On Wafer S-Parameters & Uncertainties

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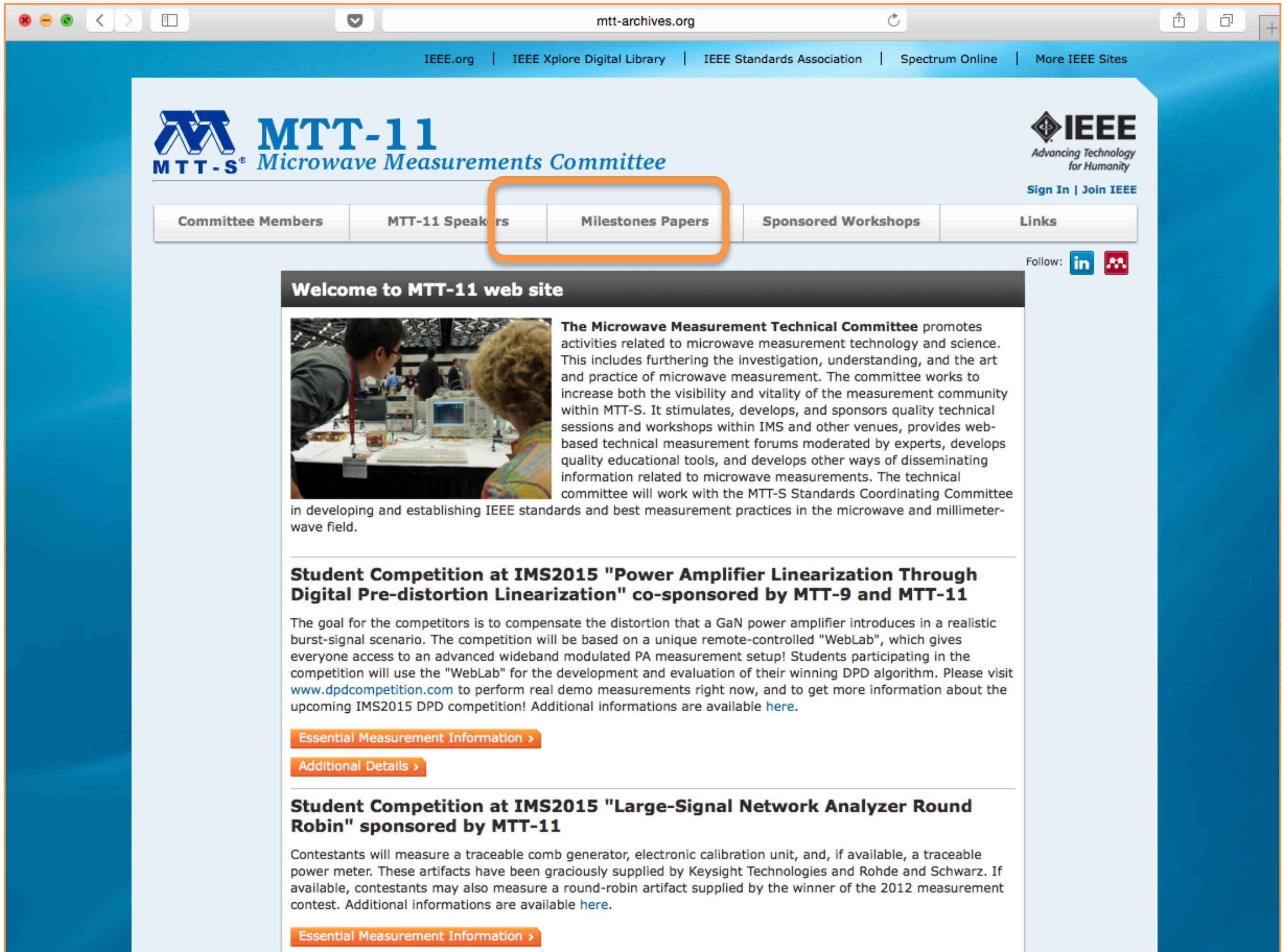
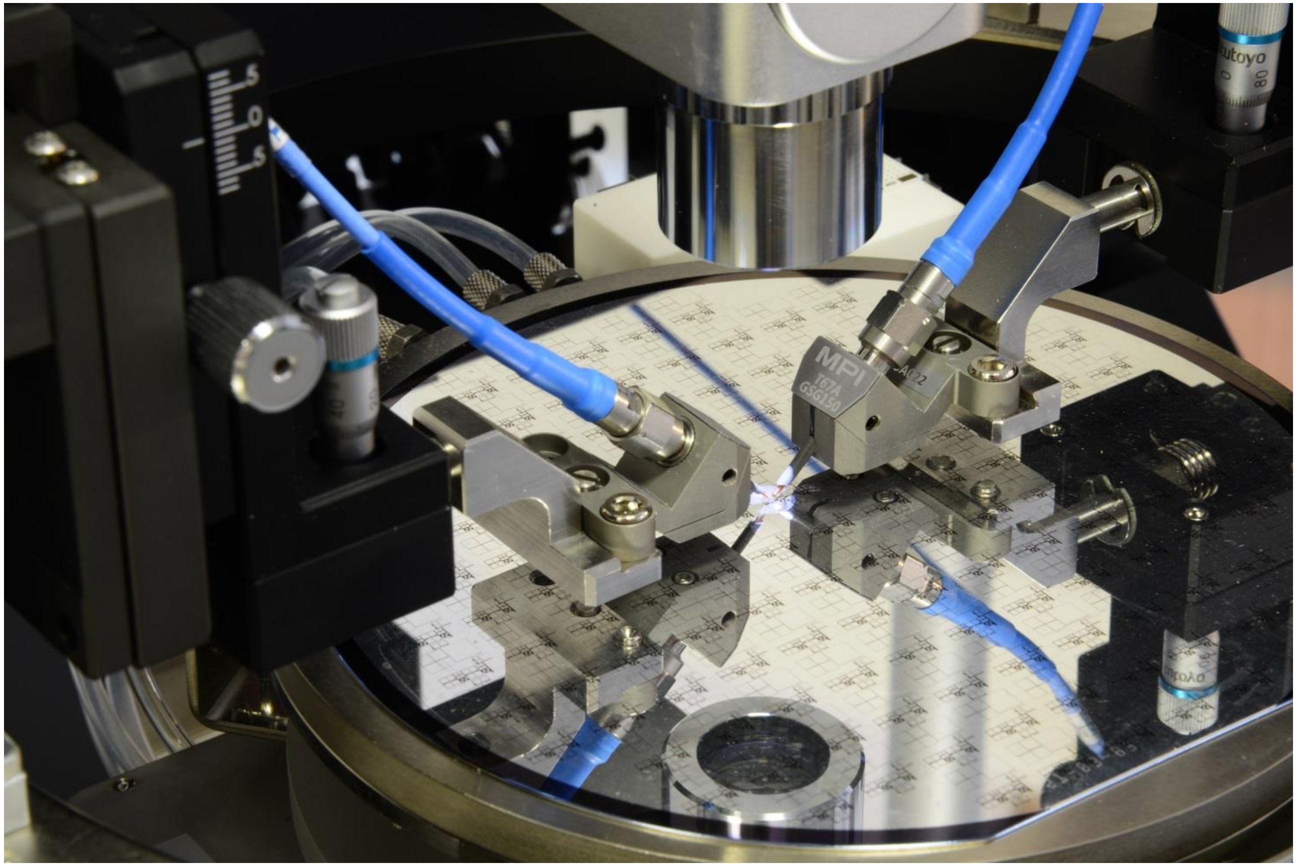
visit: www.mtt-archives.org/~mtt11



Outline

- Introduction
- Criteria for the “right method”
- Calibration residual errors
- Conclusion

The Last Inch to the DUT



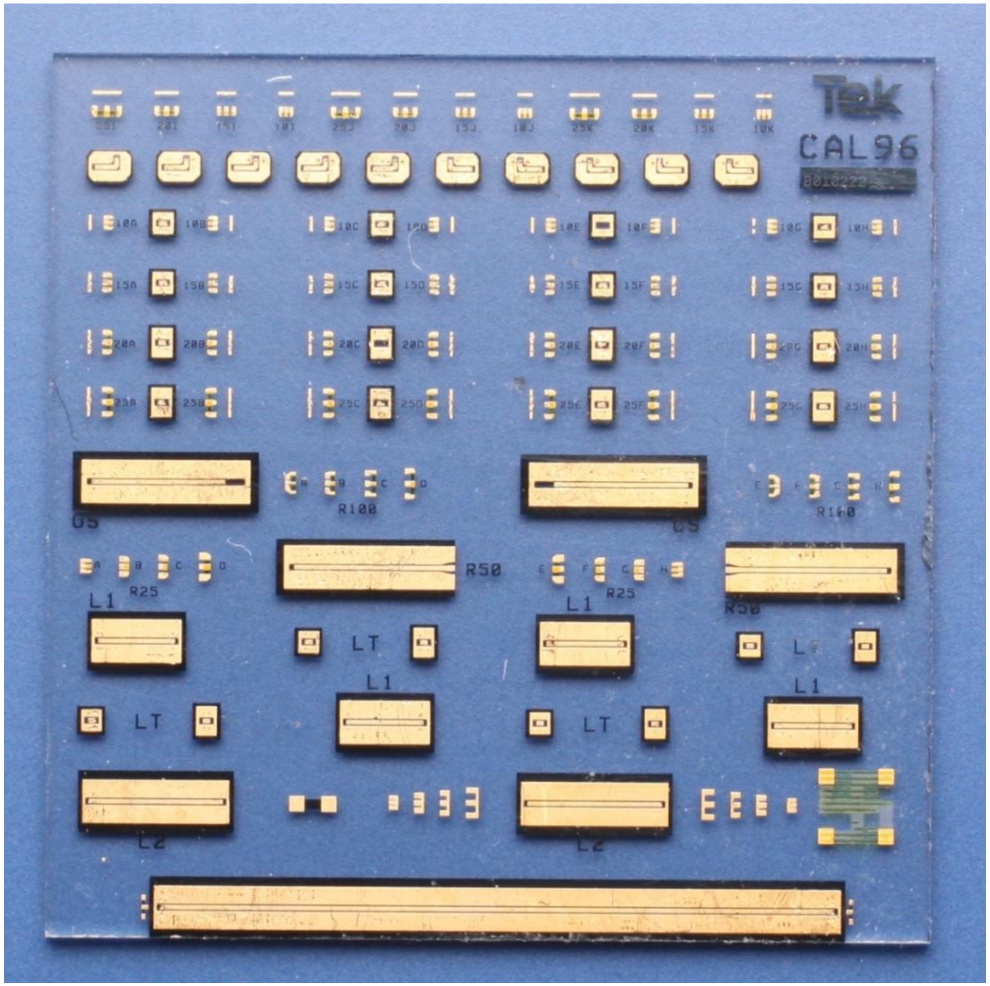
…leads to a different world

Coaxial Calibration Standards

Picture: Spinner Group

- Same media
- Well-defined electrical characteristics at the calibration plane

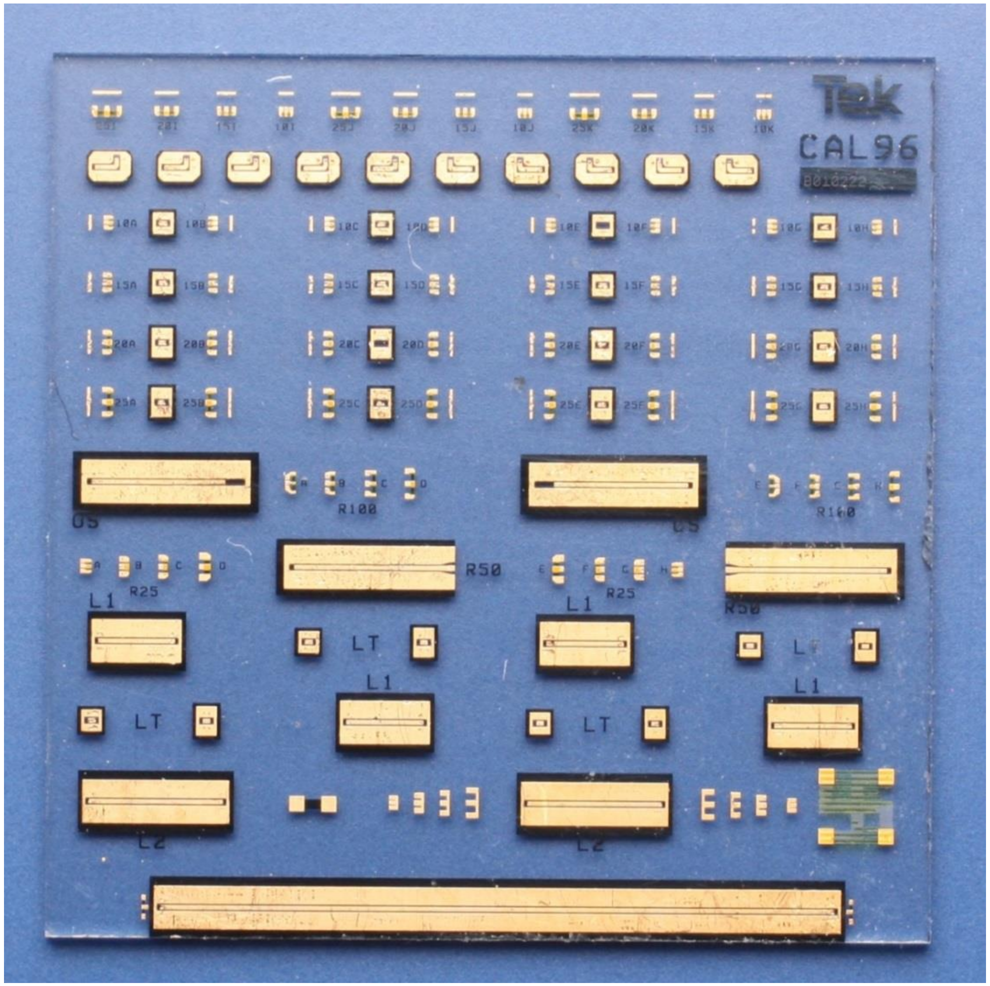
Wafer-Level Standards



Picture: FBH, Berlin

- Coplanar design:
  - Dispersion
- Not shielded:
  - Coupling and radiation
- Manufacturing inaccuracy

Wafer-Level Standards (cont.)



