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Traceable Source Match Calibration of RF & MW Generators

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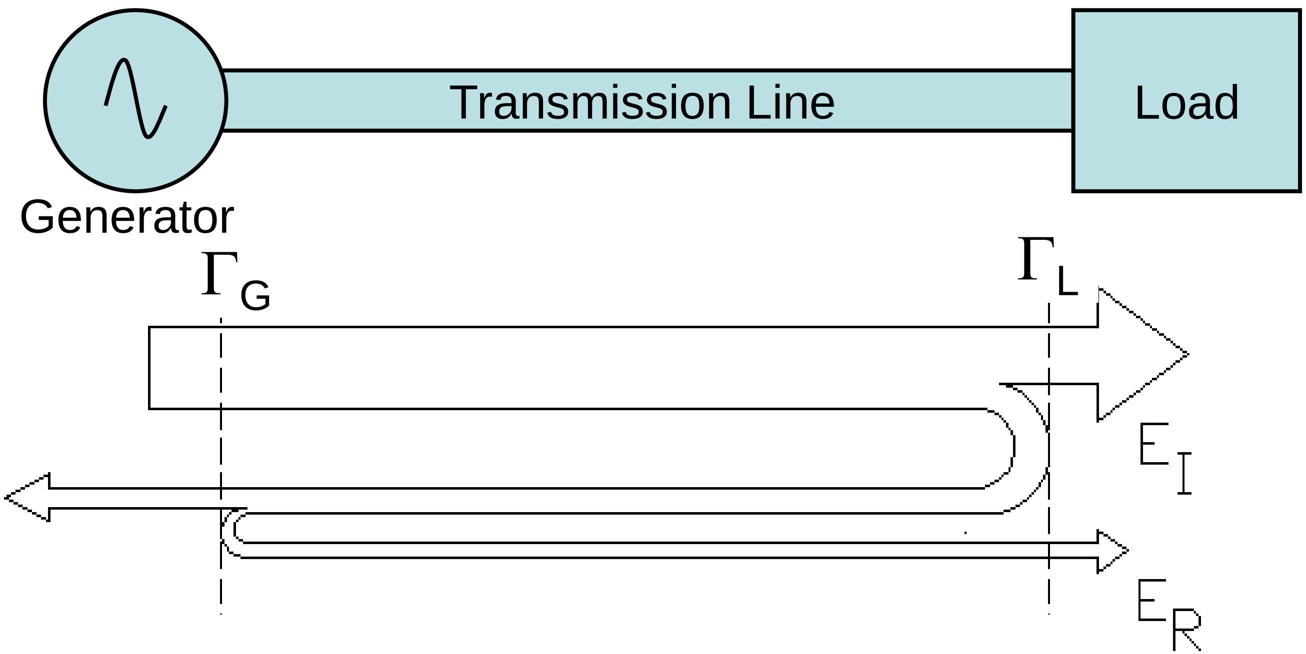
Source Match Γ_G of RF & MW Generators

Why is Γ_G of interest ?

- Loss of power due to mismatch between generator and load
- Source match of RF & MW generators can be quite high
- In many cases a major uncertainty contribution
- Source match of RF & MW generators is often not known
- Measurement of Γ_G is not easy
- Worst case specs (manufacturer) have to be used
- For some RF & MW generators Γ_G is not even specified

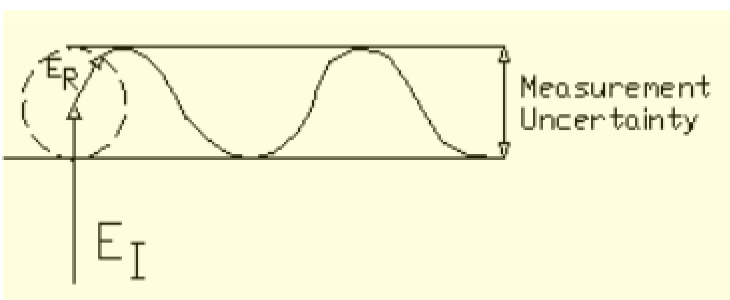
Loss of Power due to Mismatch between Generator and Load
(Mismatch Factor, Mismatch Uncertainty)



Loss of Power (due to Mismach)

a) calculable, if Mag/Phase of Γ_G and Γ_L are known (Mismatch Factor) MF

b) not calculable, if only Mag $|\Gamma_G|$ and $|\Gamma_L|$ are known (Mismatch Uncertainty) 1 ± MU

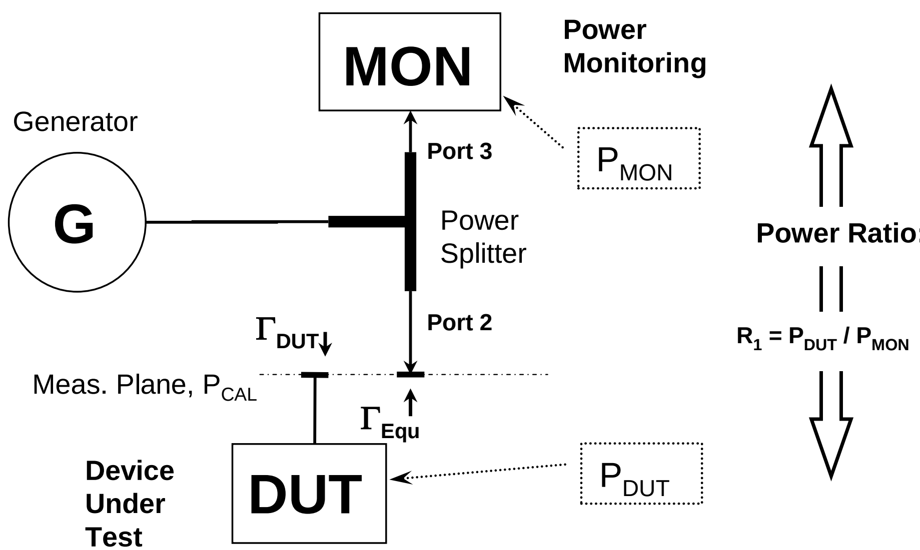


Source Match of RF & MW Generators

Avoiding critical situations

- Add an S-parameter characterized powersplitter to the RF & MW generator and apply ratio method:

  The source match of such a ***virtual generator*** depends only on the splitter S-parameters (Γ_{Equ}, equivalent source match)



$$\Gamma_{Equ} = \Gamma_2 = S_{22} - \frac{S_{21} \cdot S_{32}}{S_{31}}$$

Source Match of RF & MW Generators

Critical situations ?

- Characterisation (calibration) of generator power
- Feeding a calibrated generator signal to an unknown load with high load reflection coefficient
- Typical for oscilloscope calibrators where load = Γ_{Scope} can reach $\geq$ 0.33 (VSWR = 2)

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Characterisation of a Generator with P_{GZo}

- Generator should be characterized by its power output
- Power should be P_{GZo} (power delivered into Z_0 = 50Ω Load)
- Powermeters (Thermocouple, Diode Sensor) are calibrated with Calibration Factor which is related to P_{inc}

- Power incident to load:

$$P_{inc} = |b_s|^2 \cdot \frac{1}{|1 - \Gamma_g \Gamma_l|^2}$$

- Power into a Z_0 - matched load:

$$P_{GZo} = |b_s|^2$$

- the ratio between the two power levels is:

$$\frac{P_{inc}}{P_{GZ_0}} = \frac{1}{|1 - \Gamma_g \Gamma_l|^2}$$

we need to know Γ_G !!

Measuring Source Match Γ_G of RF & MW Generators

Several methods are known (see references on last page)

- active methods (injection method):
  feeding an external test signal into the DUT generator
- passive methods:
  using DUT generator signal as test signal and known mismatch to create ripple
- main drawbacks:
  - some methods are not suitable for some DUT generator types
  - often not usable at lower frequencies (< 1 GHz) due to airlines
  - often very time-consuming … how to sell such a service ?

Measuring Source Match Γ_G of RF & MW Generators

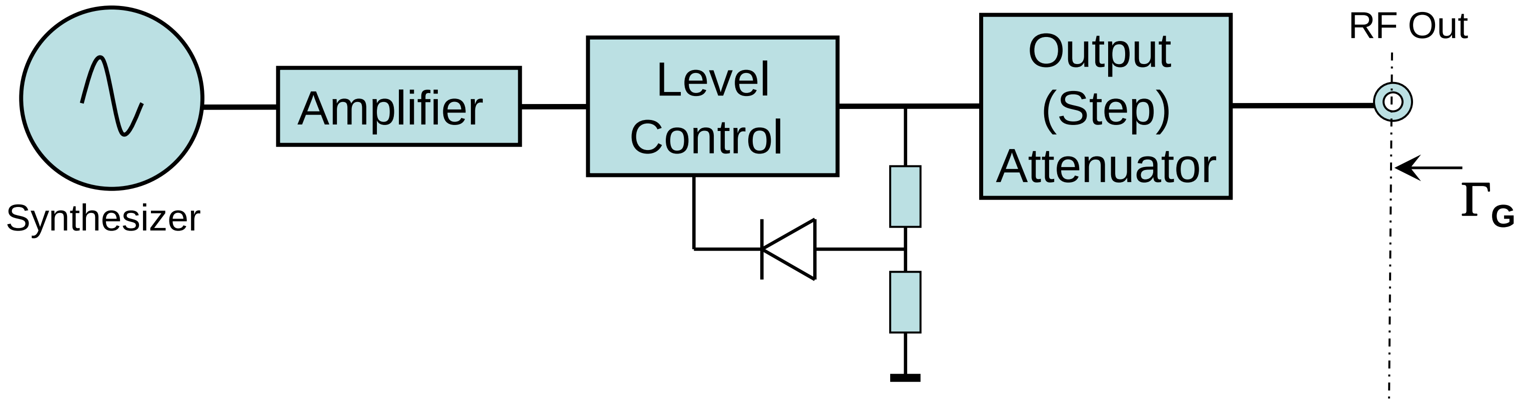
Using a VNA ?

- Generator (DUT) has to be „RF ON“
- Γ_G of DUT depends on output level
- Γ_G of DUT is of interest at „level of usage“ and has to be evaluated at this level (e.g. + 13 dBm)
- input overload of VNA
- interference of VNA- and DUT- signal
- VNA can be used (with external couplers) for S-parameter characterisation of amplifiers

Measuring Source Match Γ_G of RF & MW Generators

Typical block diagram of a RF / MW generator

- Output step attenuator is masking / stabilizing Γ_G
- Γ_G of DUT is critical at high output levels
- external test signal can have influence on leveling control (active / injection method)
- exact output circuit topology in most cases not known



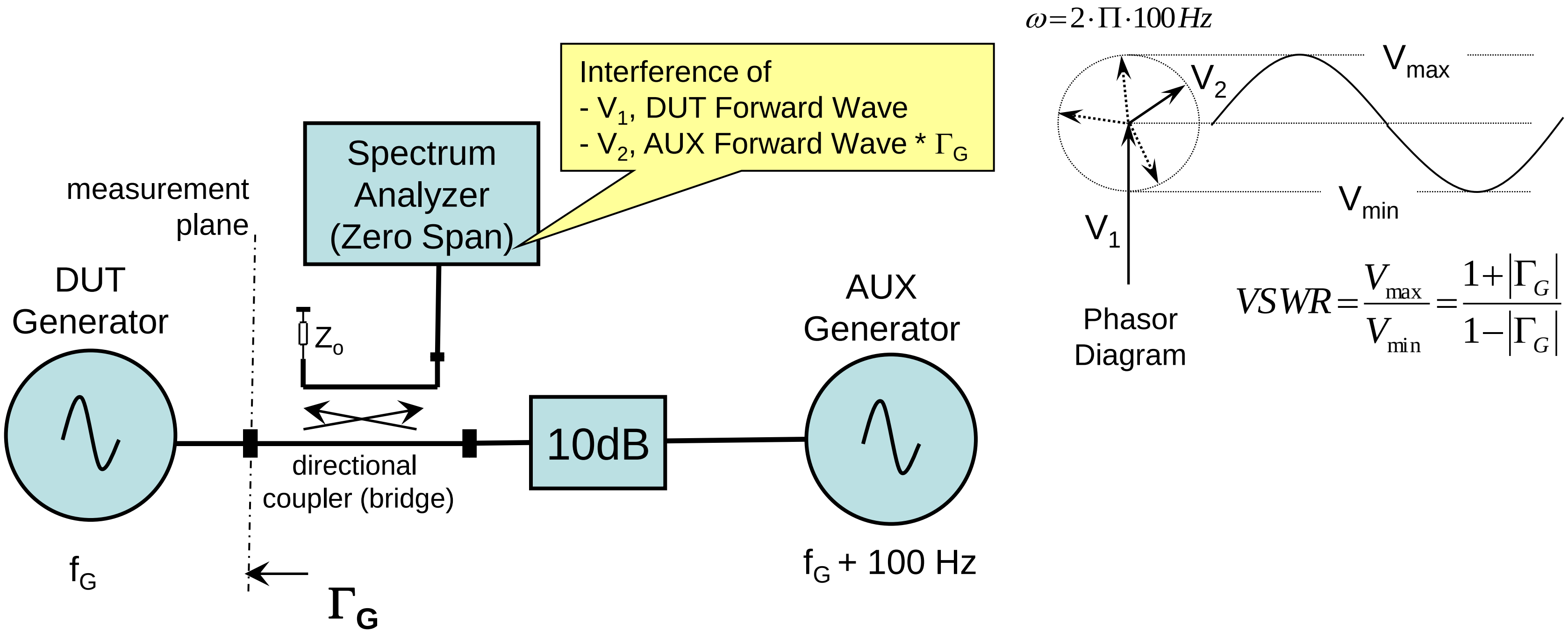
Measuring Source Match Γ_G of RF & MW Generators

„Must" criterias for a new Γ_G measuring system

- frequency range starting at 10 MHz to 6 GHz / 18 GHz
- must work for generators with „critical output stages" (leveling circuit)
- must work fully automated:
  source match Γ_G depends (mostly) on used P_{Gen}
  → many measurement sequences required
- must work for power meter reference sources (leveling circuit at power output)

Measuring Source Match Γ_G of RF & MW Generators

„Active (injection) method 1" (tested at metas)

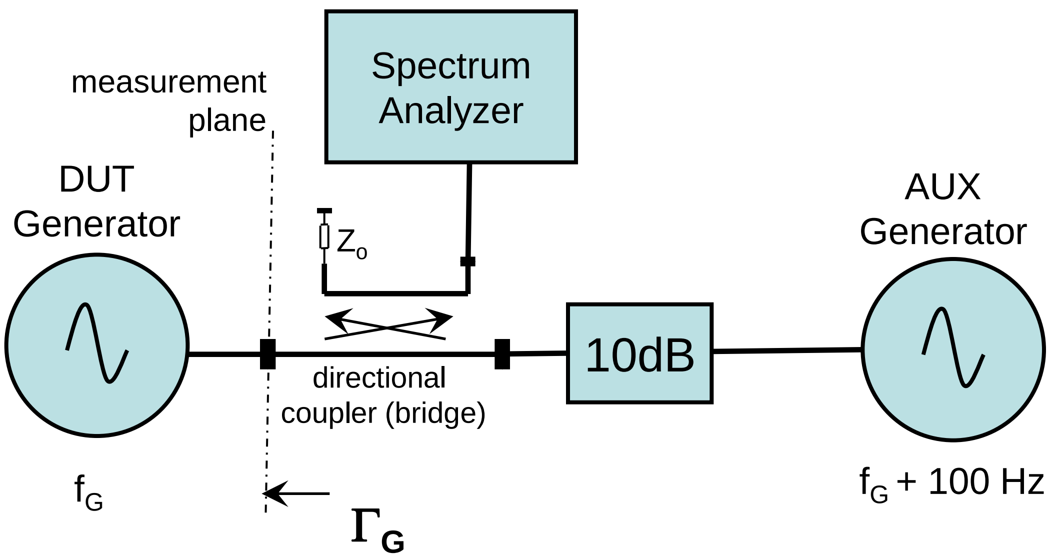


$$VSWR = \frac{V_{max}}{V_{min}} = \frac{1+|\Gamma_G|}{1-|\Gamma_G|}$$

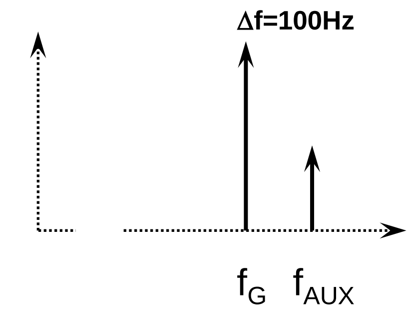
Maintain specified DUT test level and adjust it on spectrum analyzer (P_{AUX} = Off)
Disconnect DUT at measurement plane and adjust P_{AUX} to the same indication on spectrum analyzer
Connect DUT at measurement plane
Spectrum analyzer (zero span) displays interference (Δf = 100 Hz) of
- DUT Forward Wave (100%)
- AUX Forward Wave * Γ_G (100% * Γ_G)

