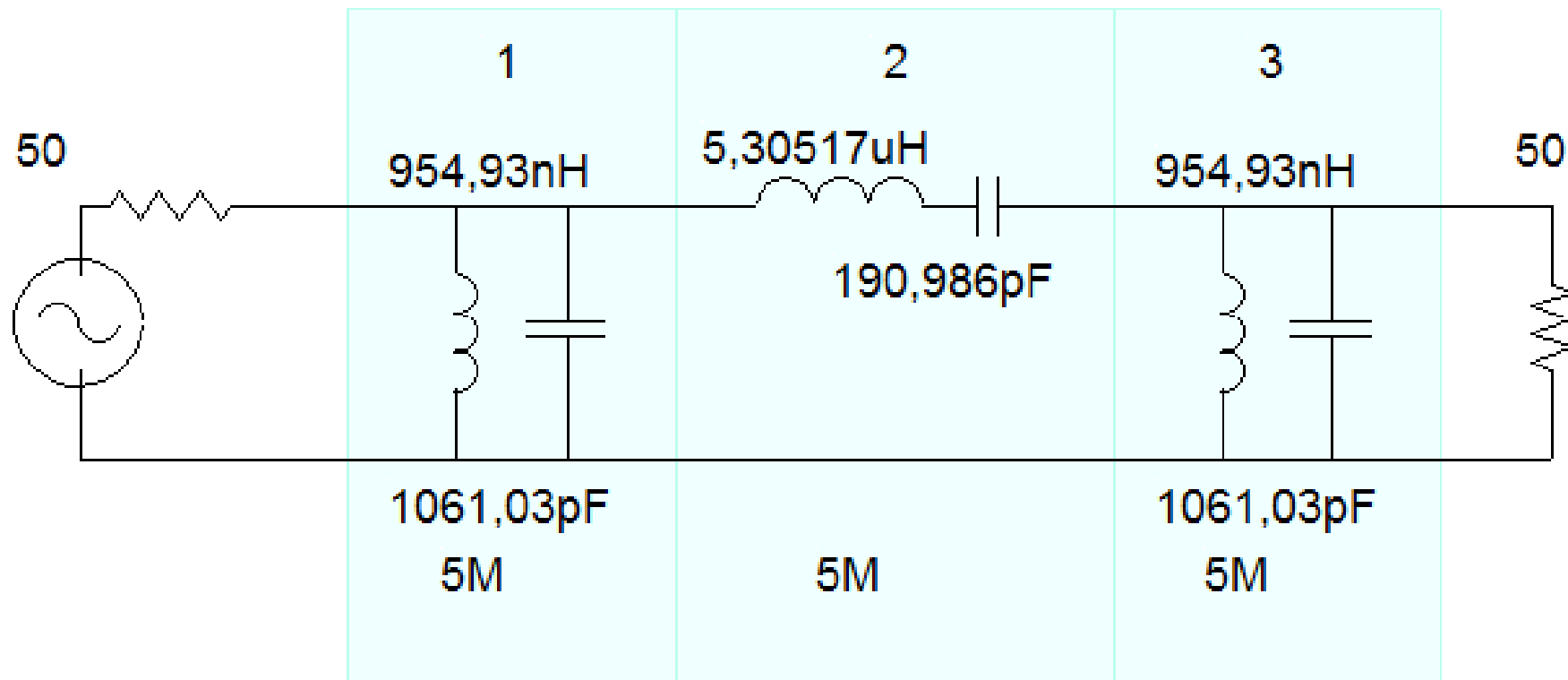
- <http://aade.com/filter32/download.htm>
- **Universal filter designer and analyzer**
- **Free, but with nag screen**
- **Easy to use**
- **Numerical simulation results cannot be exported**

Hochschule Ulm



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# Design 3 Pole Butterworth $\pi$ -Band Pass for 5 MHz with 3 MHz Bandwidth at 50 $\Omega$



