Calibration Uncertainty Estimation for the S-Parameter Measurements at the Wafer Level

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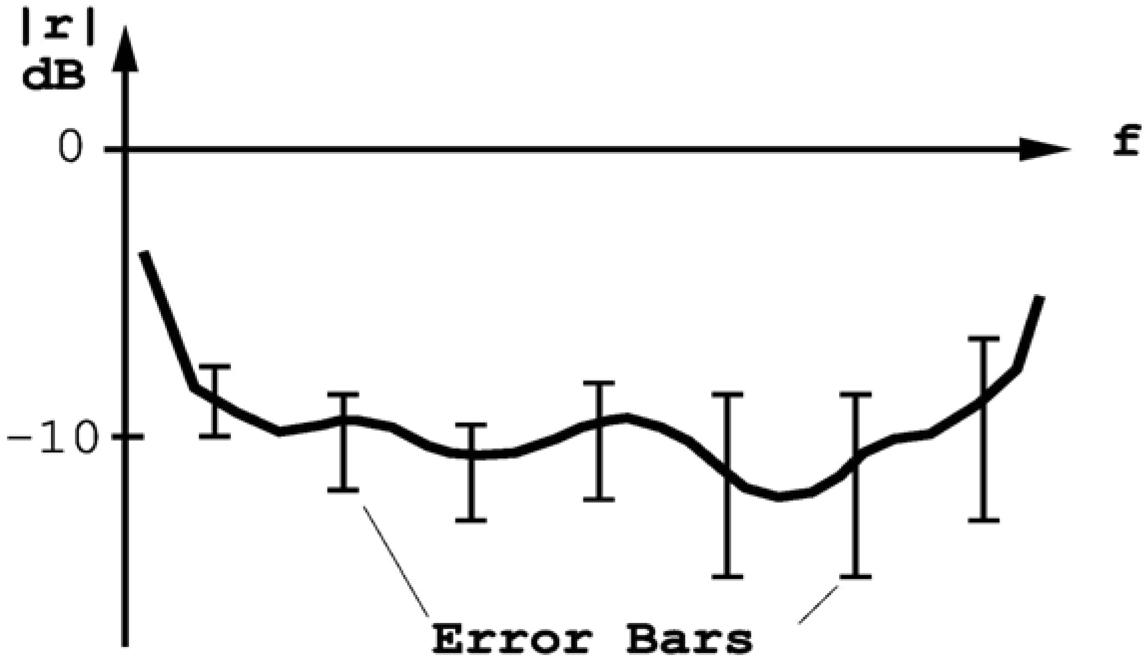
Outline

- Motivation
- Error Sources
- Calibration Standards
- Calibration Procedures
- Uncertainty Analysis Methods
- Conclusion

Motivation

Everybody's dream: results with uncertainty budgets (error bars)



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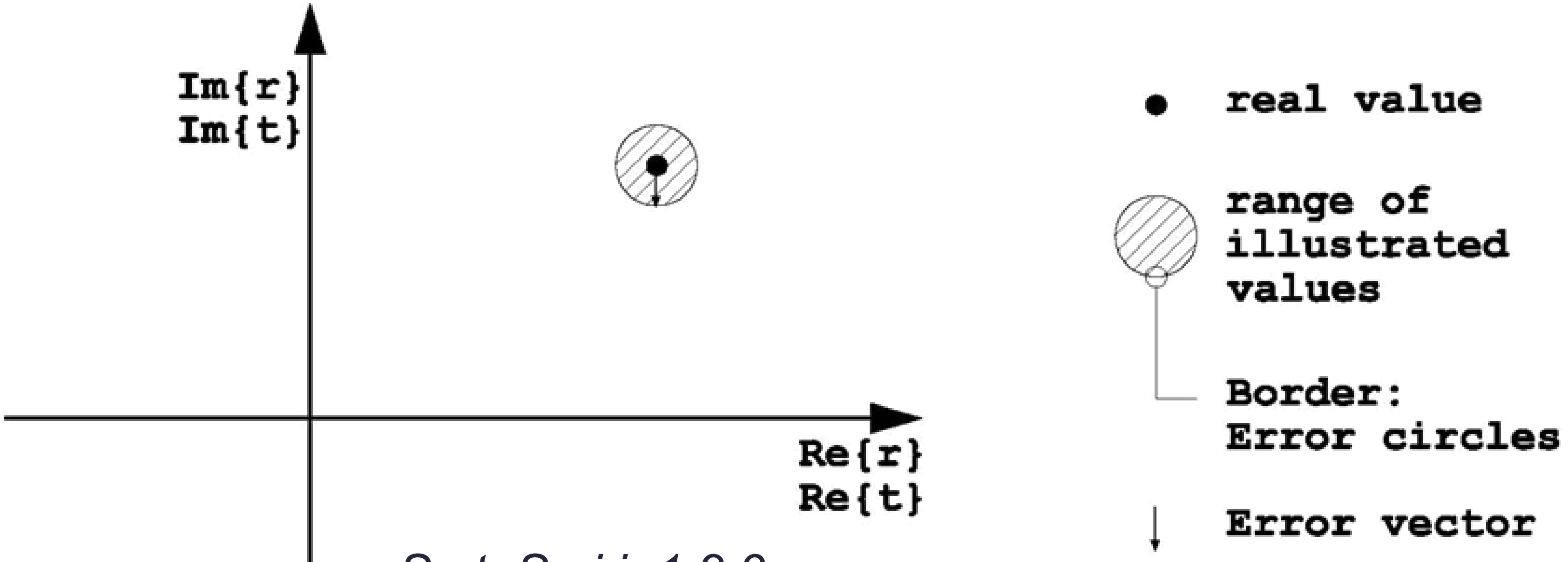
Error Sources