Measuring Source Match Γ_G of RF & MW Generators

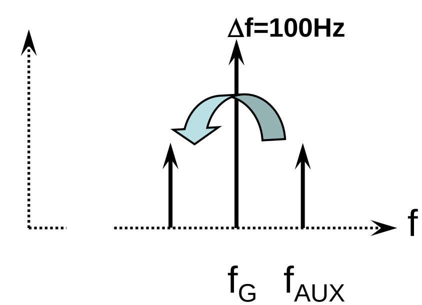
„Active (injection) method 1“: Drawbacks



Spectrum
without AUX modulating DUT



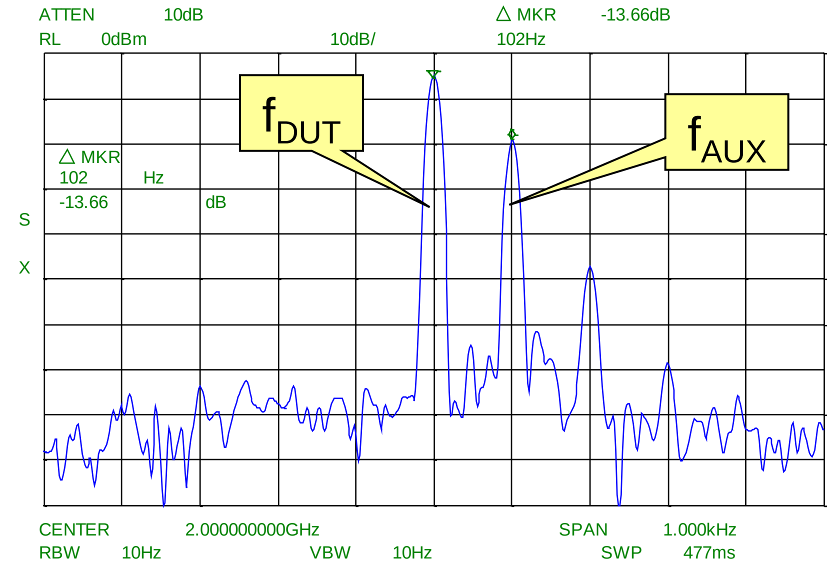
Spectrum
AUX is modulating DUT



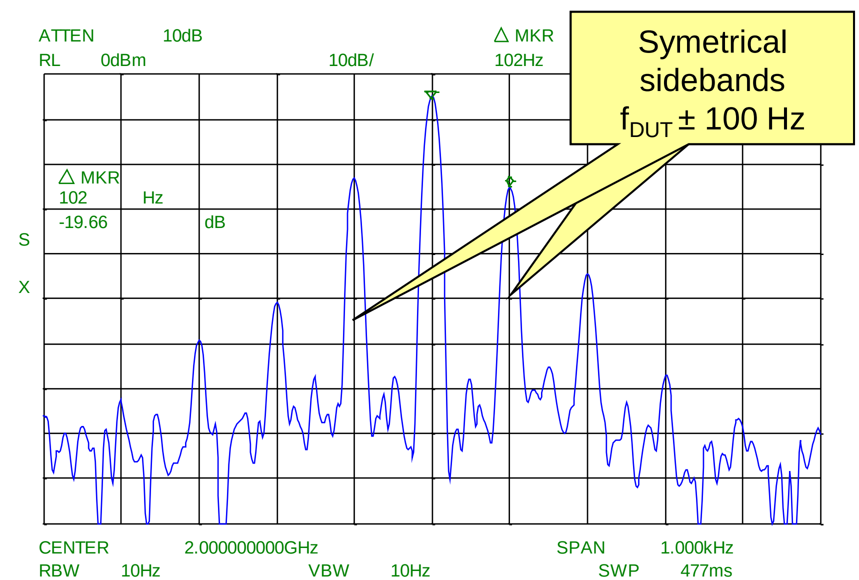
AUX test level (at measurement plane) relatively high (identical to DUT level)
DUT generator output circuit is „biased“ by AUX test level
→ AUX test signal is modulating the amplitude of the DUT in case of „critical output stage“ by $f_{mod} = \Delta f$ (100 Hz)
→ measured Γ_{G_DUT} useless (depending on DUT generator type and condition)

„Active (injection) method 1": Drawbacks

Spectrum of measured interference voltage at directional coupler output



Case 1: „active (injection) methode 1" works correctly
DUT level is low (Step Atten)



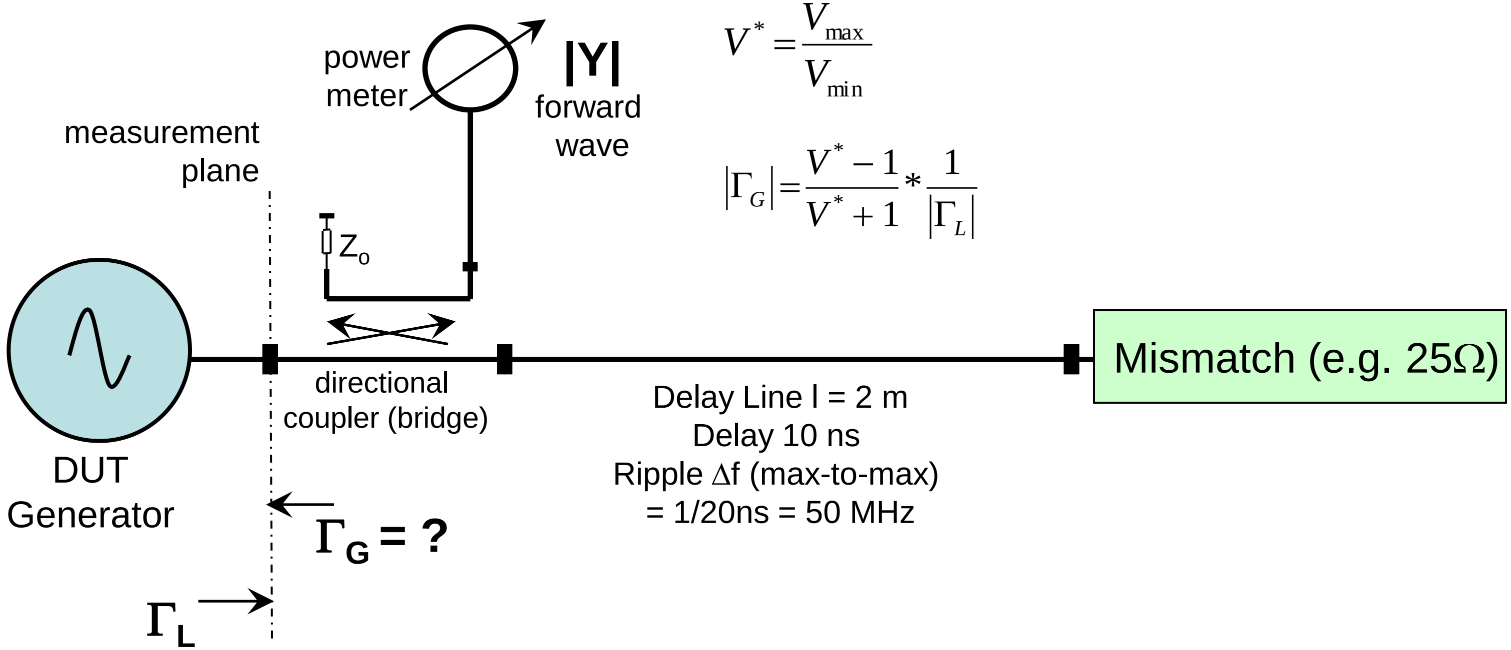
Case 2: „active (injection) methode 1" does not work correctly
DUT generator is amplitude modulated by AUX test signal
DUT Step Atten = 0 dB

Measuring Source Match Γ_G of RF & MW Generators

„Passive ripple method / one mismatch / Δf" (tested at metas)

$$V^* = \frac{V_{max}}{V_{min}}$$

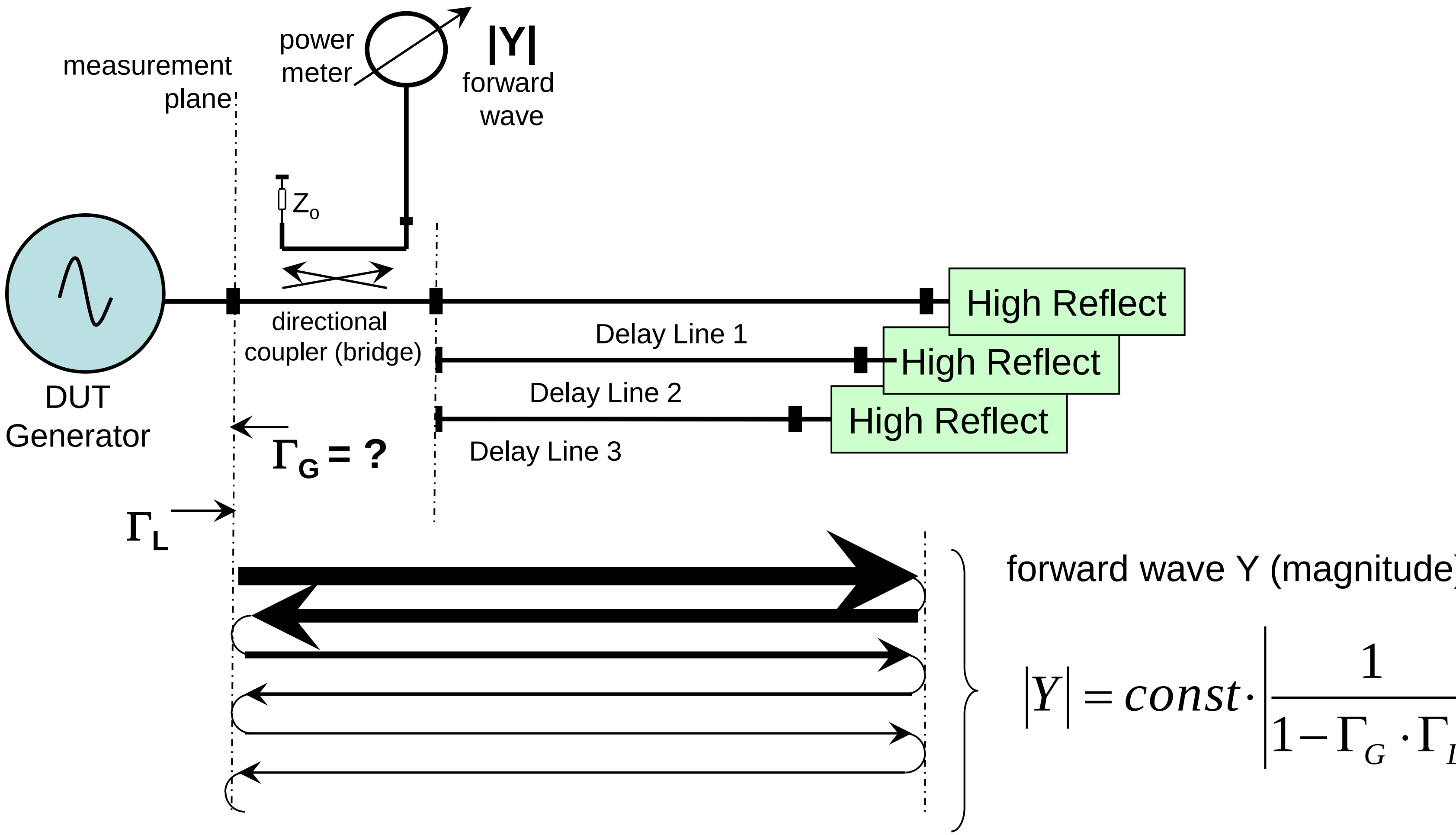
$$|\Gamma_G| = \frac{V^* - 1}{V^* + 1} * \frac{1}{|\Gamma_L|}$$



- Delayline and mismatched load creates a ripple at coupler forward output
- Length of delayline determines lowest operating frequency
- $|\Gamma_G|$ can be calculated by knowing $|\Gamma_L|$ and p-p ripple amplitude
- DUT generator frequency must be changed to find ripple min or max amplitude
- Gives not $|\Gamma_G|$ at defined frequency steps, but somewhere inbetween

New Measurement Setup, Principle (1)

passive, using DUT signal as test signal and different mismatches
$\geq$ 3 known mismatches Γ_L required

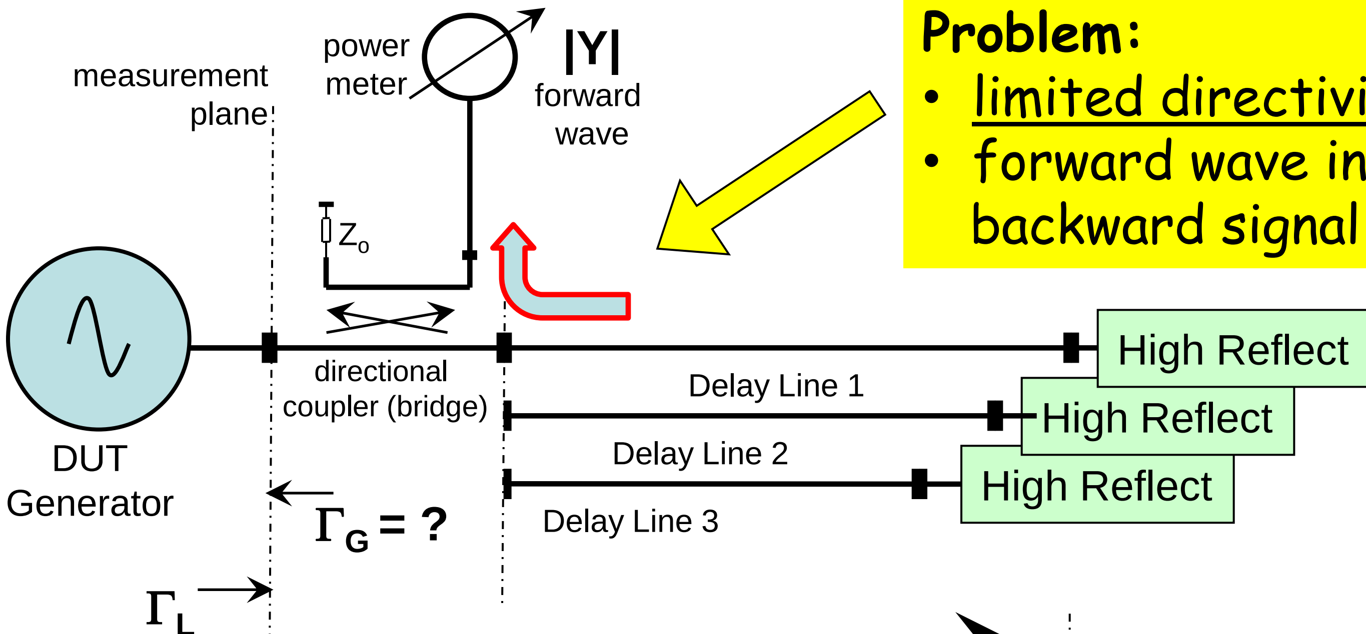


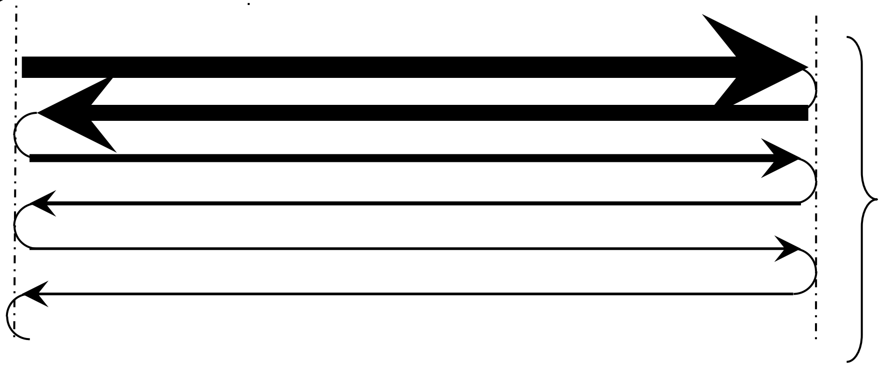
$$|Y| = const \cdot \left| \frac{1}{1 - \Gamma_G \cdot \Gamma_L} \right|$$