**Filter Design with Elsie**

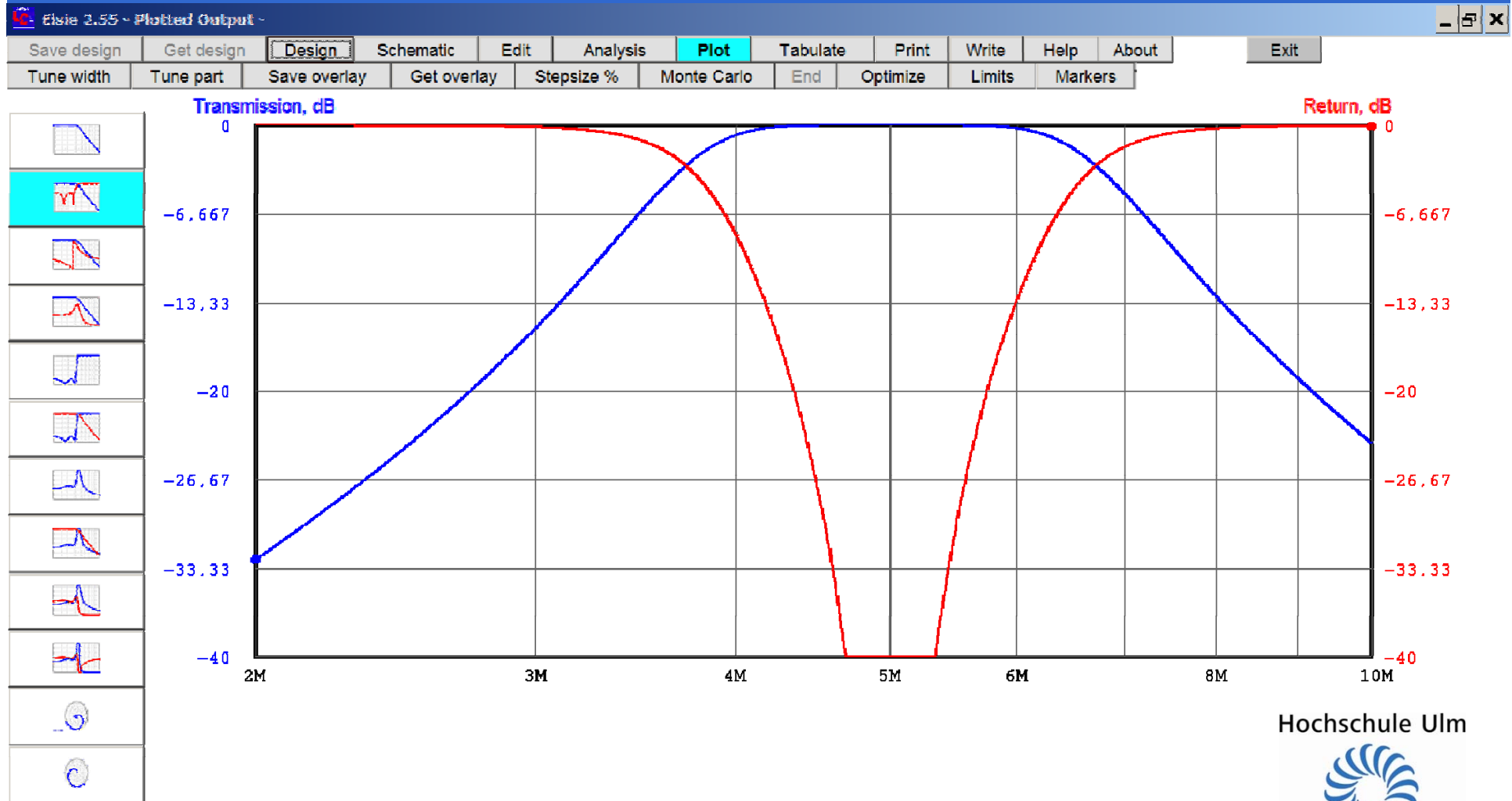
Hochschule Ulm



80

80

# Elsie Simulation Result



Hochschule Ulm



# Modify Components to standard Values and finite Q ...

Schematic

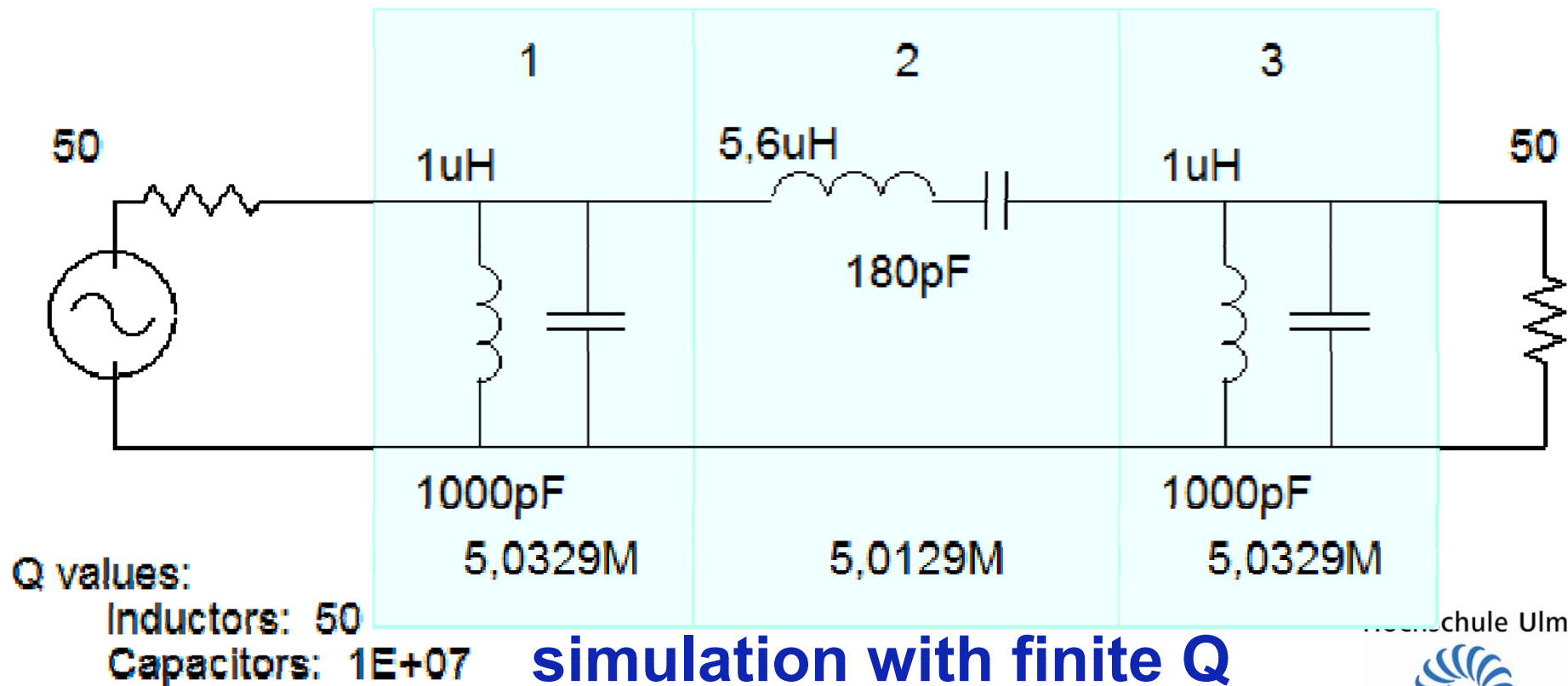
