Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Traceable planar S-parameter measurements on industrial substrates

Dr. Uwe Arz, AG 2.23

Physikalisch-Technische Bundesanstalt (PTB)

Motivation: EMPIR-Project 14IND02 PlanarCal

Microwave measurements for planar circuits and components [1]

Scientific goals

- Establish traceability of planar scattering parameter measurements
- Extension to higher frequencies (at least 325 GHz)
- Develop methods for measurements of RF nano-devices

Partners:

PTB, NPL, FAU, FBH Leibniz Ferdinand-Braun-Institut, Fraunhofer IAF, Université de Lille, TU Delft, University of Leeds, Rohde & Schwarz, TDK, METAS

Support from Industry

Thales, Airbus, NXP, Cascade Microtech, Intel, Infineon, Rohde & Schwarz, Anritsu, Keysight Technologies, ST, MPI

Duration: 1.10.2015-30.9.2018

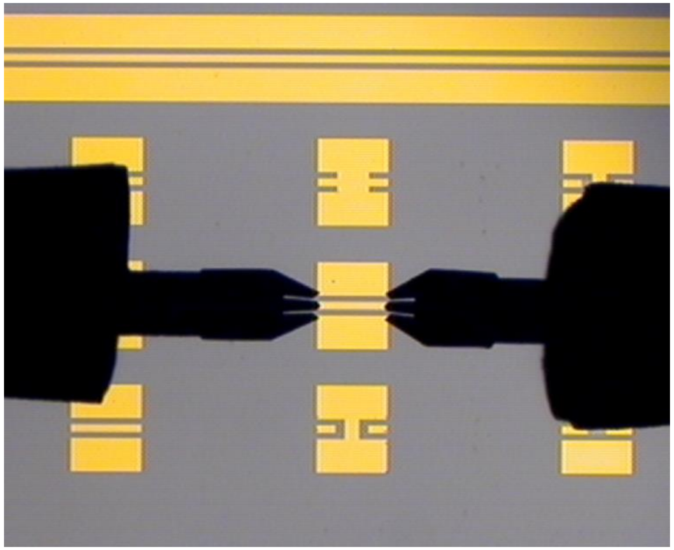
Outcomes: Guides [33], [34]

[1] https://planarcal.ptb.de

Traceability of S-Parameter Measurements

Metrological traceability requires the establishment of an unbroken chain of calibrations, each contributing to the measurement uncertainty, to specified references.

- (almost) solved in coaxial and waveguide connectors
- planar transmission lines: no complete solution prior to PlanarCal project



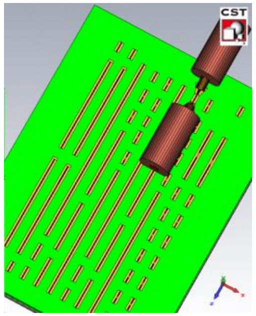
Fundamental questions:

- How do we reduce uncertainties in calibration standards?
- Which path should we choose to achieve traceability?

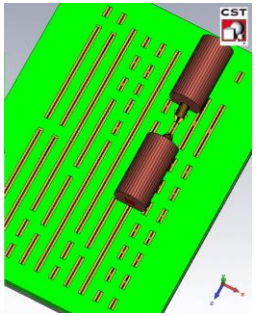
Influence of Neighborhood on Multiline TRL Calibrations [2]

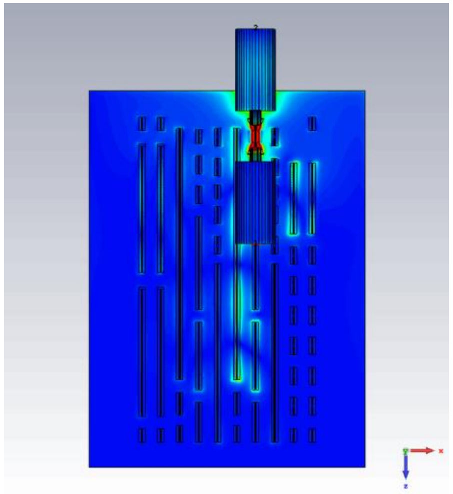
DUT measurement and simulation results on GaAs wafer

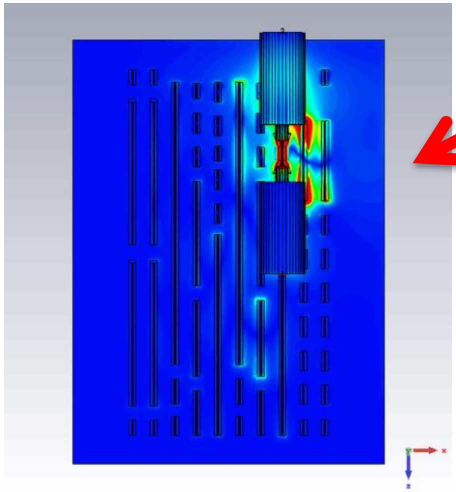
thru_2a

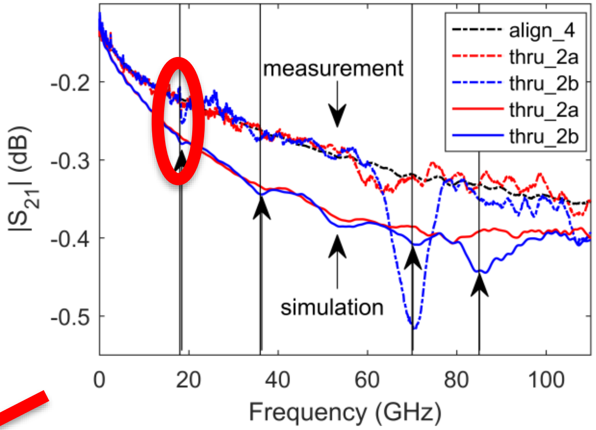


thru_2b









(Simulations: FBH)

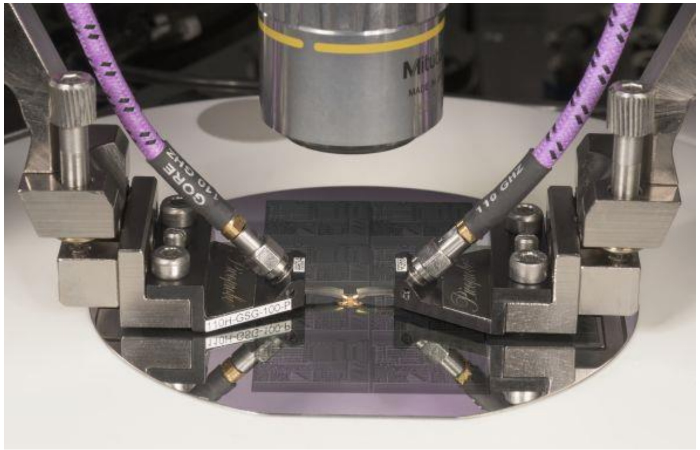
- despite identical DUT geometry different measurement results (from [3])
- <u>Major result:</u> Design guidelines for calibration substrates [33] (available from [1])

Only possible conclusion:

Reliable uncertainties can only be specified in a given environment/ DUT neighborhood for a selected combination of

- substrate materials
- planar waveguides
- <u>and</u> microwave probes!

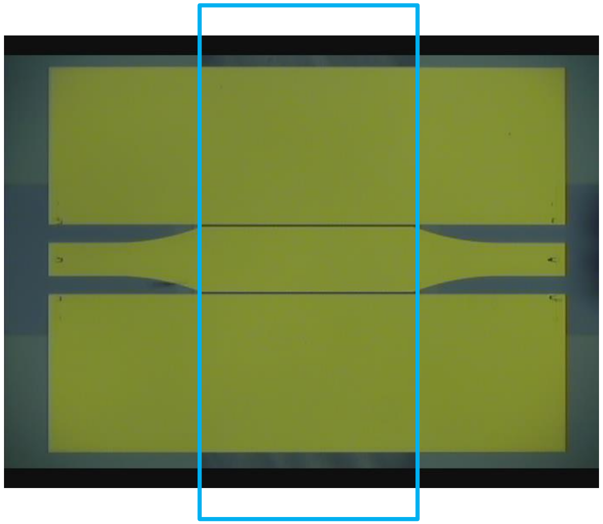
PTB on-wafer measurement setup



- Anritsu VectorStar VNA
- Suess PA 200 semi-automated wafer prober
- choice of ceramic/metal chuck
- GGB microwave probes with 100 um pitch

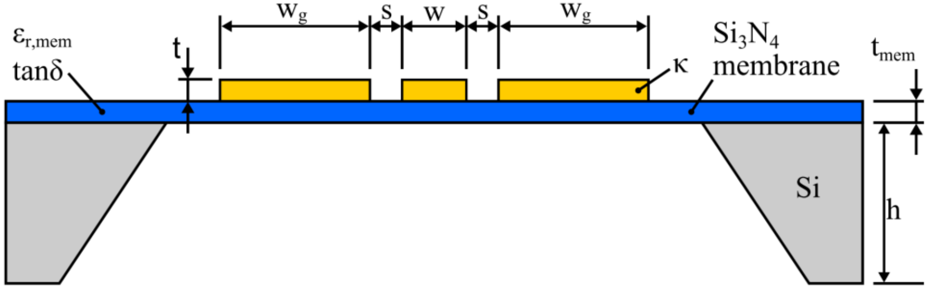
Calibration Standards in Membrane Technology [7]

Layout refinement + better technology:



membrane area

Cross section



Parameters after characterization:

Parameter	value
w_g	$(408.6 \pm 0.5)\ \mu$m
w	$(168.7 \pm 0.5)\ \mu$m
s	$(6.3 \pm 0.5)\ \mu$m
t	$(0.550 \pm 0.05)\ \mu$m
k	(16.5 ± 1) MS/m
$\varepsilon_{\mathrm{r,\ LHP}}$	(1.706 ± 0.1)
t_{mem}	$1.2\ \mu$m
$\tan\delta_{\mathrm{LHP}}$	$(1 \pm 0.5) \cdot 10^{-4}$
h	$295\ \mu$m