New Measurement Setup, Principle (2)

passive, using DUT signal as test signal and different mismatches
≥ 3 known mismatches Γ_L required

Problem:
- <u>limited directivity</u> of coupler
- forward wave interfered by backward signal





forward wave Y (magnitude)

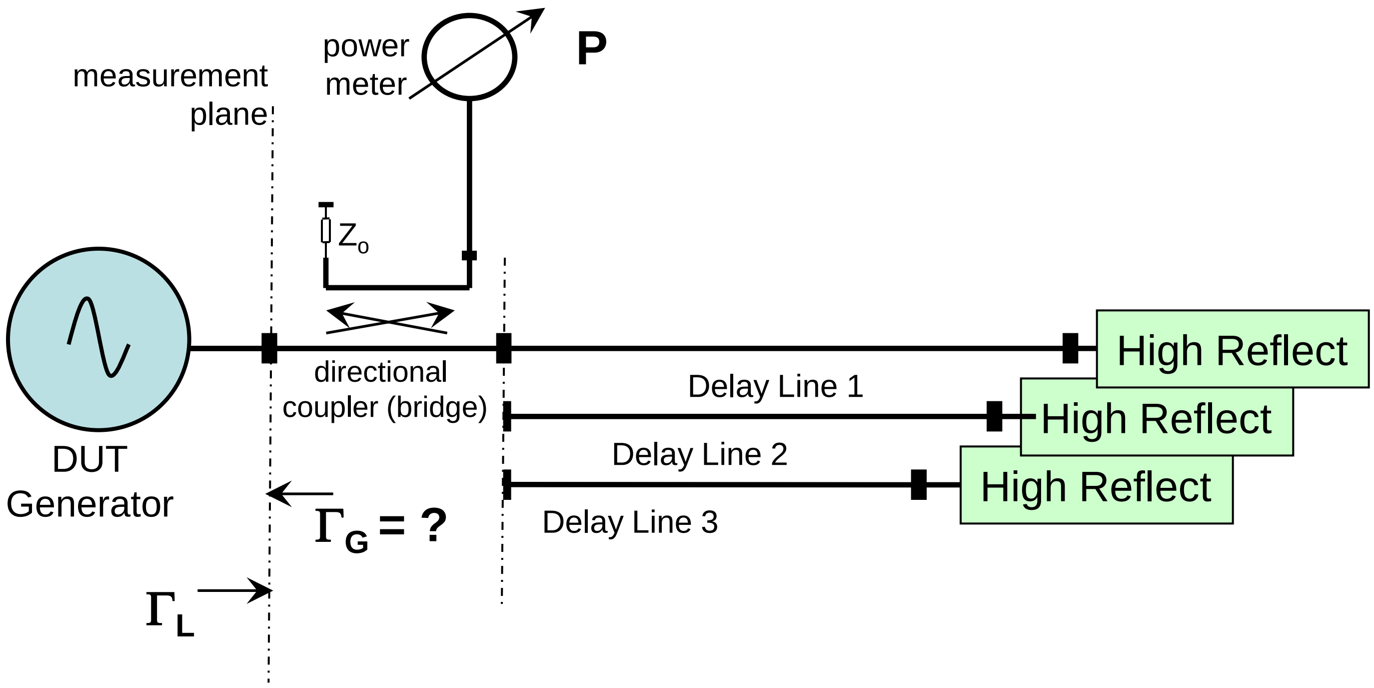
(for ideal directional coupler)

$$|Y| = const \cdot \left| \frac{1}{1 - \Gamma_G \cdot \Gamma_L} \right|$$

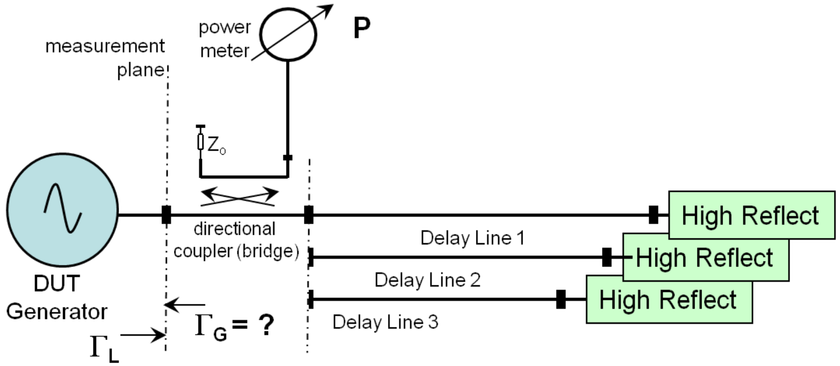
New Measurement Setup: Used Model (1)

Goal:

Find the relationship between the measured power P and Γ_L & Γ_G

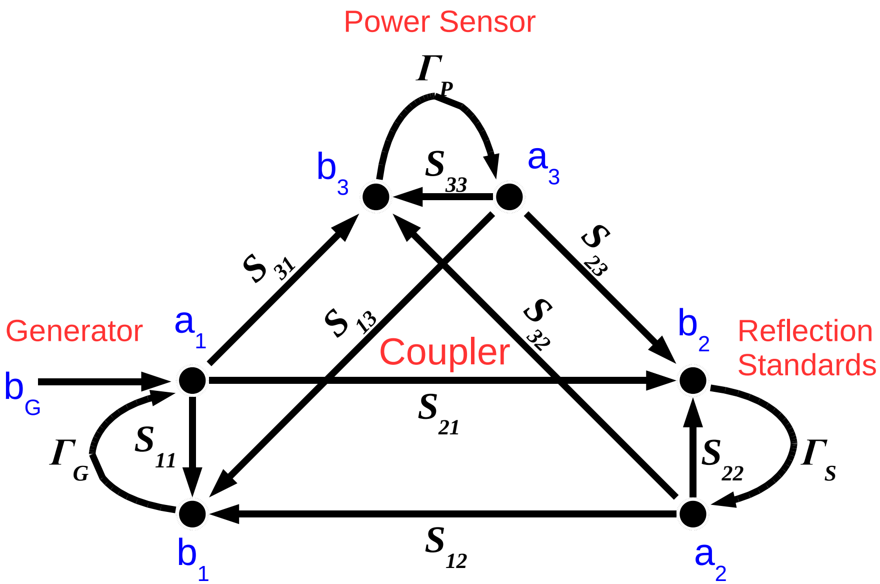


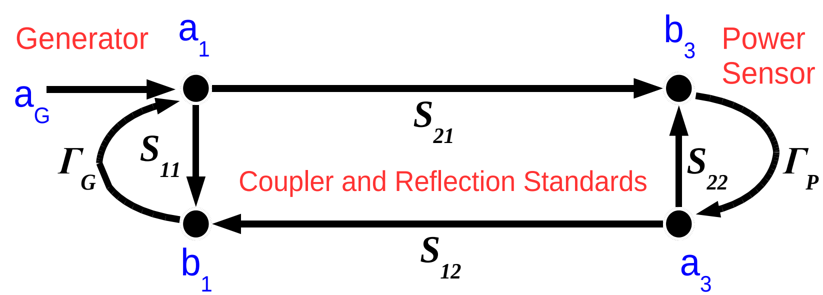
New Measurement Setup: Used Model (2)



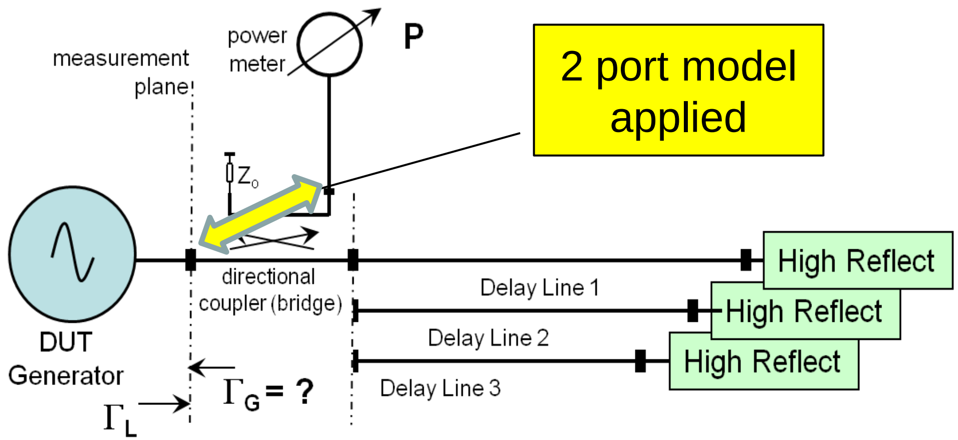
Directional coupler, general case:
3 port model

in this case:
2 port model

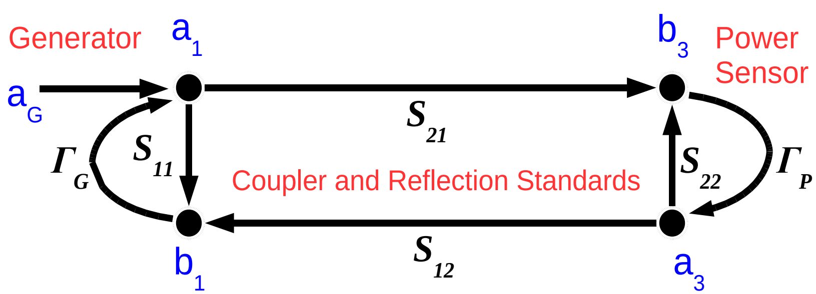




New Measurement Setup: Used Model (3)



2 port model:



$$P \propto \frac{|S_{21}|^2\left(1-|\Gamma_P|^2\right)}{|(1-\Gamma_G S_{11})(1-\Gamma_P S_{22})-\Gamma_G \Gamma_P S_{12} S_{21}|^2}$$

Advantages of 2 port model:

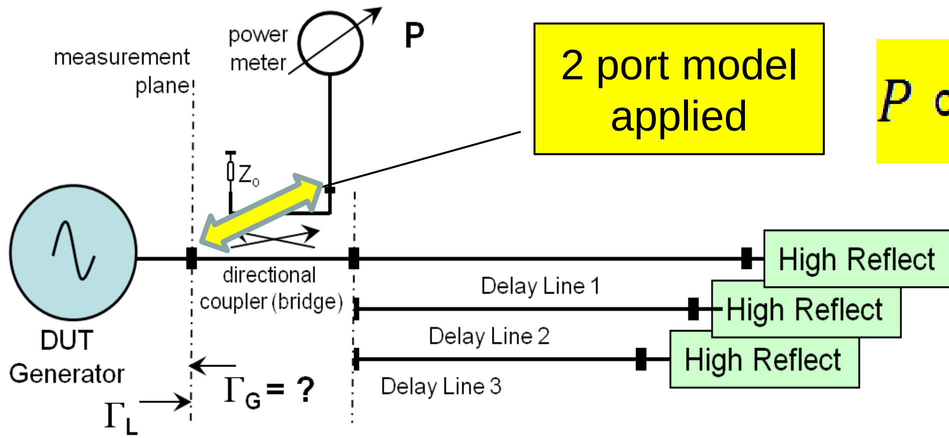
Coupler and HR-standards can be characterized as one unit

Formula represents general case, no neglections

One set of 2-port S-param. for each HR-standard

New Measurement Setup: Used Model (4)

relationship between the measured power P and Γ_L & Γ_G



2 port model applied

$$P \propto \frac{|S_{21}|^2\left(1-|\Gamma_P|^2\right)}{|(1-\Gamma_G S_{11})(1-\Gamma_P S_{22})-\Gamma_G \Gamma_P S_{12} S_{21}|^2}$$

basicaly the same formula

Microwave attenuation measurement

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Great Malvern
England

Basic definitions and equations related to attenuation 7

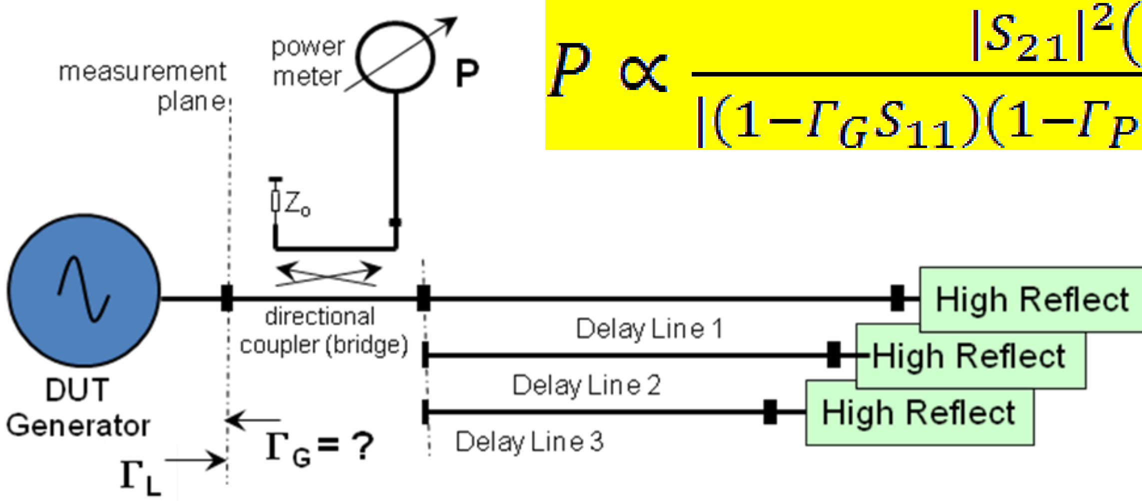
Inserting eqn. 2.4 into 2.5 and rearranging the denominator, we get

$$P_2 = \frac{|e|^2\,|s_{21}|^2\,(1-|\Gamma_L|^2)}{Z_0\,|(1-\Gamma_G s_{11})(1-\Gamma_L s_{22})-\Gamma_G\Gamma_L s_{12}s_{21}|^2} \qquad (2.6)$$

The power P_1 dissipated in the load when the generator is connected directly to it can be found immediately from eqn. 2.6 by letting $s_{11}=s_{22}=0$ and $s_{12}=s_{21}=1$.