Reflection or transmission measurement:



$r = S_{ii},\ t = S_{ij},\ i,j = 1,2,3,\ldots$

Measurement results contain errors

Error Sources

- Instability of the instrument and accessories
  - Temperature drift
  - Trace noise, etc..
  - Cable phase instability
  - Contact repeatability (connections, probes)
- Non-ideal calibration standards
  - Modeling and fabrication tolerances
- Calibration and error correction method

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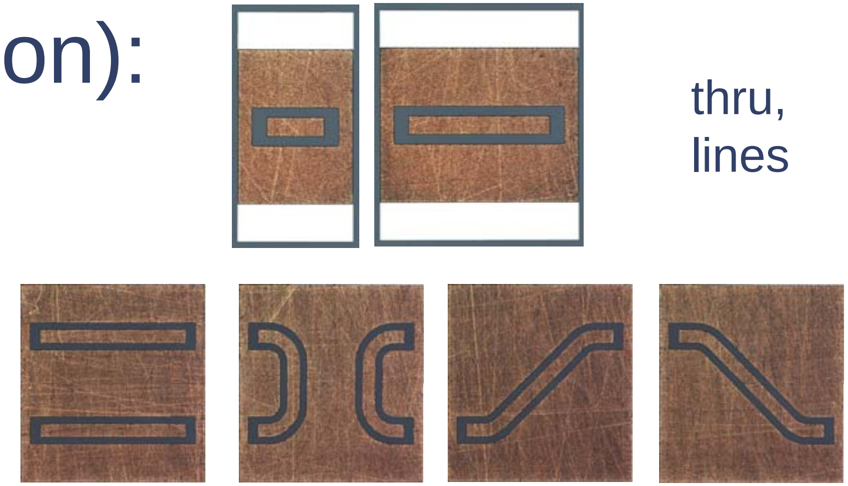
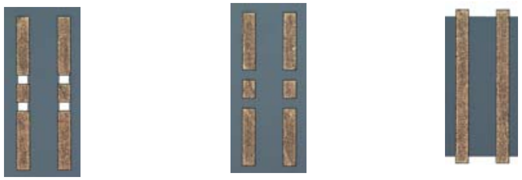
Calibration Standards

- Distributed (transmission):
  - Dispersive
  - Frequency limited
    (loop-back, etc)



thru,
lines

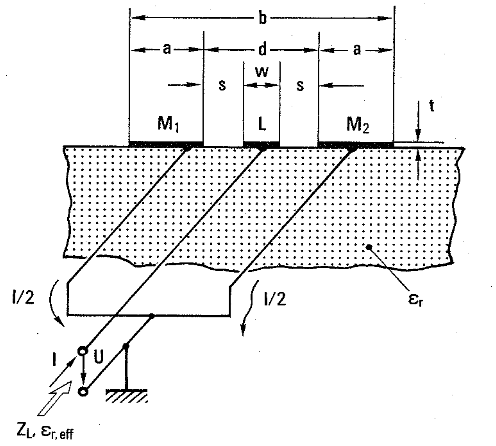
- Lumped (reflection):
  - Not ideal
  - Insufficiently modeled
  - May not be symmetrical



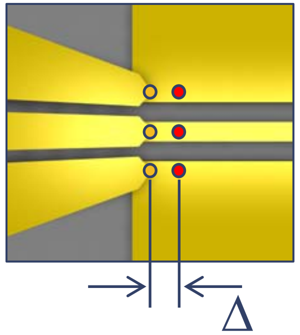
load open short

Calibration Standards

- Fabrication tolerances:
  - – Dielectric properties
  - – Tolerances of the mask
  - – Metal thickness and form



- Contact tolerances:
  - – Positioning accuracy
  - – Repeatability
  - – Contact resistance



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Calibration Procedures

- SOLT calibration
  - Requires fully known (or ideal) standards
  - 10-Term error model
- Self-calibration algorithms
  - TRL, LRM/LRM+, SOLR, QSOLT, RRMT+..
  - 7-Term error model
  - Some standards can be partly known
  - Recommended for the wafer-level

Calibration Procedures

Influence of transmission standards

	SOLT	SOLR	QSOLT	TRL	LRM	RRMT
THRU (4 terms)	☑		☑	☑	☑	☑
LINE (2 terms)				☑		
RECIP. (1 terms)		☑				
TERMS	4	1	4	6	4	4

Calibration Procedures

Influence of reflection (lumped) standards

	SOLT	SOLR	QSOLT	TRL	LRM	RRMT
OPEN (1 terms)	☑ 2x	☑ 2x	☑			
SHORT (1 terms)	☑ 2x	☑ 2x	☑			
LOAD (1 terms)	☑ 2x	☑ 2x	☑		☑ 2x	☑ 2x
REFLECT (1 terms)				☑	☑	☑ 2x
TERMS	6	6	3	1	3	4

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Uncertainty Analysis Methods

1. Analysis of calibration standards
   – Statistical
   – Analytical
2. Calibration comparison method
   – Analysis with respect to the reference calibration
3. Measurement method
   – Analysis with respect to the reference element
      • Classical ripple-test
      • Wafer-level implementation if the ripple-test

Ad 1.: Analysis of Calibration Standards

- Statistical analysis
  - Specify uncertainty of standards
  - Run simulation (i.e. Monte-Carlo)
  - Apply results to the calibration procedure