S-Parameter Uncertainty Evaluation

Software packages for S-parameter uncertainty evaluation (compared in [16]):

- NIST Microwave Uncertainty Framework [13]
- METAS VNATools [14]
- Keysight firmware (originally MMS4 by HFE)

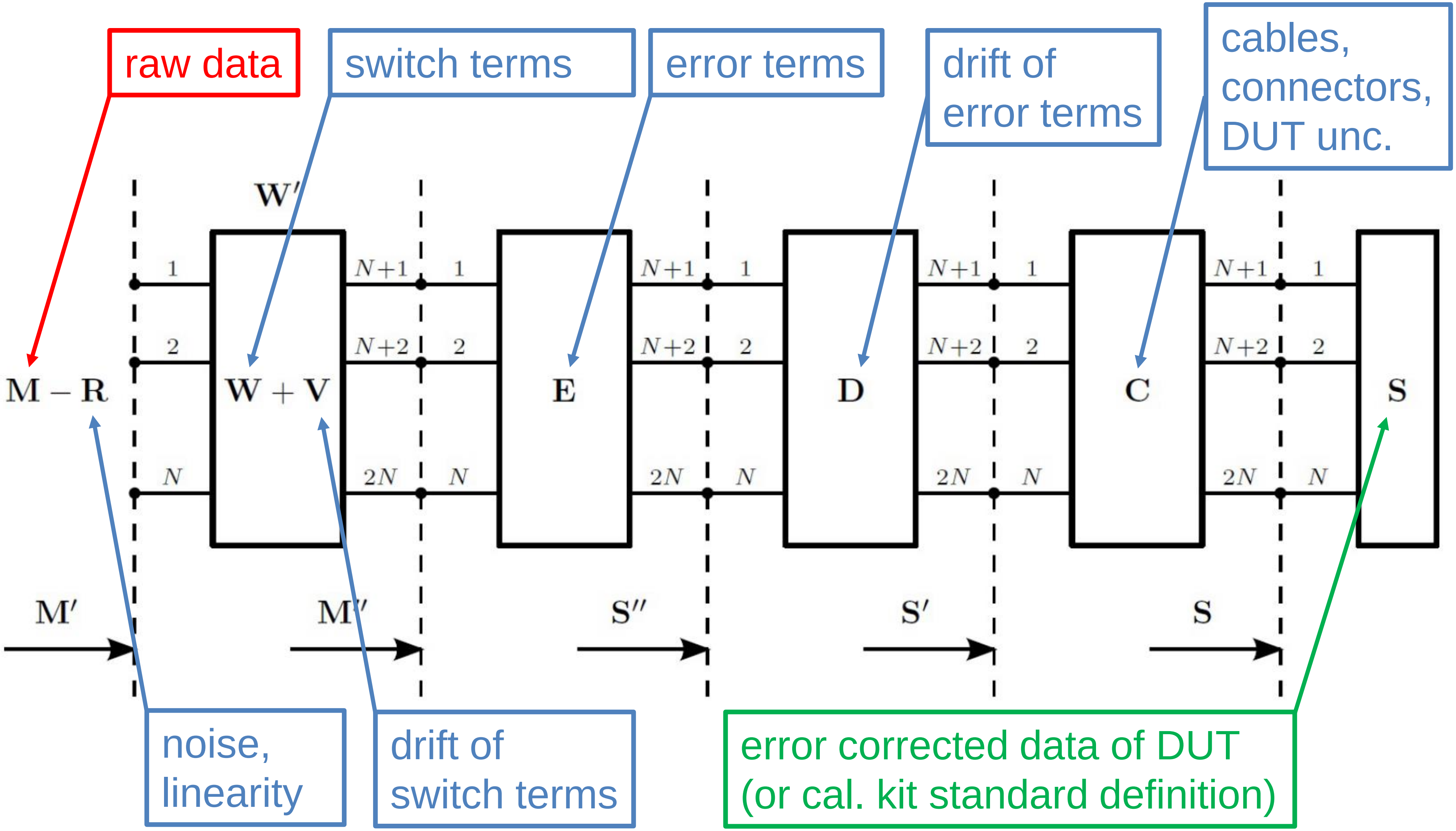
Generic software for automatic calculation of uncertainty propagation:

- MSL GUM Tree Calculator (GTC)
- METAS UncLib [17]
- …

This work:

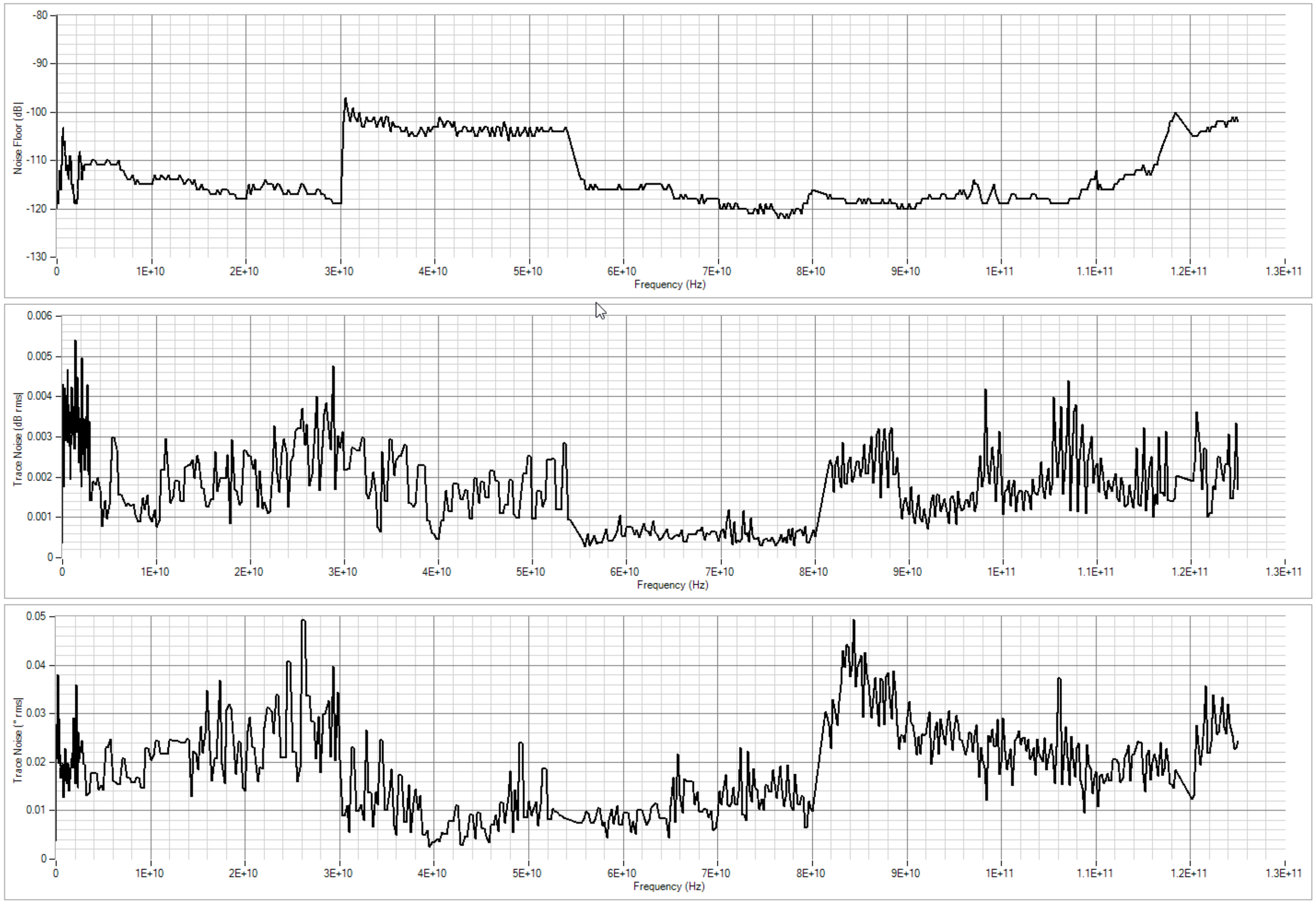
- Matlab multiline TRL implementation using METAS UncLib (see [2], [20])
- VNA characterization in accordance with new EURAMET guide CG-12 [19]

VNA Measurement Model (from [14])