New Measurement Setup: Evaluating Γ_G (1)

$$P \propto \frac{|S_{21}|^2(1-|\Gamma_P|^2)}{|(1-\Gamma_G S_{11})(1-\Gamma_P S_{22})-\Gamma_G \Gamma_P S_{12} S_{21}|^2}$$



- measured power P as magnitude only
- unknown Γ_G and known Γ_L are complex numbers
- 3 unknown terms: Γ_{G_Real}, Γ_{G_Imag}, α (const)
- at least 3 known ***High Reflect Standards*** Γ_L (loads) required
- if > 3 known *HR Standards* → overdetermined system
- solving equation by applying least square fit
- more ***High Reflect Standards*** Γ_L → better fit condition
  → reduced uncertainty

Evaluating Γ_G (2)

3 Step Process

- characterisation of ***High Reflect Standards*** Γ_L at measurem. plane
- DUT measurement: power P vs. HR Standards
- evaluation of Γ_G: Least Square Fit

$$P \propto \frac{|S_{21}|^2 \left(1-|\Gamma_P|^2\right)}{|(1-\Gamma_G S_{11})(1-\Gamma_P S_{22})-\Gamma_G \Gamma_P S_{12} S_{21}|^2}$$

measured (P)

fited (α)

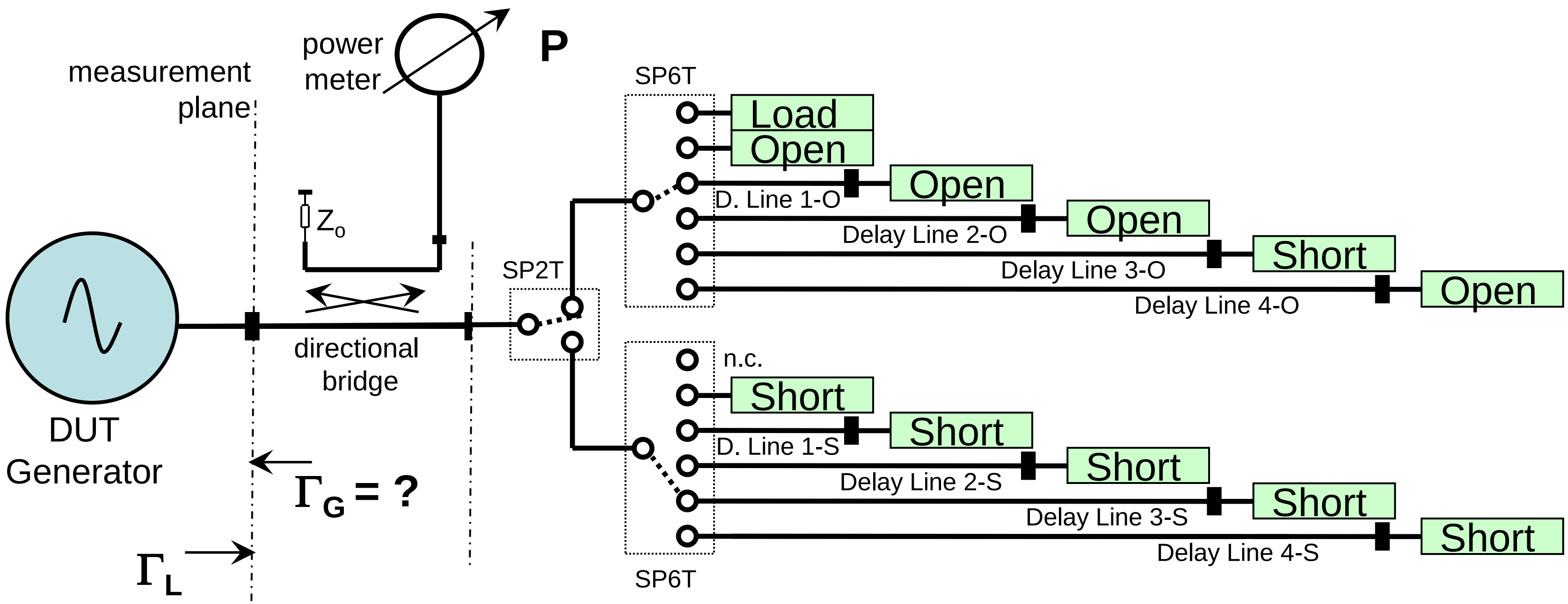
fited (Re, Ima)

characterized (S-param, Γ_P)

Realisation of the automated system

Remote Switched High Reflect Standards

11 Γ_L Standards, automated, directional bridge, 10 … 6000 MHz



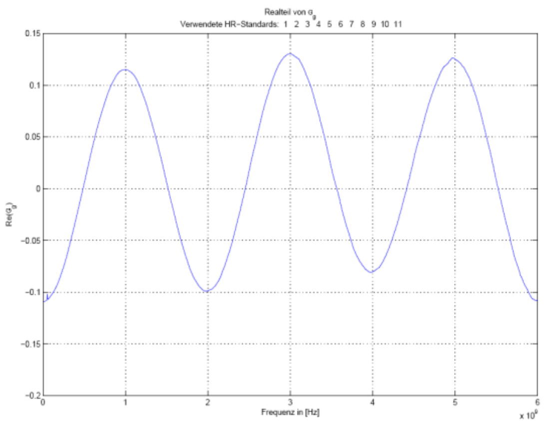
$$P \propto \frac{|S_{21}|^2(1-|\Gamma_P|^2)}{|(1-\Gamma_G S_{11})(1-\Gamma_P S_{22})-\Gamma_G \Gamma_P S_{12} S_{21}|^2}$$

METAS

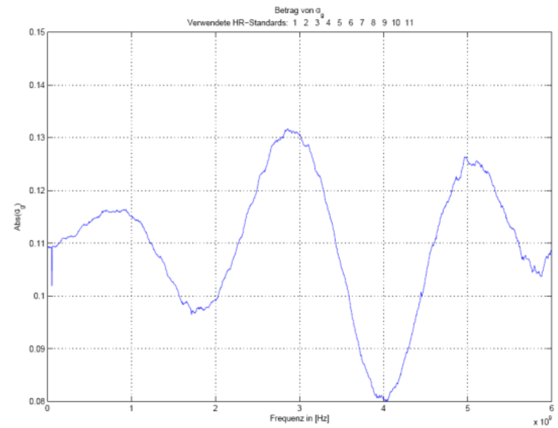
Evaluating Γ_G (3)

Matlab software for evaluation of Γ_G by applying Least Square Fit:

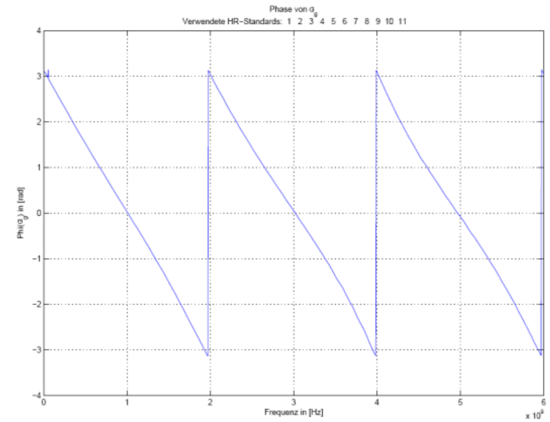
Γ_{G_Real} , Γ_{G_Imag}



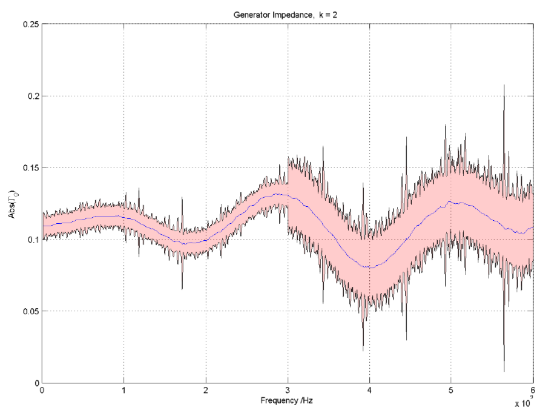
Γ_{G_Mag}



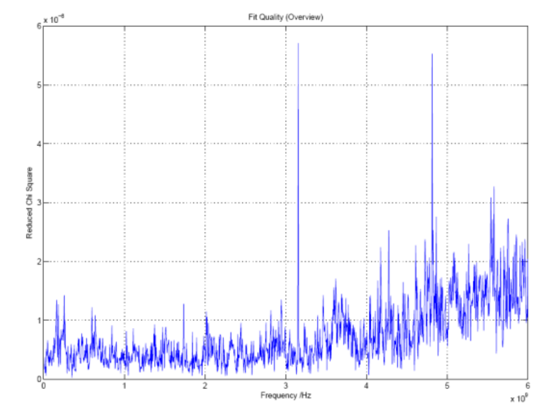
Γ_{G_Phase}



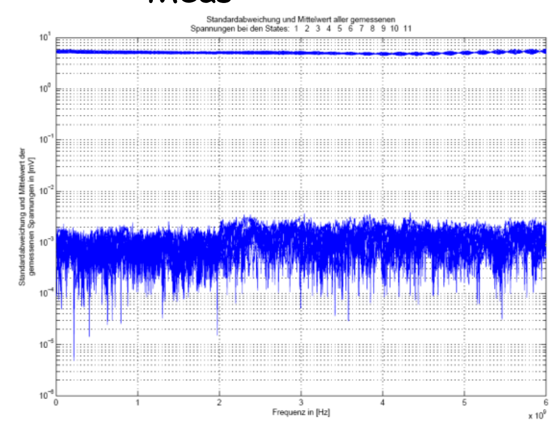
Unc Γ_G Re Ima Mag Phase



fit quality Σ meas² - fit²



P_{Meas} & StdDev



Evaluating Γ_G (4)

Matlab software for evaluation of Γ_G by applying Least Square Fit:

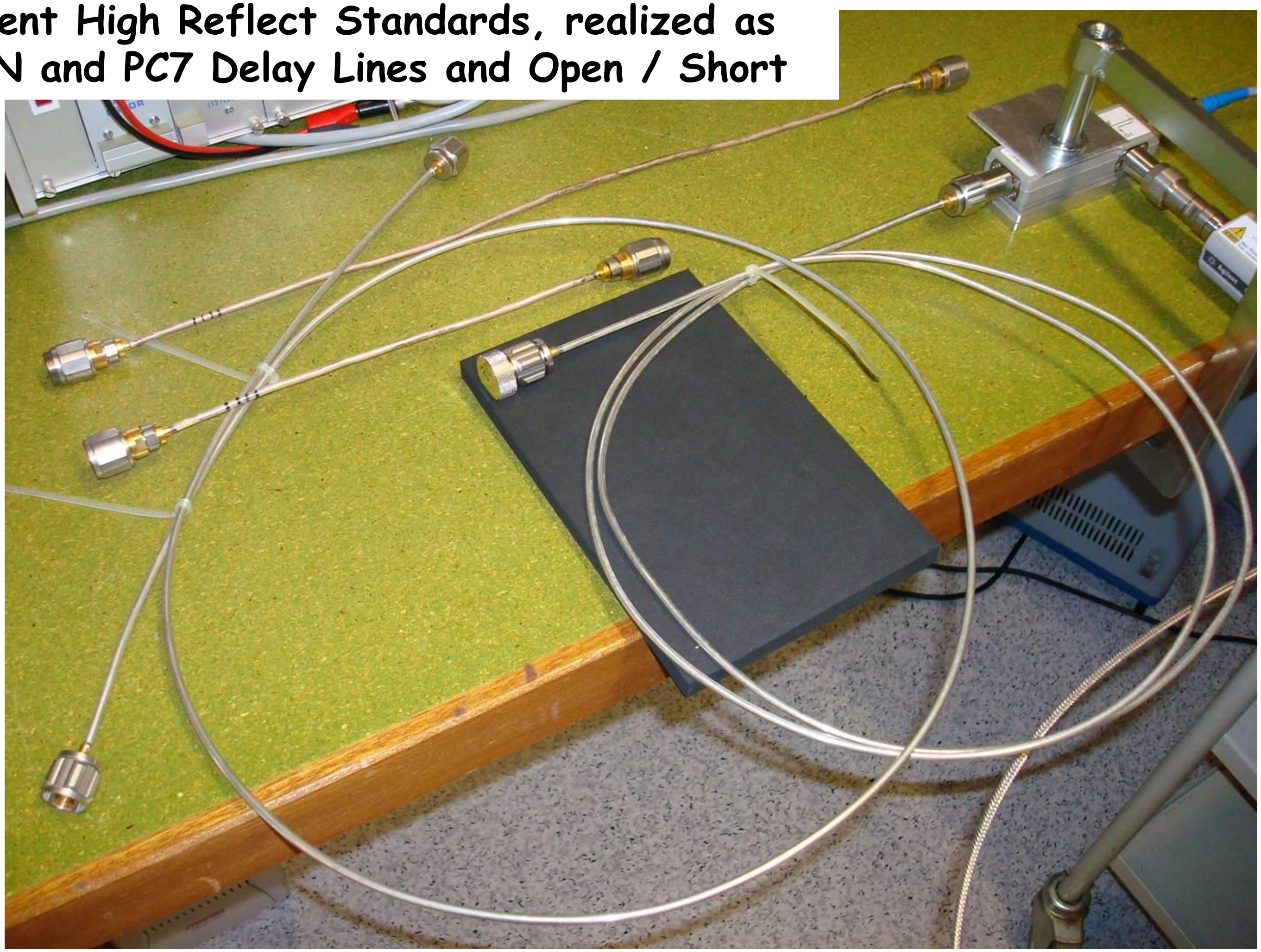
Example:

10 MHz to 6 GHz in 5 MHz steps, 1199 points

- Evaluation runs in about 10 min
- Measurement (3 repeats) runs in about 13 hrs

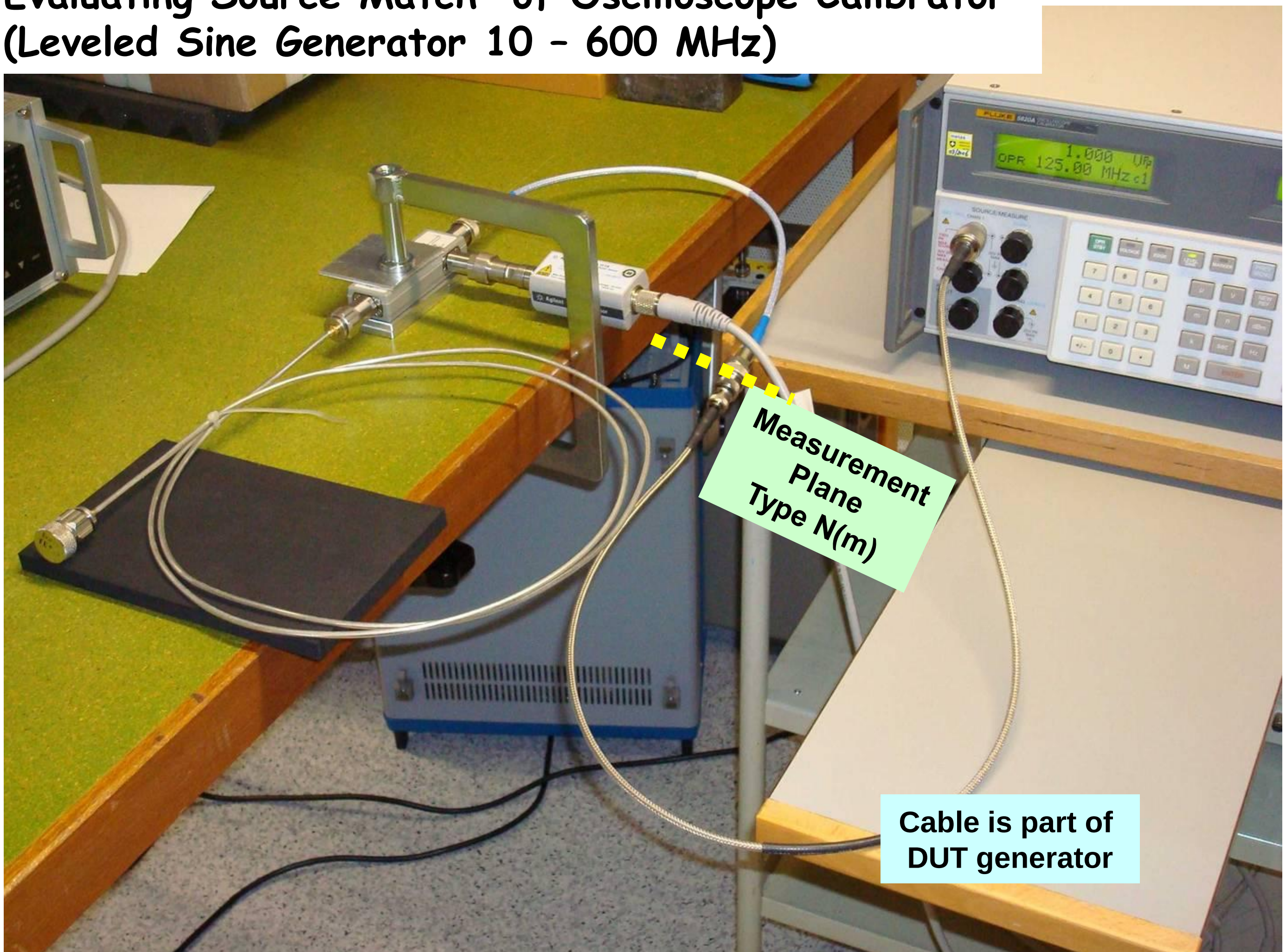
First realisation 10 – 2000 MHz (2007)
Connecting High Reflect Standards manually (1)