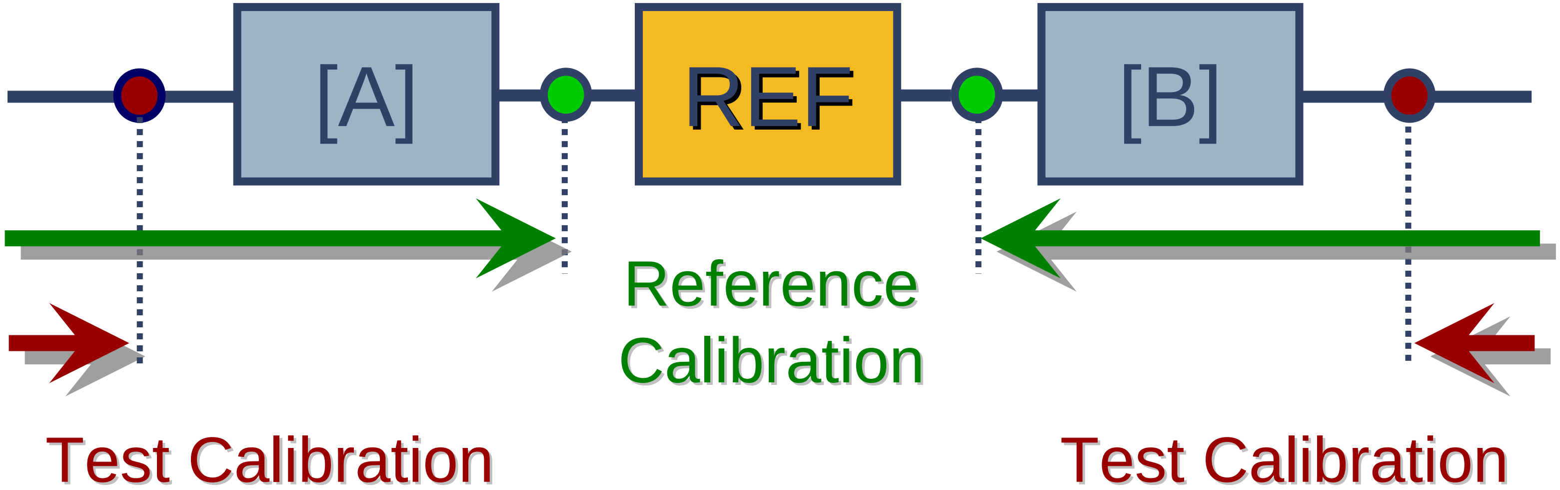
- Analytical analysis
  - $\delta S_{XY.DUT}$ from deviations of error terms δET_{IJ}
  - δET_{IJ} from deviations of standards $\delta S_{ST.XY}$

Ad 2.: Calibration Comparison Method

- Requires two calibrations:
  - Reference (well-known)
  - Test
- Addresses variations in:
  - Calibration standards
  - Calibration methods
  - Measurement setup (drift)
- Results:
  - Max. error bounds