VNA Characterization (CG-12): Noise floor/Trace noise

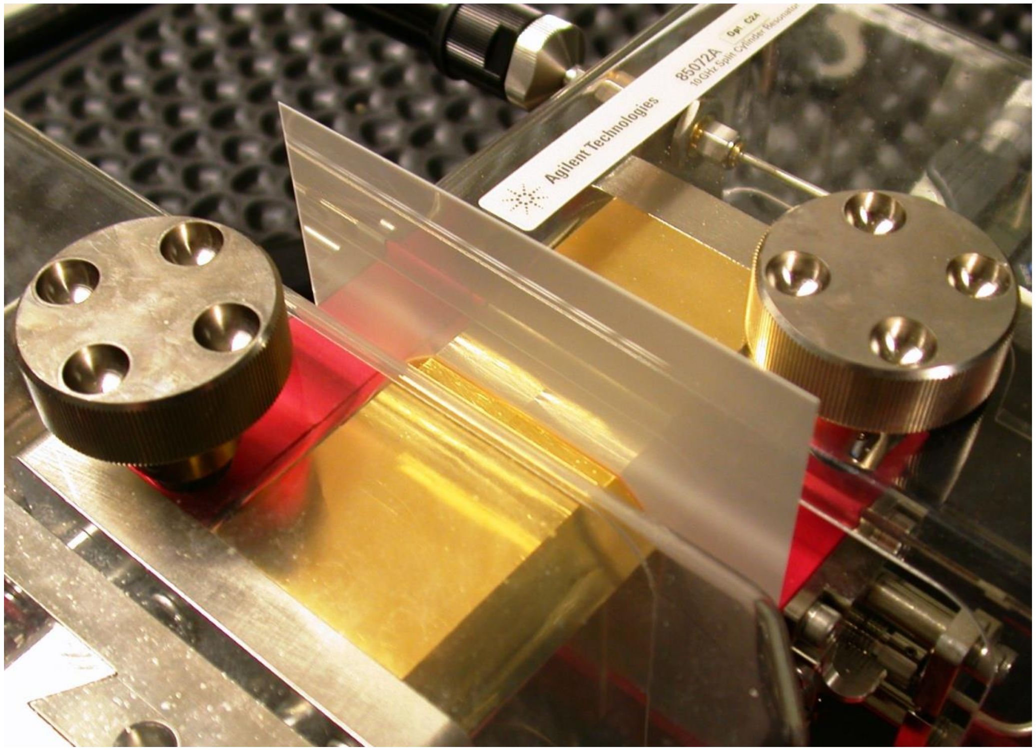
Frequency (Hz)	Noise Floor (dB) (k = 1)	Trace Noise Mag (dB) (k = 1)	Trace Noise Phase (°) (k = 1)
70.000e+03	-80	0.002486	0.017047
100.000e+03	-84	0.001701	0.010775
200.000e+03	-92	0.001375	0.009441
300.000e+03	-90	0.000646	0.004852
400.000e+03	-91	0.000483	0.003550
500.000e+03	-94	0.001337	0.009476
600.000e+03	-97	0.001337	0.009476
700.000e+03	-98	0.000345	0.004127
800.000e+03	-100	0.000458	0.005466
900.000e+03	-101	0.000787	0.005870
1.000e+06	-94	0.000912	0.005446
2.000e+06	-103	0.002240	0.010981
3.000e+06	-112	0.002647	0.015578
4.000e+06	-117	0.002647	0.016568
6.000e+06	-117	0.002283	0.013514
7.000e+06	-118	0.002522	0.017431
8.000e+06	-118	0.003042	0.016584
9.000e+06	-119	0.003042	0.016703
10.000e+06	-110	0.001784	0.017533
20.000e+06	-118	0.001865	0.018216
30.000e+06	-118	0.001865	0.017124
40.000e+06	-120	0.002178	0.027732
50.000e+06	-118	0.003583	0.022279
60.000e+06	-115	0.002785	0.022279
70.000e+06	-120	0.003250	0.020886
80.000e+06	-118	0.003250	0.020886
90.000e+06	-118	0.004306	0.020631
100.000e+06	-119	0.004023	0.020861
150.000e+06	-116	0.001765	0.026502
200.000e+06	-116	0.003343	0.037994
250.000e+06	-112	0.004220	0.019781
300.000e+06	-115	0.002919	0.028960
350.000e+06	-114	0.003253	0.028960
400.000e+06	-116	0.004004	0.021389
450.000e+06	-113	0.004004	0.019075
500.000e+06	-111	0.003726	0.016748
550.000e+06	-105	0.004678	0.016748
600.000e+06	-105	0.002867	0.018864
650.000e+06	-103	0.003811	0.019642
700.000e+06	-107	0.003321	0.019850
750.000e+06	-106	0.003614	0.013257
800.000e+06	-106	0.002781	0.012674
850.000e+06	-108	0.001950	0.016340



Extension to Fused Silica Substrates

<u>Again:</u> Reliable uncertainties can only be specified in a given environment for a selected combination of substrate materials, planar waveguides and probes!

Wideband extraction of dielectric material properties



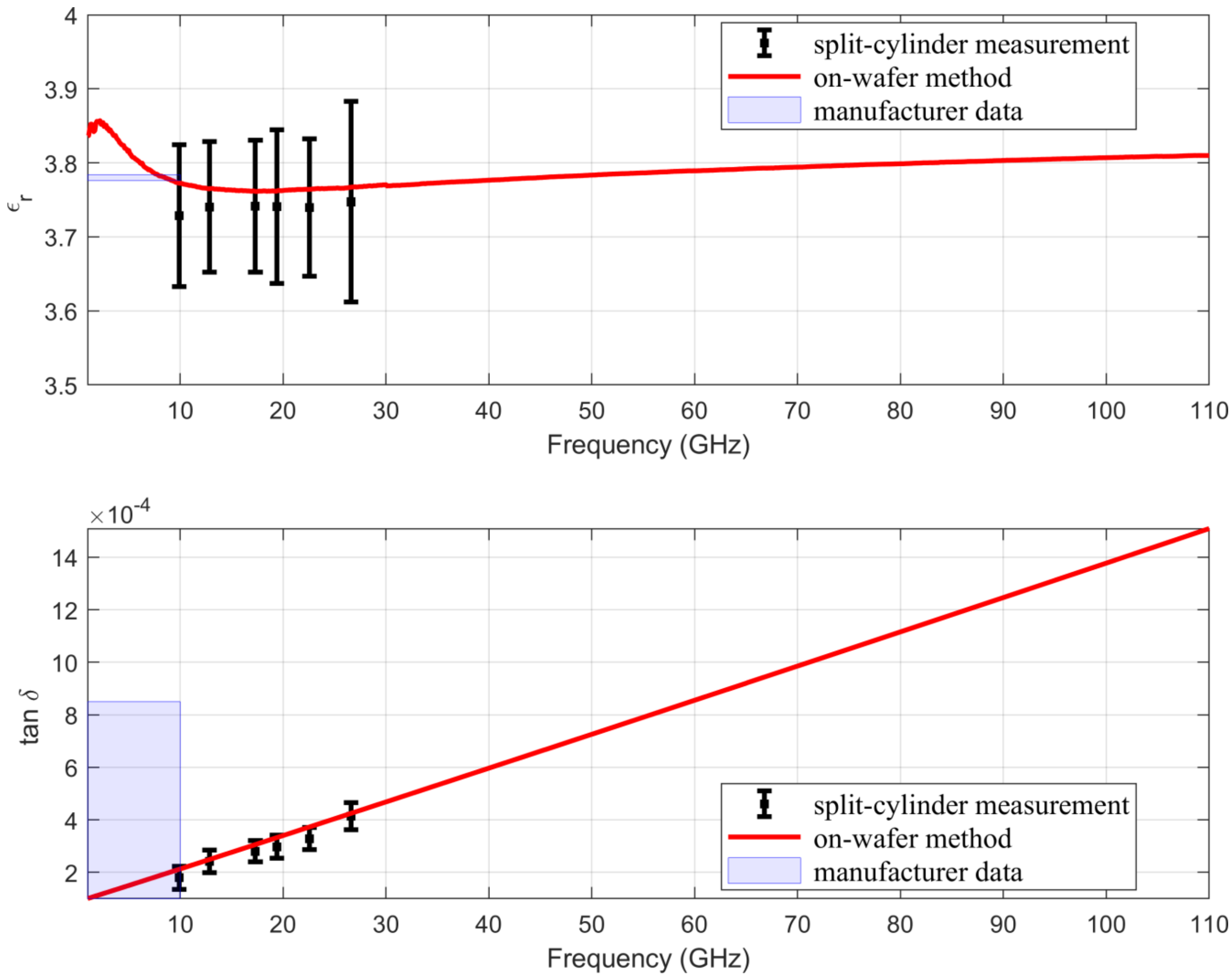
Reference method:

- split-cylinder resonator [23]

Other methods/sources:

- on-wafer methods [24-26]
- manufacturer data

Relative Permittivity and Loss Tangent of Fused Silica [30]



<u>Result:</u>

ε_r =3.78±0.15

tanδ=(8±7)·10^{-4}

(uniform pdfs assumed)

Uncertainties Revisited

- Cable effects from repeated measurements of shorts/matched devices [19]

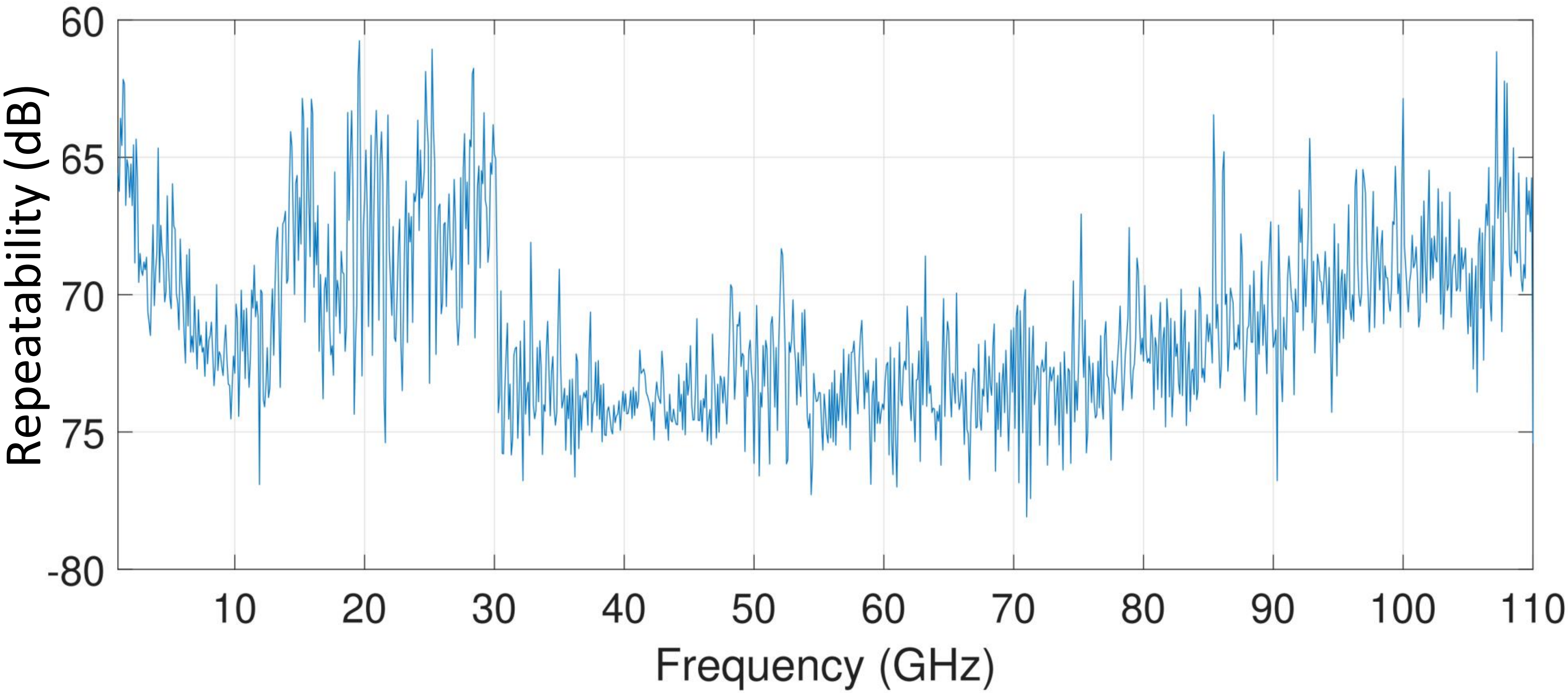
Frequency / GHz	Reflection stability / dB	Transmission stability Mag / dB	Transmission stability Phase / °
00.000	-50	0.05	0.1
30.000	-50	0.05	0.4
30.001	-60	0.01	0.1
120.00	-60	0.01	0.1