Picture: FBH, Berlin

Two discontinuities:

- Coaxial media to planar probe tips
- Probe tips to coplanar devices (standards)

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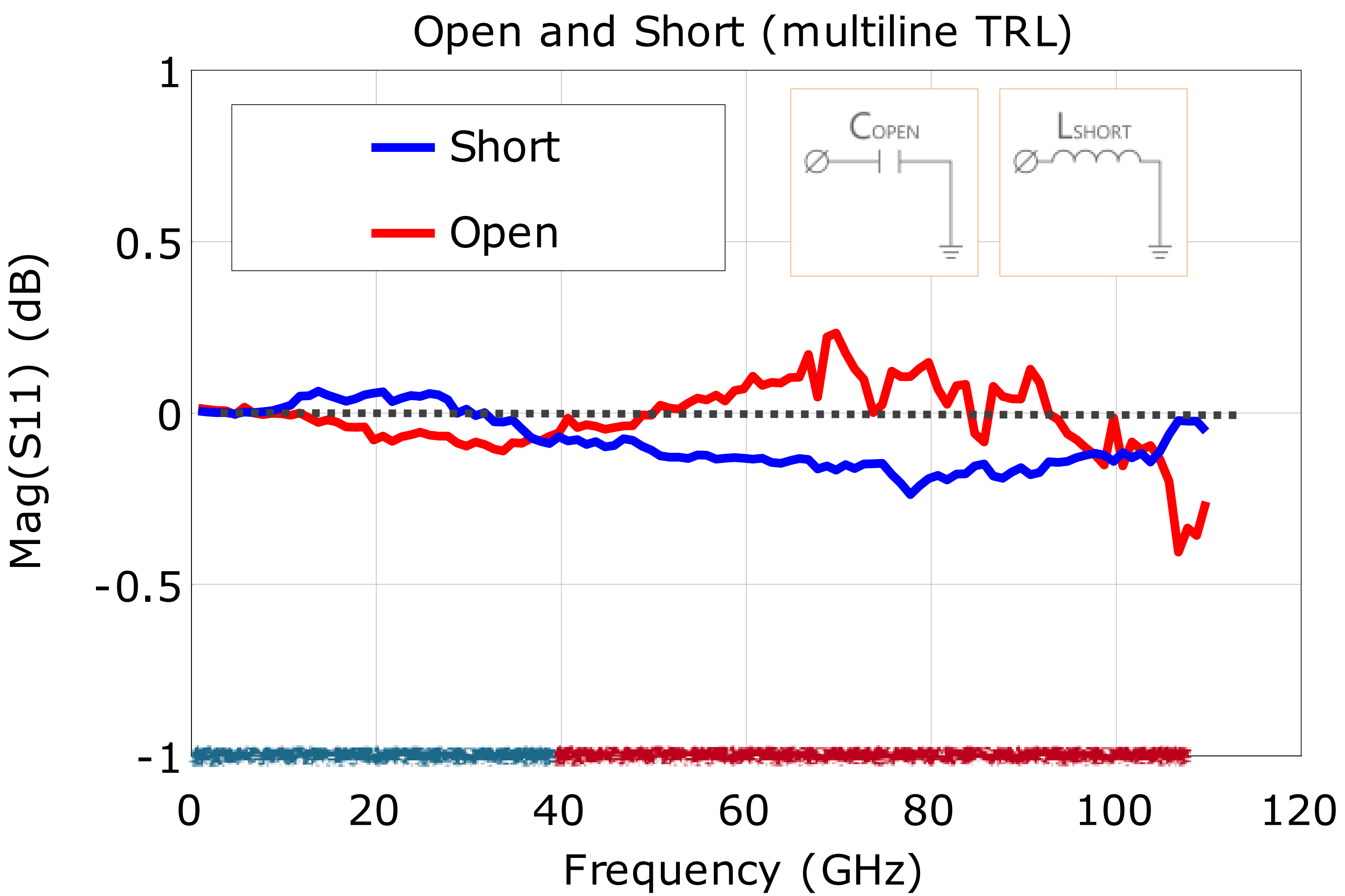
Calibration and Self-Calibration

- Calibration methods: known standards
  - SOL, SOLT, QSOLT
- Self-calibration standards:
  - Reflect, reciprocal thru, line
- Solution criteria:
  - Frequency range
  - Self-calibration methods with optimal set of standards

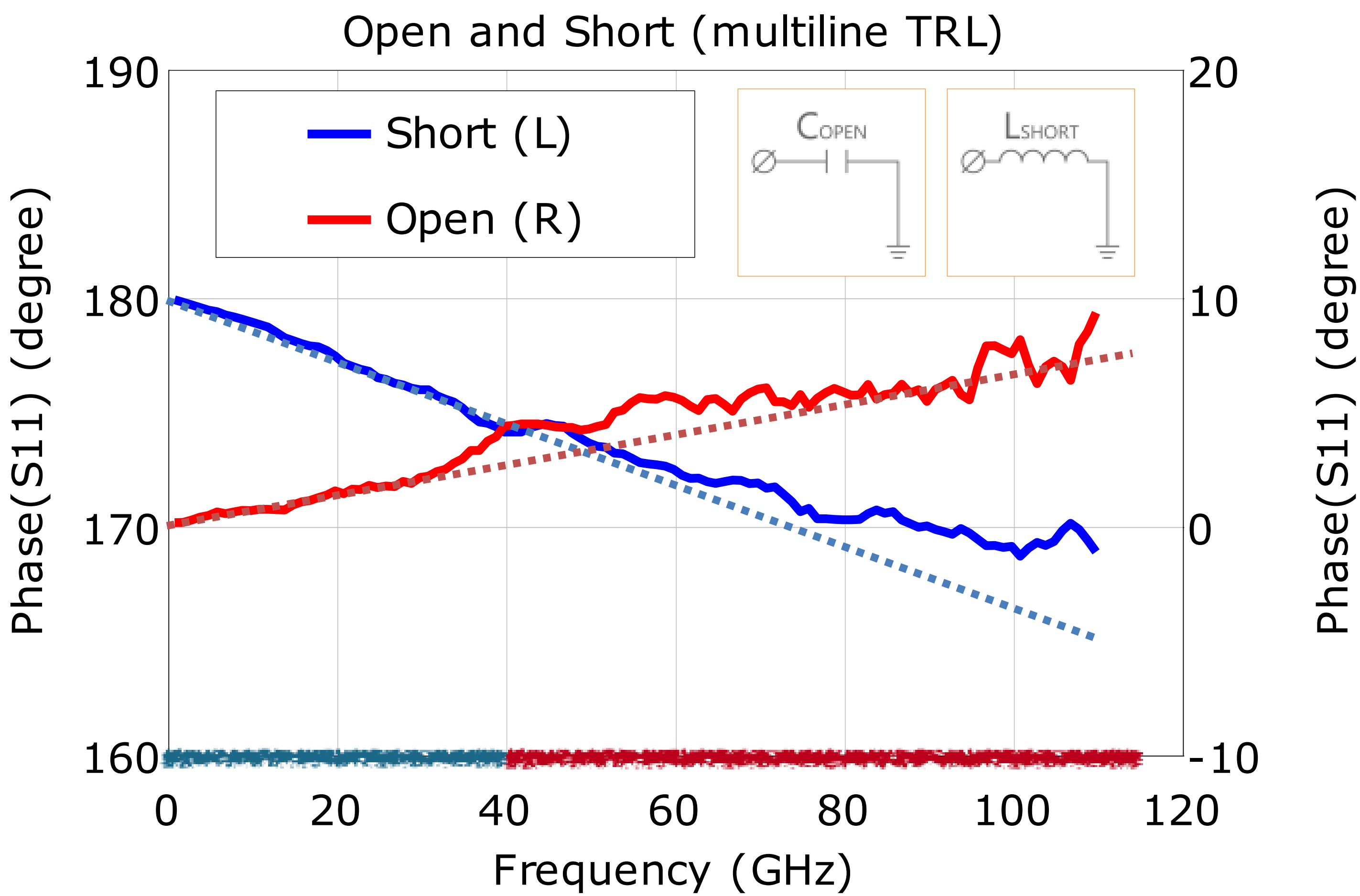
Example: SOLT

Standard	Requirements	Typical Definition	Error Terms
Short	Fully known	R=0; L=9pH	2
Open	Fully known	R=inf; C=0.3fF	2
Load	Fully known	R=50; L=10.6pH	2
Thru	Fully known	Z_0=50Ω α=0, τ=1ps	4

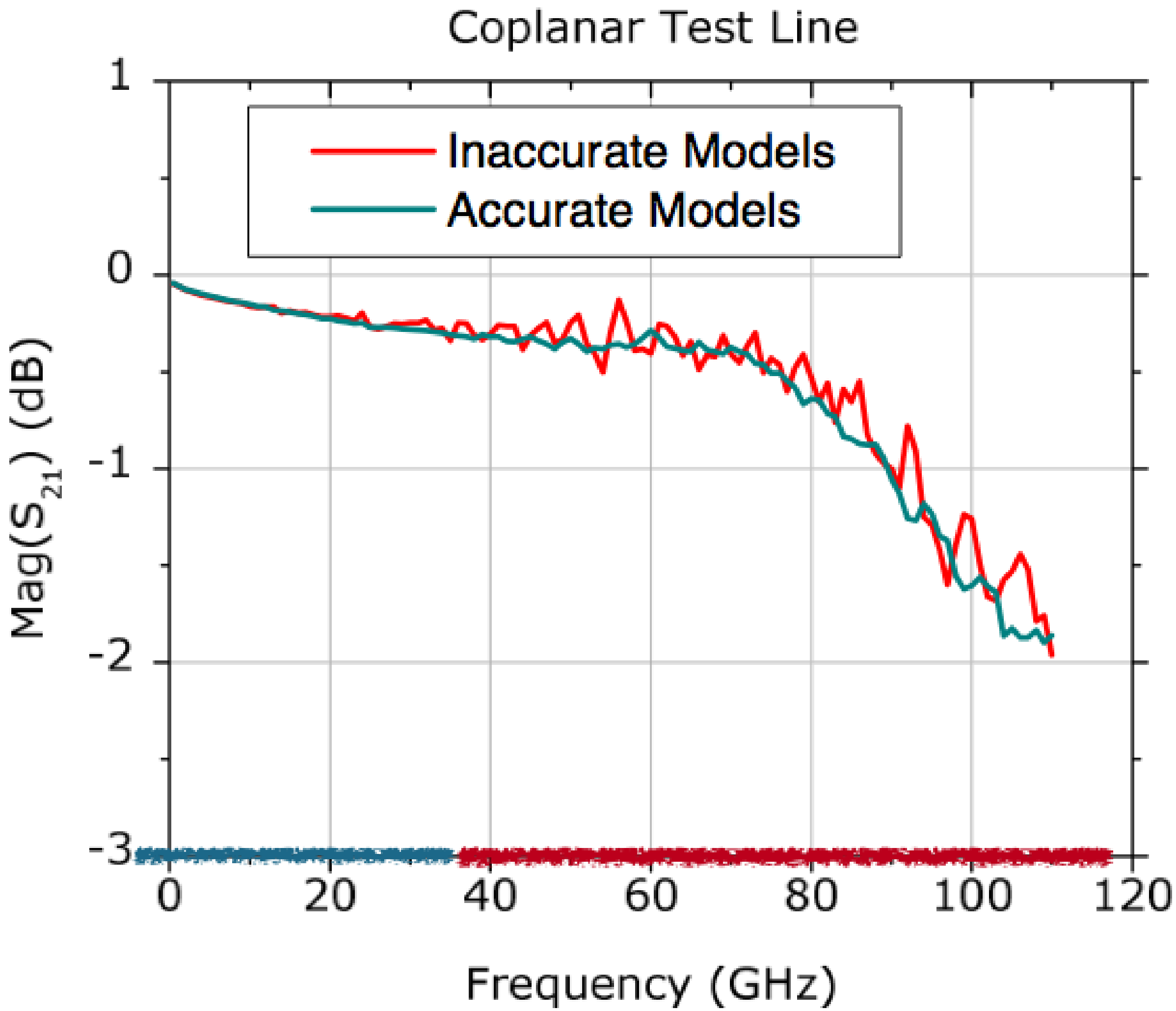
Open/Short are not Ideal



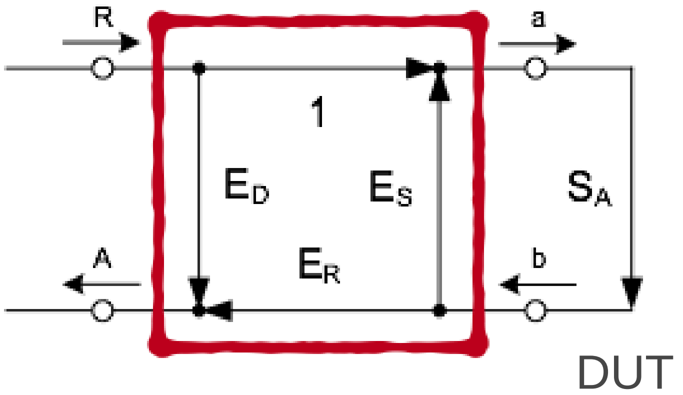
Open/Short are not Ideal



Test DUT: SOLT



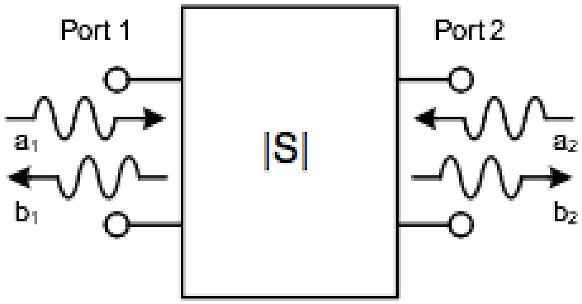
Calibration Outcome



Error Model

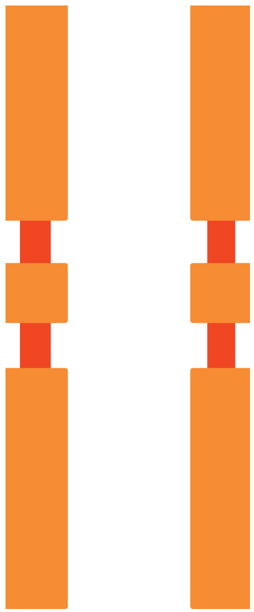
Removes systematic errors:

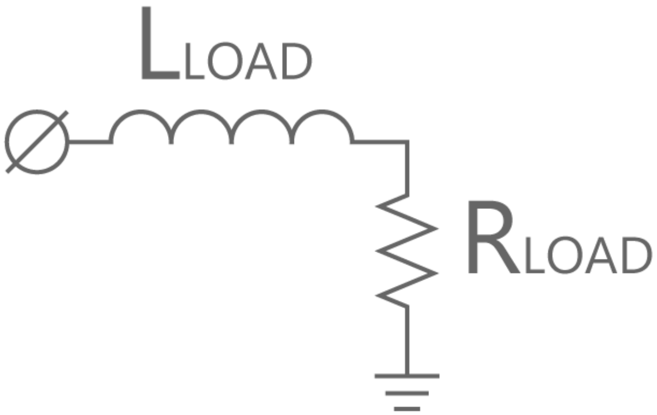
- Shifts the reference plane
- Defines reference impedance Z_{REF}



$$S_{ii} = \frac{b_i}{a_i} = \frac{Z_{DUT} - Z_{REF}}{Z_{DUT} + Z_{REF}}$$

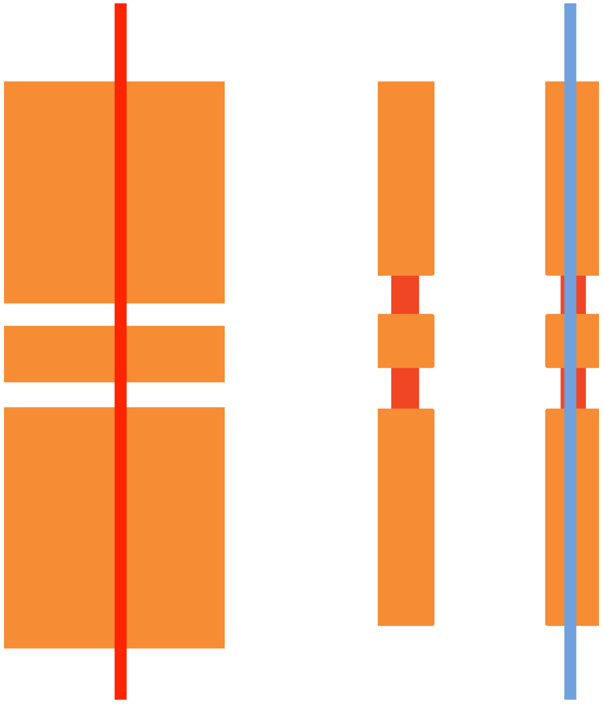
Reference Impedance: Lumped Methods

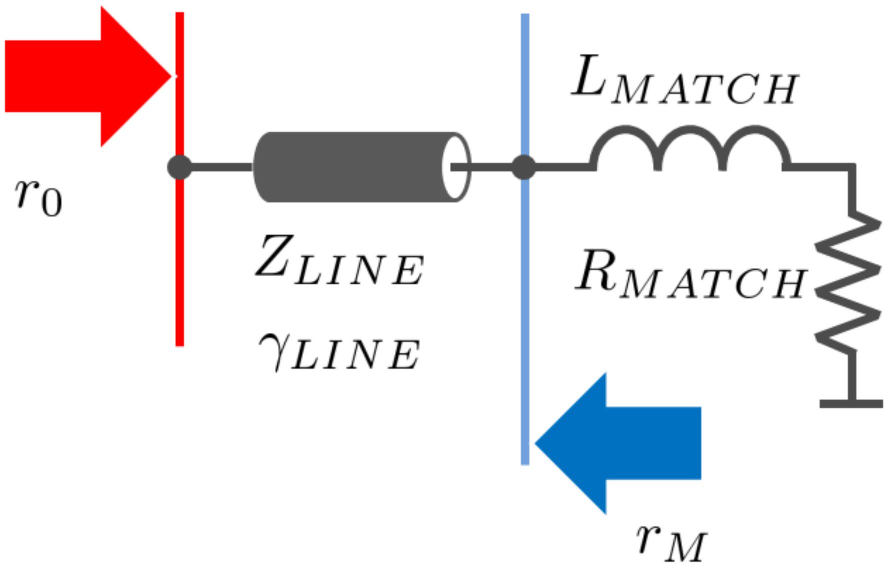




- Z_{REF} is defied by the load Z_{LOAD}

Calibration Plane: Middle of the Thru

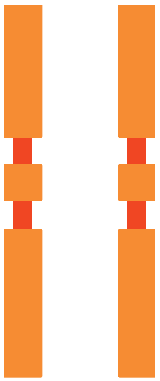




- Thru must be fully known – crucial!

Calibration Challenges at mm-Wave Frequencies

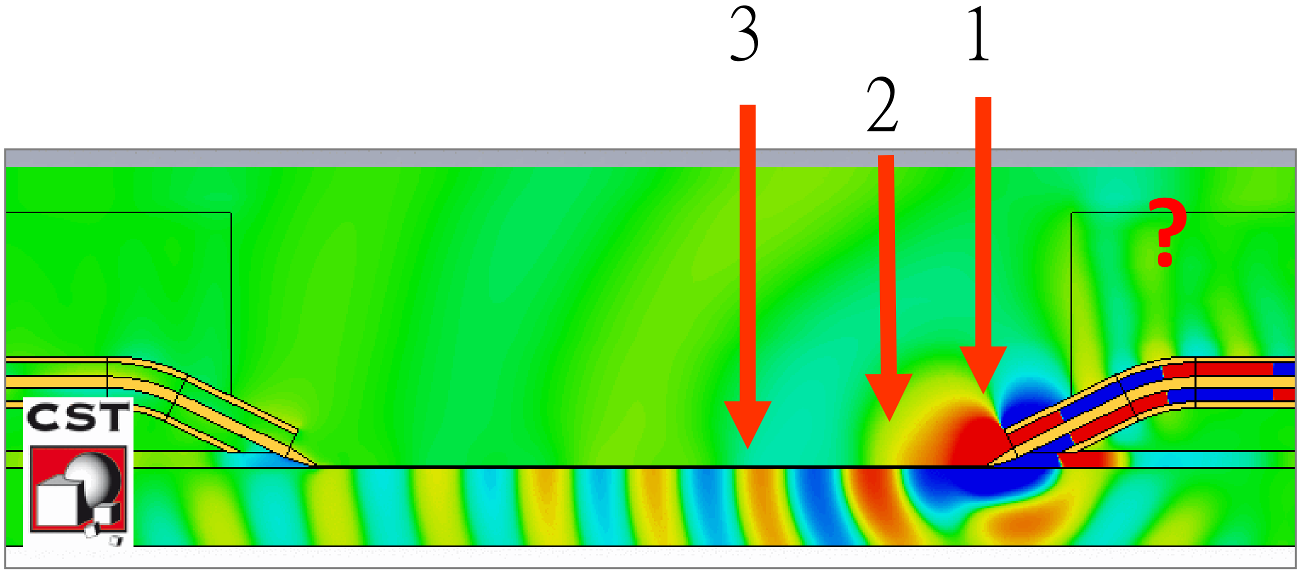
- Probe tip Load:
  - Less space on the calibration substrate
  - More elements on the same size
- Acceptable compromize for low-frequency measurements



- Load impedance at mm-wave range?
- Calibration accuracy above 110 GHz?

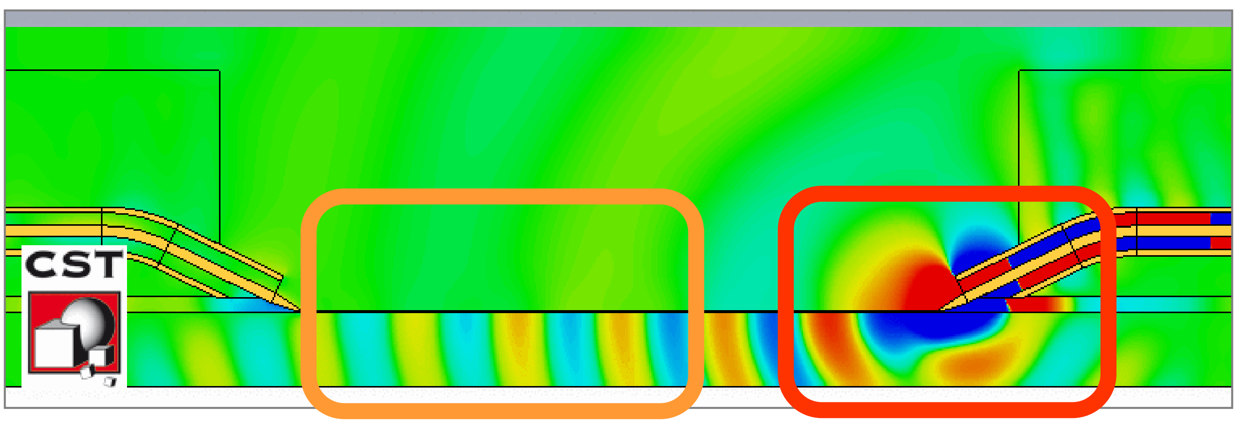
Calibration Challenges at mm-Wave Frequencies

- Accurate definition of the equivalent impedance requires uniformed structure of the E/M waves at the reference point
- Where is the point of the uniformed waves?



Calibration Challenges at mm-Wave Frequencies

- Away from the probe tips:
  - Transition to CPW complete
  - Uniformed fields
  - Well-established traveling waves
  - Well-defied reference impedance!
- At the probe tip:
  - Transition point from tip to standard
  - Discontinuity
  - Not-uniformed fields
  - Load impedance??? (undefined!)



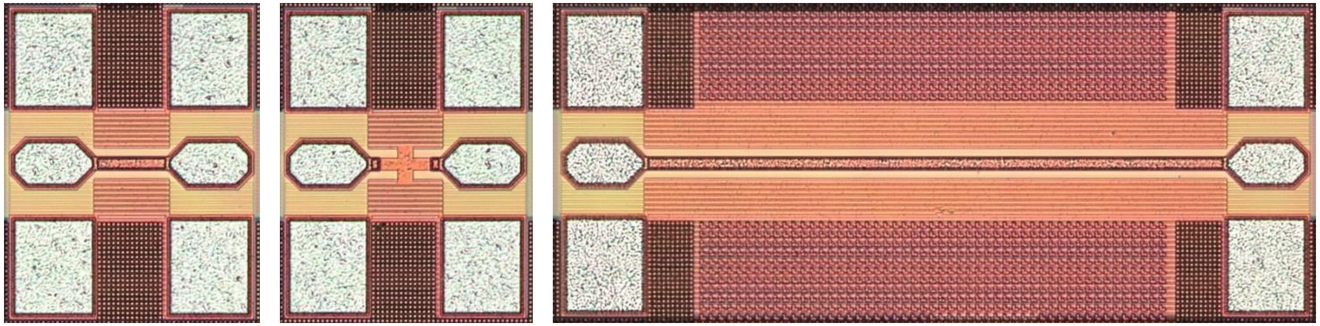
Solution for Calibration at mm-Wave Frequencies

- Move load away from the probe-tips.
- However:
  - Load with long offset impractical
  - How to define its equivalent impedance in wide frequency range?

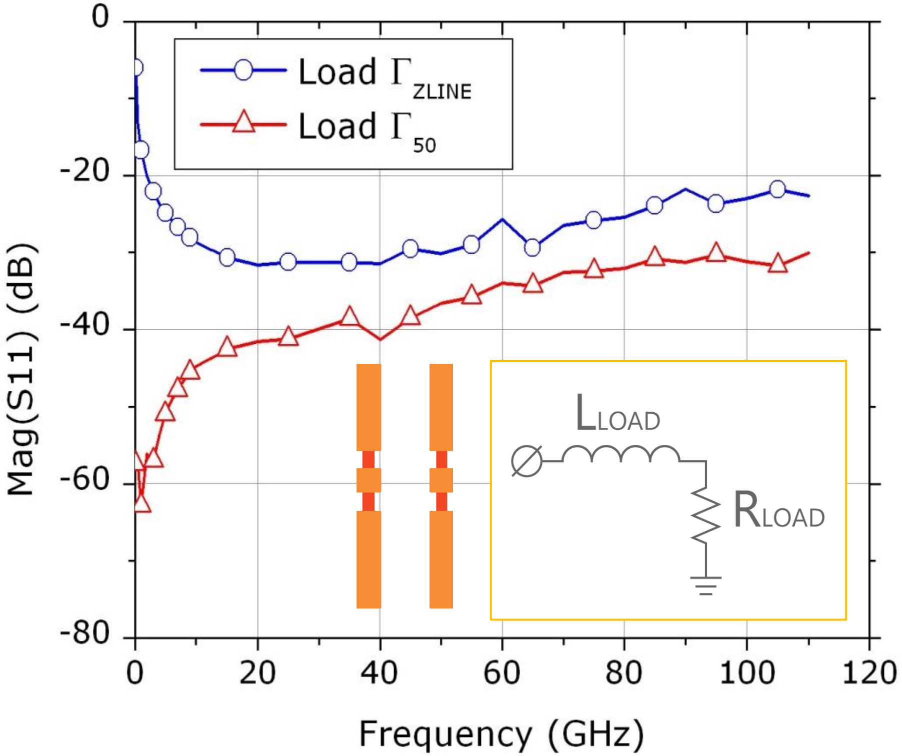
- Solution: NIST multiline TRL
  - Load not required!
  - Requires just sections of transmission lines
  - Calibration standards easy to make on-wafer

Distributed Standard-Based Methods: TRL and mTRL

- Calibration reference impedance is the characteristic impedance of the line
- Lines are dispersive



Dispersion Phenomenon

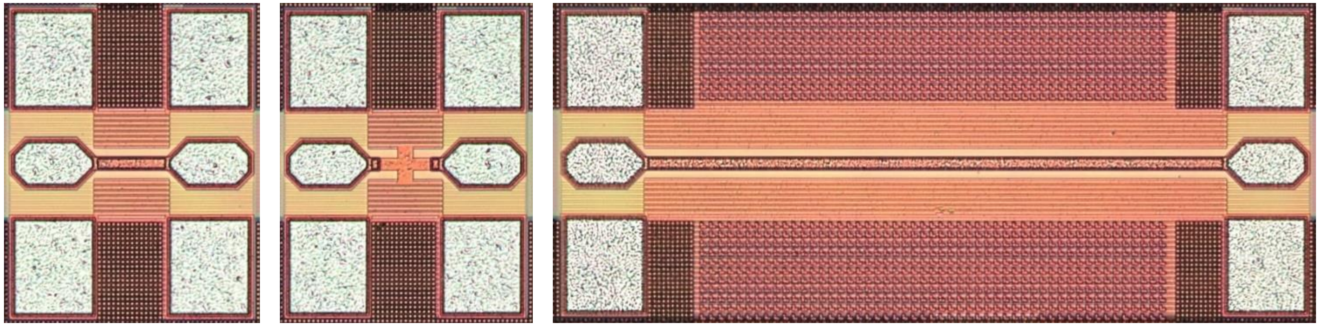


- S-parameters:
  - $Z_{REF}=Z_{LINE}$
- Pseudo S-parameters:
  - $Z_{REF}=50\ \Omega$

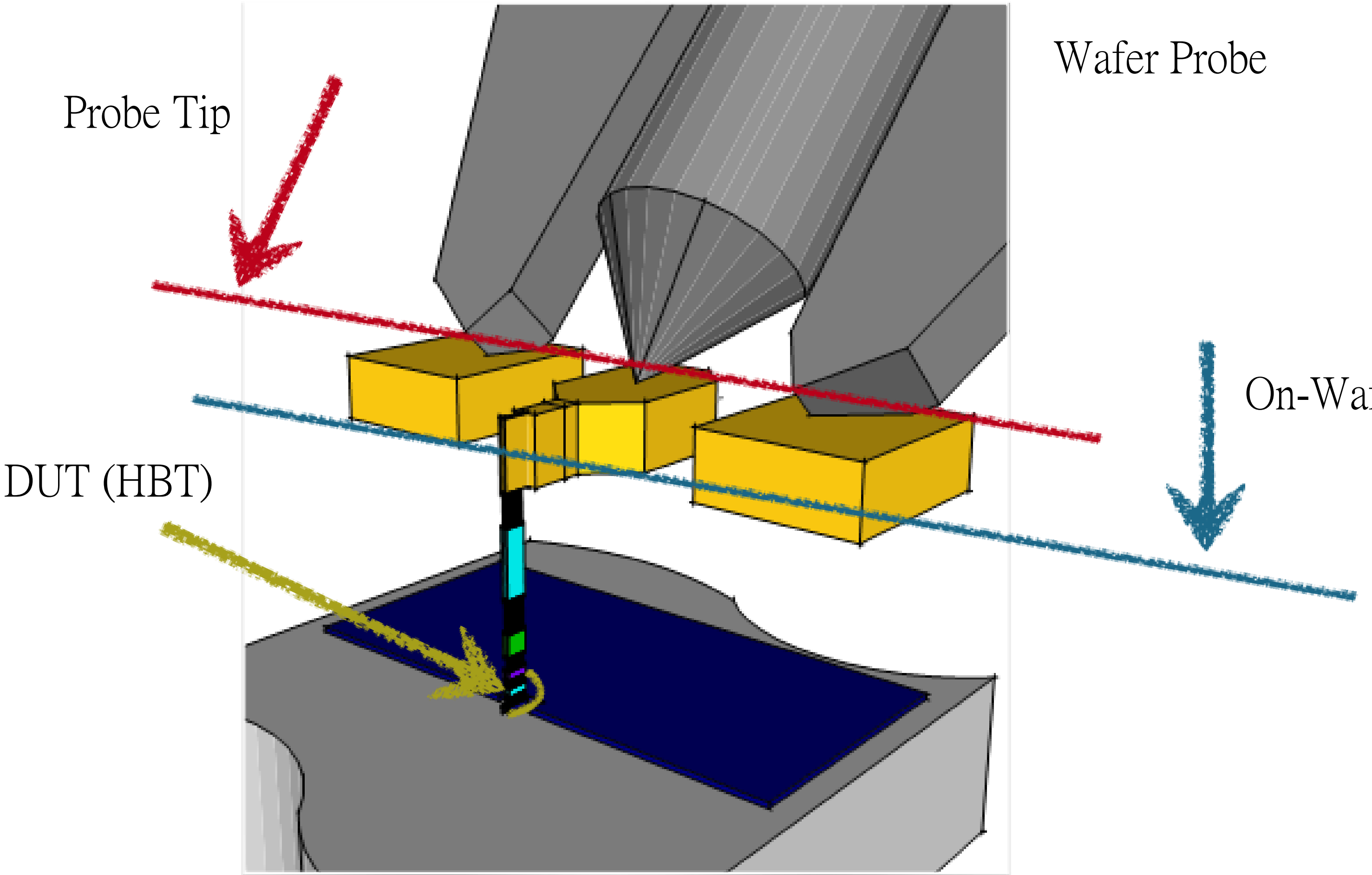
Useful reading: D. Williams, “Traveling waves and power waves”, *Microwave Magazine*, Nov-Dec 2013.