**Edit**

Analysis

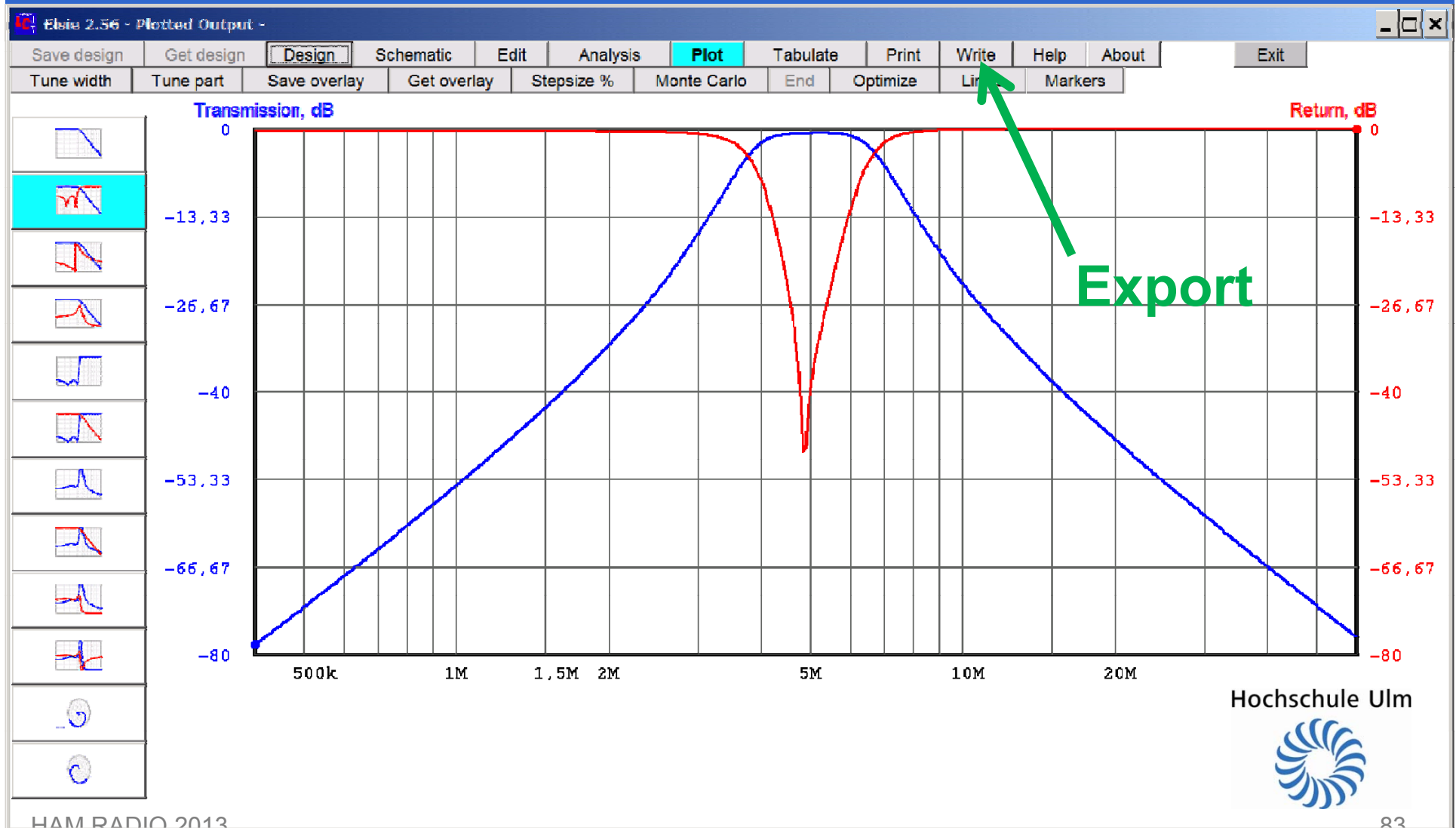
Plot

Tabulate

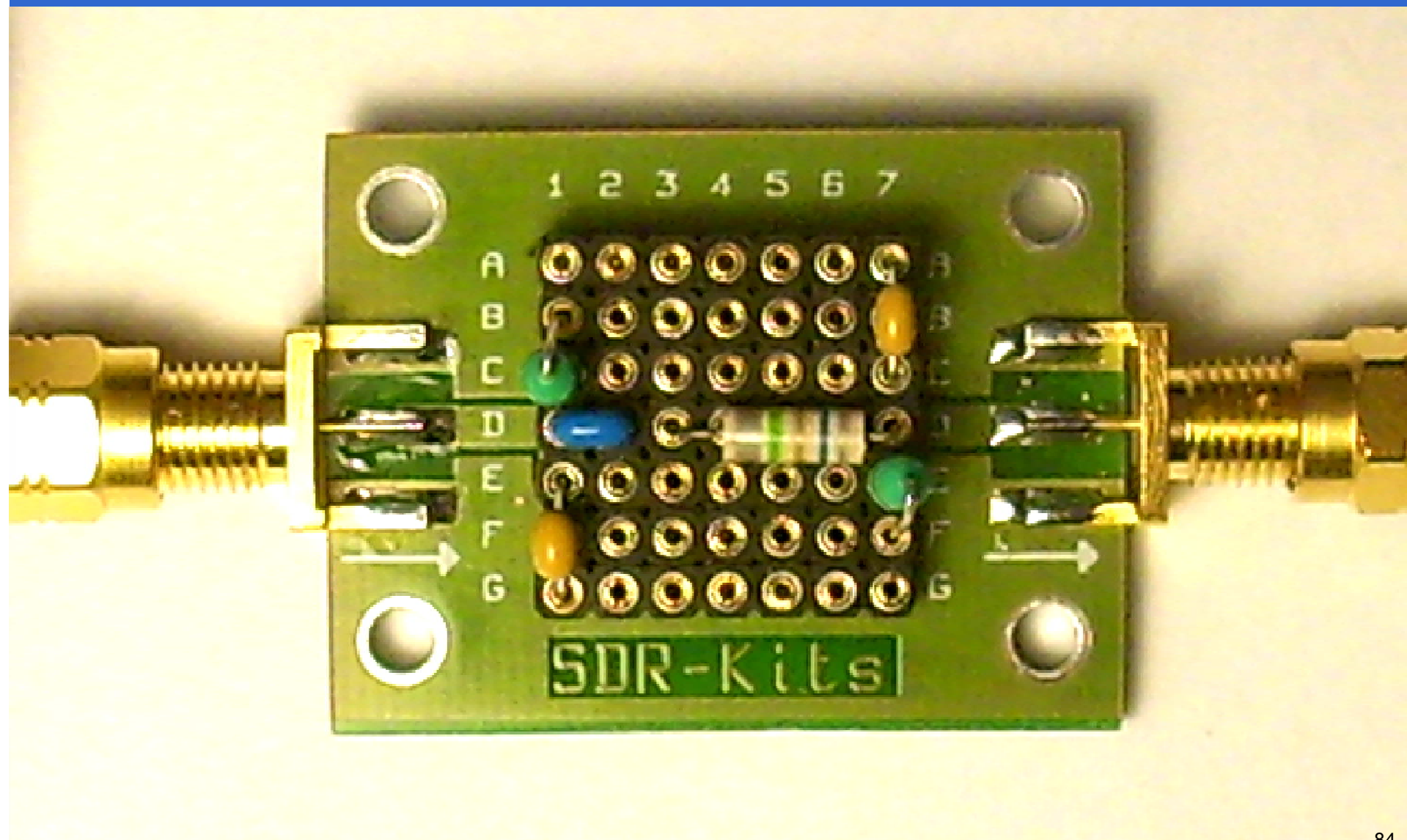
Print



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



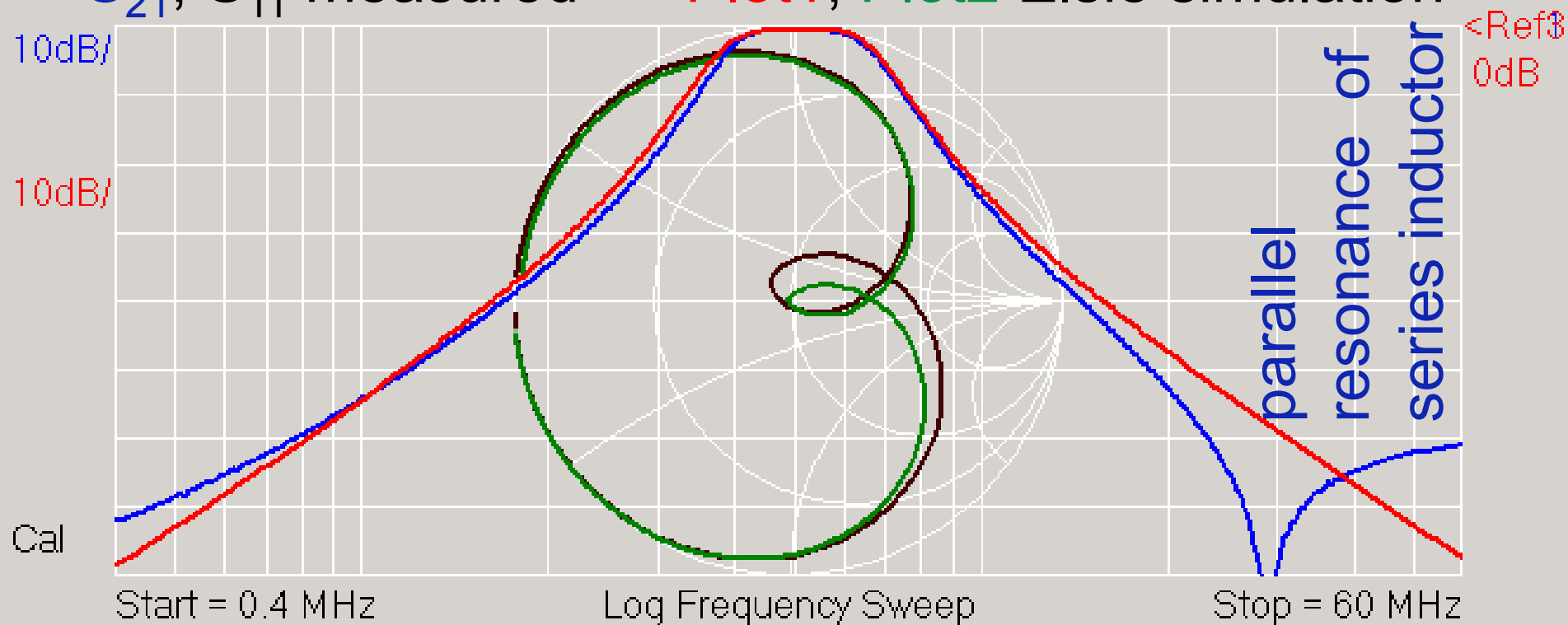