- DUT uncertainty in transmission (instead of crosstalk correction of [9])

Reflection	Frequency (GHz)			
Mag (lin. mag.)	0	20	50	120
0.0	-60	-55	-50	-45
0.2	-60	-55	-50	-45
0.8	-60	-40	-35	-20
1.0	-60	-40	-35	-20

- Calibration standard uncertainties now calculated with "recursive approaches" from [21-22]

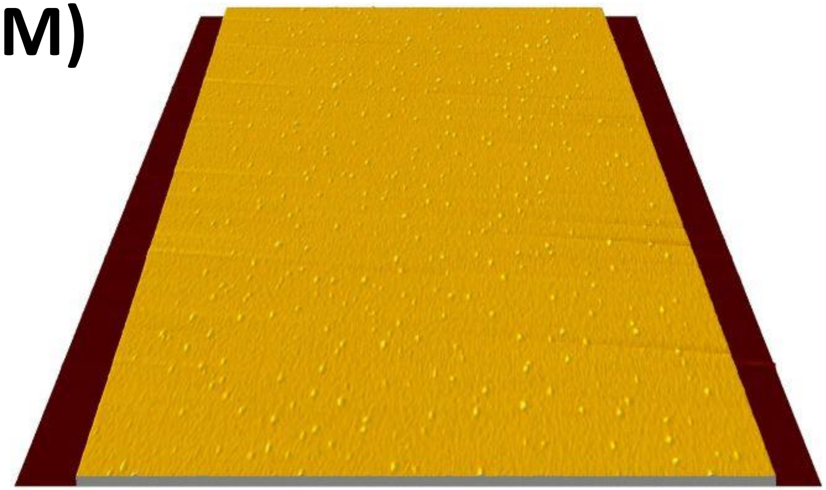
Connection Repeatability (CG-12, Annex G.5) [19]

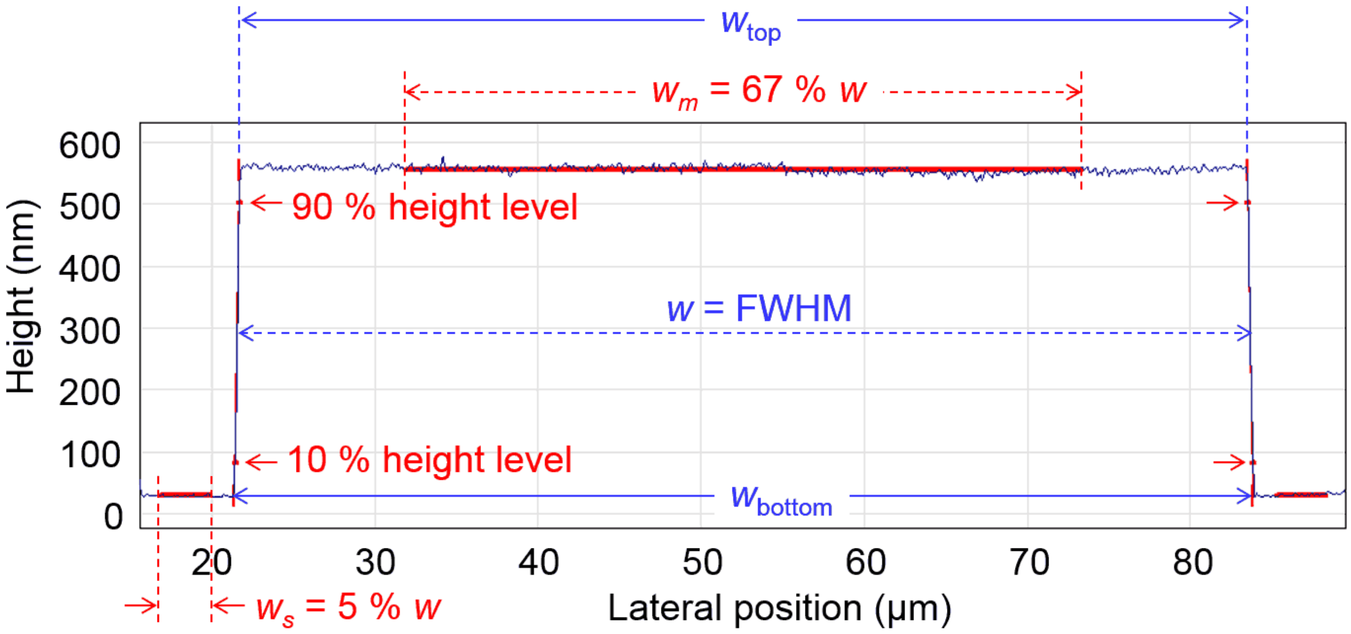


N.B.: Repeatability defined here as maximum of differences in real and imaginary parts between all reflection measurements.

Dimensional Characterization (AFM)

3D view of
center conductor
(z shown 3x enlarged)