Distributed Standard-Based Methods: TRL and mTRL

- Transformation to 50 Ω reference impedance required
- Measurement of line characteristic impedance

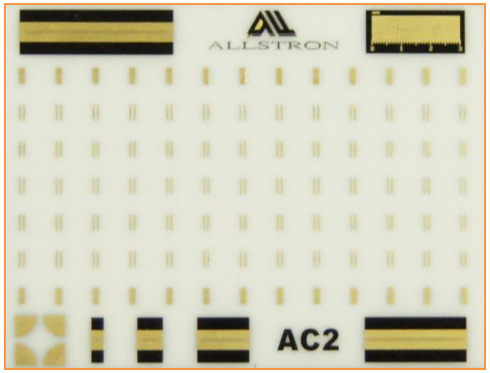


Probe Tip vs. on-Wafer Calibration

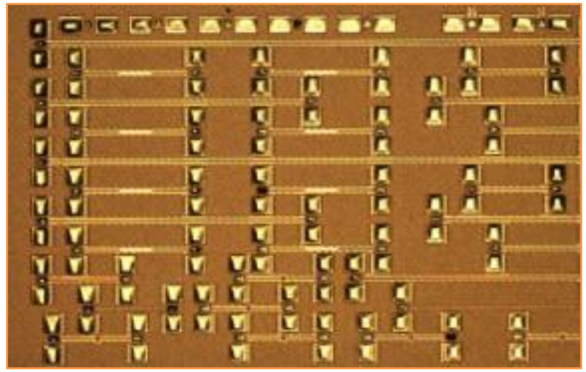


A. Rumiantsev, "On-Wafer calibration techniques enabling accurate characterization of high-performance silicon devices at the mm-wave range and beyond," Fakultät für Maschinenbau, Elektrotechnik und Wirtschaftsingenieurwesen, BTU Cottbus, Cottbus, 2014.

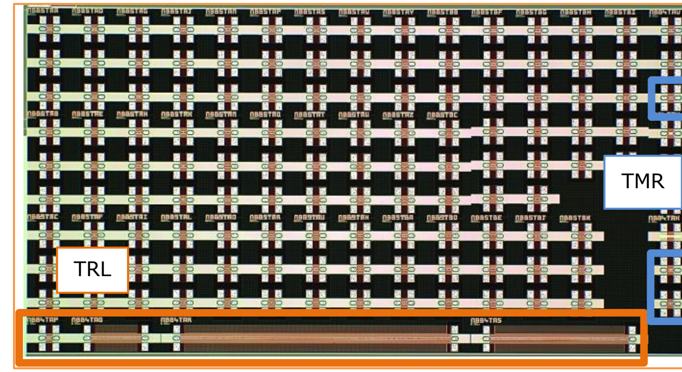
Probe Tip vs. on-Wafer Calibration



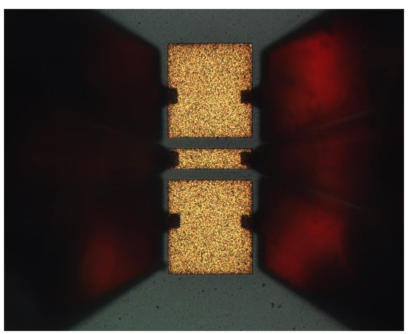
Off-wafer standards

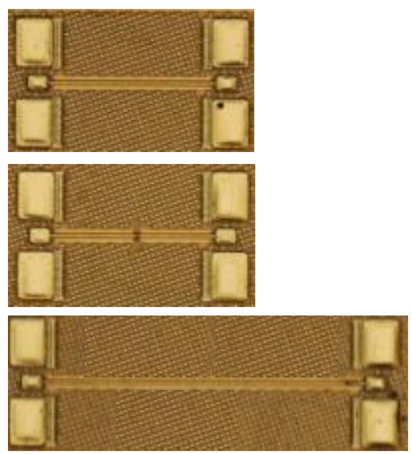


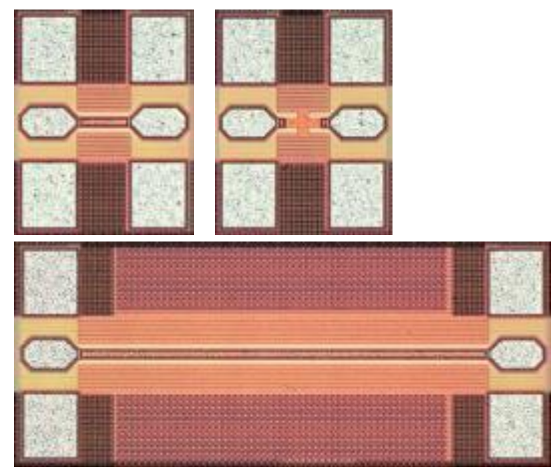
On-wafer: CMOS



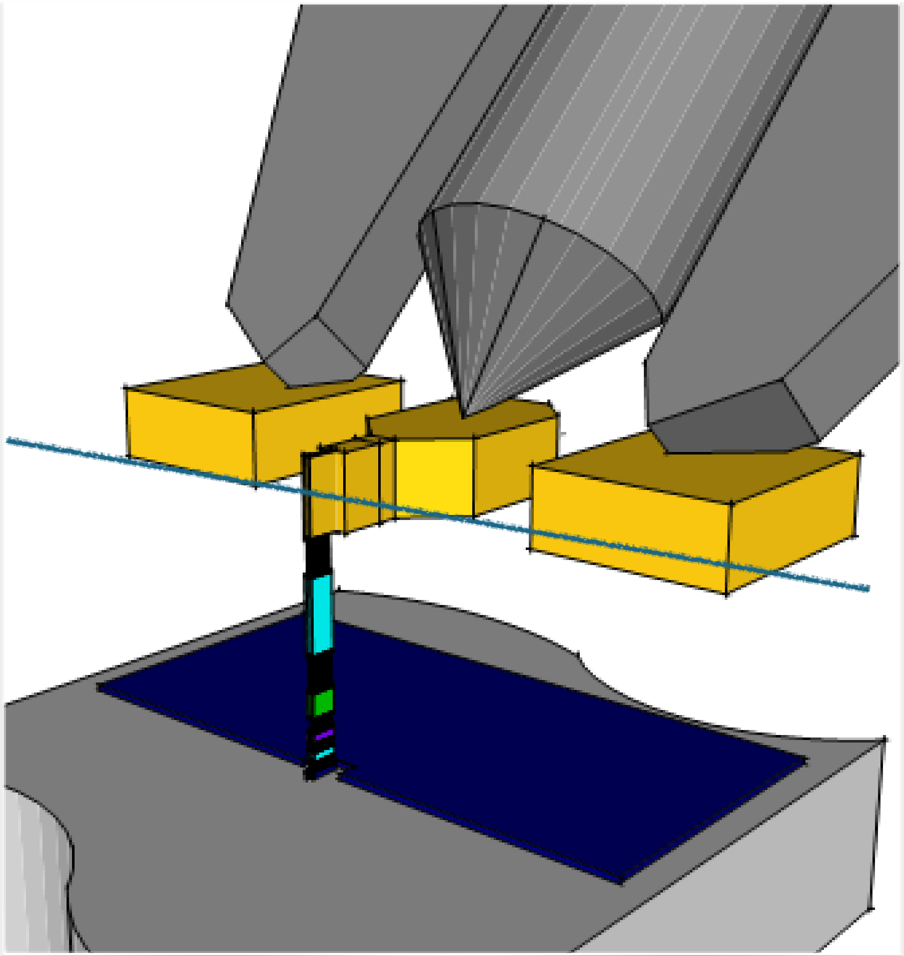
On-wafer: BiCMOS

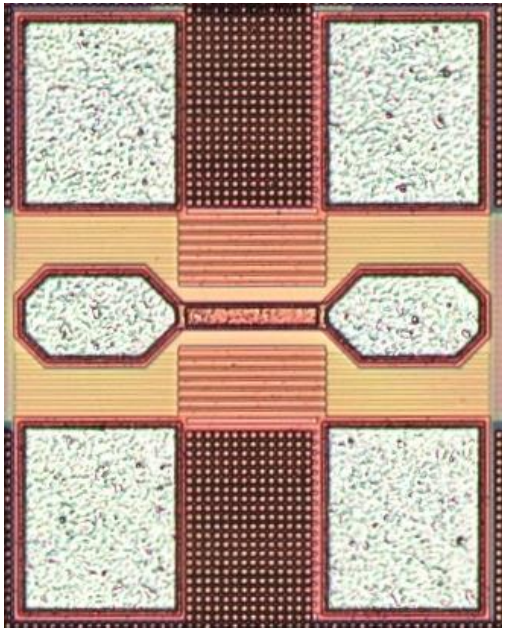






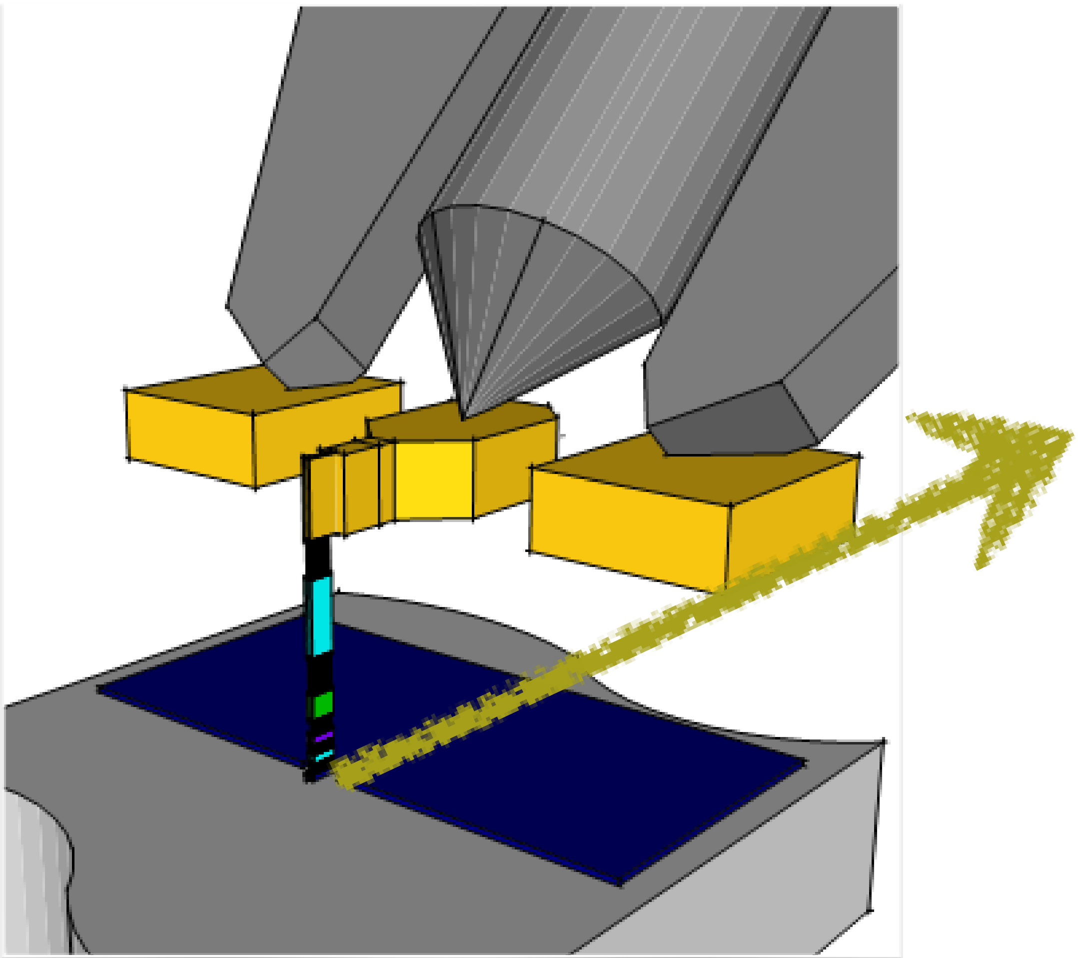
On-Wafer Cal: Distributed Standards

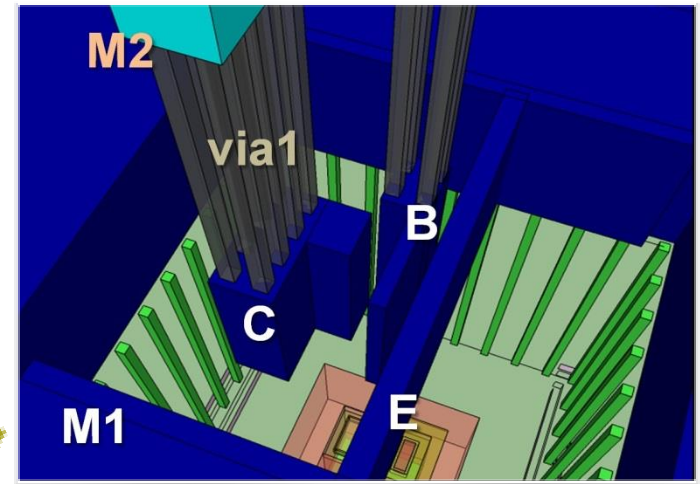




Top metal

On-Wafer Cal: Lumped Standards





Metal1 (2)