# Filter Hardware





# 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

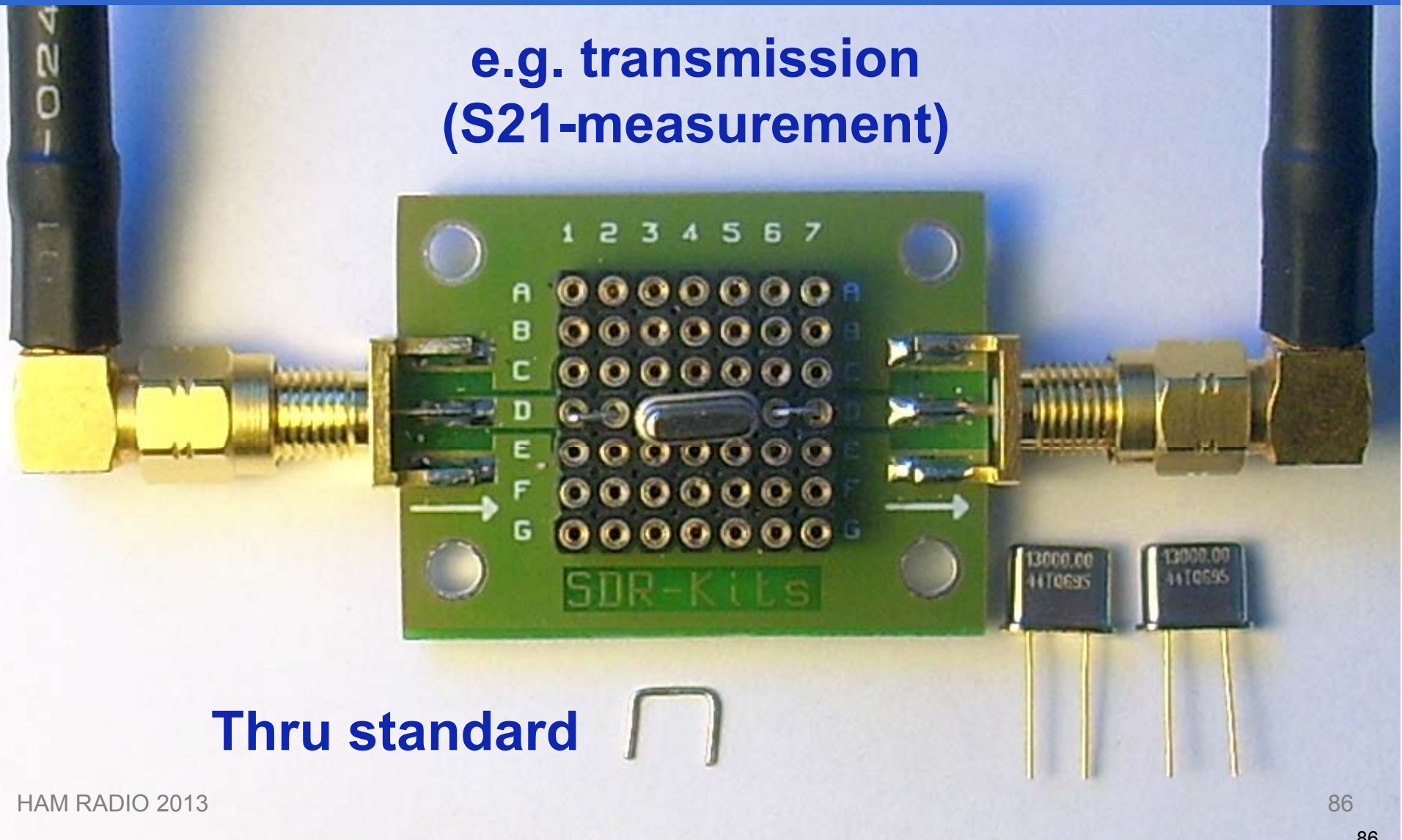
Plot2 Smith

Continuous

Single Sweep

# Measuring / Selecting Crystals: VNWA Crystal Analyzer

e.g. transmission  
(S21-measurement)