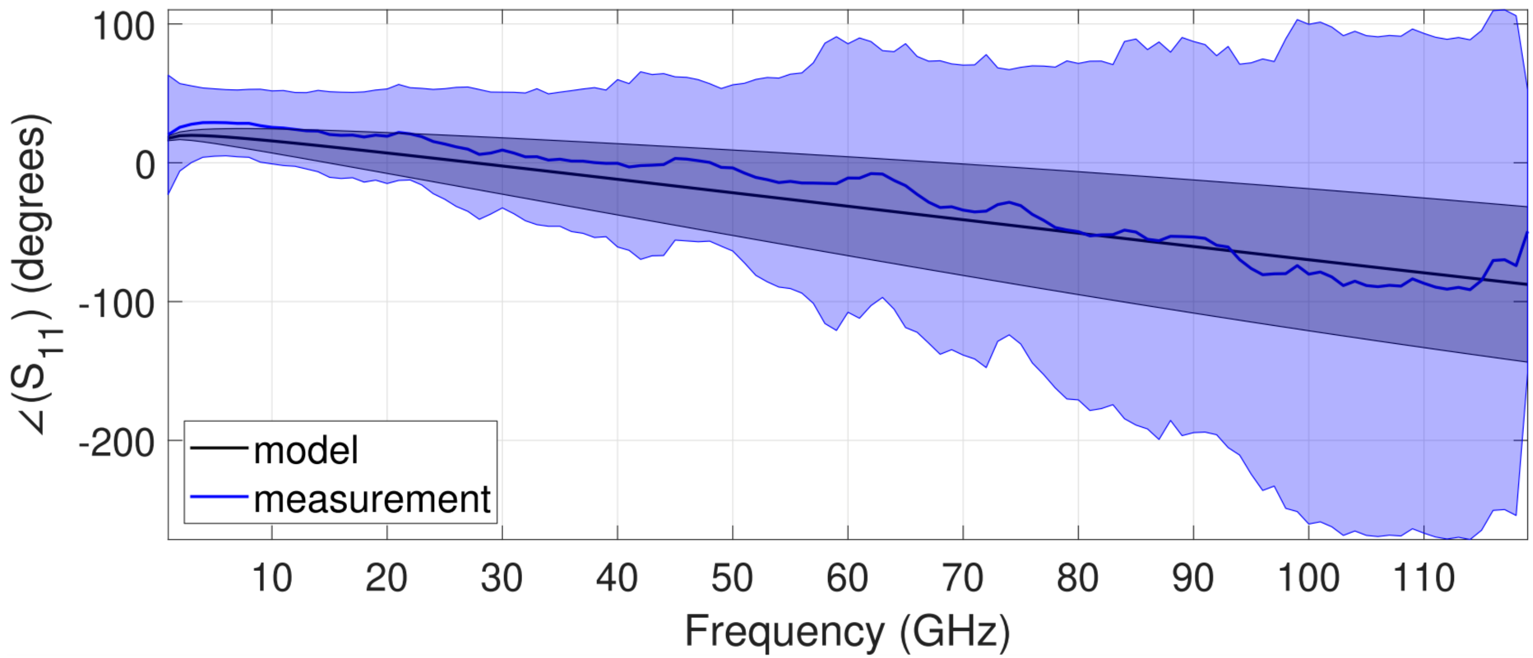




measured profile
of center conductor

Measurement vs Model

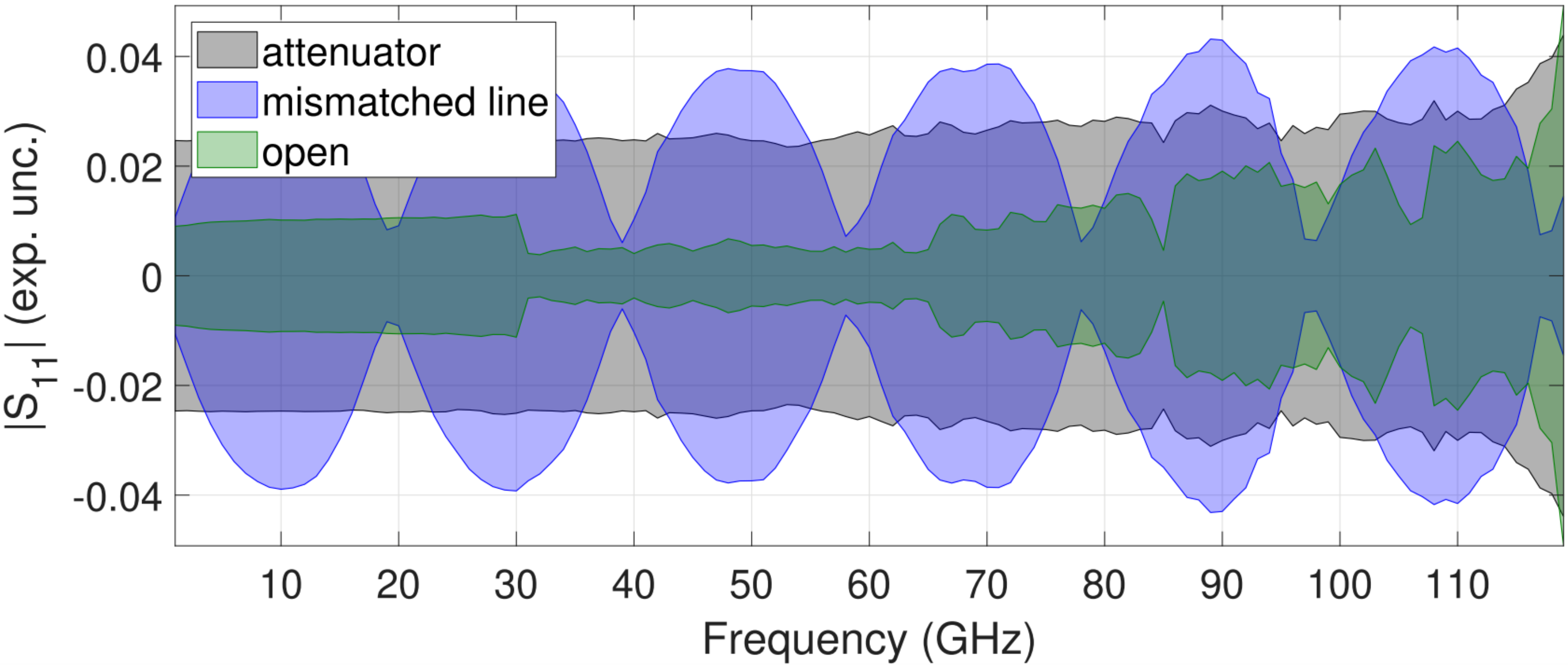
400 µm long matched line on fused silica substrate



- better dimensional characterization as a result of atomic-force microscope (AFM)
- uncertainties similar to membrane technology, despite material influence
- limitations of membrane technology budget overcome (full propagation of uncertainties for multiline TRL via recursive approach a la Stumper/Hall, cable effects now included)

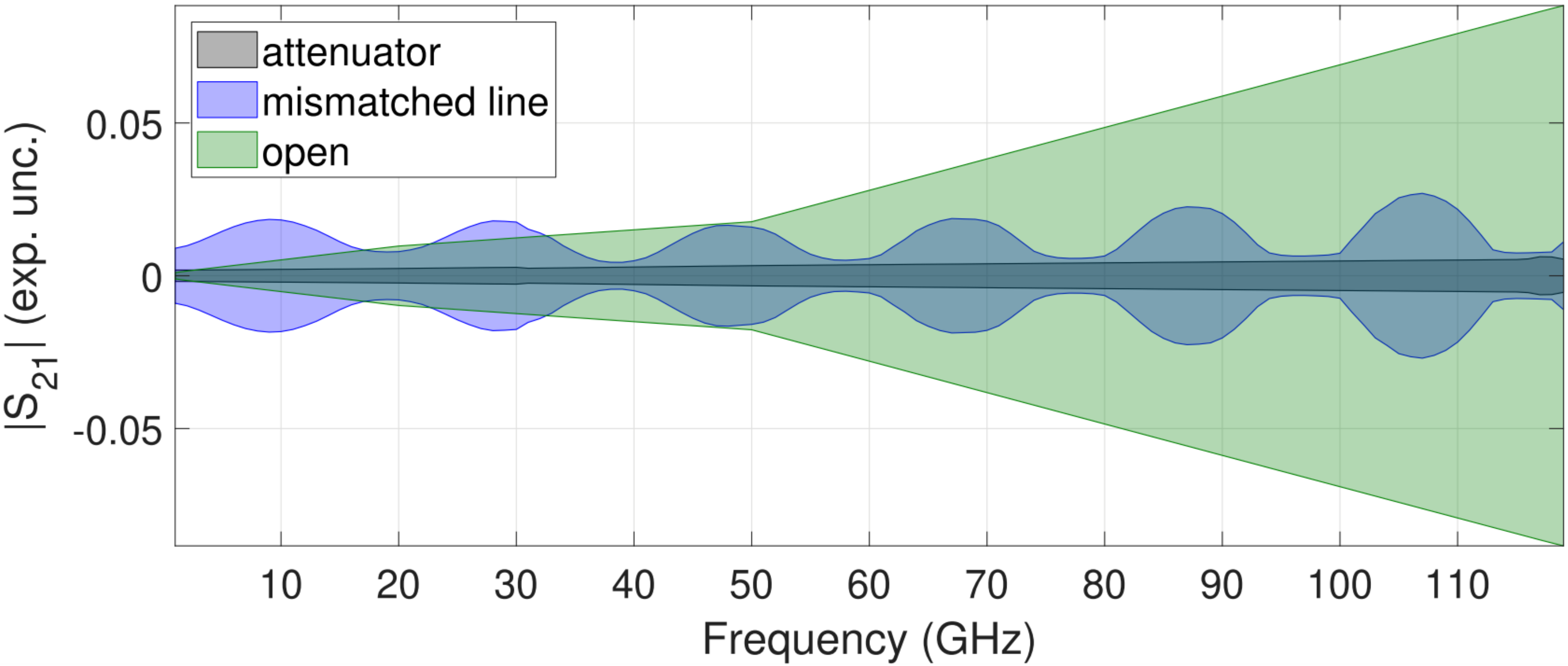
|S11| Expanded Uncertainty Intervals (k=2)

Different DUTs on fused silica substrate



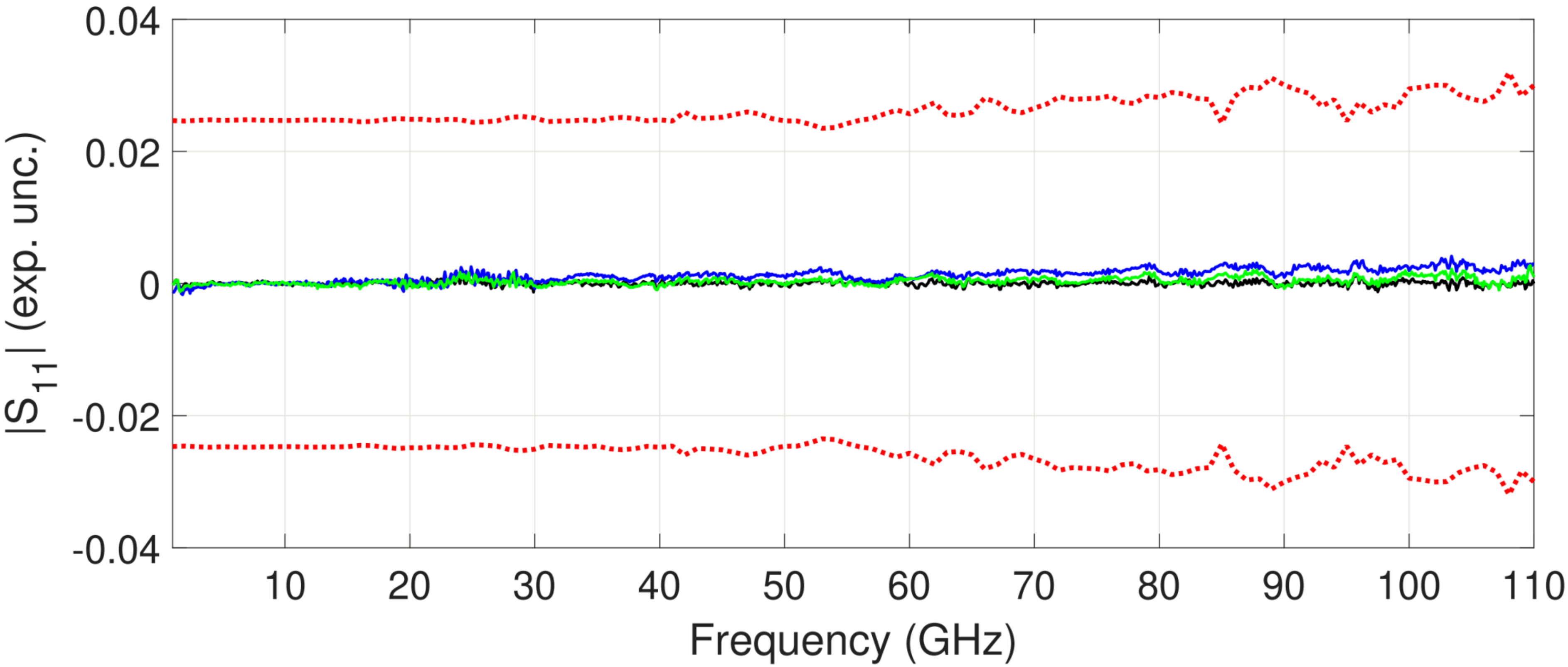
|S21| Expanded Uncertainty Intervals (k=2)

