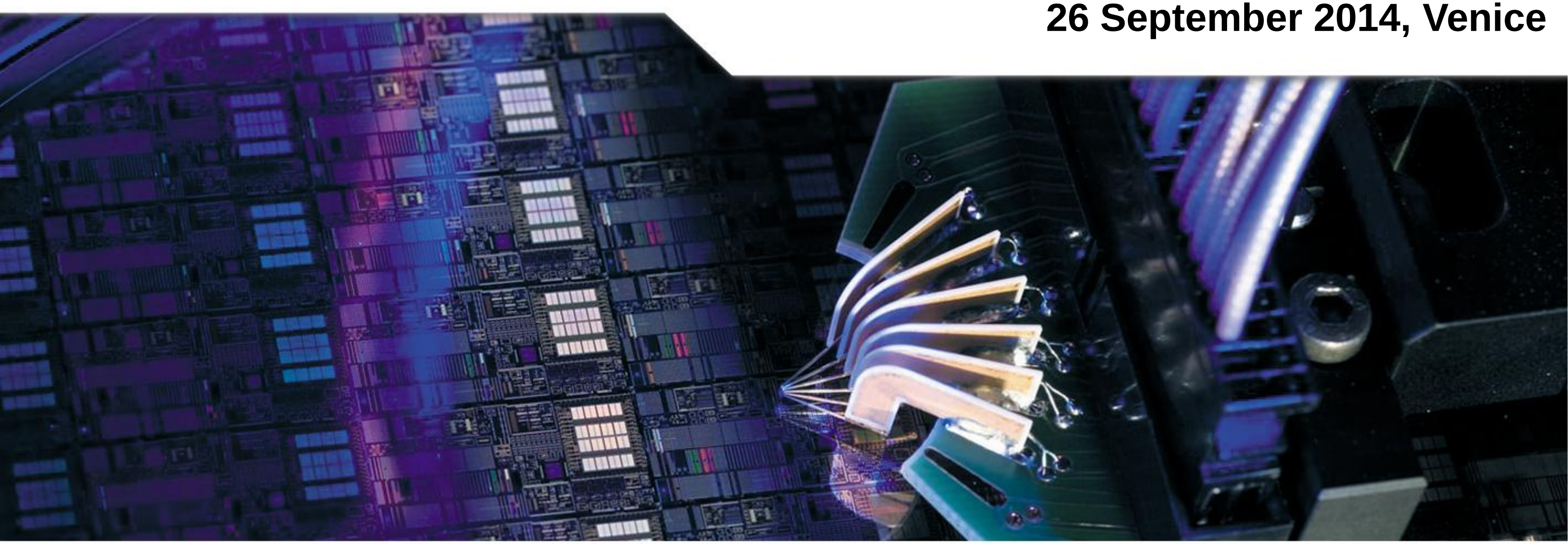
Title: *Measurement and characterization of circuits in the mm-wave and sub-THz range*

Author: Marco Spirito

Affiliation: TU Delft

THz-Workshop: Millimeter- and Sub-Millimeter-Wave circuit design and characterization

26 September 2014, Venice



A European Project supported within the Seventh Framework Programme for Research and Technological Development

Outline

- Motivations, needs and challenges at (sub)mm-wave
- EM simulation setup
- Multi-mode propagation in CPWs
    - PPW mode
    - CPW common mode
    - Surface wave modes
- Fused silica substrate
- TRL - *a quick recall*
- Measurement results
- Conclusions

Motivations

- SiGe bipolar technology is continuously increasing the device max operating frequencies (i.e., f_T and f_{max}), and currently approaching 0.5THz [Hei10].
- The current development of SiGe HBTs, in EU, is supported by several public research funded projects.

Technology development

Applications

Technology and Demos

[Hei10] B. Heinemann et al. "SiGe HBT technology with fT/fmax of 300GHz/500GHz and 2.0 ps CML gate delay", IEDM Tech. Dig., pp. 688-691, 2010.

Needs at (sub)mm-wave

To fully exploit the capabilities of these advanced technologies and aim at commercial applications there is a strong need for:

- Accurate and verified models of active and passive (BEOL) at (sub)mm-wave.
- Large signal characterization of the transistor (both power and load pull).
- Noise characterization of devices and receiver chains.

All these measurement require accurate probe-level S-parameter calibrations as a first step.

(Sub)mm-wave challenges

What is different at (sub)mm-wave frequencies?

Measurement accuracy:

- Higher losses
- Lower available power, thus lower dynamic range

Wafer probes:

- Probe tips from the different vendors don't scale with frequency, always requiring ~20-25μm of signal line.

Calibration substrates:

- Substrate thickness (for single layer substrates) cannot scale linearly with frequency for mechanical stability (handling).

(Sub)mm-wave challenges

What is different at (sub)mm-wave frequencies?

Measurement accuracy:

- Higher losses
- L

CPW lines for probe-level calibration will <u>support several higher order modes</u>, which should be accounted for and minimized.