Directional Coupler (Bridge),
different High Reflect Standards, realized as
Type N and PC7 Delay Lines and Open / Short



First realisation 10 – 2000 MHz (2007)
Connecting High Reflect Standards manually (2)

Evaluating Source Match of Oscilloscope Calibrator (Leveled Sine Generator 10 – 600 MHz)



Two methods, results compared (1)

A) „Passive ripple method / one mismatch / Δf"
B) New passive method with different HR-Standards (manual)

DUT: Oscilloscope calibrator (Leveled Sine Generator 10 – 600 MHz)

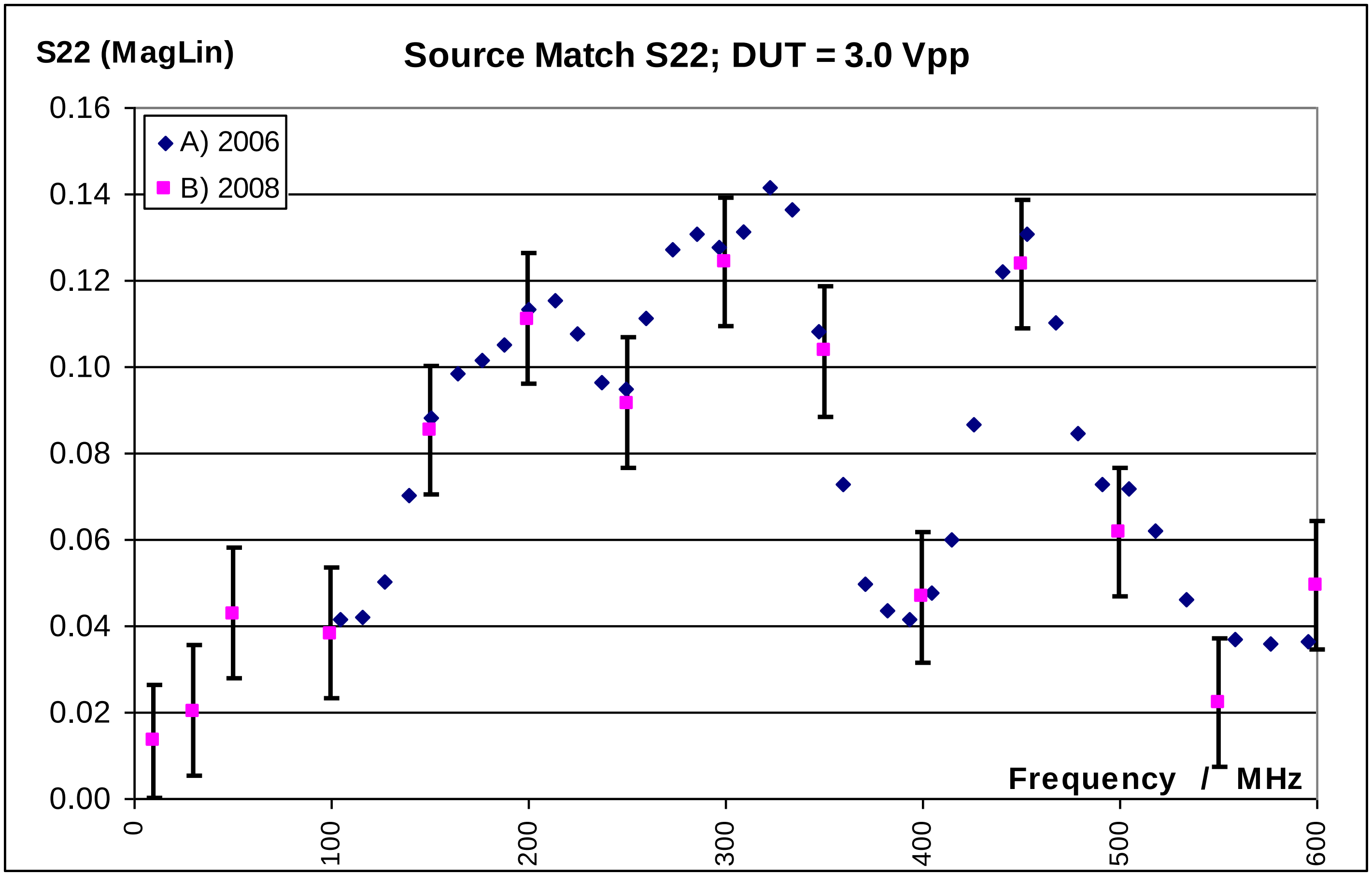
Preliminary conclusions

- results are encouraging
- total 11 HR Standards used, manually connected
- Γ_G depends on output level
  → many measurement series required
- time consuming work → too expensive as a service
- need for a fully automated system

Two methods, results compared (2)

A) „Passive ripple method / one mismatch / Δf", 2006
B) New passive method with different HR-Standards (manual), 2008

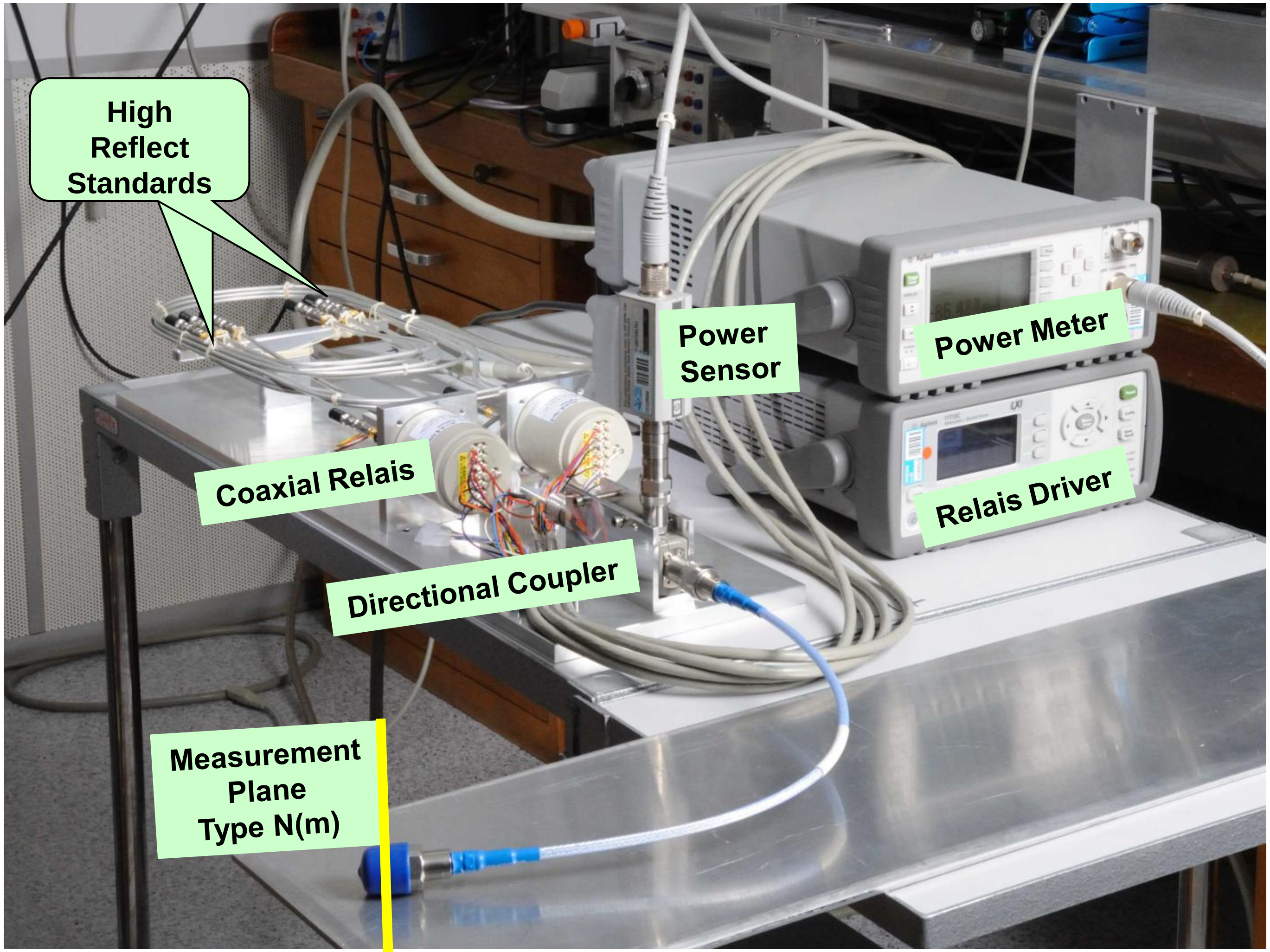
DUT: Oscilloscope calibrator (Leveled Sine Generator 10 – 600 MHz)



Realisation of a fully automated system for Calibrating Source Match of RF & MW Generators (April 09)

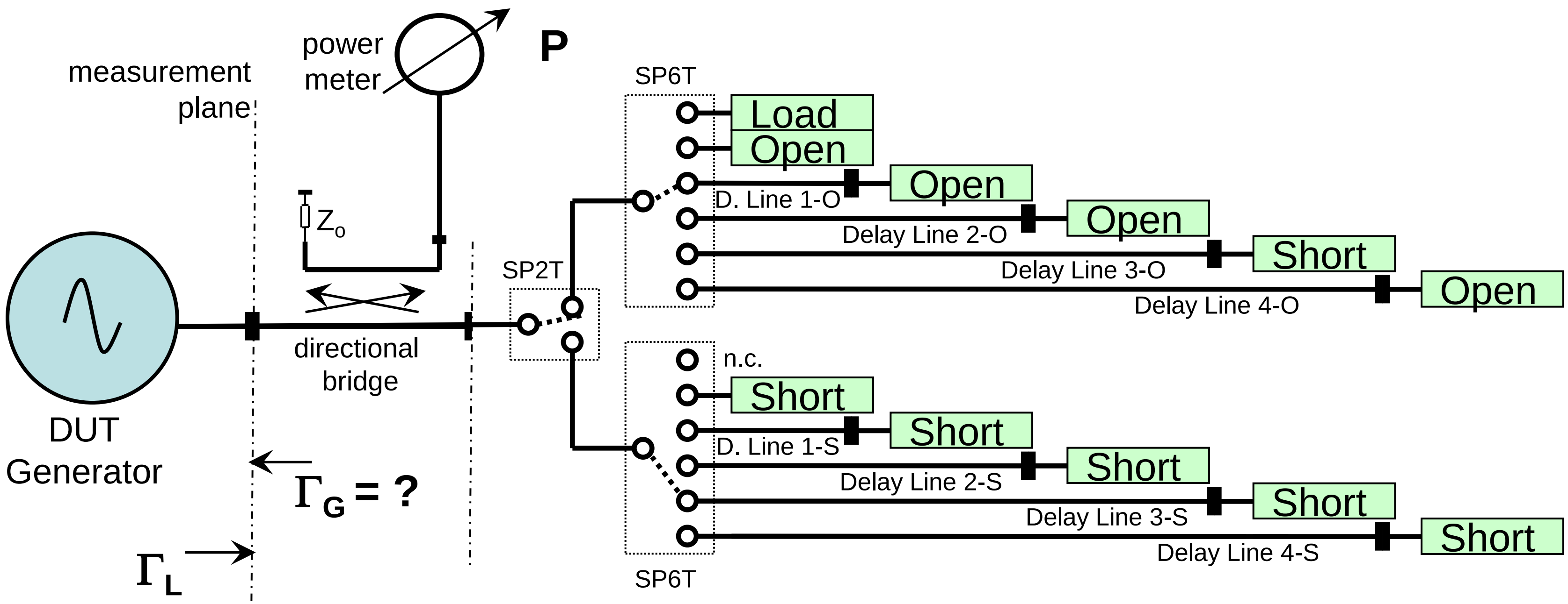
Realisation of a fully automated System (April 09)

Remote Switched High Reflect Standards



Remote Switched High Reflect Standards

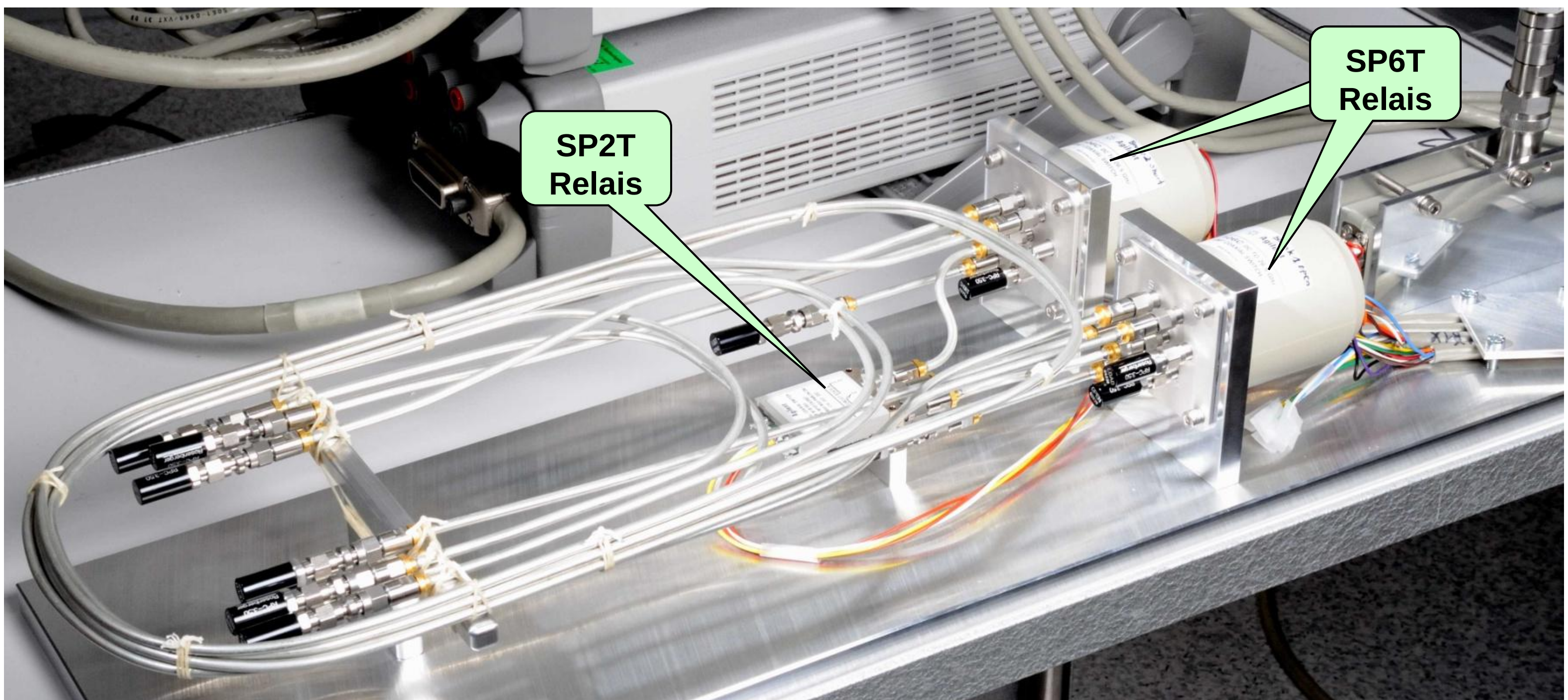
11 Γ_L Standards, automated, directional bridge, 10 … 6000 MHz



$$P \propto \frac{|S_{21}|^2(1-|\Gamma_P|^2)}{|(1-\Gamma_G S_{11})(1-\Gamma_P S_{22})-\Gamma_G \Gamma_P S_{12} S_{21}|^2}$$