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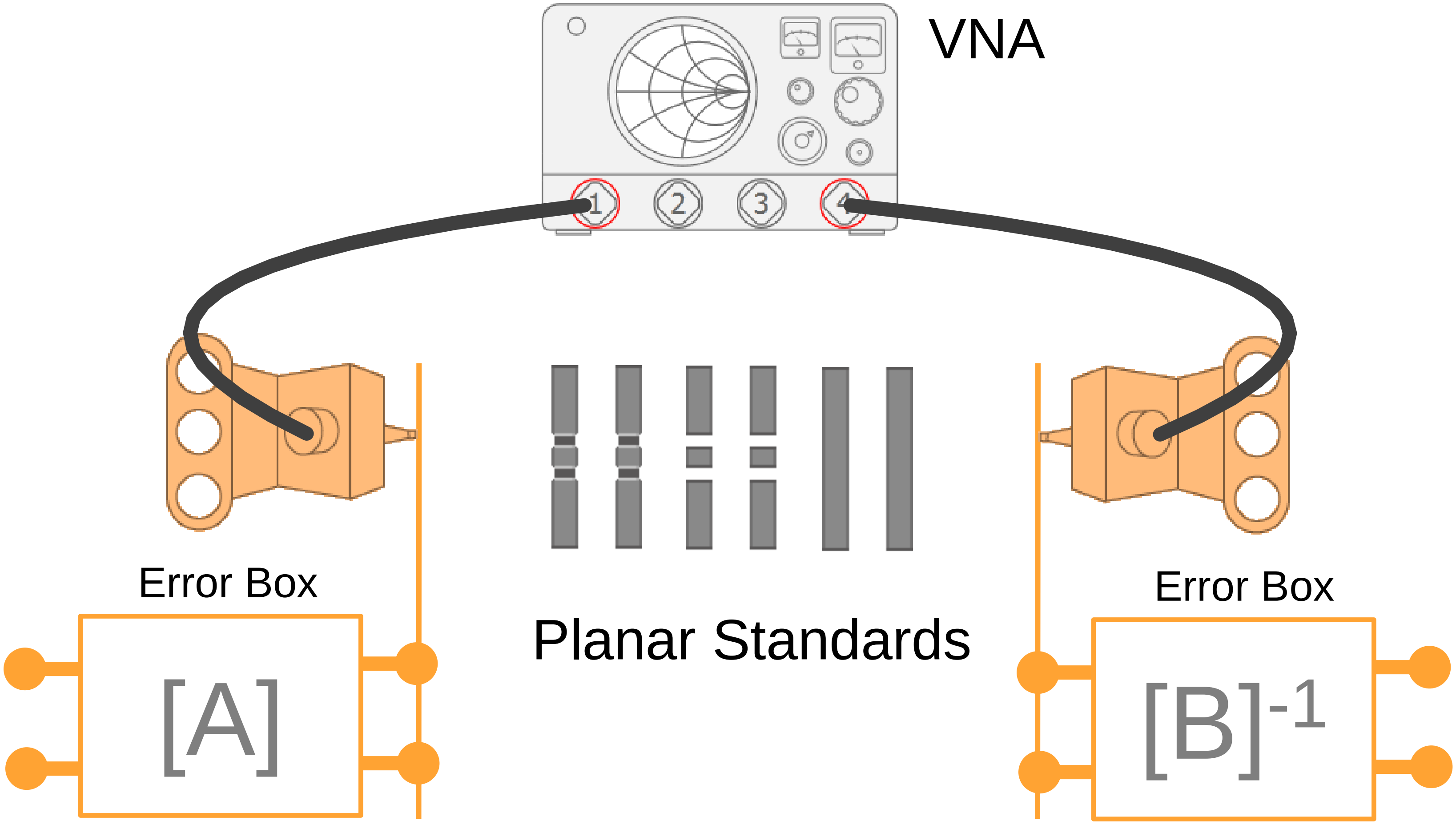
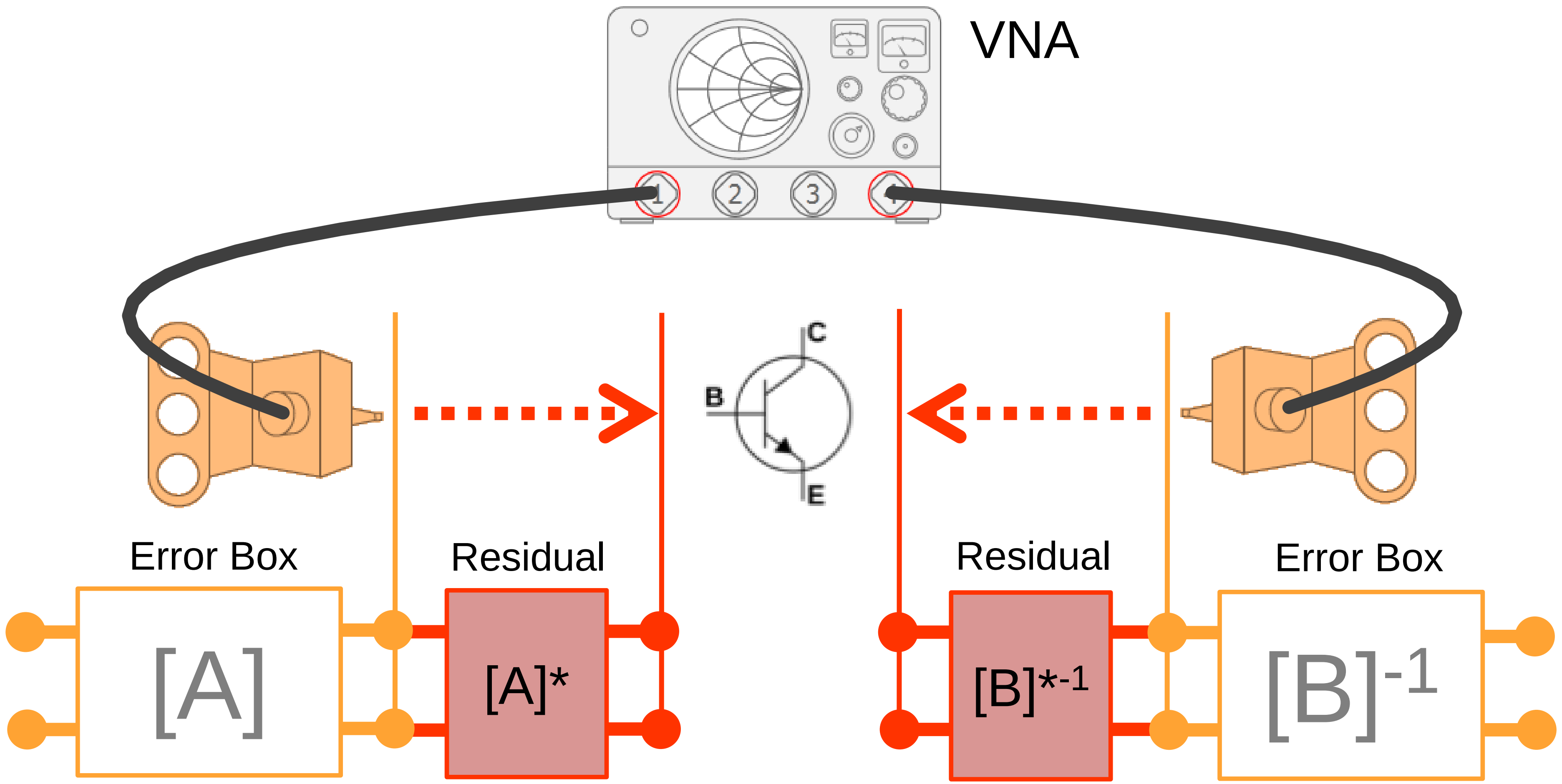
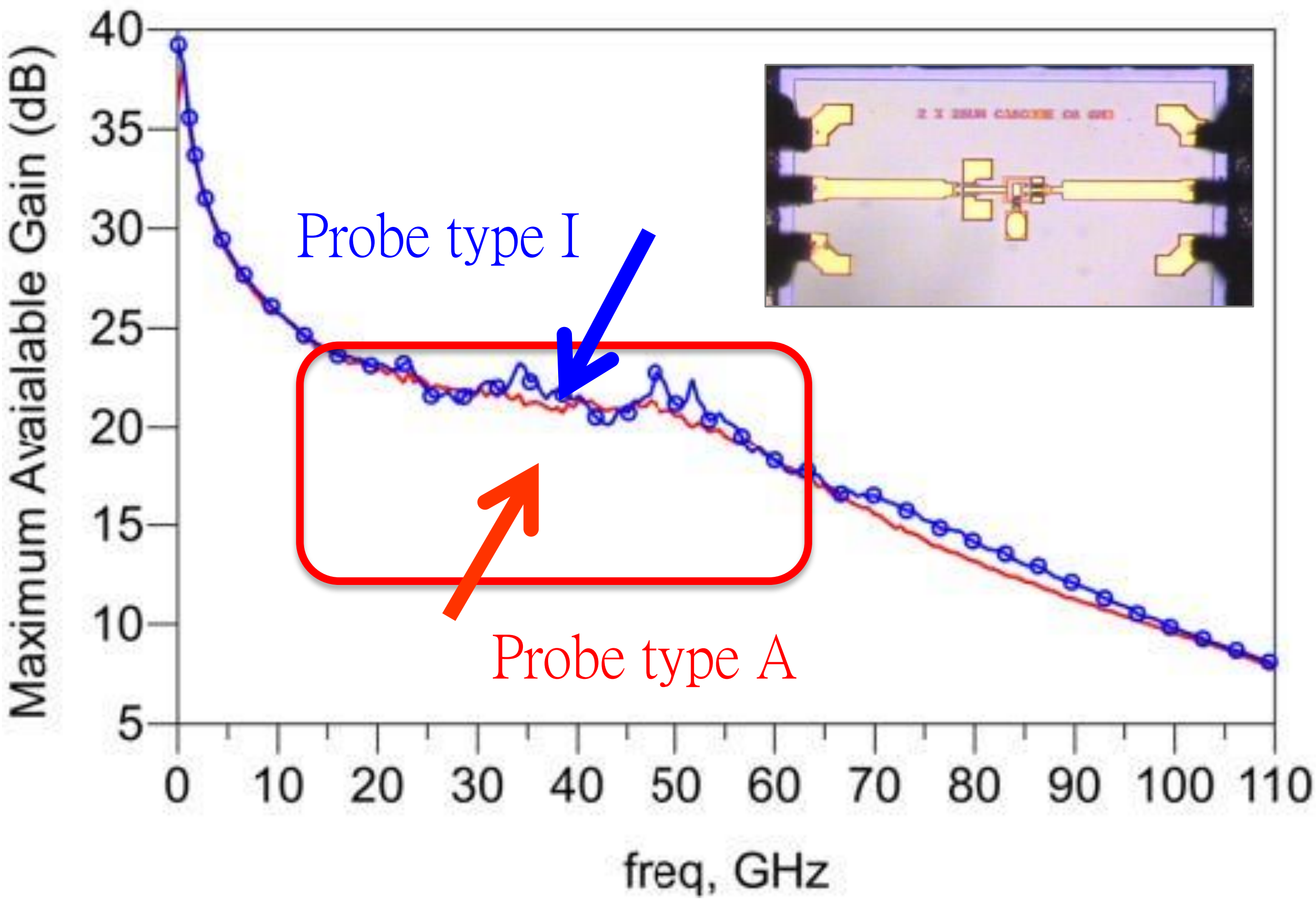
Calibration



Real Situation: Residual Errors



Example: MAG 2x25µm Cascode Cell

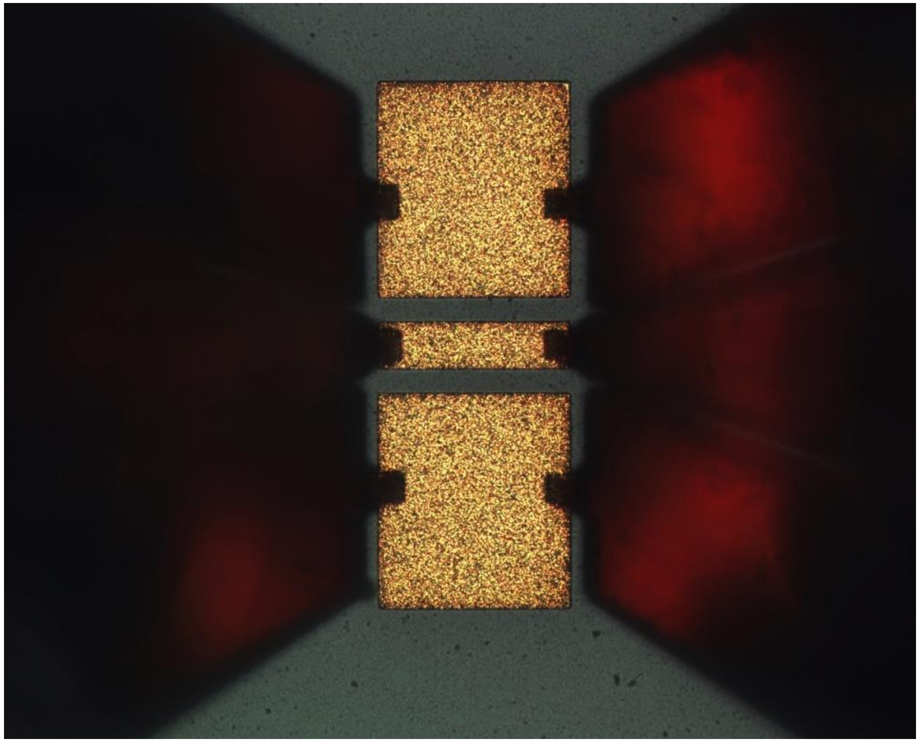


Shinghal, P.; Sloan, R.; Duff, C.I.; Cochran, S., "Observations on the sensitivity of on-wafer cascode cell S-parameter measurements due to probing uncertainties," *ARFTG Microwave Measurement Conference (ARFTG), 2014 83rd*, vol., no., pp.1,3, 6-6 June 2014

Sources of Calibration Residual Errors

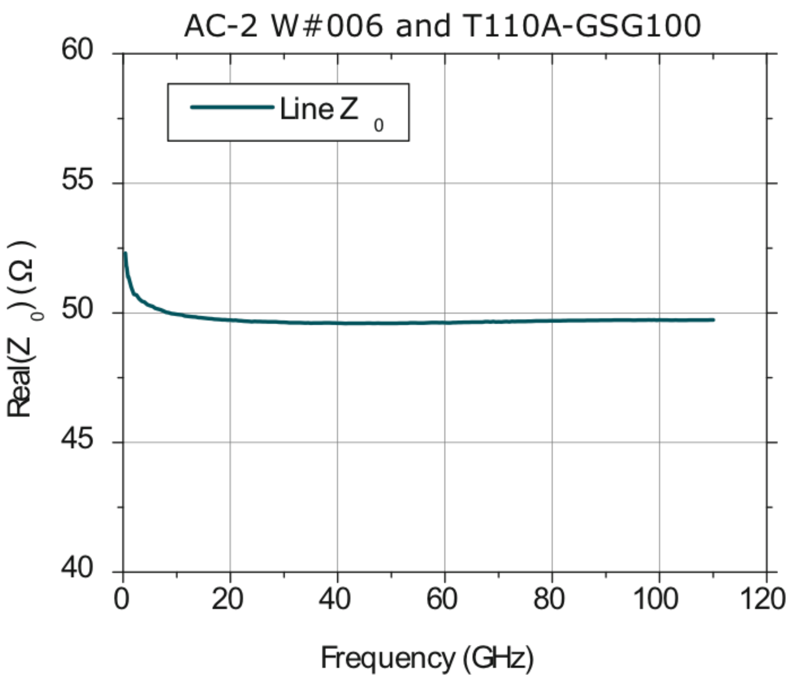
- Inaccuracies of calibration standards
  - Design, fabrication and probe positioning
- Higher-order mode propagation
  - Calibration standards and DUT
- Coupling with nearby structures
  - Between elements
  - RF probes and elements
- Limitations of calibration methods