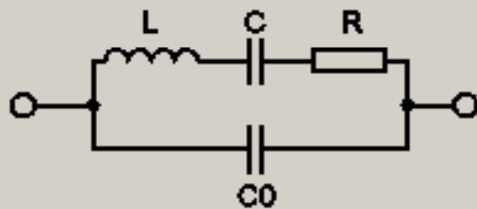


Thru standard

# 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

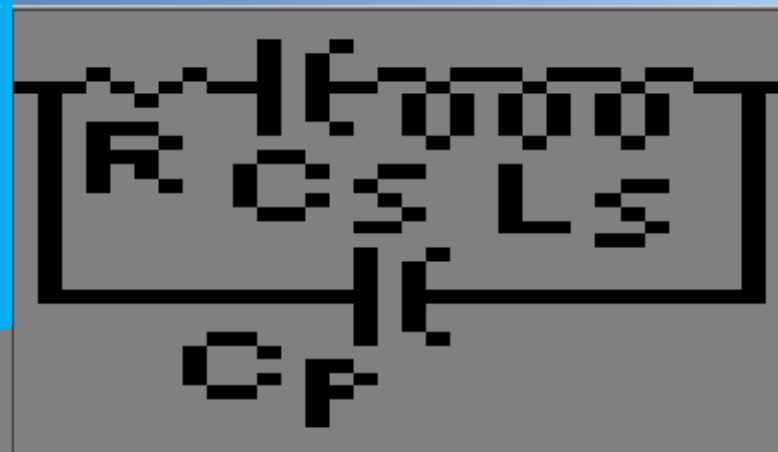
# With these we want to build a Crystal Filter → Enter Crystal Parameters into AADE