Ad 2.: Calibration Comparison Method

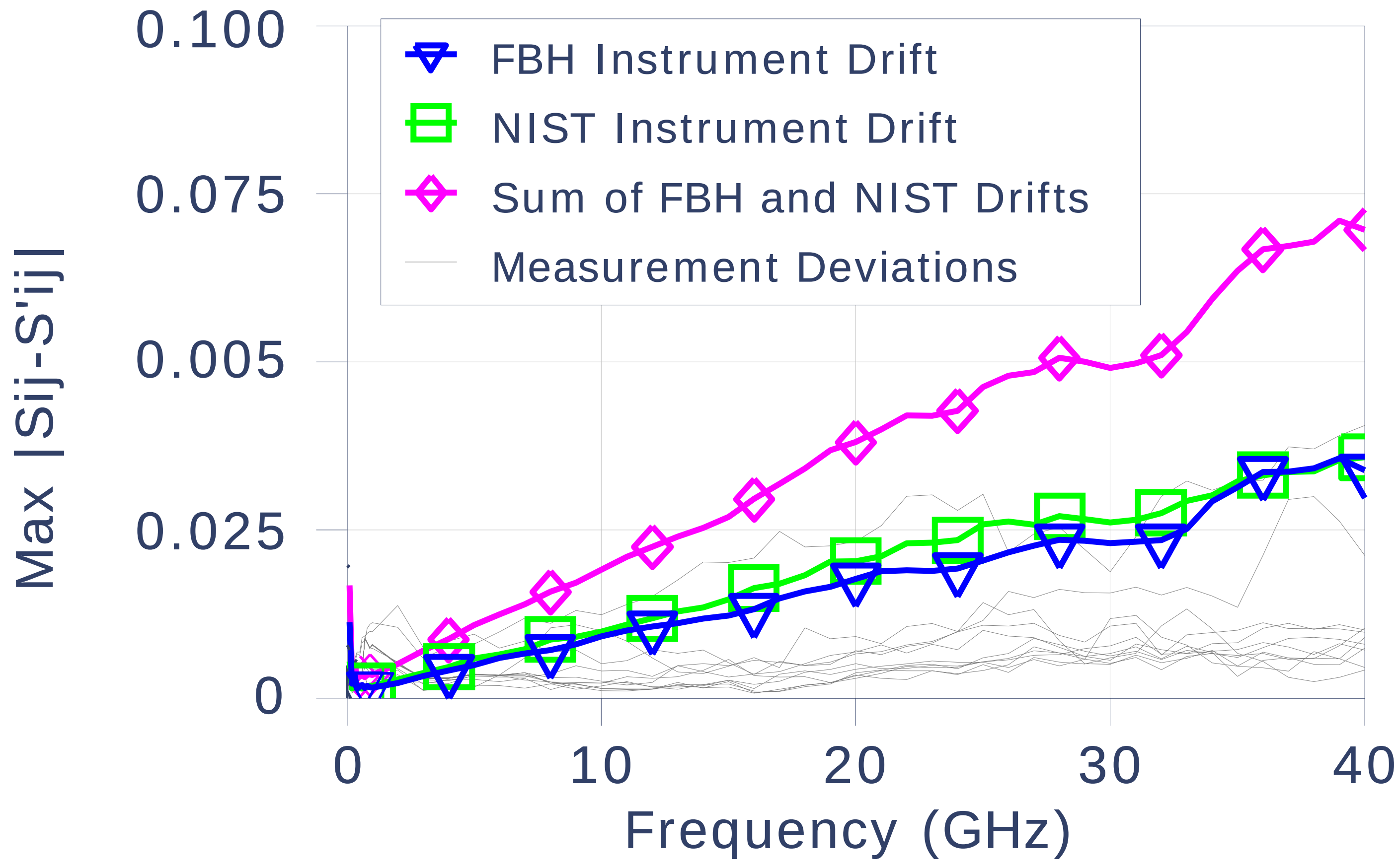
Block-diagram representation



[A] and [B] quantitatively describe the difference in **Test** and **Reference** calibration

Ad 2.: Calibration Comparison Method

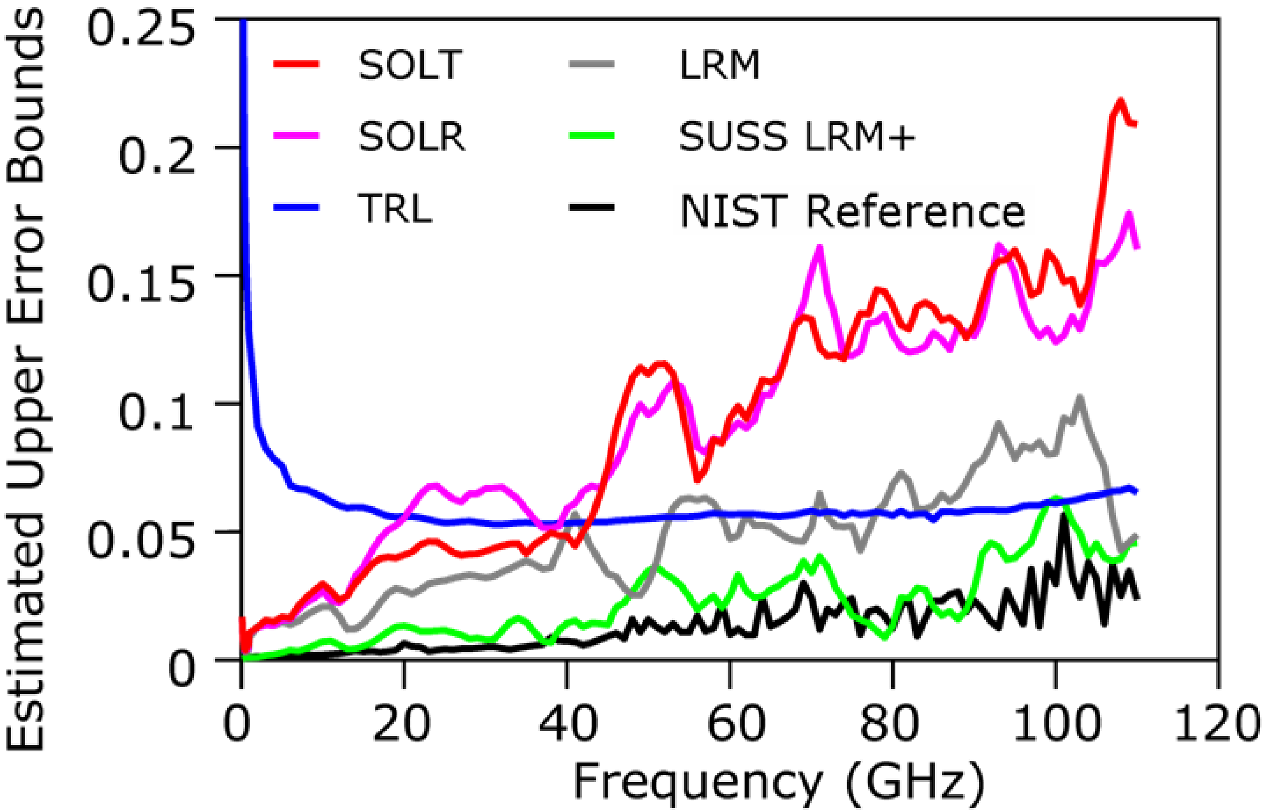
Example: verification of the system integrity*



*NIST Verify Program

Ad 2.: Calibration Comparison Method

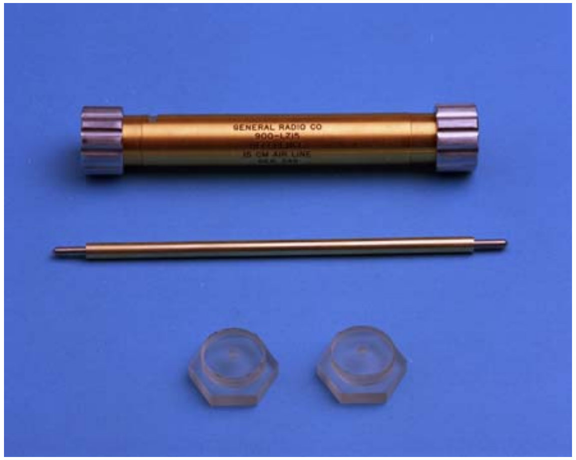
Analysis of different coplanar calibrations