Different DUTs on fused silica substrate



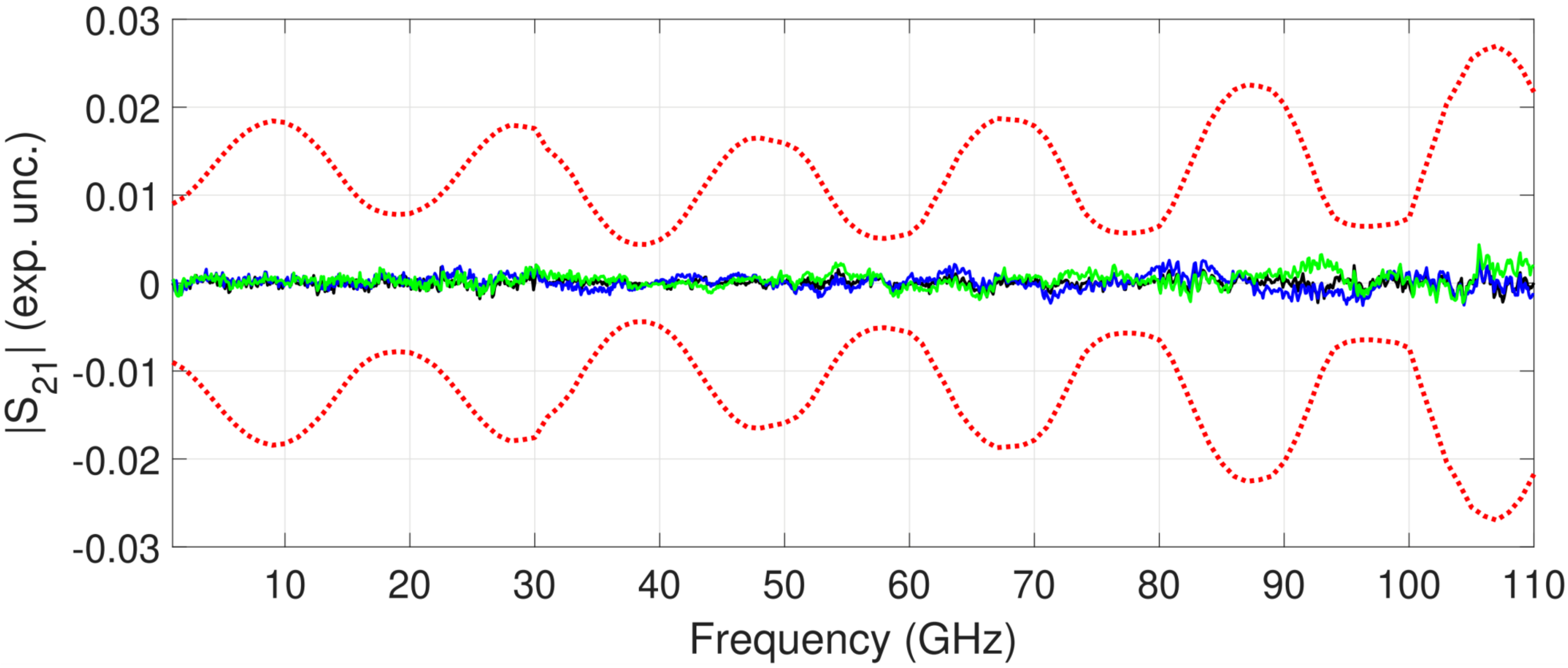
|S11| Measurement Spread vs Expanded Uncertainties

Attenuator on fused silica substrate



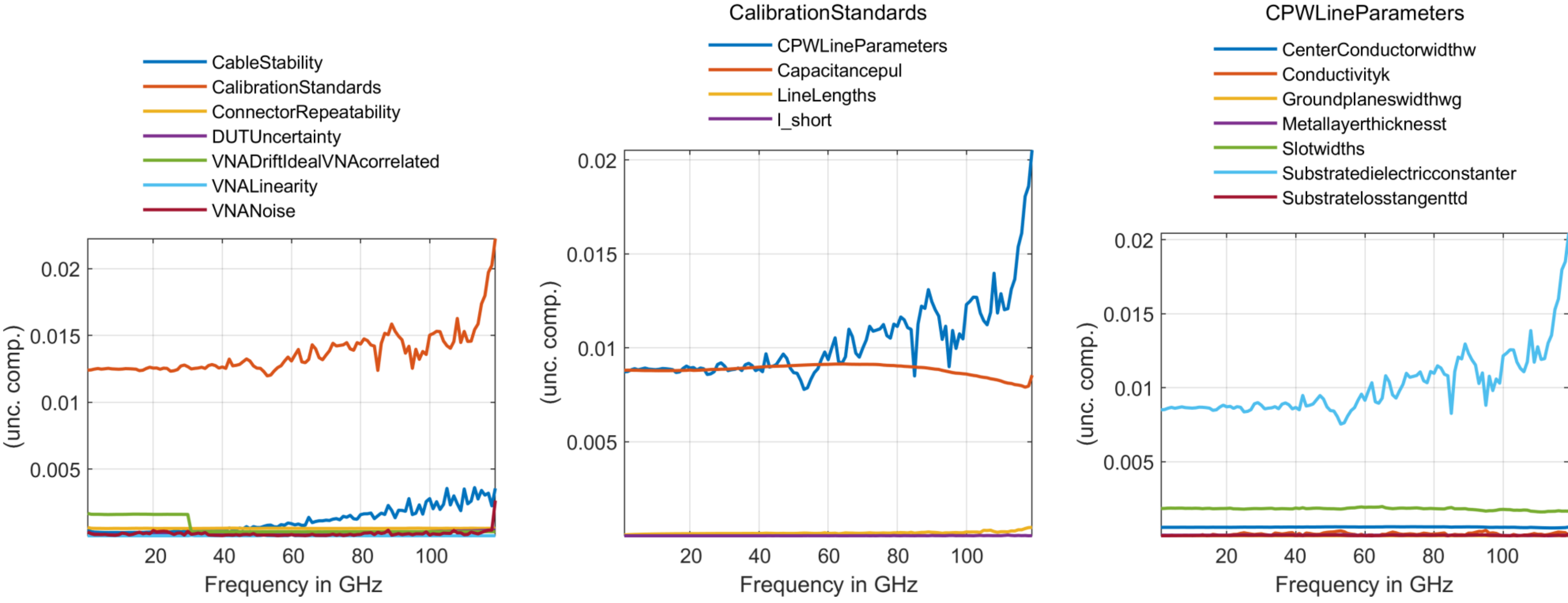
|S21| Measurement Spread vs Expanded Uncertainties

Mismatched line on fused silica substrate



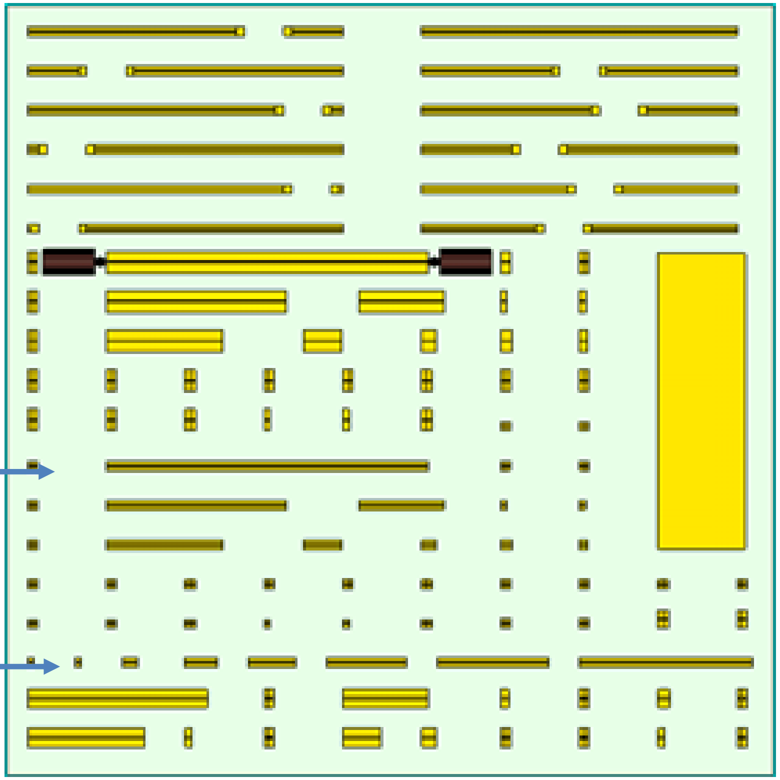
|S11| Uncertainty Budget

Attenuator on fused silica substrate

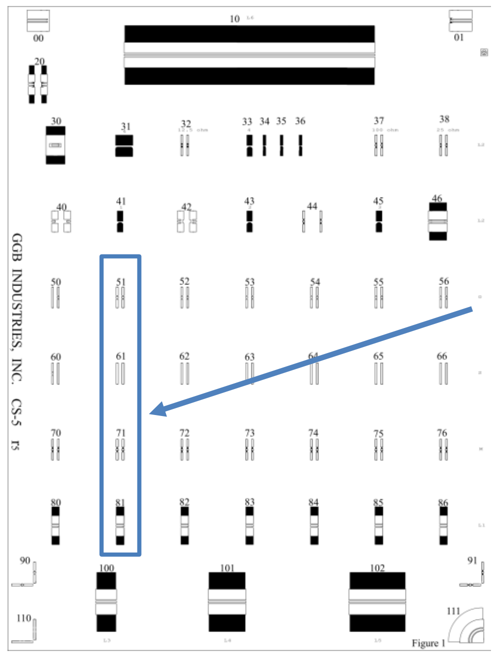


Transfer of Uncertainties (Fused Silica)