Remote Switched High Reflect Standards

- 11 Standards available: Direct — Open, Short, Load
  Delayline 1 … 4 — Open, Short
  (Delaylines l = 90 … 2000 mm)
- „One out of 12" - Switch, realized by using one SP2T and two SP6T mechanical coaxial switches
- best possible switch quality → to maintain good repeatability (repeatability to compare with the best step attenuators)



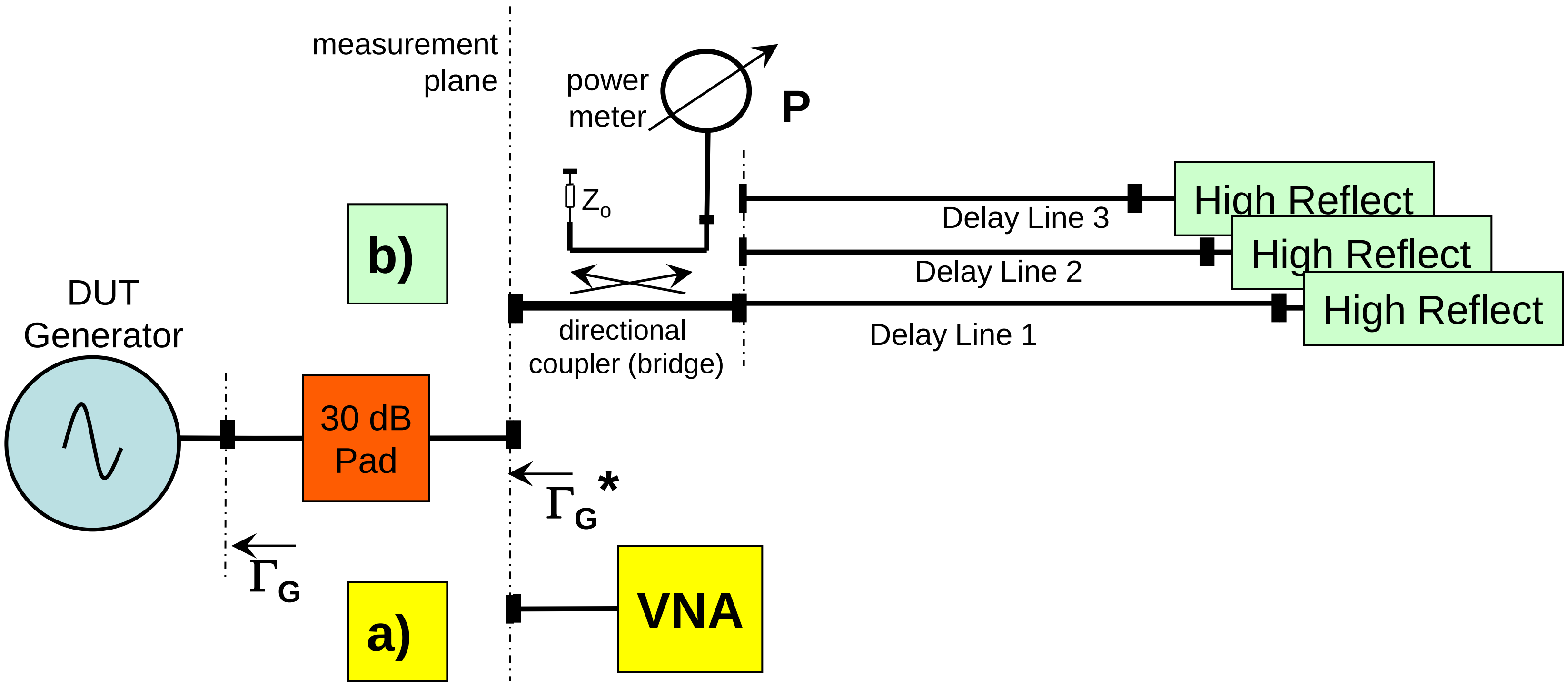
Verification using a padded generator

Virtual* DUT generator: Generator and 30 dB pad at the output

Γ_G* depends solely on characterisics of 30 dB pad

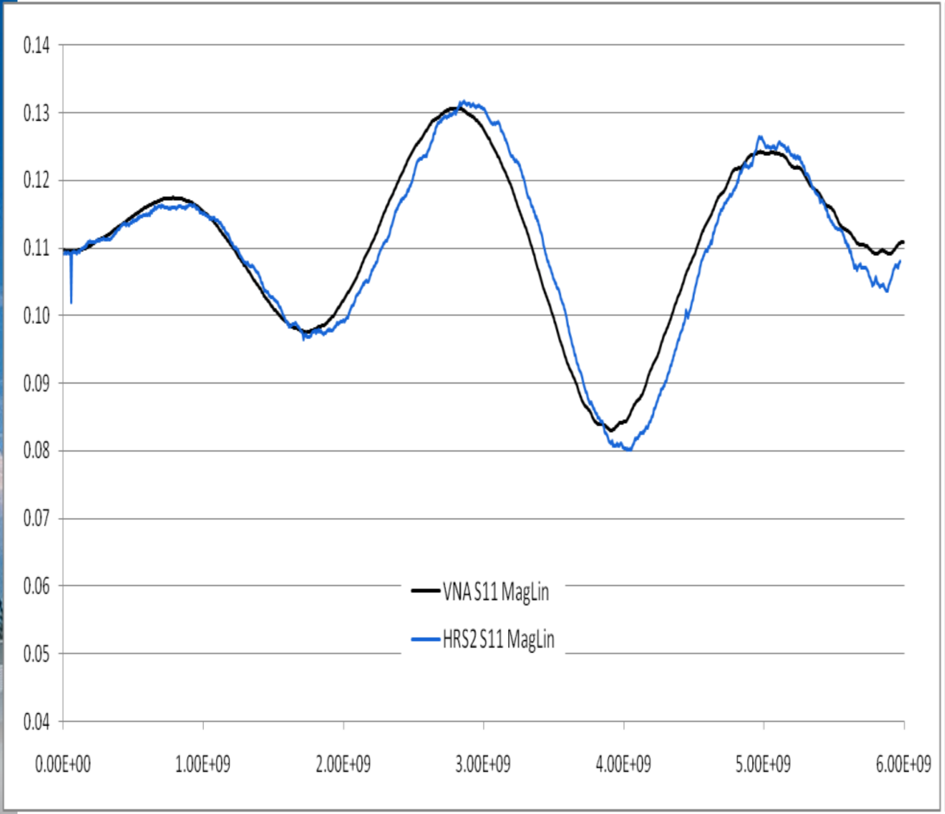
a) Γ_G* is isolated from Γ_G by a 30 dB pad about 60 dB (≈ 0.1 %)
   Γ_G* can be measured using a VNA (generator is switched off)

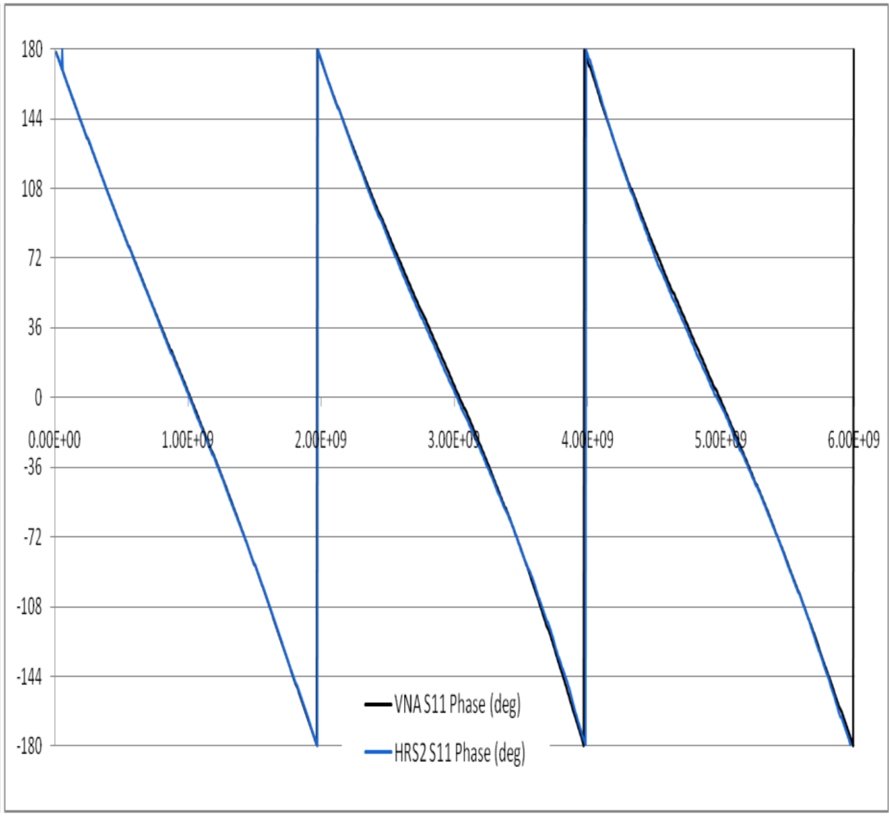
b) Comparing with results of *Remote Switched HRS method*



Verification using a padded generator **(Pad 1, $\Gamma_G^* \approx 0.11$)**

black: VNA measurement (generator is switched off)
blue: results of *Remote Switched HRS method*

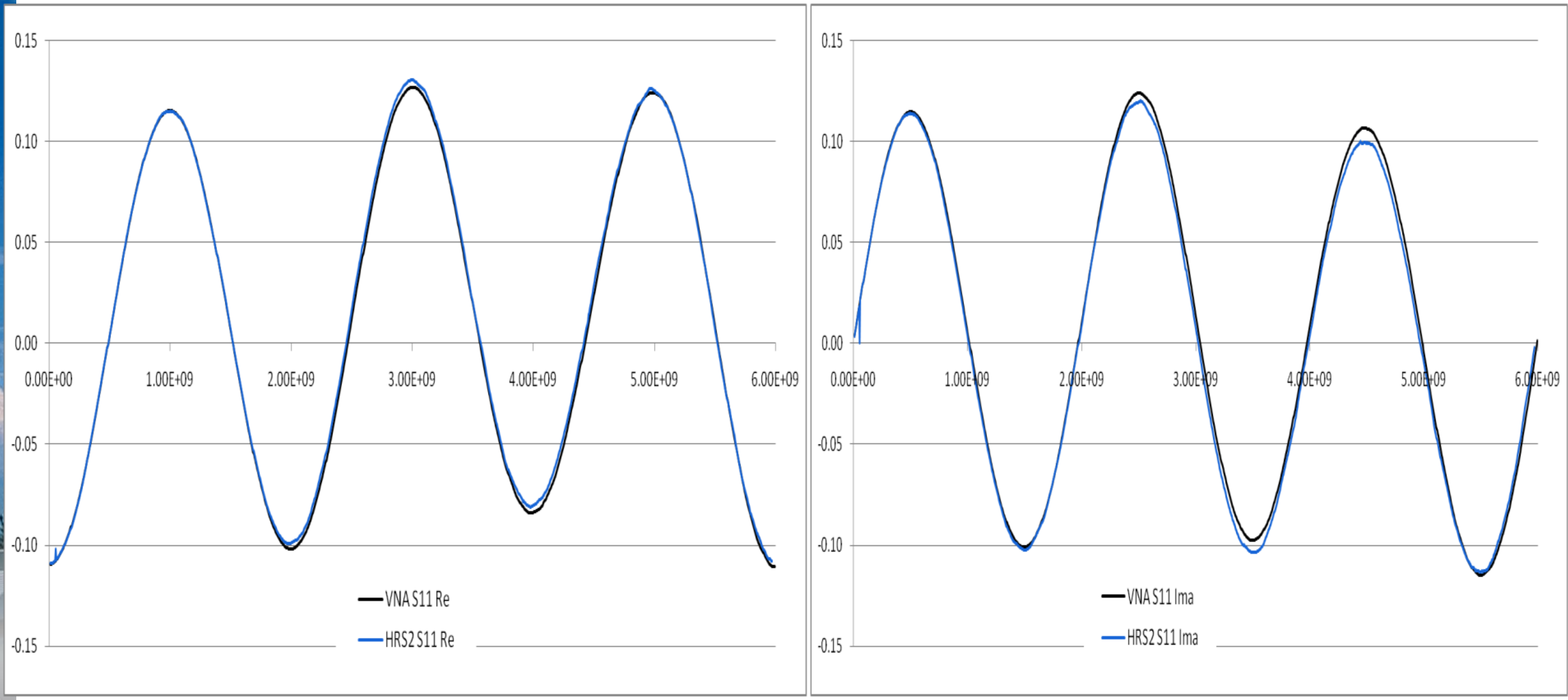




Vergl VNA & HRS2_8257D Pad30_5_1.xlsx

Verification using a padded generator **(Pad 1, Γ_G*≈0.11)**

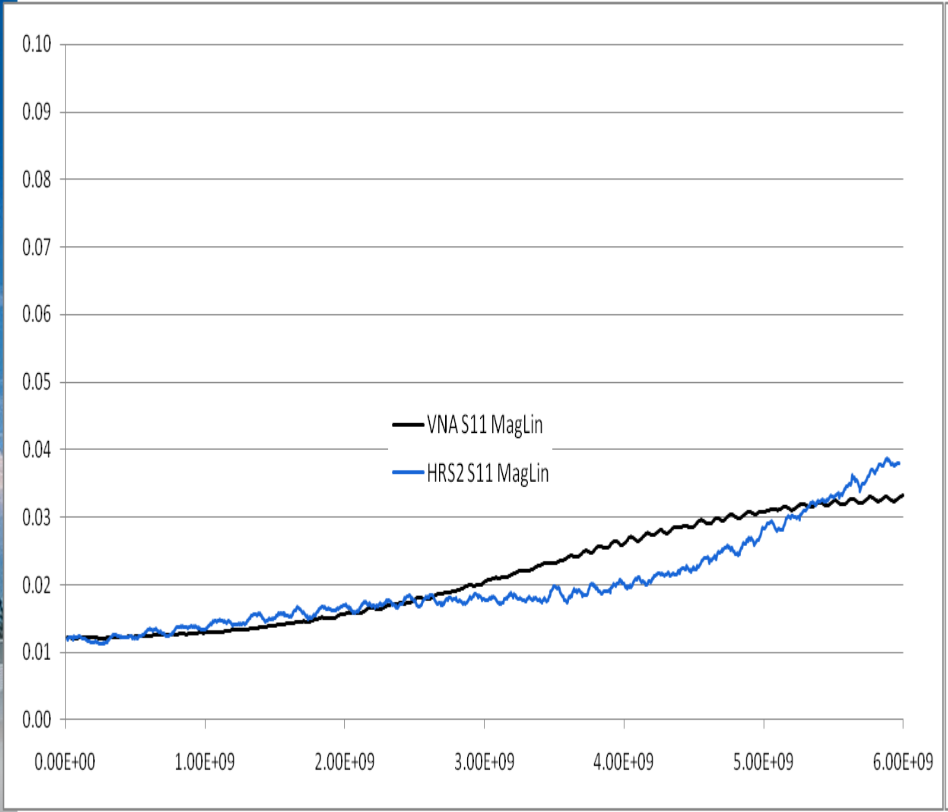
black: VNA measurement (generator is switched off)
blue: results of *Remote Switched HRS method*