SUSS, 2007

Ad 3.: Reference Measurements

- Reference element (coaxial applications):
  - Air-isolated lines
  - Well-defined characteristics: Z_0, αl, βl



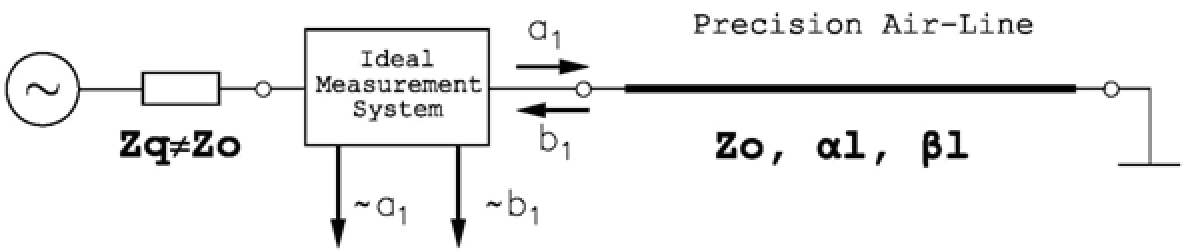
- Wafer-level equivalent?

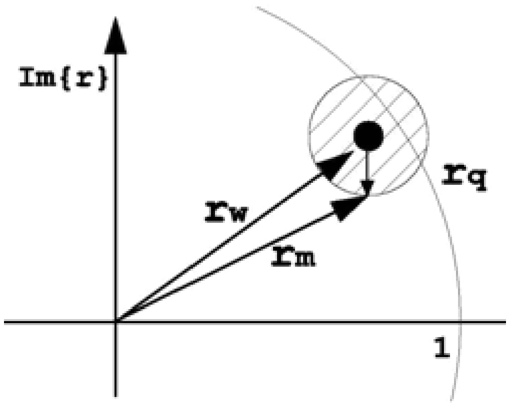
Picture source: NPL

Ad 3.: Reference Measurements

- Reference measurements (*ripple-test*):
  - line, loaded with the short
- All errors are included in the final *Source Match* (as error vector $\boldsymbol{r_q}$)

Setup for the r_q- calculation (ripple test)

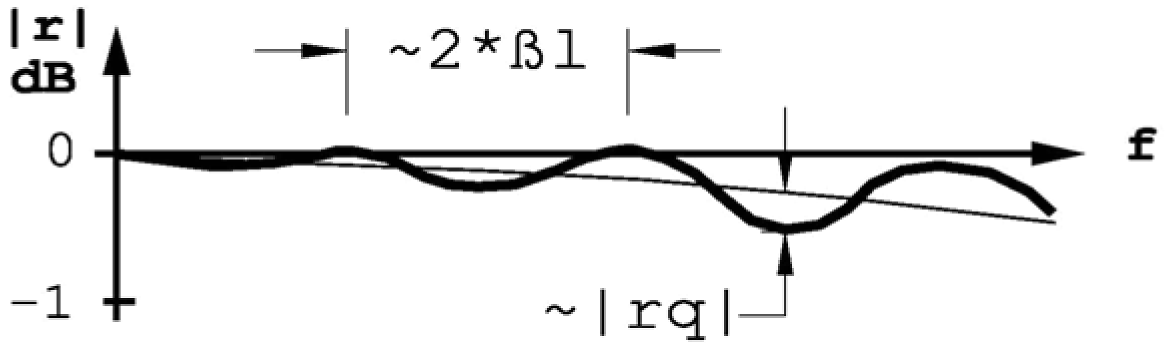




Classical Ripple Test

- *Perfect* VNA : $Z_0 = Z_q$

- *Real* VNA : $Z_0 \neq Z_q$



Wafer-Level Implementation

- Wafer-level challenge:
  - Fabrication tolerances reduce accuracy
  - Reference (planar) line is dispersive
- Solution:
  I. Line characterization (e.g. NIST methods)
  II. Renormalization from/to the line Z_0