## 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 <sup>2</sup>	μ	
tab	bksp	CLR	n		
ENTER	Cancel	p			

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



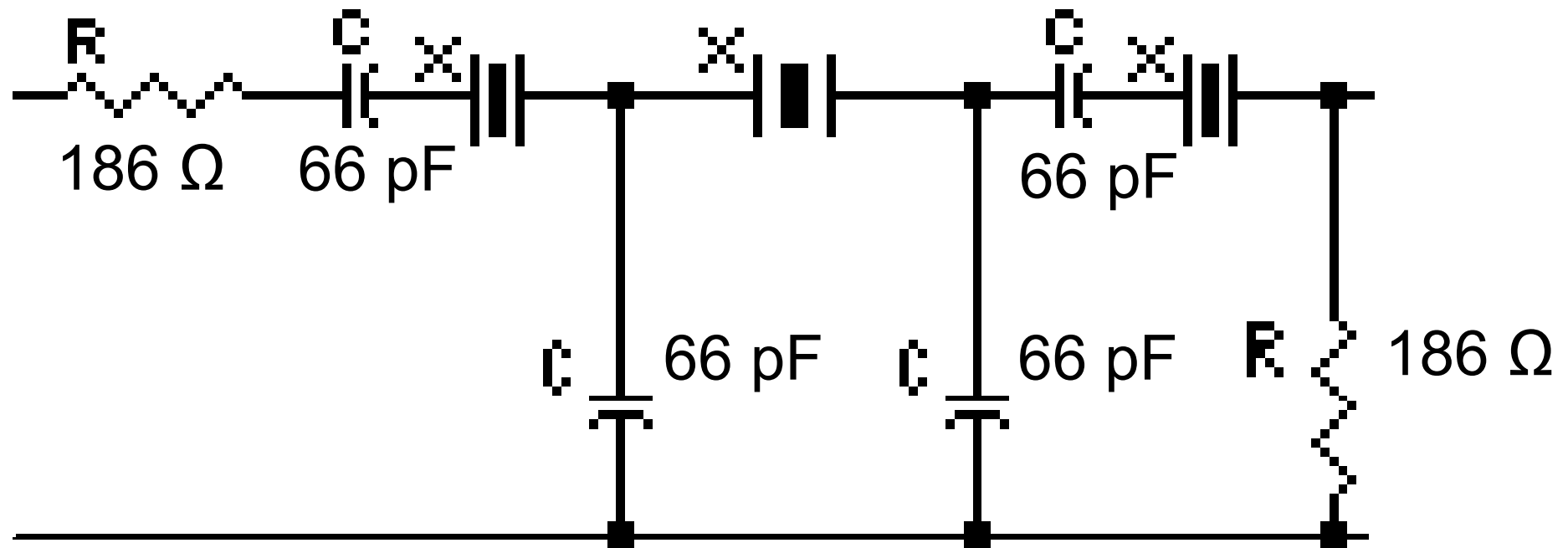
Daten vom  
VNWA  
Crystal  
Analyzer  
übertragen

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 $\Omega$ using standard Component Values