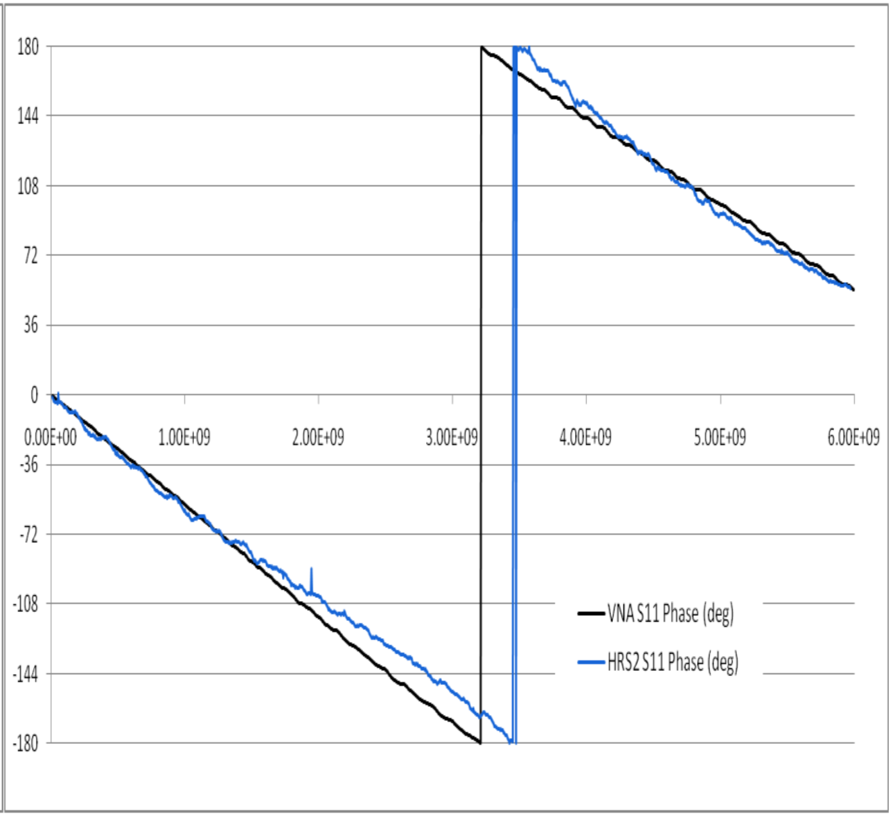


Vergl VNA & HRS2_8257D Pad30_5_1.xlsx

Verification using a padded generator **(Pad 2, $\Gamma_G^* \approx 0.01$)**

black: VNA measurement (generator is switched off)
blue: results of *Remote Switched HRS method*

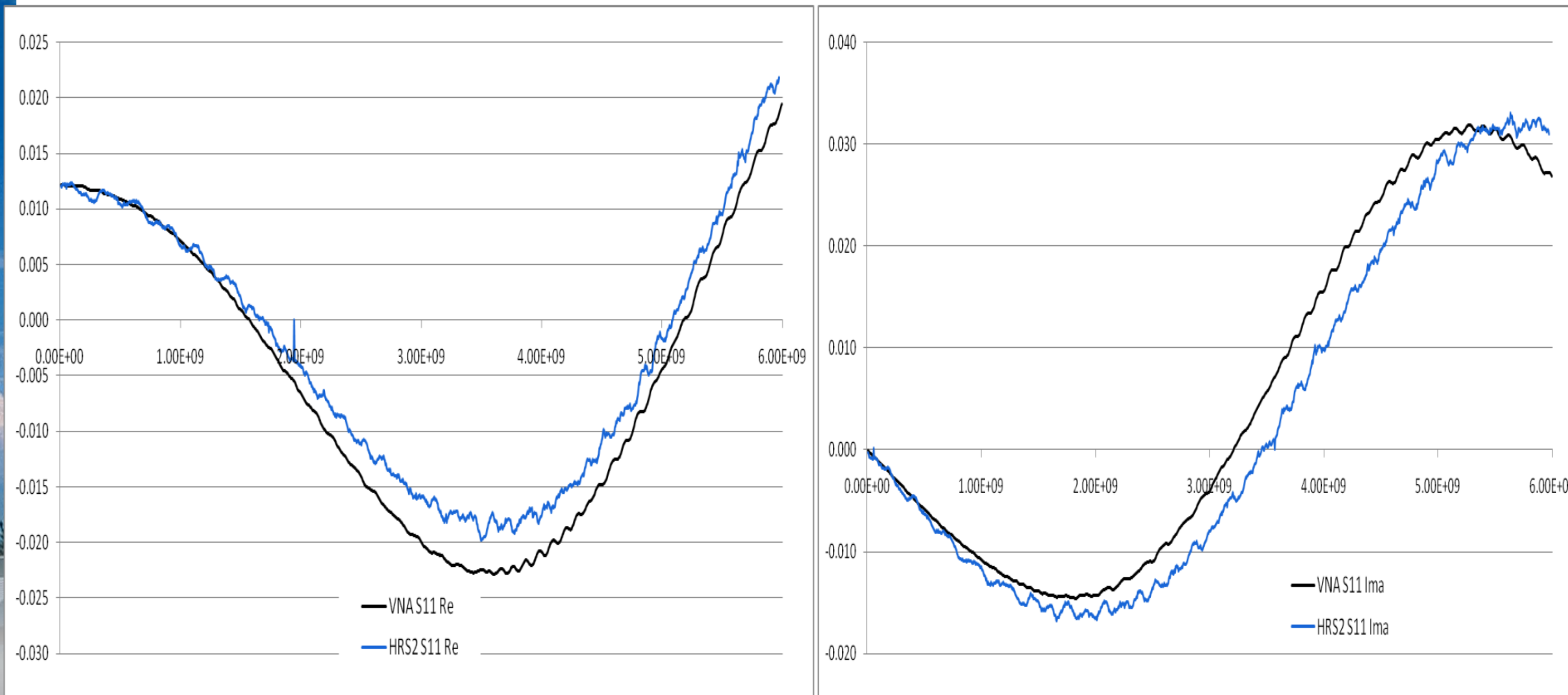




Vergl VNA & HRS2_8257D Pad30_4_2.xlsx

Verification using a padded generator (Pad 2, $\Gamma_G^* \approx 0.01$)

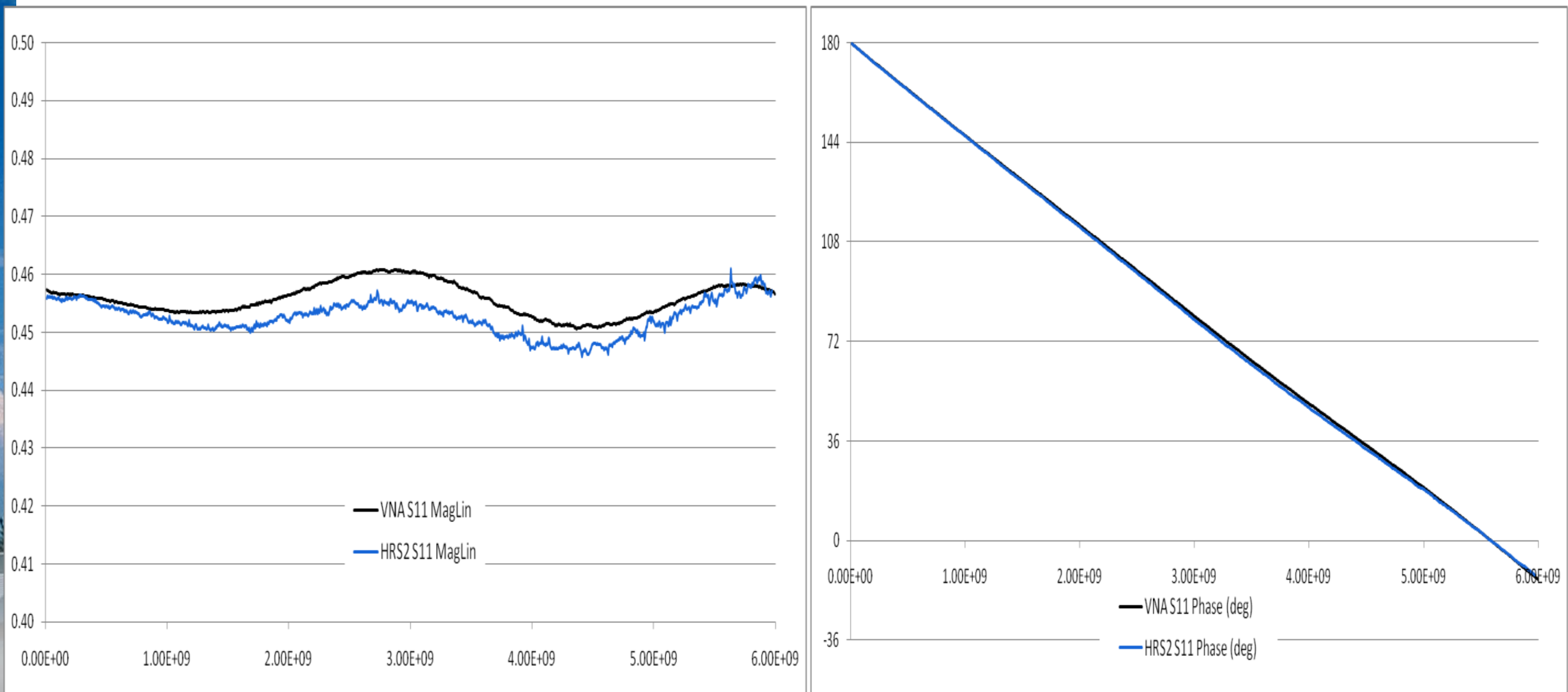
black: VNA measurement (generator is switched off)
blue: results of *Remote Switched HRS method*



Vergl VNA & HRS2_8257D Pad30_4_1.xlsx

Verification using a padded generator **(Pad 3, $\Gamma_G^* \approx 0.46$)**

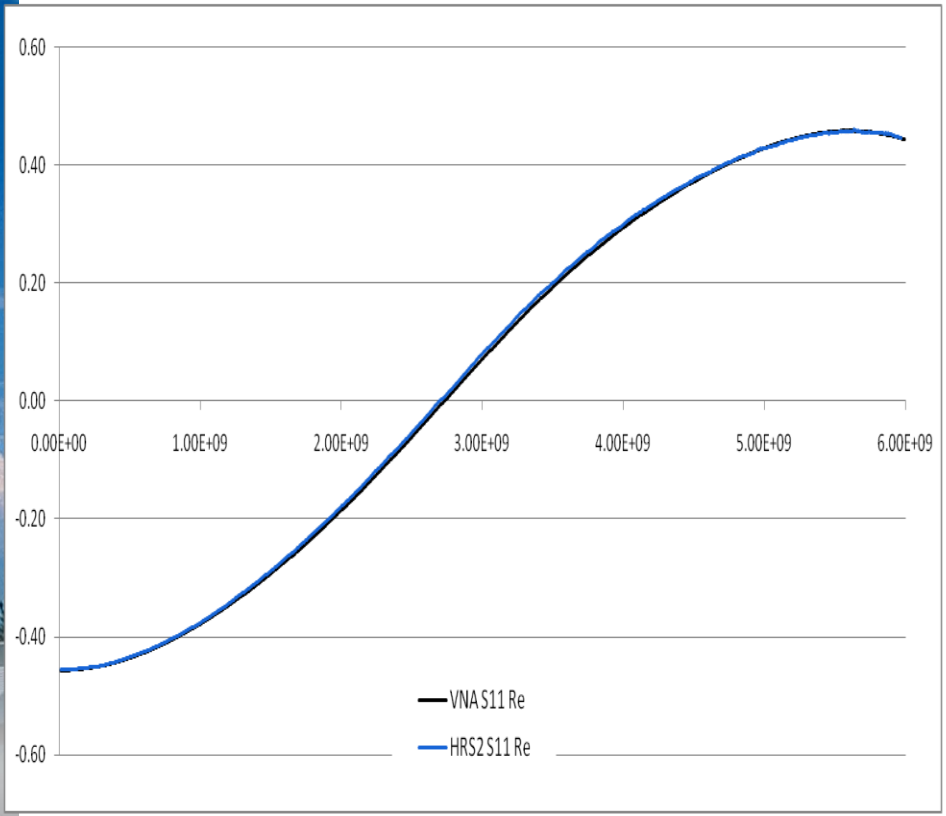
black: VNA measurement (generator is switched off)
blue: results of *Remote Switched HRS method*

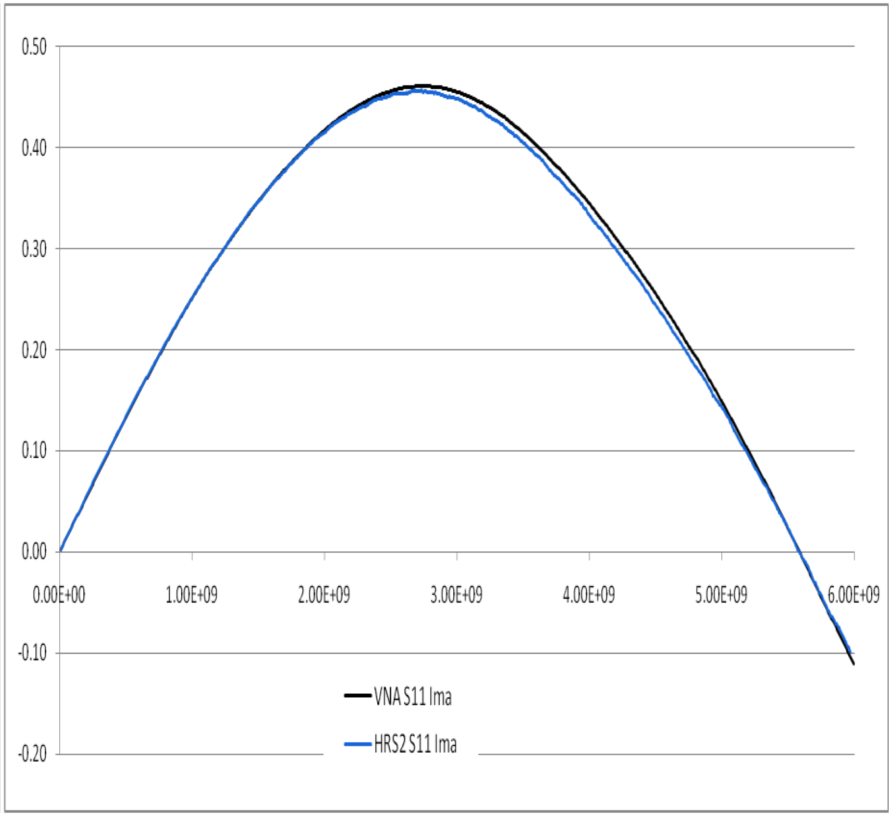


Vergl VNA & HRS2_8257D Pad30_6_1.xlsx

Verification using a padded generator **(Pad 3, $\Gamma_G^* \approx 0.46$)**

black: VNA measurement (generator is switched off)
blue: results of *Remote Switched HRS method*