Ad I: Characterization of Commercial CPW

- Measurement of the line's C

Substrate	C (pF/cm)
A	1.57
B	1.51
CSR-8	1.50

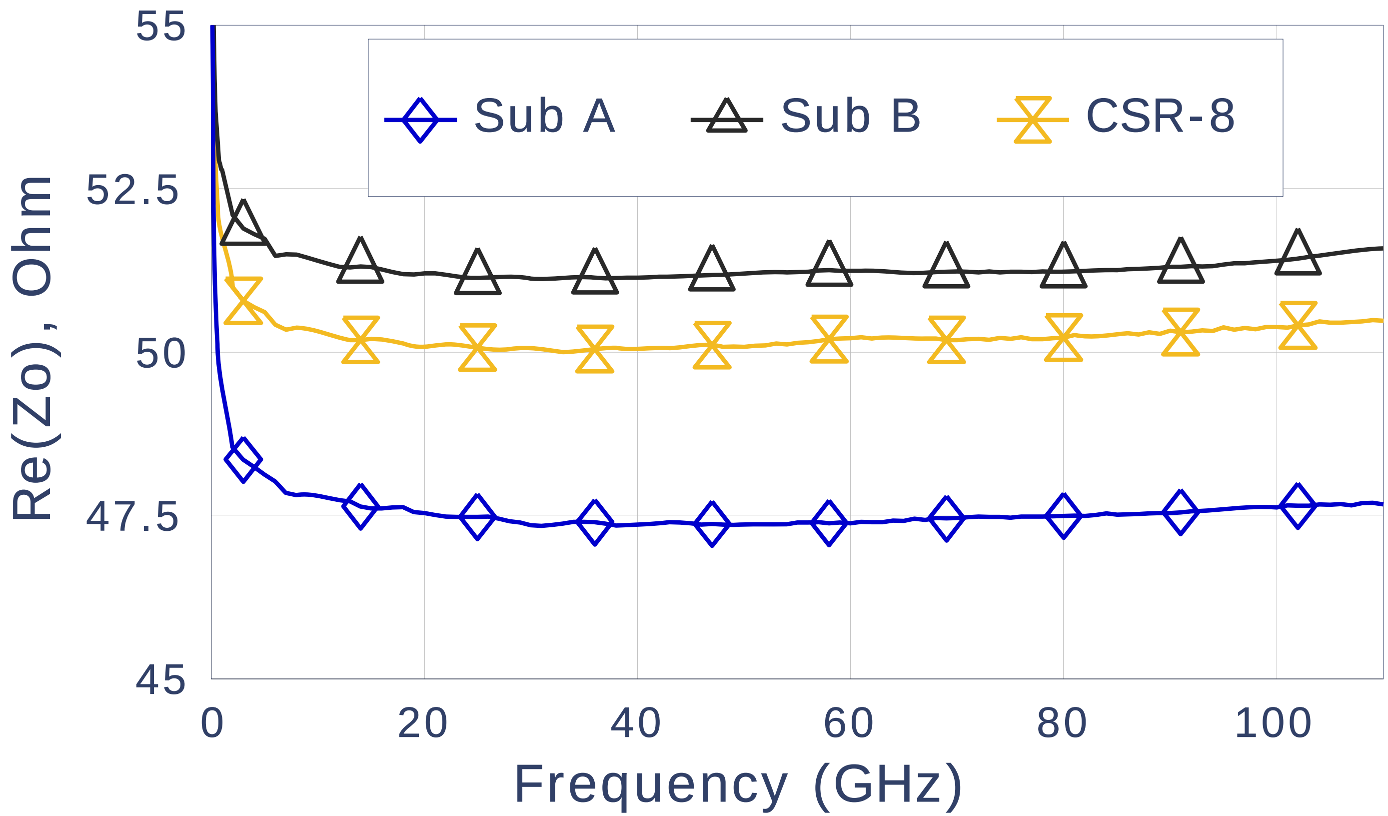
- Definition of the line's propagation constant γ (multiline TRL)*
- Calculation of the line's Z_0:

$$Z_0 \cong \frac{\gamma}{j\omega C}$$

*Available from MultiCal software package, NIST

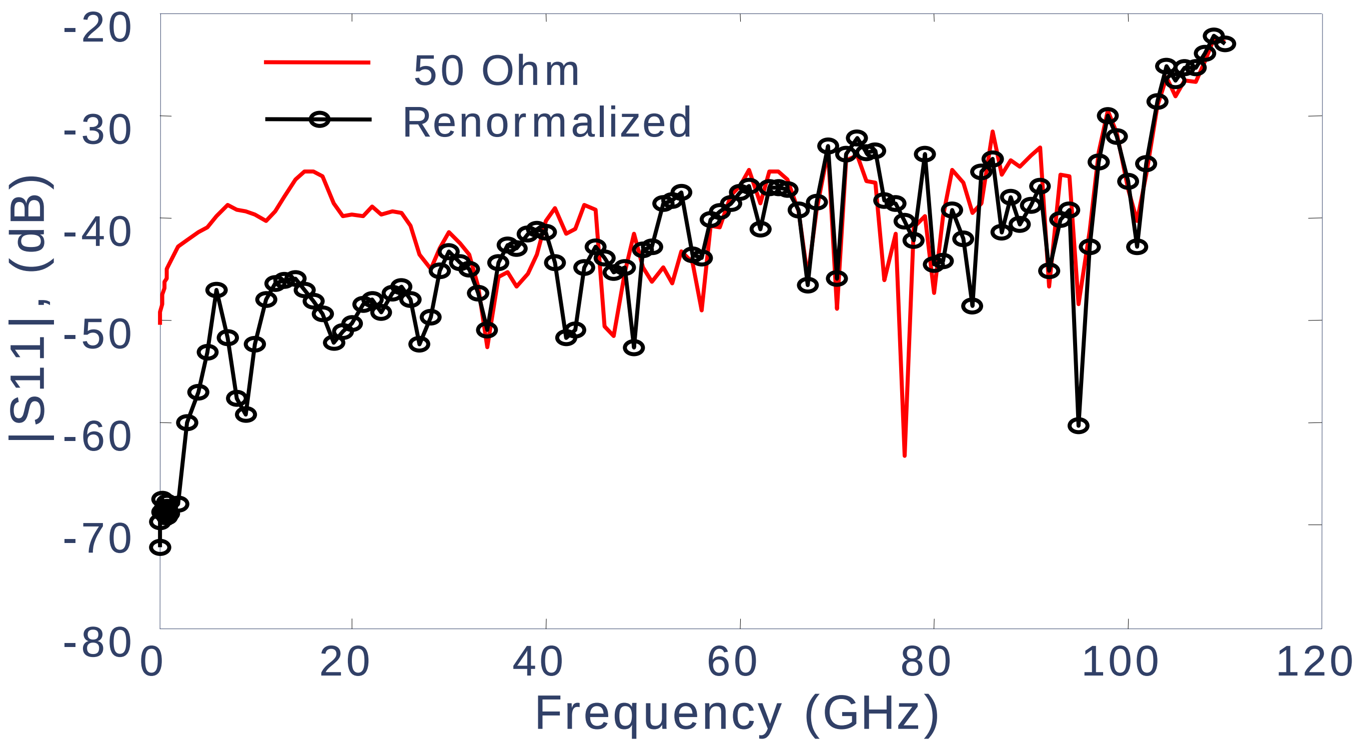
Ad I: Characterization of Commercial CPW