## S parameter simulation

SP1

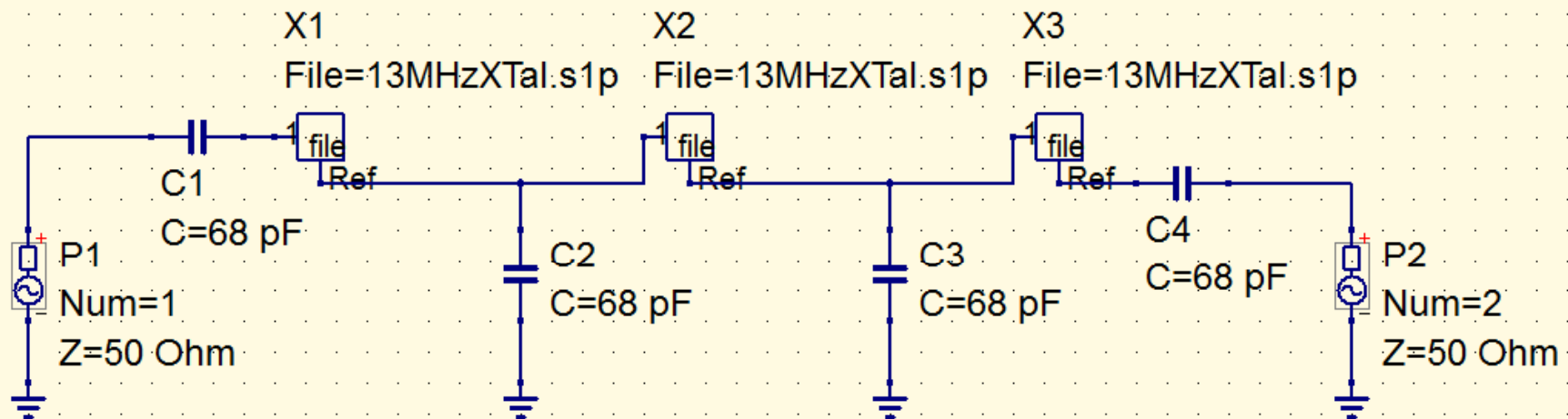
Type=lin

Start=12.987 MHz

Stop=13.007 MHz

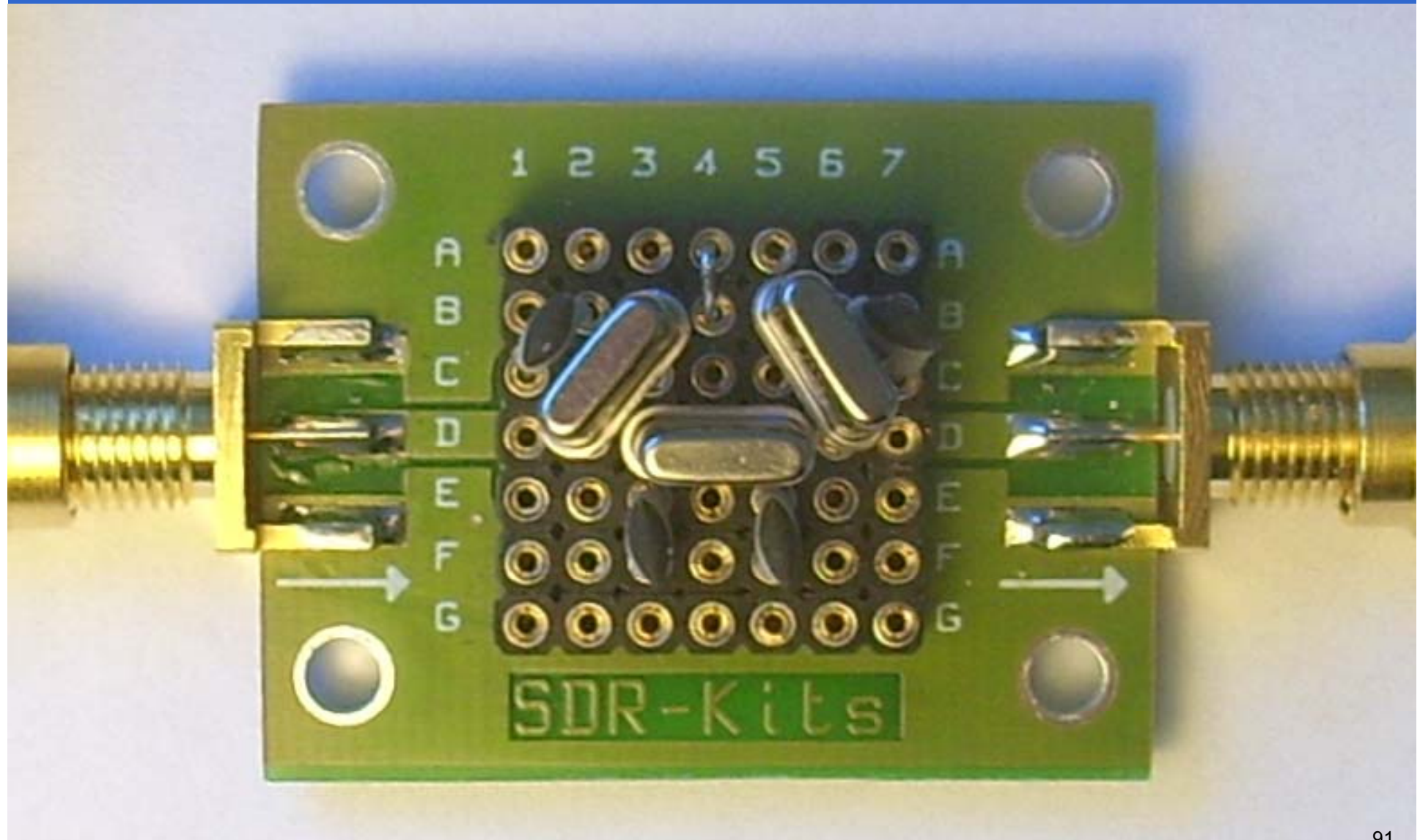
Points=800

## Crystals simulated with s1p-file obtained by VNWA measurement!

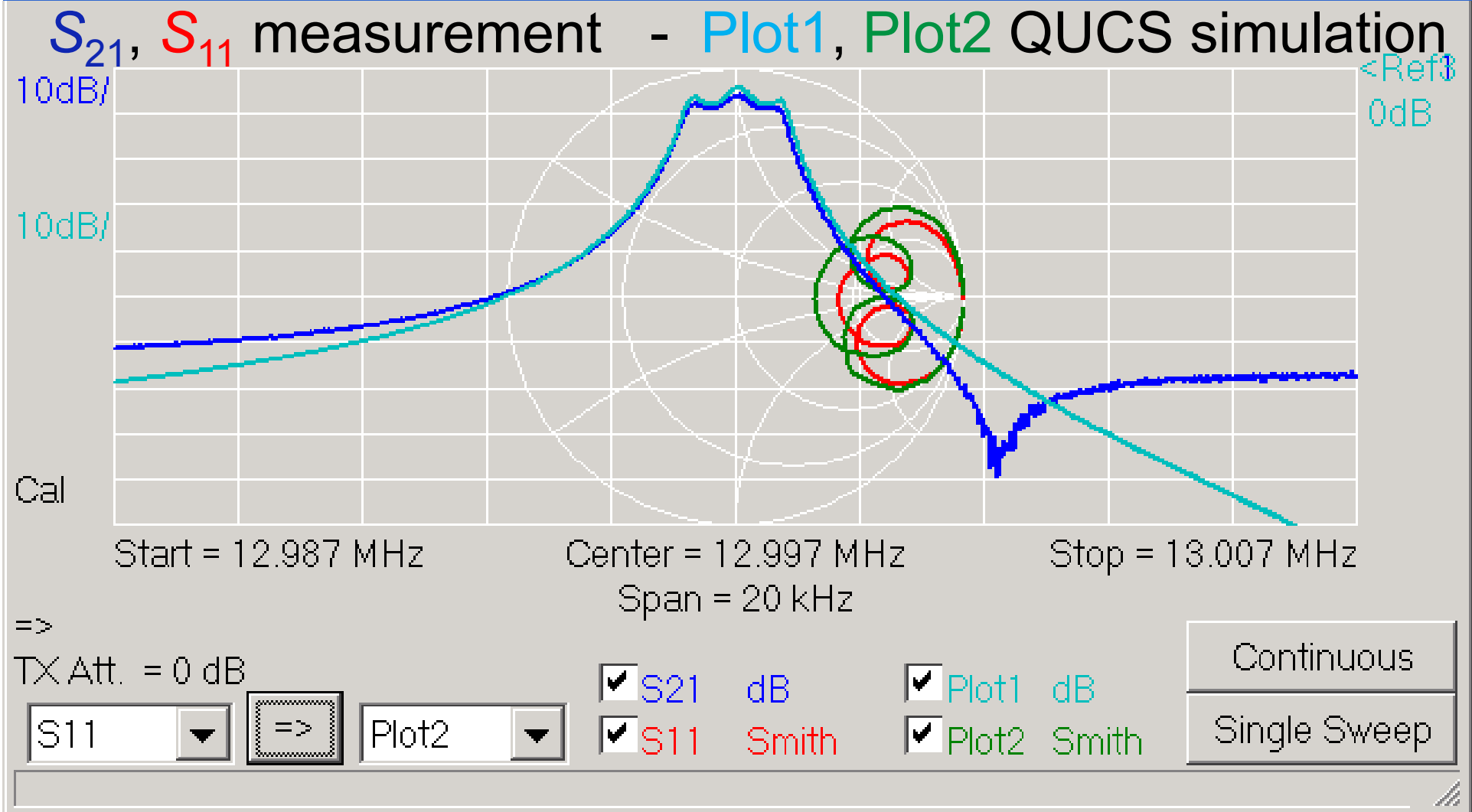