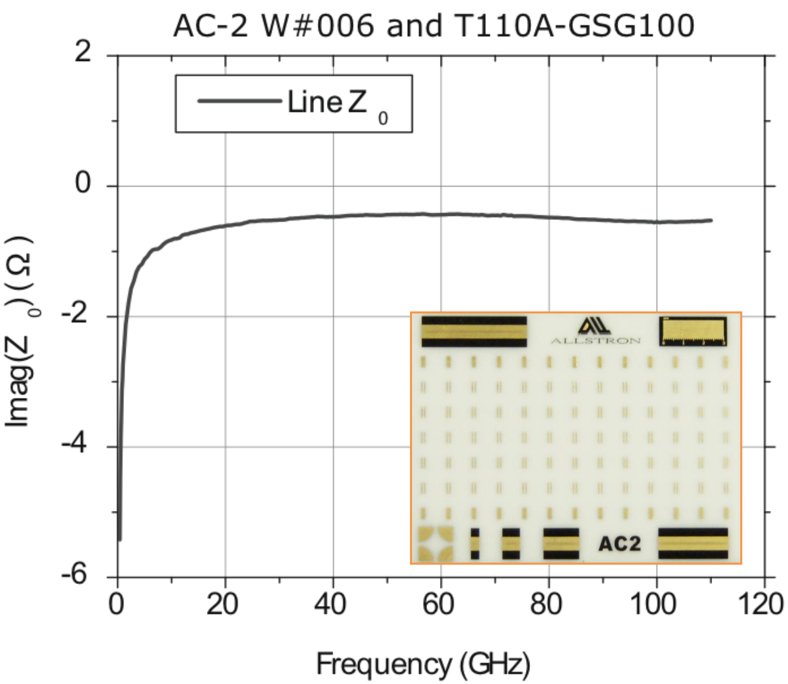
(Co)Planar Calibration Standards



- Dispersion
- Manufacturing inaccuracy
- Probe positioning

Dispersion: Example for AC-2



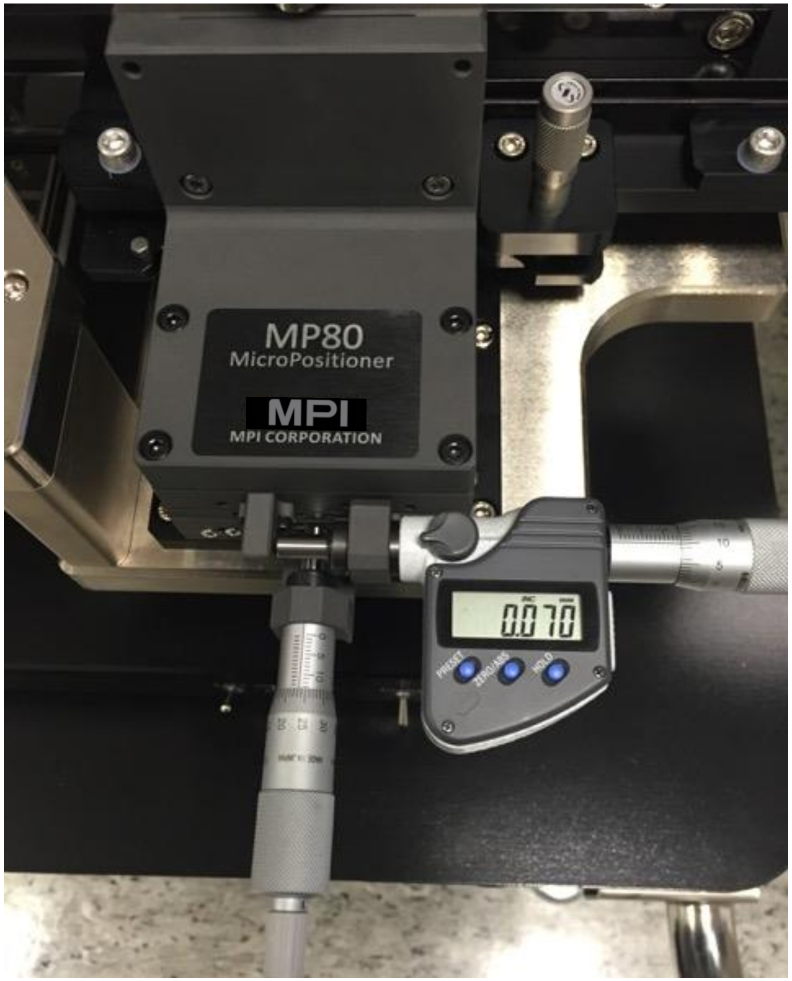


MPI Probe Selection Guide. MPI Corporation, Hsinchu, Taiwan, 2014

Operating with Multiple Lines

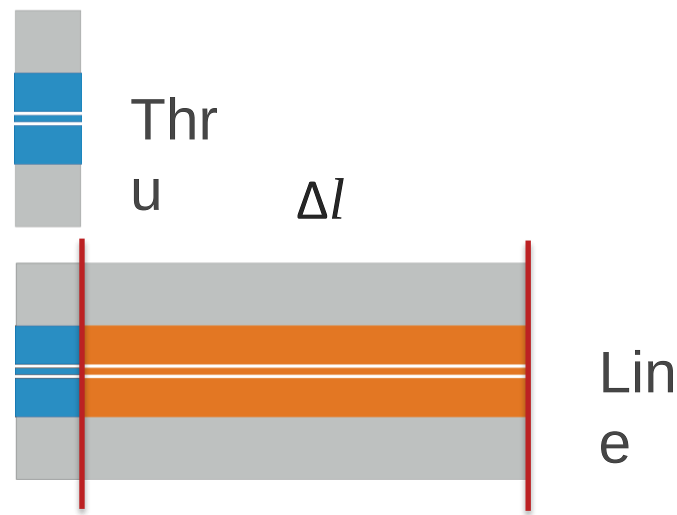
- Multiline TRL definition:
  - Offset of each line vs. Thru.
  - Just physical length, not electrical parameters needed
- Wafer-level multiline TRL system requirements:
  - Motorized positioner(s)
  - Typical positioning error +/- 5 micrometers
  - Painful investment

Minimize Positioning Error



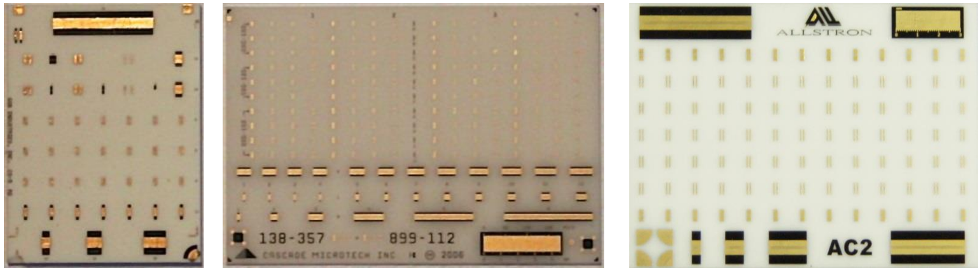
Picture: MPI

- Digital gauge for X-axes
- Positioning resolution 1µm
- Set/adjust/measure *Δl* for multilne TRL

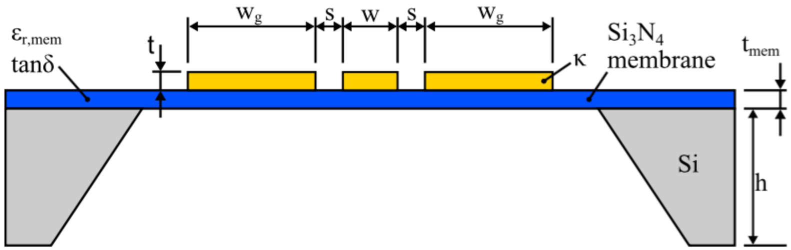


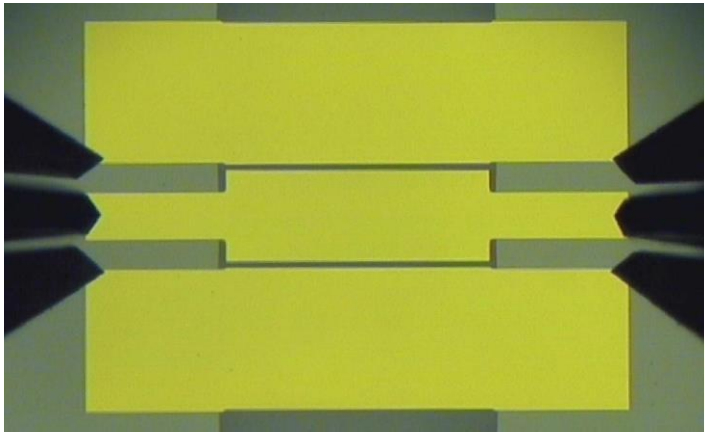
Membrane CPW Design for Improved Line Characteristics

Conventional CPW



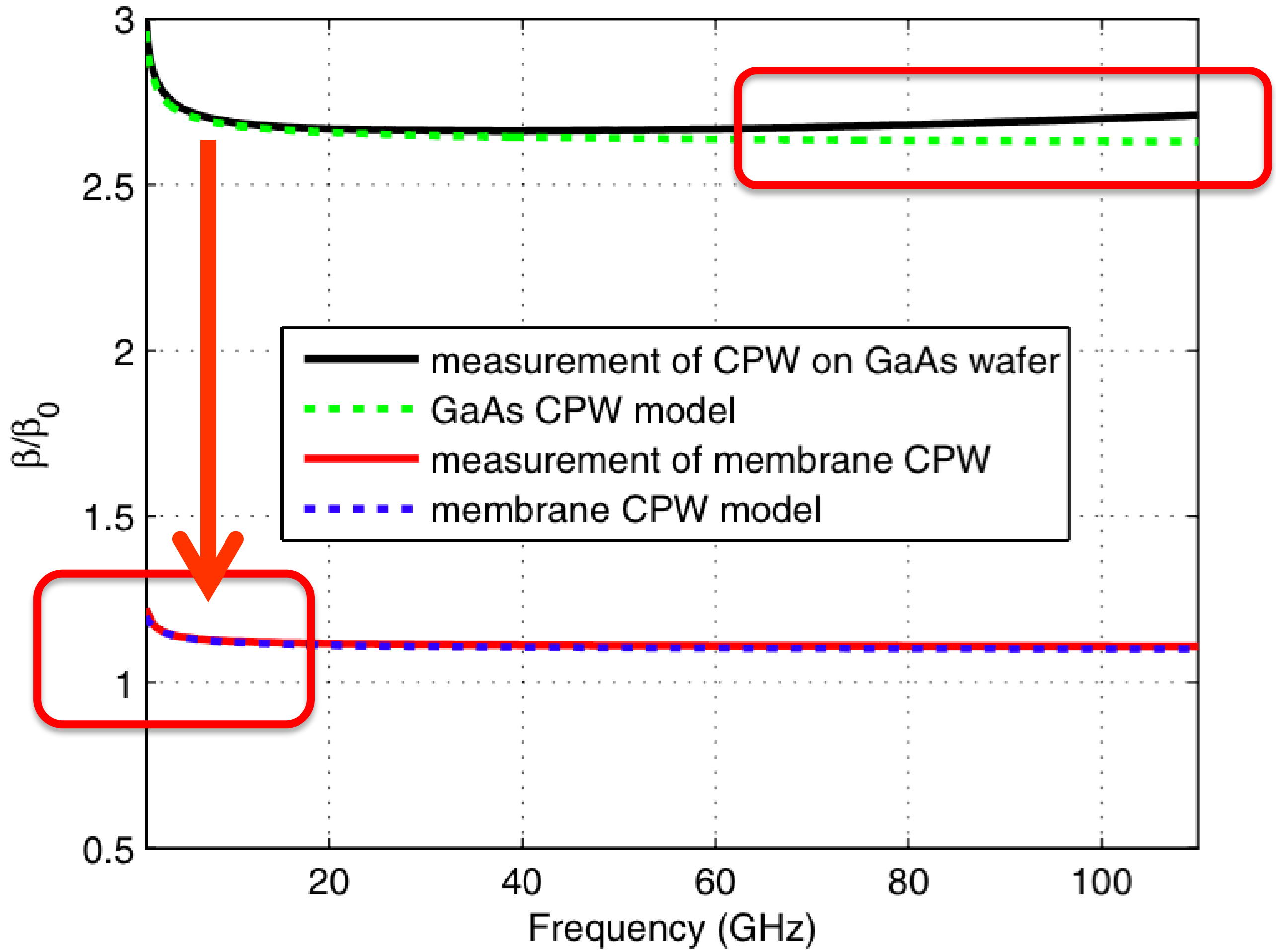
Membrane CPW





U. Arz, M. Rohland, and S. Büttgenbach, Improving the Performance of 110 GHz Membrane-Based Interconnects on Silicon: Modeling, Measurements, and Uncertainty Analysis, in *EEE Trans. on Components, Packaging and Manufacturing Tech.*, vol. 3, No. 11, Nov. 2013