Measurement results



Ad II: Renormalization

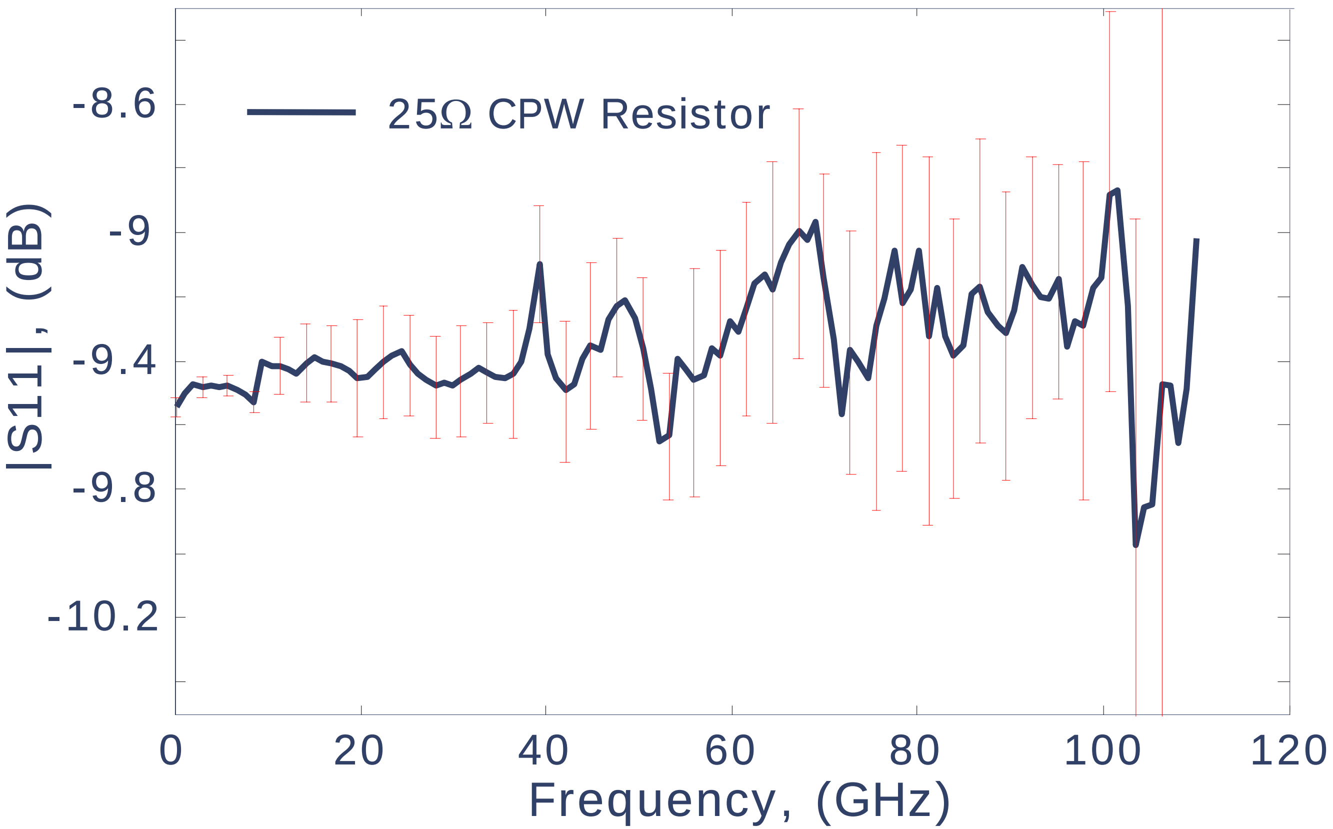
Return loss of the reference line



Automated ripple-test can be applied

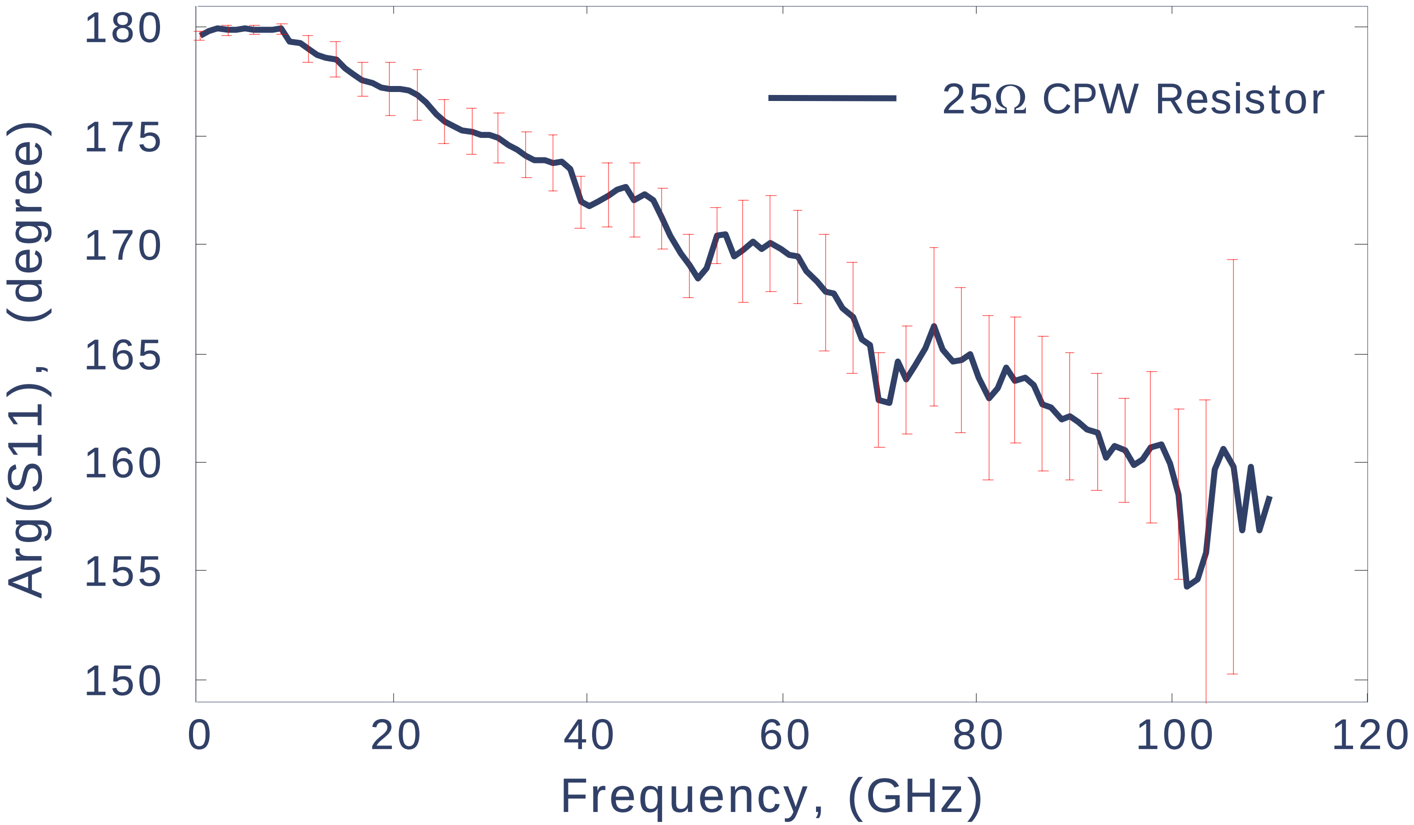
Uncertainty Estimation: LRM+ Calibration

Measurement results of a 25Ω resistor



Uncertainty Estimation: LRM+ Calibration

Measurement results of a 25Ω resistor



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- Multiple sources of calibration errors
- Different analysis methods are available
- Characterized CPW lines can be used as reference elements
- Results of the automated wafer-level ripple-test were demonstrated

References

European co-operation for Accreditation, Expression of the Uncertainty of Measurement in Calibration, EA-4/02, 12.1999.

Eul, H.J., Schiek, B., A Generalized Theory and New Calibration Procedures for Network Analyzer Self-Calibration, *IEEE Trans. Microwave Theory Tech*., MTT-39, Apr. 1991, pp. 724-731.

Heuermann, H., Schiek, B., Robust Algorithms for Txx Network Analyzer Procedures, *IEEE Trans. Instrum. Meas*., Feb. 1994, pp. 18-23.

Marks, R., Williams, D., Characteristic Impedance Determination Using Propagation Constant Measurements, *IEEE Microwave and Guided Wave Lett*., vol. 1, pp. 141-143, June 1991.

A. Rumiantsev, H. Heuermann, S. Schott, A Robust Broadband Calibration Method for Wafer-Level Characterization of Multiport Devices, *69th ARFTG Conference Digest*, June 2007

Rumiantsev, A., Doerner, R., Thies, S., Calibration Standards Verification Procedure Using the Calibration Comparison Technique, *36th European Microwave Conference Digest*, September 2006.