# Crystal Filter Hardware

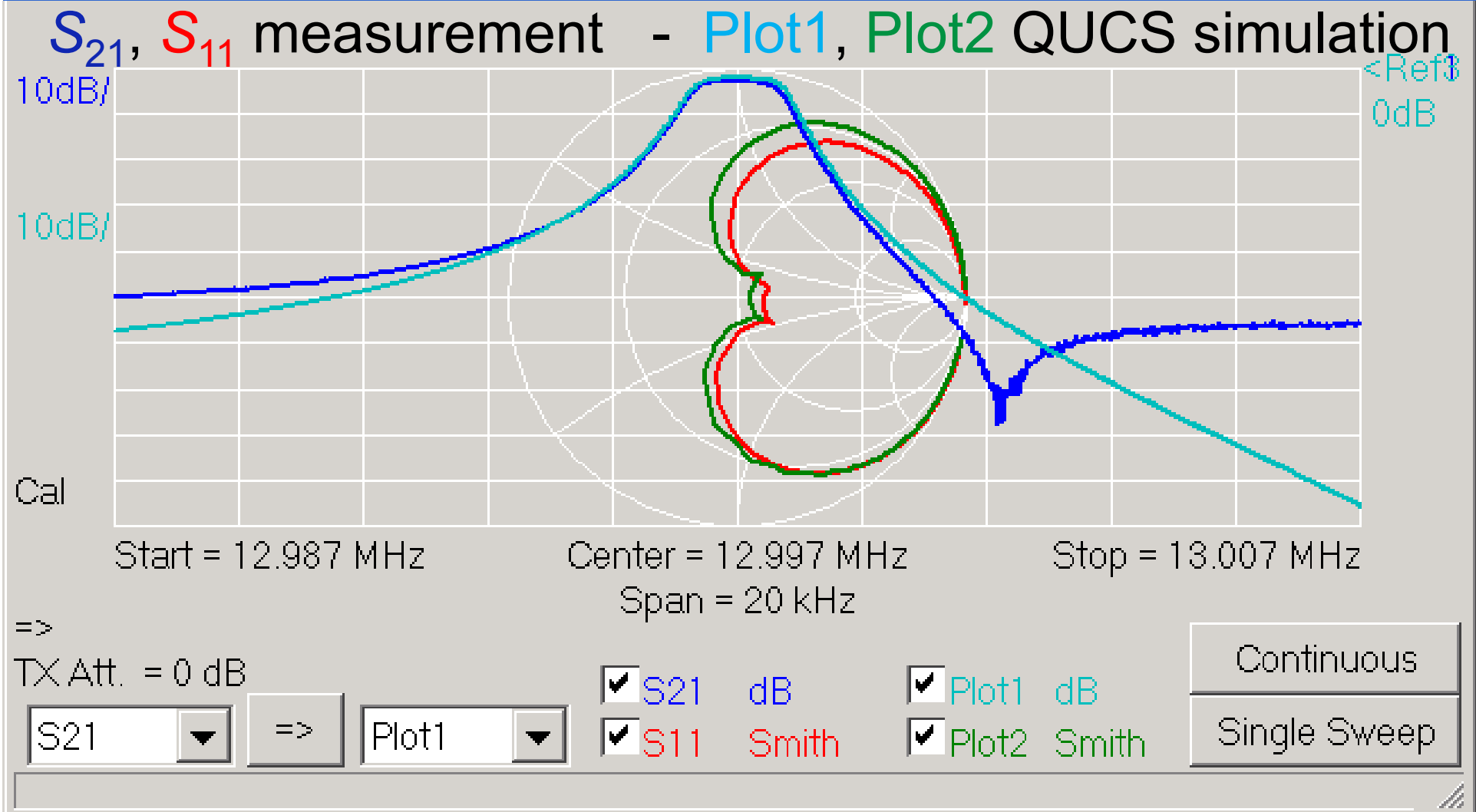


# Crystal Filter: Measurement vs. Simulation at 50 $\Omega$





# Crystal Filter: Measurement vs. Simulation at 186 $\Omega$



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