Vergl VNA & HRS2_8257D Pad30_6_1.xlsx

Uncertainty Contributions

Main Unc. - Contributions (10 MHz – 6000 MHz version)

- Characterisation of Coupler / High Reflects (Γ_L typical 0.6 … 0.7)
  S11 / S22: U ≤ 0.005 MagLin (one sigma, 10 … 3000 MHz)
  S11 / S22: U ≤ 0.01 MagLin (one sigma, 3000 … 6000 MHz)
  S21 / S12: U ≤ 0.1 dB MagLog (one sigma, 10 … 6000 MHz)

- StdDev of switching the High Reflect Standards
  S11: U ≤ 0.001 MagLin (one sigma, 10 … 6000 MHz)

- StdDev of measured power P, ≥ 3 repeated measurements
  U ≤ 0.0007 (one sigma, 10 … 6000 MHz)
  depending on DUT (test level and stability)

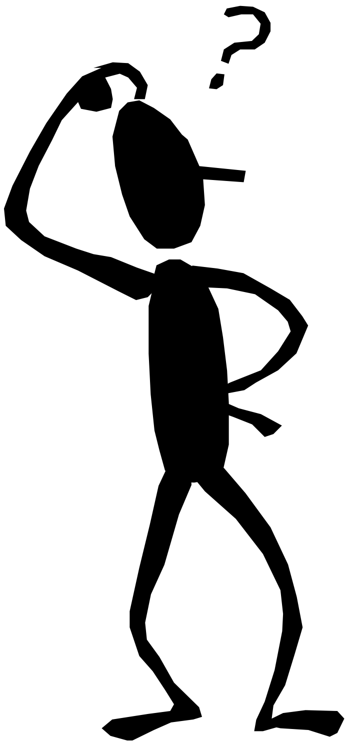
- Used VNA: hp8753D
  Uncertainties can be reduced by using hp8510

METAS

Evaluation of Total Uncertainty

By using uncertainty propagation library

Metas.UncLib



Metas.UncLib

General Purpose Uncertainty Library

It does

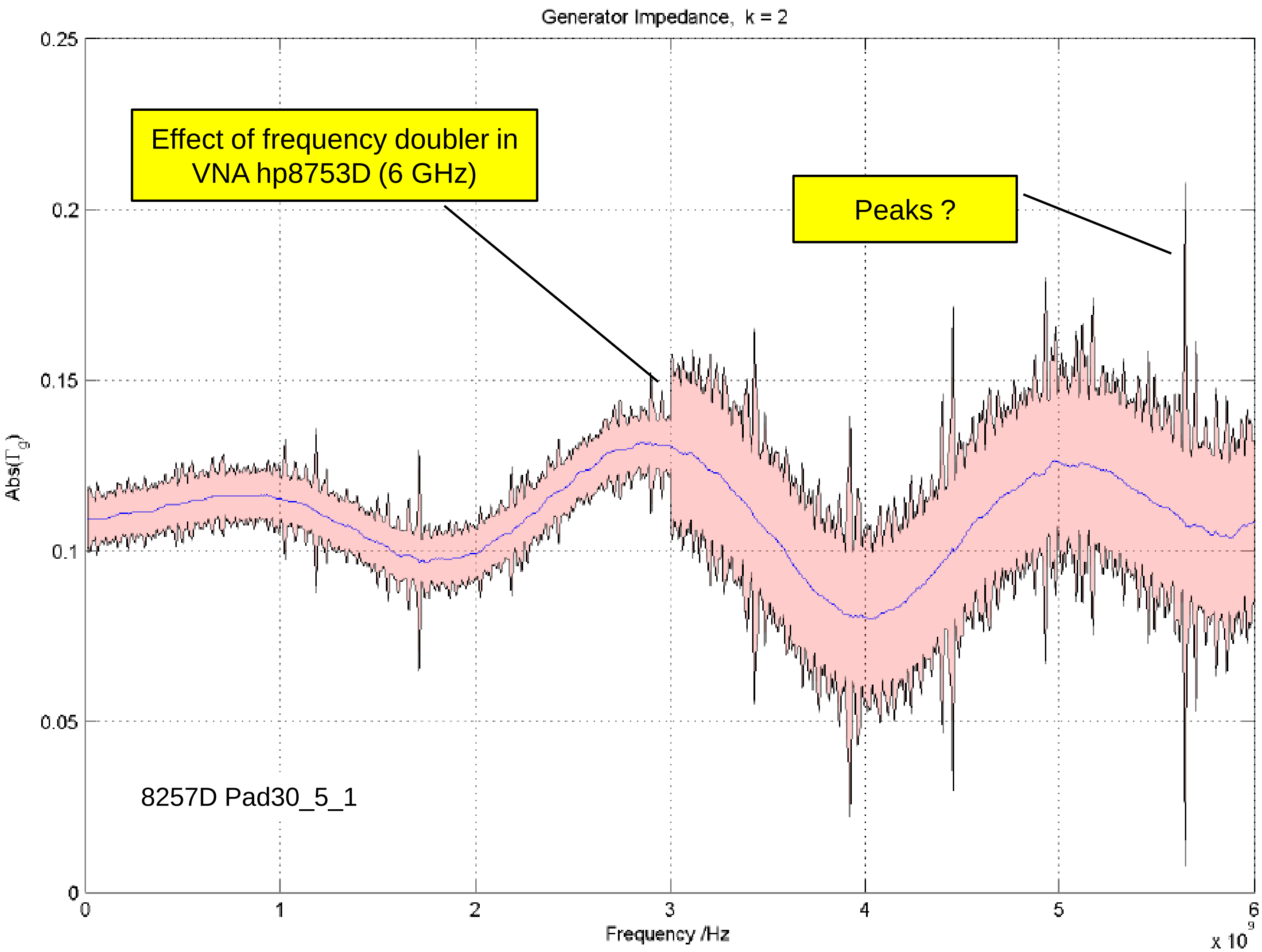
- support multidimensional uncertainty calculation
- advanced math (Complex, Vector, Matrix)
- automated linear uncertainty propagation
- Monte Carlo uncertainty propagation (preliminary)
- take care of correlations
- advanced storage / archiving (keeps full information)
- interfacing with other applications

It does NOT

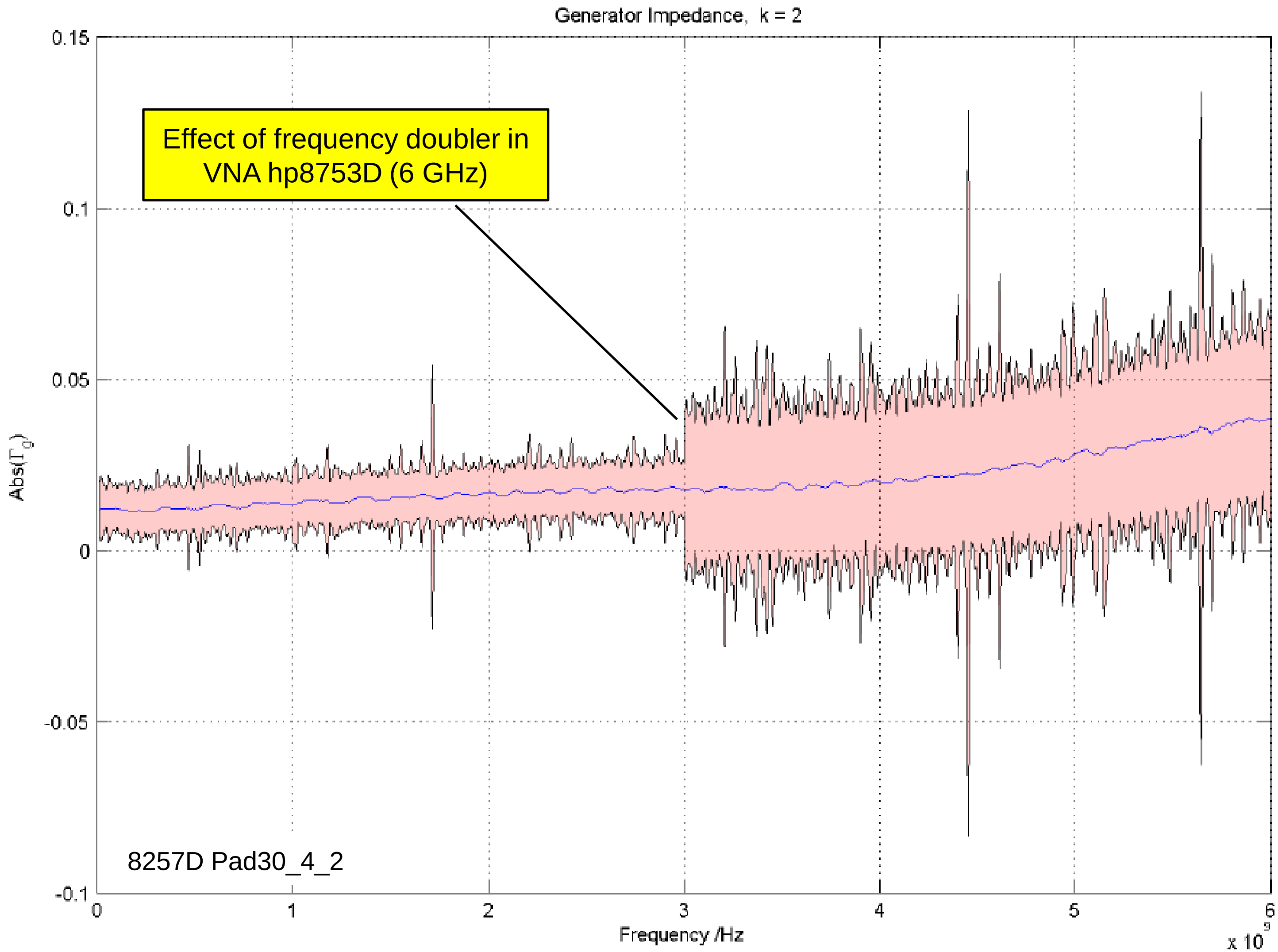
- help to build a measurement model
- have a nice graphical interface
- produce „fancy“ output

Presentation of *Metas.UncLib* → ANAMET Spring 2010

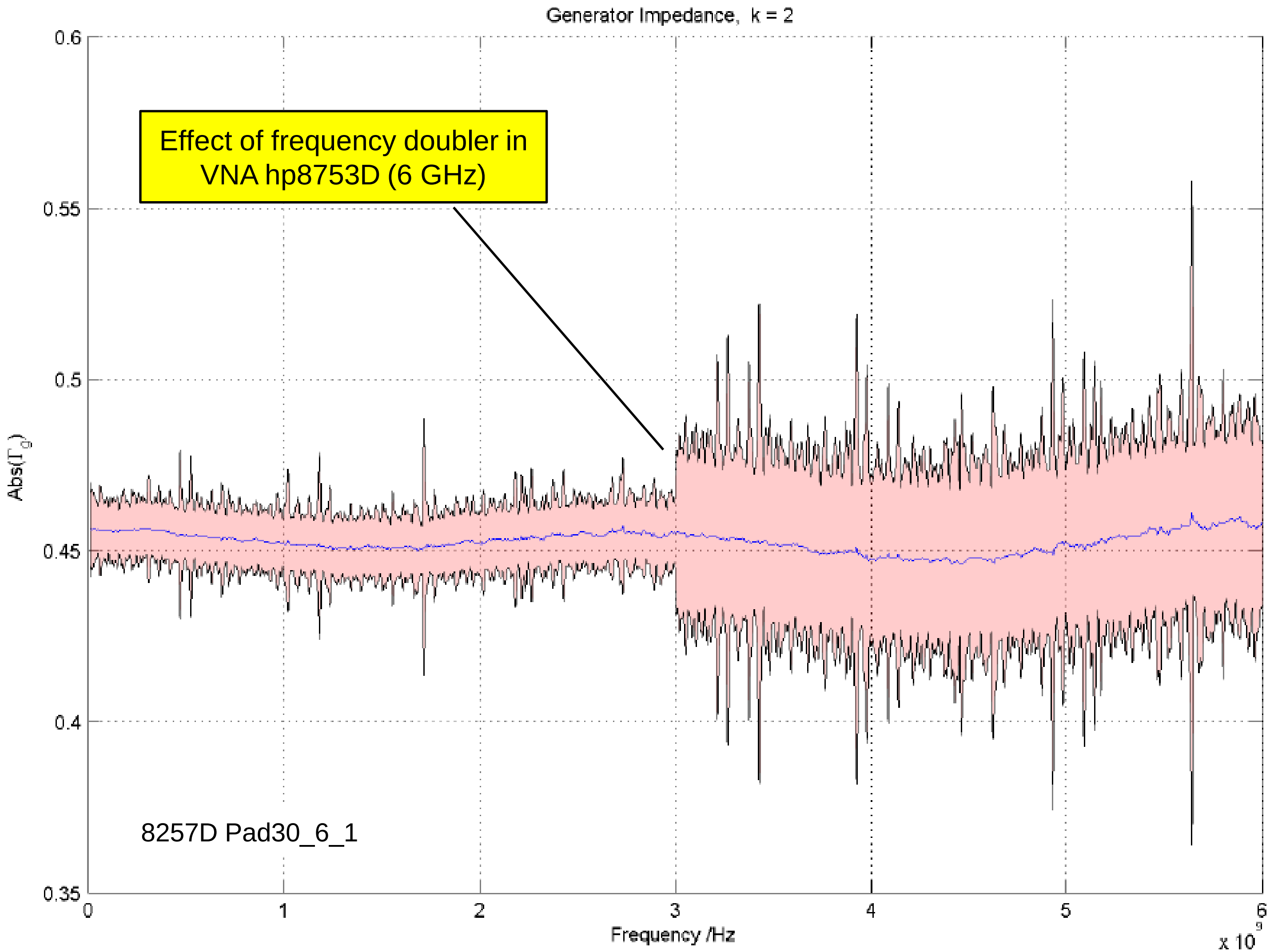
Evaluation of Total Uncertainty, $\Gamma_G \approx 0.11$ (k=2)



Evaluation of Total Uncertainty, $\Gamma_G \approx 0.01$ (k=2)



Evaluation of Total Uncertainty, $\Gamma_G \approx 0.46$ (k=2)



Verification II
Source Match of 50 MHz Power Meter Reference Source

Measurement method A)

- Using a similar manual system with coupler and 5 HRS standards
- Applying „Levenberg Marquard Algorithm"

Measurement method B)

- Remote Switched HRS method

Result method A): $|\Gamma_G|$ = 0.011, no phase information available

Result method B): $|\Gamma_G|$ = 0.010, φ ($|\Gamma_G|$) = -25°; U=0.006 (k=2)

Next Steps and Improvements

- Improving & fine tuning (uncertainty peaks)
- More detailed characterisation of the realized *Remote Switched HRS* system
- Building up a second system for 2 – 18 GHz frequency range
- Metas is open for comparisons

Conclusions

- Source Match can be a dominating uncertainty contribution
- Many methods for measuring source match known
- In general very time consuming procedure
- Some generators have „critical output stages“
- Source match Γ_G depends (mostly) on used P_{Gen} therefore many measurement sequences required
- source match measuring system must work fully automated
- an automated system was realized and verified
- improvements

Support: Thanks to

Michael von Grünigen for
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Marko Zeier for
- developing circuit model
- implementing *Metas.UncLib* in analysis tool

Michael Wollensack for
- Labview software for controlling the measuring system
- developing *Metas.UncLib*

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Thank you for your attention