Comparison for Relative Phase Constant



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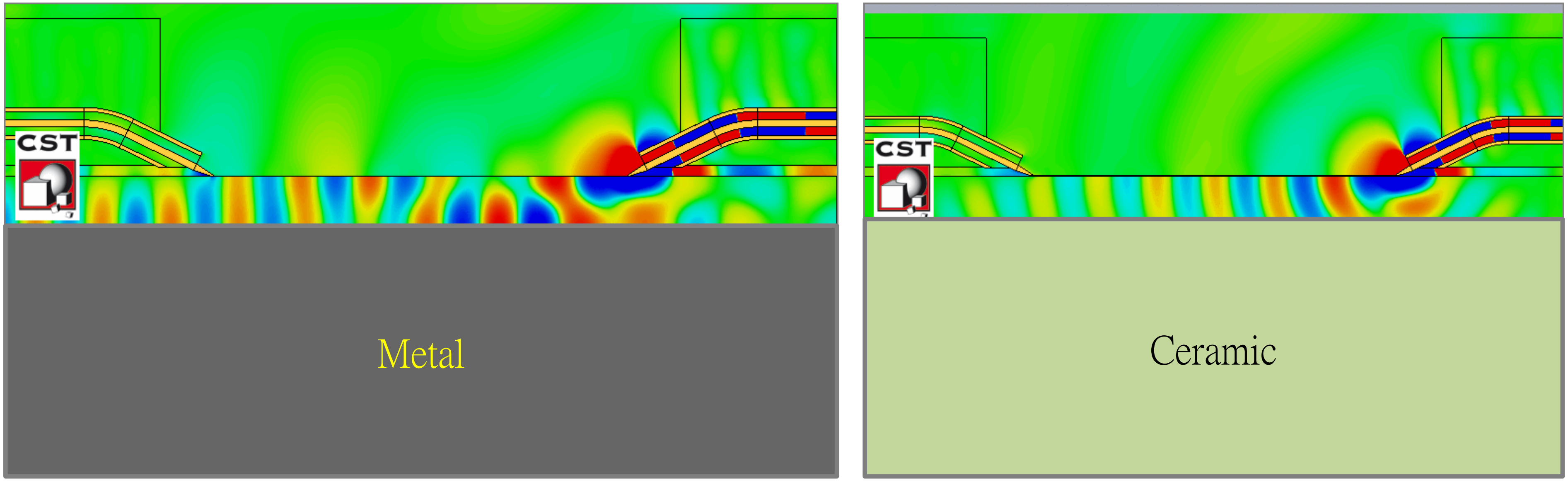
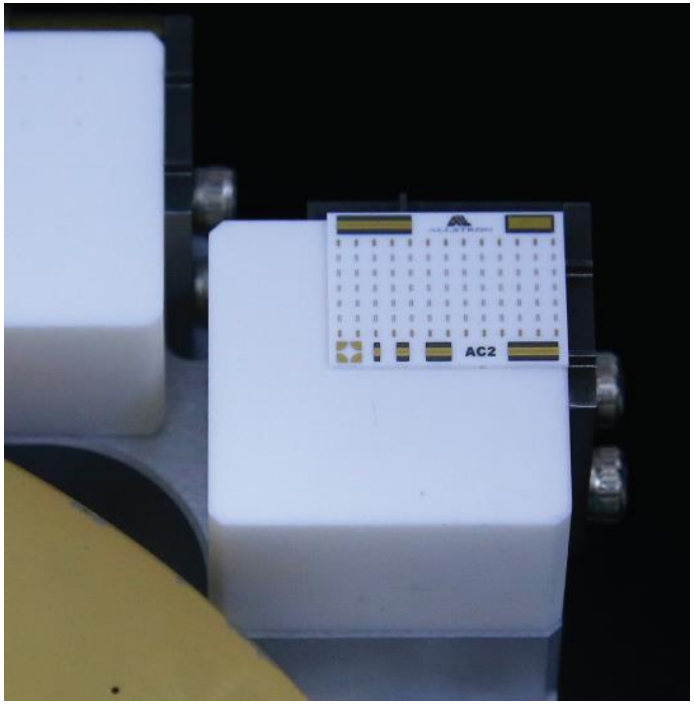
CPW Boundary Conditions

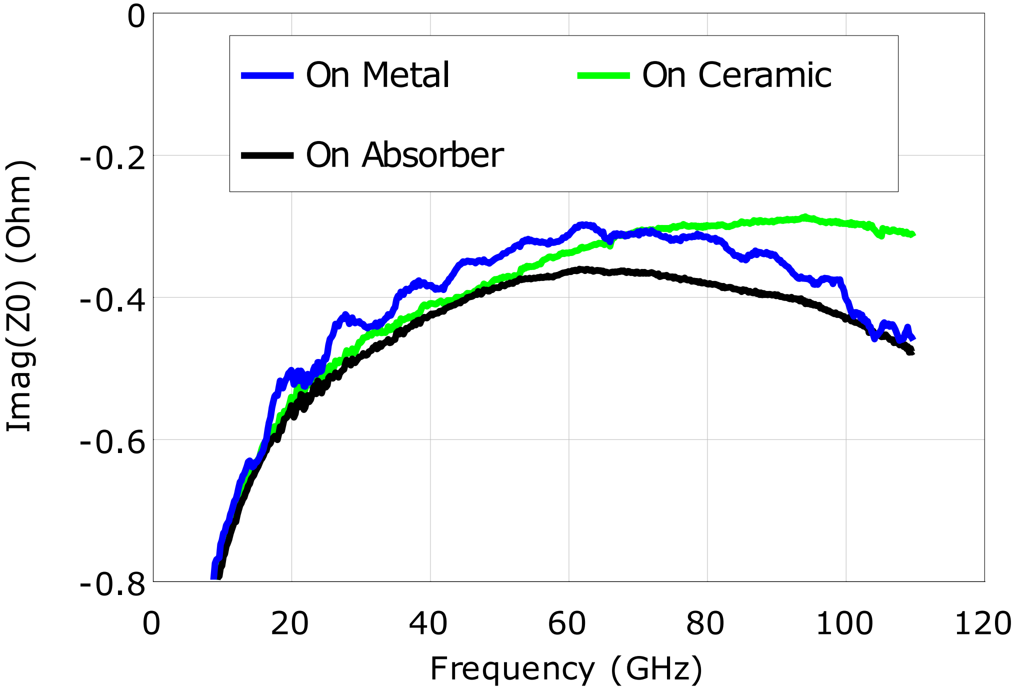
- Multi-mode propagation at mm-wave frequencies
- Critical for every calibration method



Courtesy: FBH, Berlin

Optimized Chuck Material



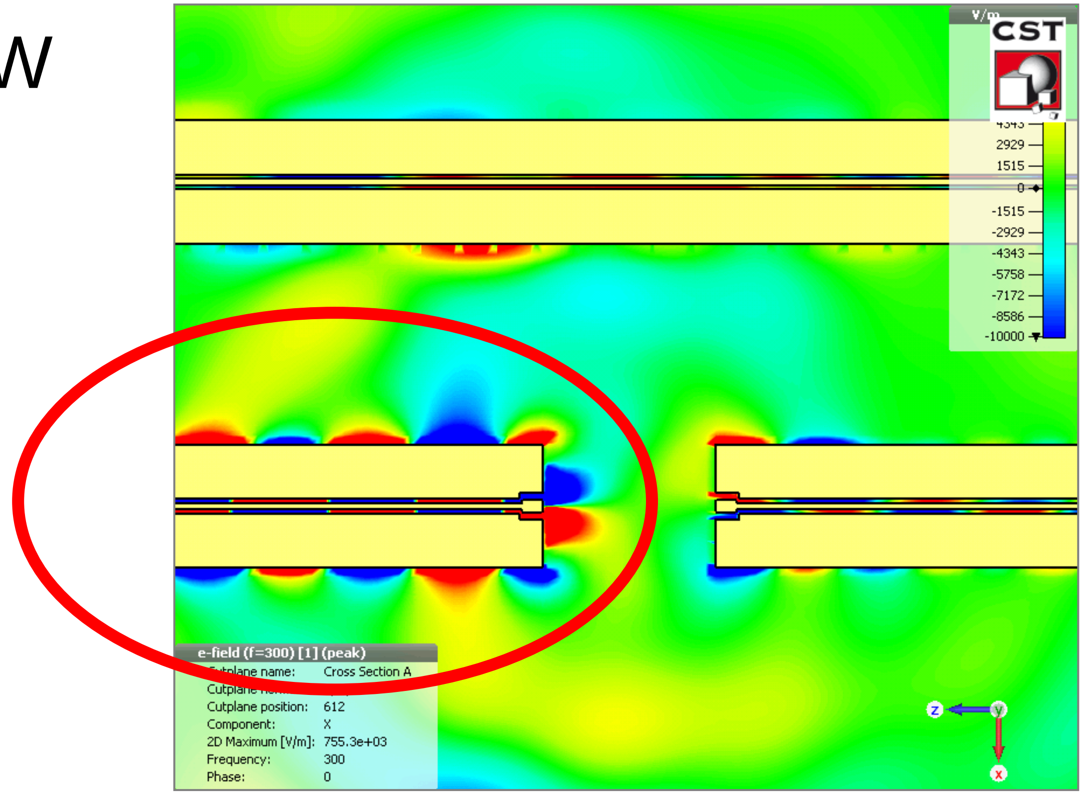


Picture: MPI

A. Rumiantsev, R. Doerner, and E. M. Godshalk, "The influence of calibration substrate boundary conditions on CPW characteristics and calibration accuracy at mm-wave frequencies," *ARFTG Microwave Measurements Conference-Fall, 72nd,* pp. 168-173, 2008.

Coupling with Nearby Structures

- Ex-field in the CPW
- CPW mode in the neighborhood

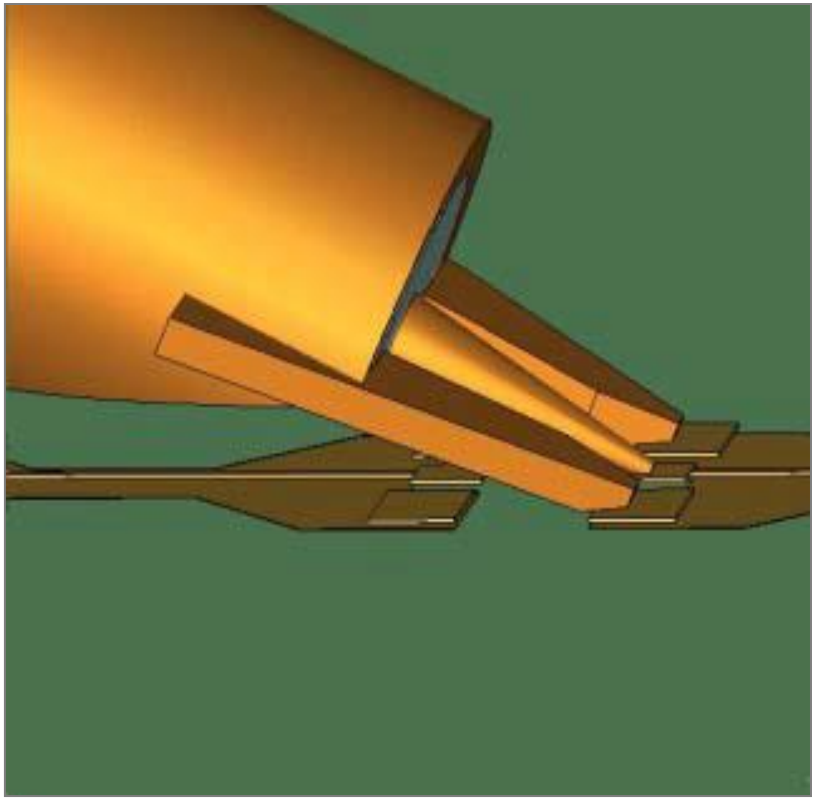


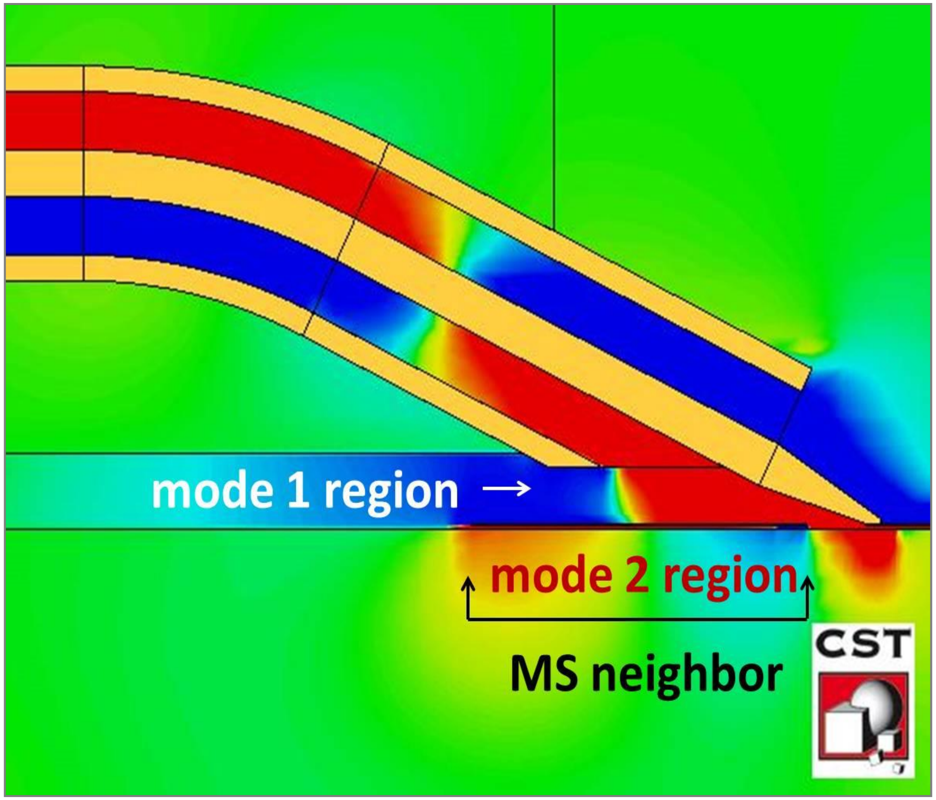
V. Krozer, R. Doerner, A. Rumaintsev, N. Weinmann, F. Schmückle, and W. Heinrich, On-Wafer Small- and Large- Signal Measurement Systems at sub-THz Frequencies, BCTM-2014, pp. 1-8, 2014.