- Situation: DUTs/calibration set built on custom-made R&S fused silica wafer
- for high-throughput measurements only ISS can be used (here: GGB CS-5)



fused silica wafer

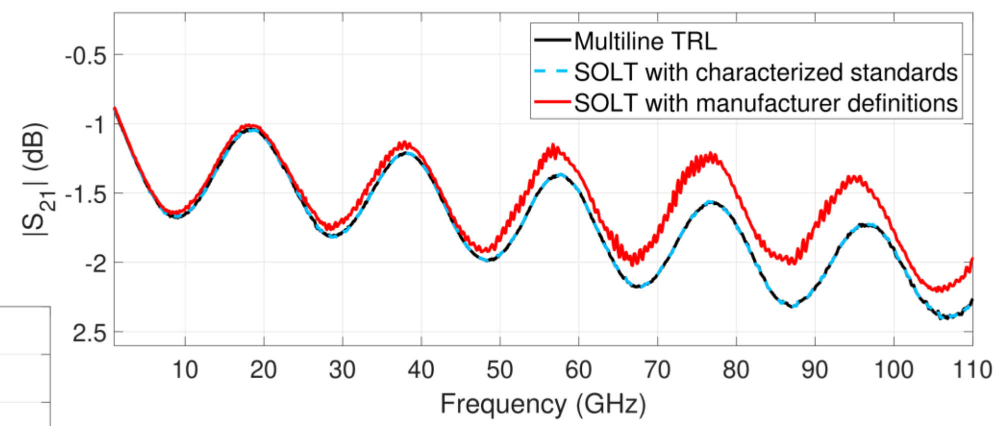


(https://www.ggb.com)

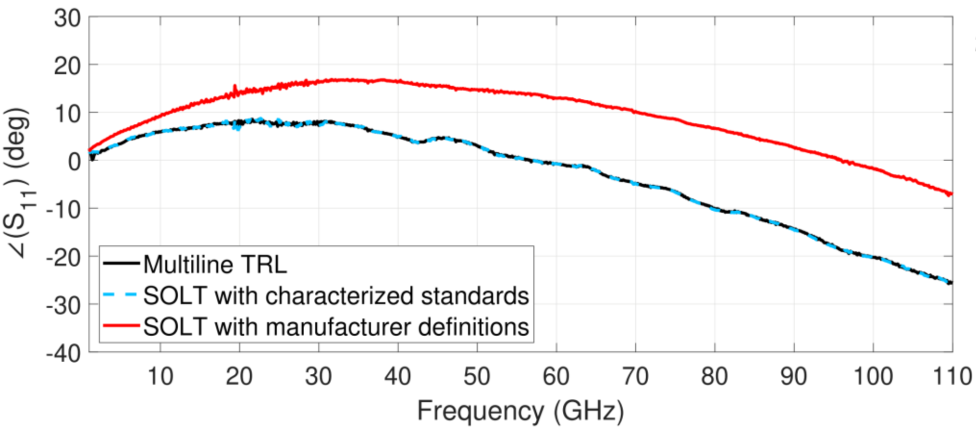
GGB CS-5

Transfer of Uncertainties (Fused Silica)

Transmission of mismatched line



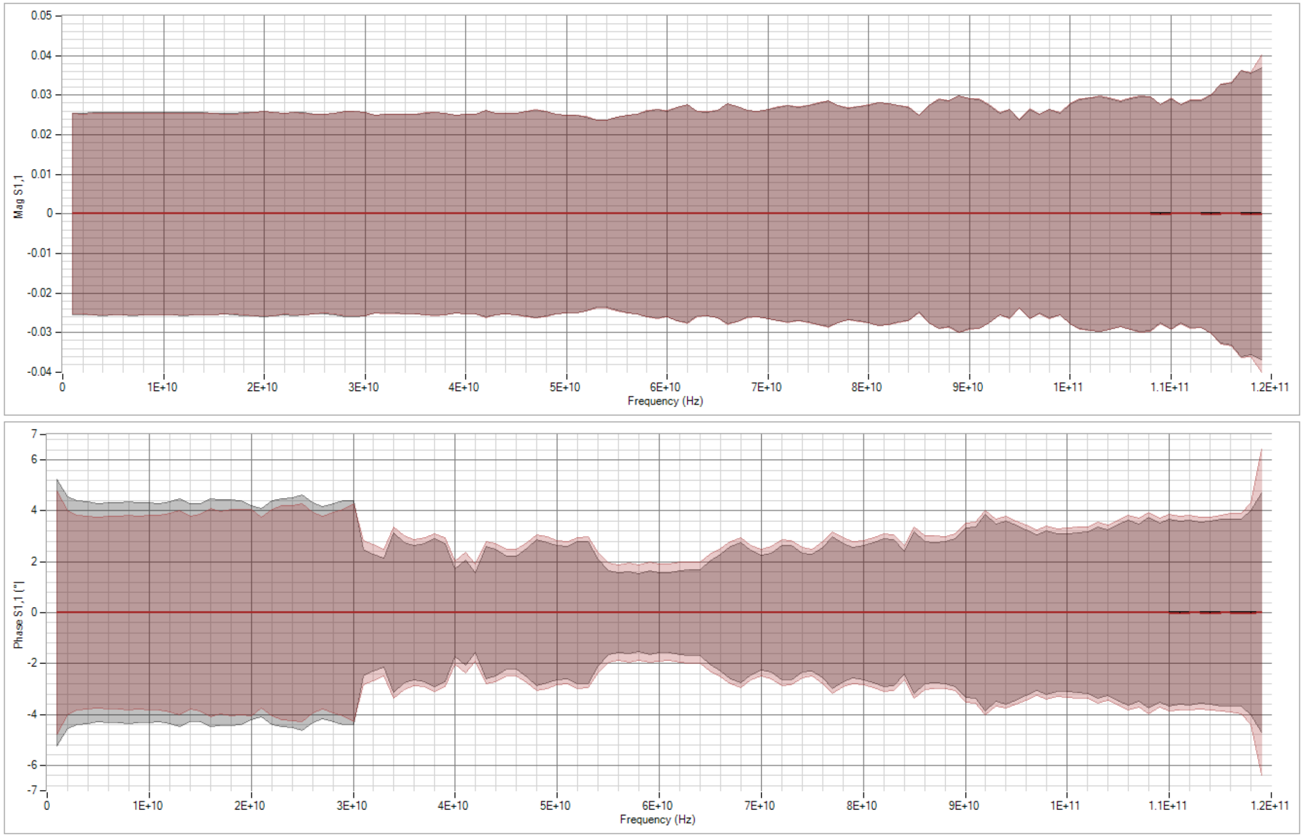
Reflection of attenuator device



- SOLT with characterized ISS standards yields <u>same result</u> as reference multiline TRL!
- ISS can be used as <u>transfer standard</u> after characterization with custom-made, application-specific calibration standards.
- Other techniques (permittivity compensation, residual error correction) have been investigated – only of limited use.

Reflection of Attenuator Device Fused Silica

Normalized S11 measurements including 95% coverage intervals



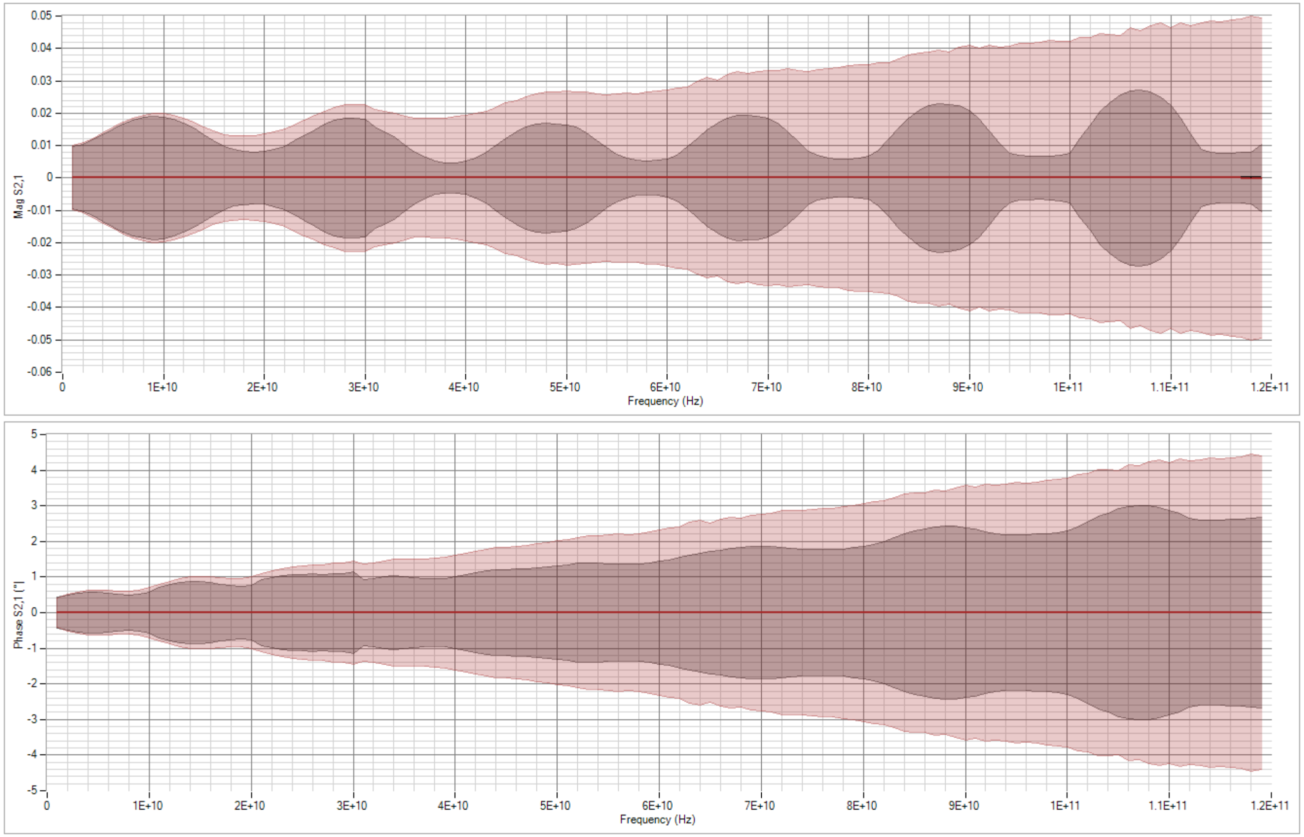
black: MTRL

red: SOLT (char. stds)

- no need for time-consuming MTRL calibration
- wear on MTRL standards reduced!