U. Arz, Traceability for On-Wafer S-Parameter Measurements, Workshop Determining Accuracy of Measurements at High Frequencies – from Error to Uncertainty, *37th European Microwave Conference*, 2007.

R. Doerner, "Evaluation of wafer-level LRRM and LRM+ calibration techniques," *ARFTG Microwave Measurements Conference-Spring*, 69th, 2007.

References (cont.)

J. P. Hoffmann, P. Leuchtmann, J. Schaub, and R. Vahldieck, "Computing uncertainties of S-parameters by means of monte carlo simulation," in *ARFTG Microwave Measurements Conference-Fall, 69th*, 2007

N. M. Ridler, A. G. Morgan, and M. J. Sadler, "Generalized adaptive calibration schemes for RF network analyzers based on minimizing the uncertainty of measurement,“ *ARFTG Microwave Measurements Conference-Digest-Fall, 60th*, 2002, pp. 1-9.

U. Stumper, "Influence of TMSO calibration standards uncertainties on VNA S-parameter measurements," *Instrumentation and Measurement, IEEE Transactions on*, vol. 52, pp. 311-315, 2003.

U. Stumper, "Uncertainties of VNA S-parameter measurements applying the TAN self-calibration method," *Instrumentation and Measurement, IEEE Transactions on*, vol. 56, pp. 597-600, 2007.

RF & Microwave Test Solutions, SUSS MicroTec Test Systems GmbH, 2007.

Heuermann, H., Old and New Accuracy Estimation of S-Parameter Measurements with the Ripple-Test, *MTT-S International Microwave Symposium Workshop TMB*, San Francisco, Juni 2006.

H. Heuermann and A. Rumiantsev, "The modified ripple test for on-wafer S-parameter measurements," *ARFTG Microwave Measurements Conference-Spring*, *69th,* 2007.