Higher-Order Modes

- Coupling between probe ground and on-wafer ground:
  - Parasitic propagating signal
- Parallel-plate mode in substrate:
  - CPW ground and the backside ground
- Other modes guiding:
  - Between coaxial probe ground and wafer backside metallization

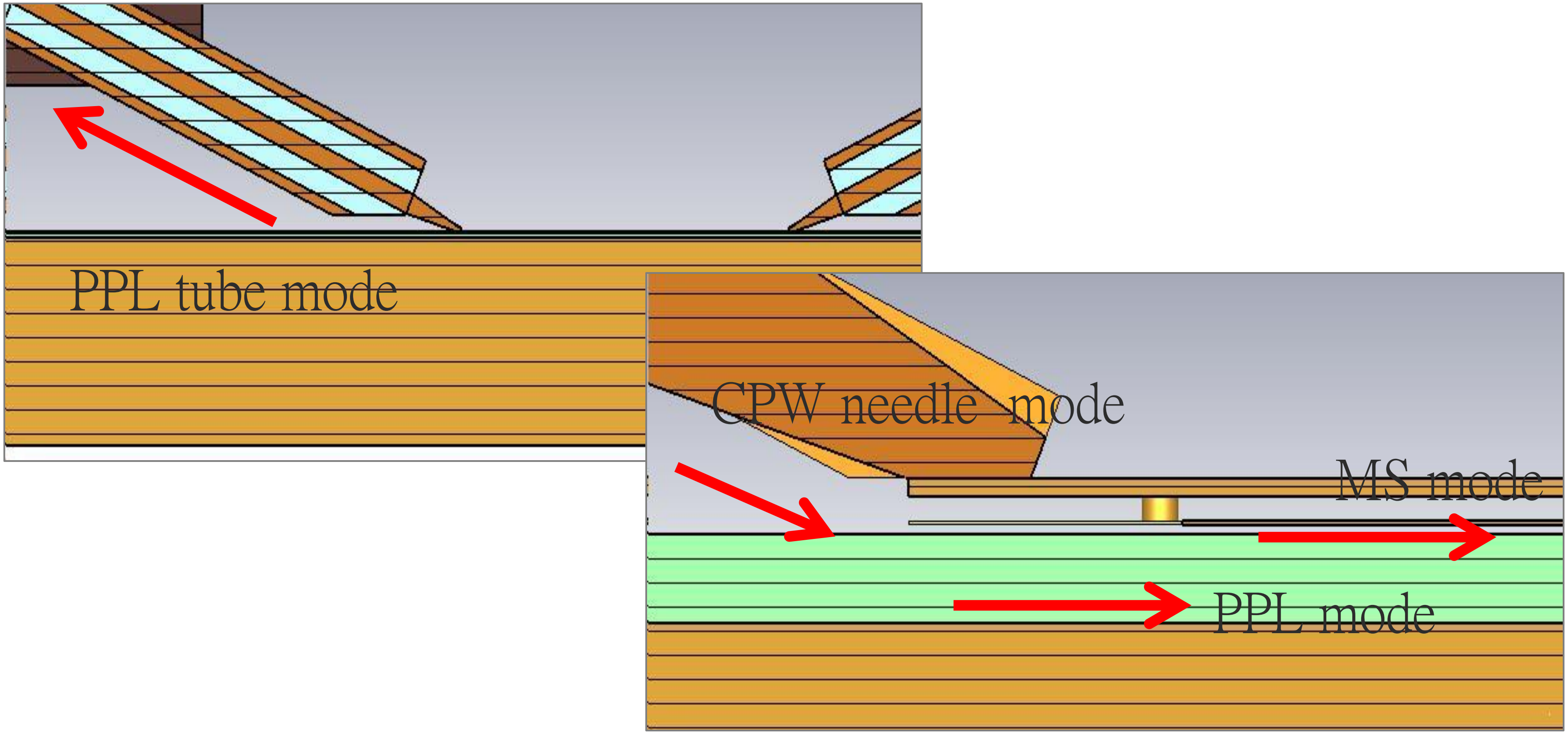
Coupling and Higher Modes





G.N. Phung, F.J. Schmückle, W. Heinrich, "Parasitic Effects and Measurement Uncertainties in Multi-Layer Thin-Film Structures," Proc. 43th European Microwave Conf. (EuMC 2013), Nuremberg, Germany, Oct. 7-10, pp. 318-321

Coupling and Higher Modes: Microstip Elements



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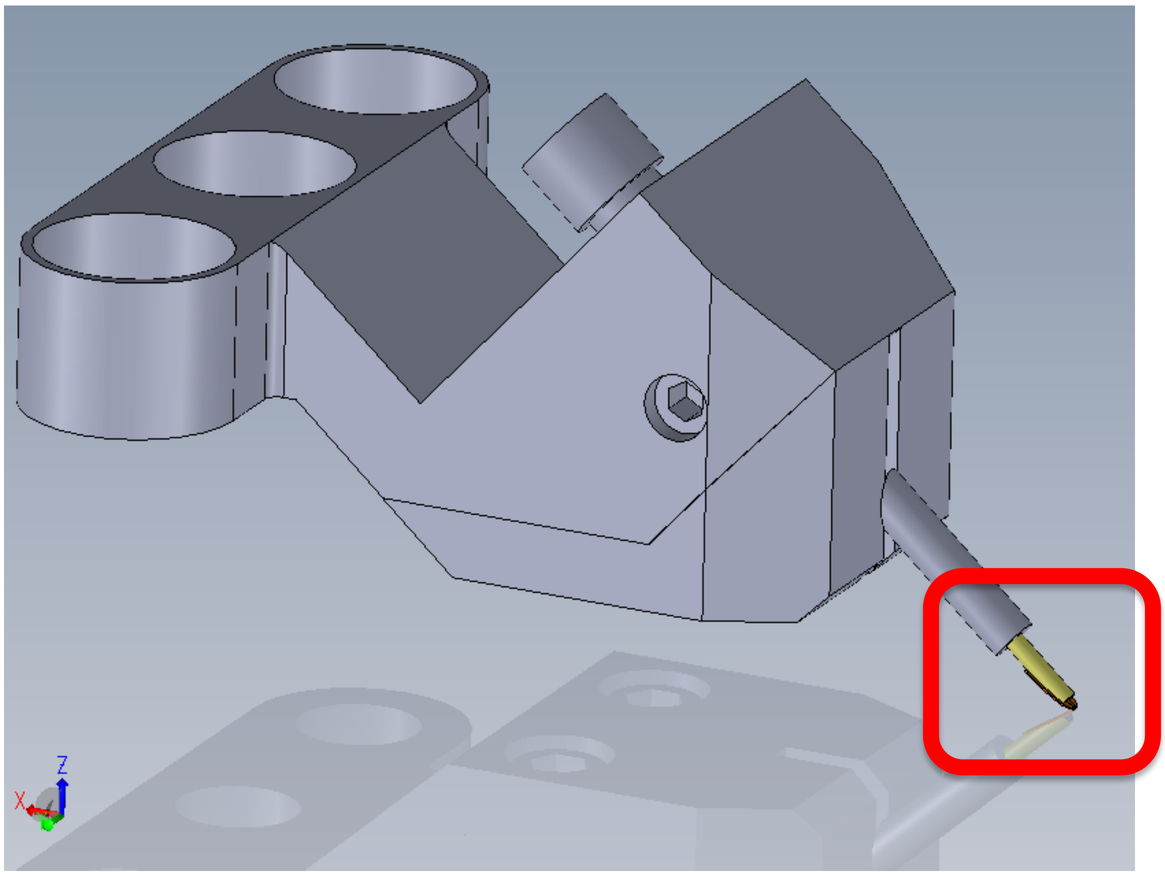
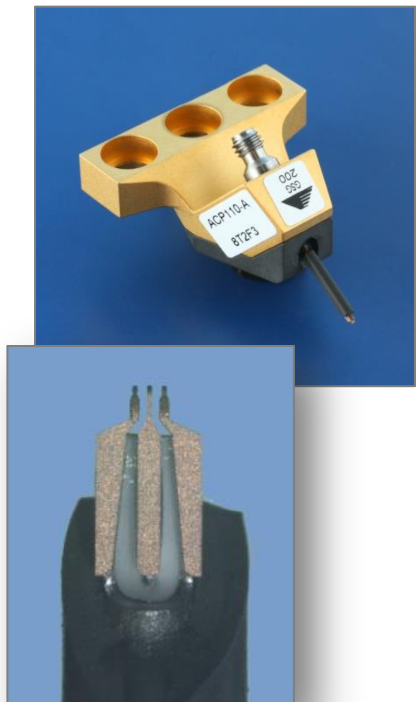
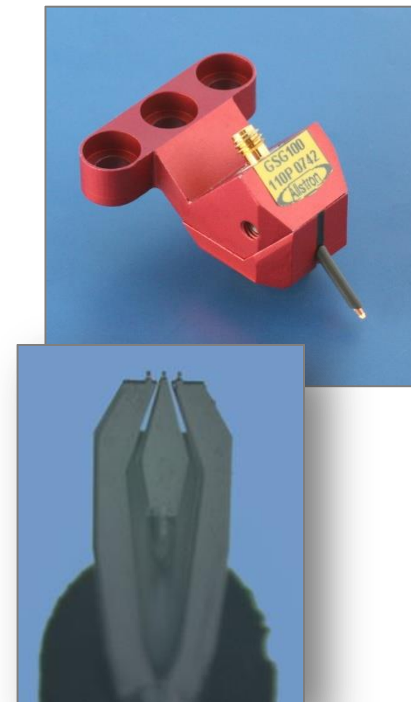
110 GHz RF Probe:
Similar Concept, Different Tip Design



RF Probe Design:
Coax-to-CPW Transmission Variety

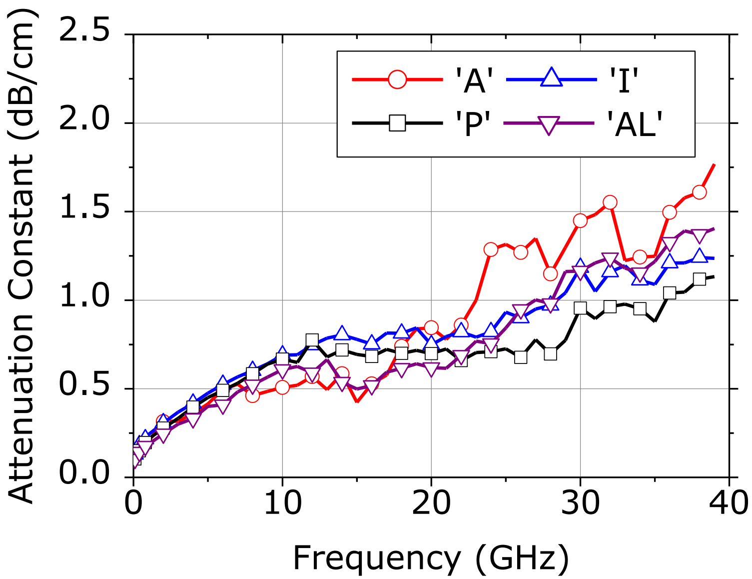
Picoprobe	ACP	Infinity	TITAN (Allstron)

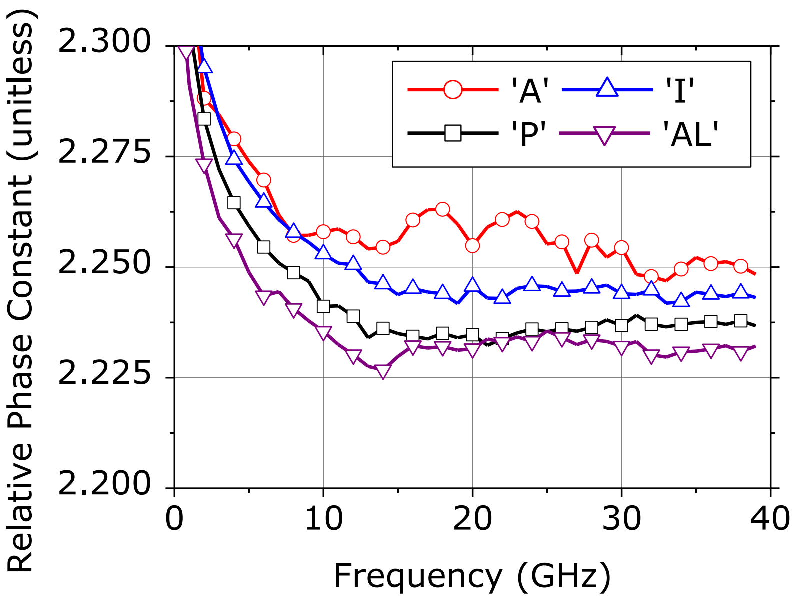




A. Rumiantsev and R. Doerner, "RF probe technology," *Microwave Magazine, IEEE,* vol. 14, pp. 46-58, 2013.

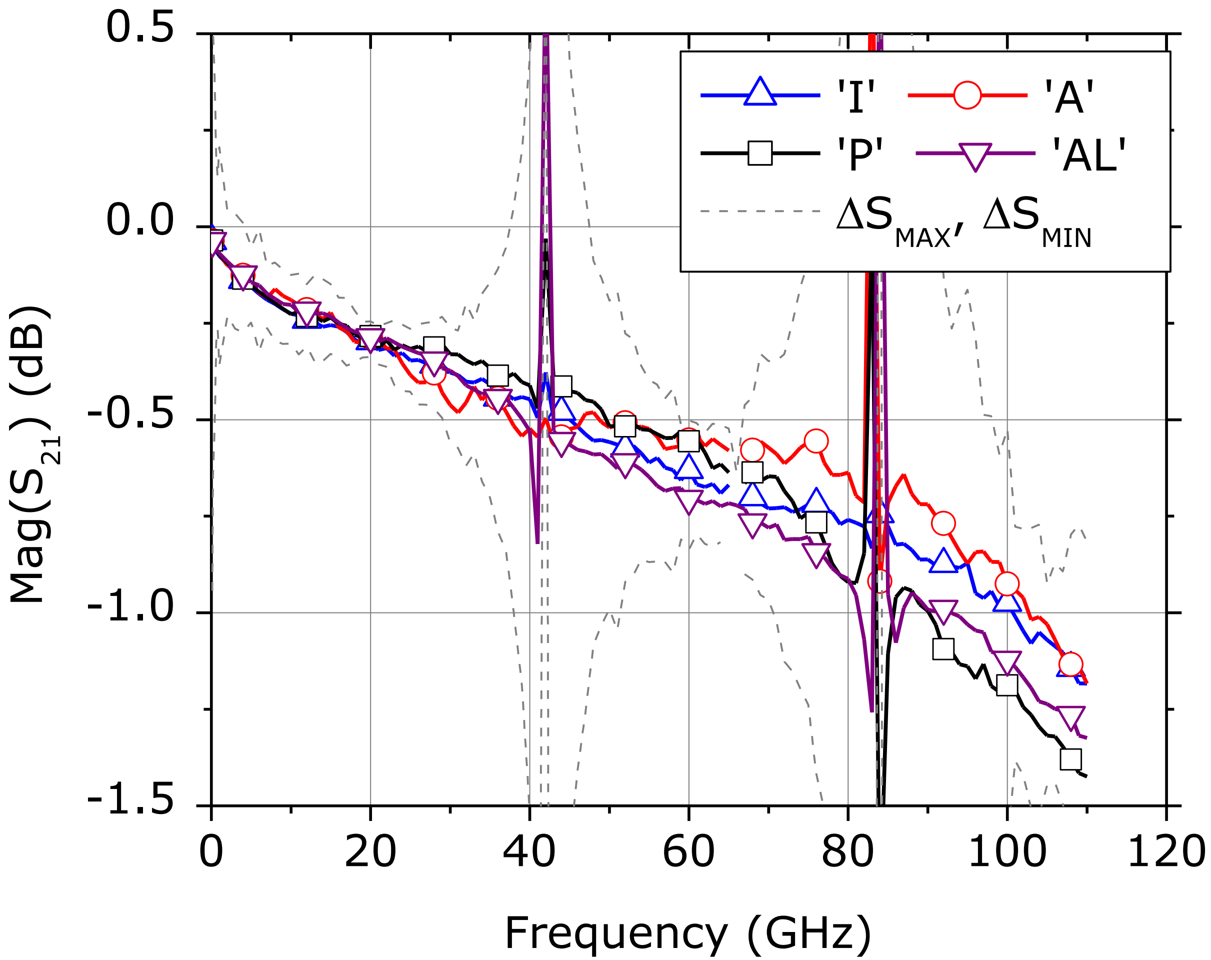
Impact of the Probe Tip Design





A. Rumiantsev, R. Doerner, Method for Estimating Probe-Dependent Residual Errors of Wafer-Level TRL Calibration, *ARFTG-83rd*, 2014.

Worst-Case Estimate: Error for Four Probe Technologies



A. Rumiantsev, R. Doerner, Method for Estimating Probe-Dependent Residual Errors of Wafer-Level TRL Calibration, *ARFTG-83rd*, 2014.

Outline

- Introduction
- Criteria for the “right method”
- Calibration residual errors
- Conclusion

Conclusion

- Calibration residual errors have complex nature
- Contributing factors:
  - Design of standards
  - Probe type
- Solutions for reference CPW line available
- Design optimization of the calibration chip:
  - Reduce support of higher-order modes
  - Minimize coupling effects

THANK YOU FOR YOUR ATTENTION

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