Transmission of Mismatched Line on Fused Silica

Normalized S21 measurements including 95% coverage intervals



black: MTRL

red: SOLT (char. stds)

- SOLT uncertainties typically increased (depending on qty.)
- ISS can be used as <u>transfer standard</u> after characterization with custom-made, application-specific calibration standards

Summary and Conclusions

- Traceability first demonstrated for membrane technology devices
- Extension to industrial substrates successful (here: fused silica) – this requires wideband dielectric measurements!
- Comprehensive uncertainty budget including instrumentation errors, repeatability and calibration standard uncertainties
- Complexity of the problem only manageable with software (here: Matlab implementation using METAS.UncLib)
- Extension to higher frequencies possible with better CPW models
- Commercial ISS together with simple calibration algorithms fully suitable as transfer standards

Acknowledgement

The author acknowledges support by the European Metrology Programme for Innovation and Research (EMPIR) Project 14IND02 "Microwave measurements for planar circuits and components".

The EMPIR programme is co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme.

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Acknowledgement

Physikalisch-Technische Bundesanstalt

- S. Zinal	AG 2.23
- T. Probst	AG 2.23
- K. Kuhlmann	AG 2.22/2.23
- D. Schubert	AG 2.22/2.23
- T. Dziomba	AG 5.25
- D. Schulz	AG 5.34

Rohde & Schwarz GmbH & Co. KG

- Gerd Hechtfischer
- Jens Leinhos

Ferdinand-Braun-Institut für Höchstfrequenztechnik

- Franz-Josef Schmückle
- Wolfgang Heinrich

Thank you!

Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
Bundesallee 100
38116 Braunschweig

Dr. Uwe Arz
Telefon: 0531 592-2297
E-Mail: uwe.arz@ptb.de

References

[1] European Metrology Programme for Innovation and Research JRP Number 14IND02, "Microwave measurements for planar circuits and components,“ https://planarcal.ptb.de.

[2] R. B. Marks, "A Multiline Method of Network Analyzer Calibration," IEEE Trans. on Microwave Theory and Techniques, vol. 39, no. 7, pp. 1205-1215, 1991.

[3] F. J. Schmückle, T. Probst, U. Arz, G. N. Phung, R. Doerner, and W. Heinrich, "Mutual interference in calibration line configurations," in 2017 89th ARFTG Microwave Measurement Conference (ARFTG), June 2017.

[4] G. N. Phung, F. J. Schmückle, R. Doerner, W. Heinrich, T. Probst, and U. Arz, "Effects degrading accuracy of CPW mTRL calibration at W band," in 2018 IEEE/MTT-S International Microwave Symposium, June 2018, pp. 1296-1299.

[5] G. N. Phung, F. J. Schmückle, R. Doerner, T. Fritzsch, and W. Heinrich, "Impact of parasitic coupling on multiline TRL calibration," in 2017 47th European Microwave Conference (EuMC), Oct 2017, pp. 835-838.

[6] M. Spirito, C. D. Martino, and L. Galatro, "On the impact of radiation losses in TRL calibrations," in 2018 91st ARFTG Microwave Measurement Conference (ARFTG), June 2018.

References

[7] U. Arz, S. Zinal, T. Probst, G. Hechtfischer, F. Schmückle, and W. Heinrich, "Establishing traceability for on-wafer S-parameter measurements of membrane technology devices up to 110 GHz," in 2017 90th ARFTG Microwave Measurement Symposium (ARFTG), Nov 2017.

[8] U. Arz, M. Rohland, and S. Büttgenbach, "Improving the Performance of 110 GHz Membrane-Based Interconnects on Silicon: Modeling, Measurements, and Uncertainty Analysis," IEEE Trans. Compon. Packag. Manuf. Technol., vol.3, no. 11, pp. 1938-1945, Nov 2013.

[9] D. F. Williams, F. J. Schmückle, R. Doerner, G. N. Phung, U. Arz, and W.Heinrich, "Crosstalk Corrections for Coplanar-Waveguide Scattering-Parameter Calibrations," IEEE Trans. Microw. Theory Techn., vol. 62,no. 8, pp. 1748-1761, Aug 2014.

[10] CST - Computer Simulation Technology AG, "Microwave Studio (MWS),“ www.cst.com/products/cstmws, 2018.

[11] W. Heinrich, "Quasi-TEM description of MMIC coplanar lines including conductor-loss effects," IEEE Trans. Microw. Theory Techn., vol. 41, no. 1, pp. 45-52, Jan. 1993.

References

[12] F. Schnieder, T. Tischler, and W. Heinrich, "Modeling Dispersion and Radiation Characteristics of Conductor-Backed CPW With Finite Ground Width," IEEE Trans. Microw. Theory Techn., vol. 51, no. 1, pp. 137-143, Jan. 2003.

[13] D. F. Williams, "NIST Microwave Uncertainty Framework, Beta Version,“ www.nist.gov/services-resources/software/wafer-calibration-software, 2012.

[14] M. Wollensack and J. Hoffmann, "METAS VNA Tools II - Math Reference V1.8," www.metas.ch, 2017.

[15] V. Teppati and A. Ferrero, "A Comparison of Uncertainty Evaluation Methods for On-Wafer S-Parameter Measurements," IEEE Trans. Instrum. Meas., vol. 63, no. 4, pp. 935-942, April 2014.

[16] G. Avolio, D. F. Williams, S. Streett, M. Frey, D. Schreurs, A. Ferrero, and M. Dieudonne, "Software tools for uncertainty evaluation in VNA measurements: A comparative study," in 2017 89th ARFTG Microwave Measurement Conference, June 2017.

[17] M. Zeier, J. Hoffmann, and M. Wollensack, "Metas.UncLib: A measurement uncertainty calculator for advanced problems," Metrologia,vol. 49, no. 6, p. 809, 2012.

References

[18] B. D. Hall, "Calculating measurement uncertainty using automatic differentiation," Measurement Science and Technology, vol. 13, no. 4, p. 421, 2002.
[19] EURAMET CG-12, "Guidelines on the Evaluation of Vector Network Analysers (Calibration Guide No. 12 Version 3.0)," www.euramet.org/publications-media-centre/calibration-guidelines, 2018.
[20] D. C. DeGroot, J. A. Jargon, and R. B. Marks, "Multiline TRL Revealed," in 60th ARFTG Conference Digest, Fall, Washington, DC, USA, 2002, pp. 131-155.
[21] U. Stumper, "Uncertainty of VNA S-Parameter Measurement Due to Nonideal TRL Calibration Items," IEEE Trans. on Instrumentation and Measurement, vol. 54, no. 2, pp. 676-679, 2005.
[22] B. Hall, "On evaluating the uncertainty of VNA self-calibration procedures," in First workshop on "Electronic Calibration Units" and European ANAMET meeting, Dec. 2013.
[23] M. D. Janezic, "Nondestructive Relative Permittivity and Loss Tangent Measurements Using a Split-Cylinder Resonator," PhD Thesis, University of Colorado at Boulder, 2003.

References

[24] U. Arz, M. D. Janezic, and W. Heinrich, "Wideband relative permittivity extraction based on CPW phase constant measurements," in 77th ARFTG Microwave Measurement Conference, June 2011, pp. 1-3.

[25] U. Arz, "Loss tangent extraction based on equivalent conductivity derived from CPW measurements," in 2014 IEEE 18th Workshop on Signal and Power Integrity (SPI), May 2014.

[26] U. Arz, "Microwave substrate loss tangent extraction from coplanar waveguide measurements up to 125 GHz," in 83rd ARFTG Microwave Measurement Conference, June 2014.

[27] R. B. Marks and D. F. Williams, "Characteristic impedance determination using propagation constant measurement," IEEE Microwave and Guided Wave Letters, vol. 1, no. 6, pp. 141-143, June 1991.

[28] D. F. Williams and R. B. Marks, "Transmission line capacitance measurement," IEEE Microwave and Guided Wave Letters, vol. 1, no. 9, pp. 243-245, Sept 1991.

[29] T. Probst, S. Zinal, R. Doerner, and U. Arz, "On the Importance of Calibration Standards Definitions for On-Wafer Measurements up to 110 GHz," 91st ARFTG Microwave Measurement Conference, June 2018.

References

[30] U. Arz et al., "Traceable Coplanar Waveguide Calibrations on Fused Silica Substrates up to 110 GHz," in IEEE Transactions on Microwave Theory and Techniques, 2019. https://doi.org/10.1109/TMTT.2019.2908857

[31] G. N. Phung et al., "Influence of Microwave Probes on Calibrated On-Wafer Measurements," in IEEE Transactions on Microwave Theory and Techniques, vol. 67, no. 5, pp. 1892-1900, May 2019. https:/doi.org/10.1109/TMTT.2019.2903400

[32] R. Lozar et al., "A Comparative Study of On-wafer and Waveguide Module S-parameter Measurements at D-band Frequencies," accepted for publication in IEEE Transactions on Microwave Theory and Techniques, 2019.

[33] M. Spirito et al., "Guidelines for the design of calibration substrates, including the suppression of parasitic modes for frequencies up to and including 325 GHz," July 2018. https:/doi.org/10.7795/530.20190424A

[34] U. Arz et al., "Best Practice Guide for Planar S-Parameter Measurements using Vector Network Analysers," September 2018. https:/doi.org/10.7795/530.20190424B