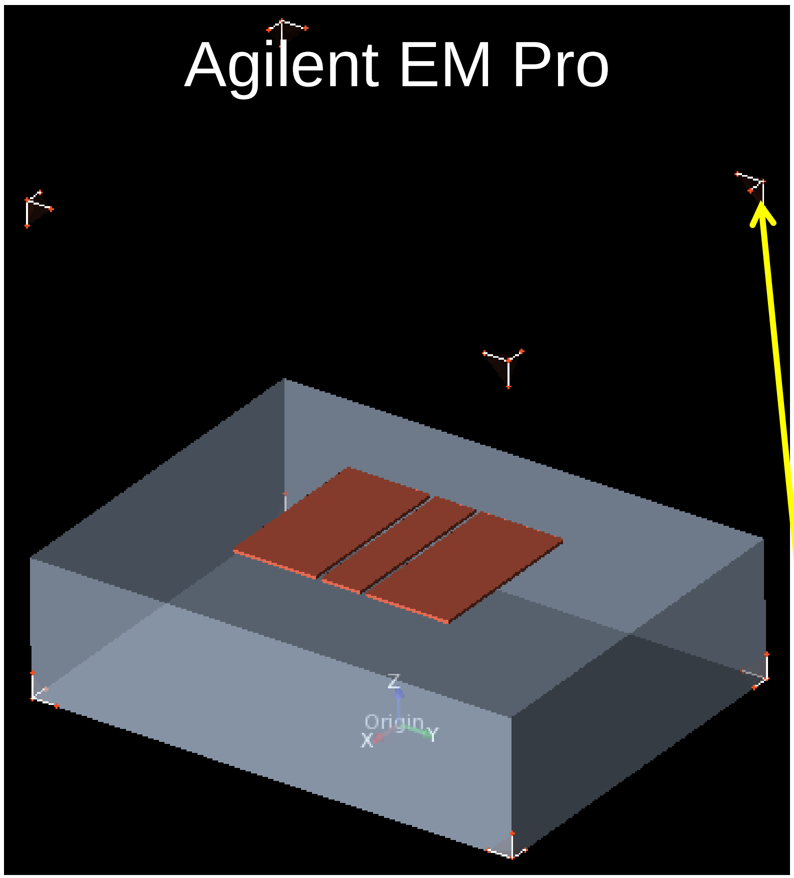
Wafer probes:

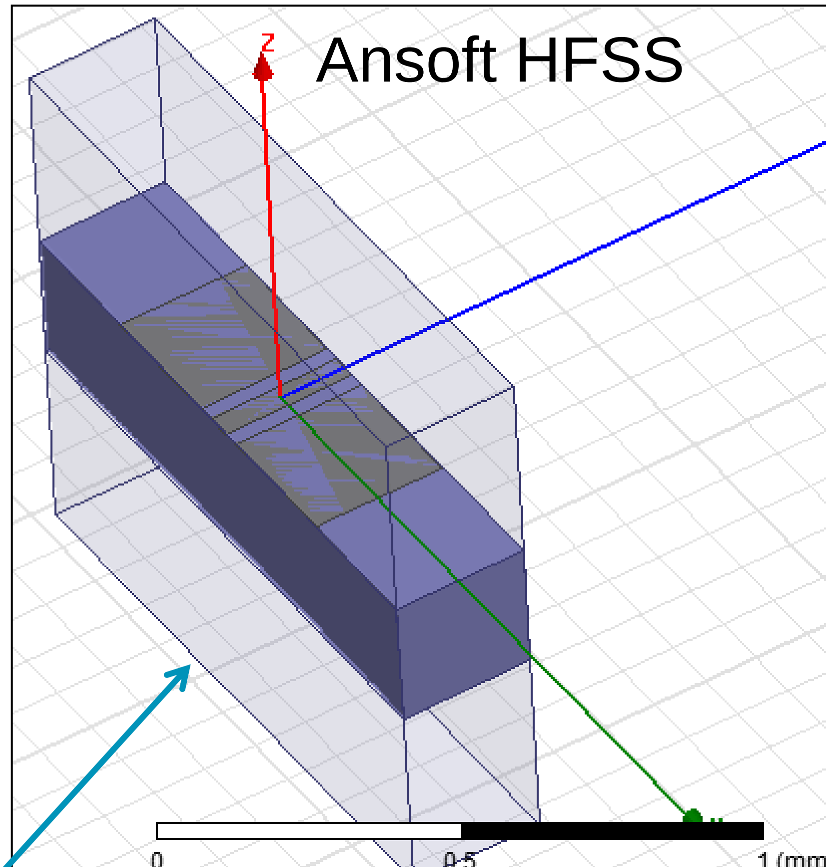
- Probe tips from the different vendors don’t scale with frequency, always requiring ~20-25μm of signal line.

Calibration substrates:

- Substrate thickness (for single layer substrates) cannot scale linearly with frequency for mechanical stability (handling).

EM simulation - environments

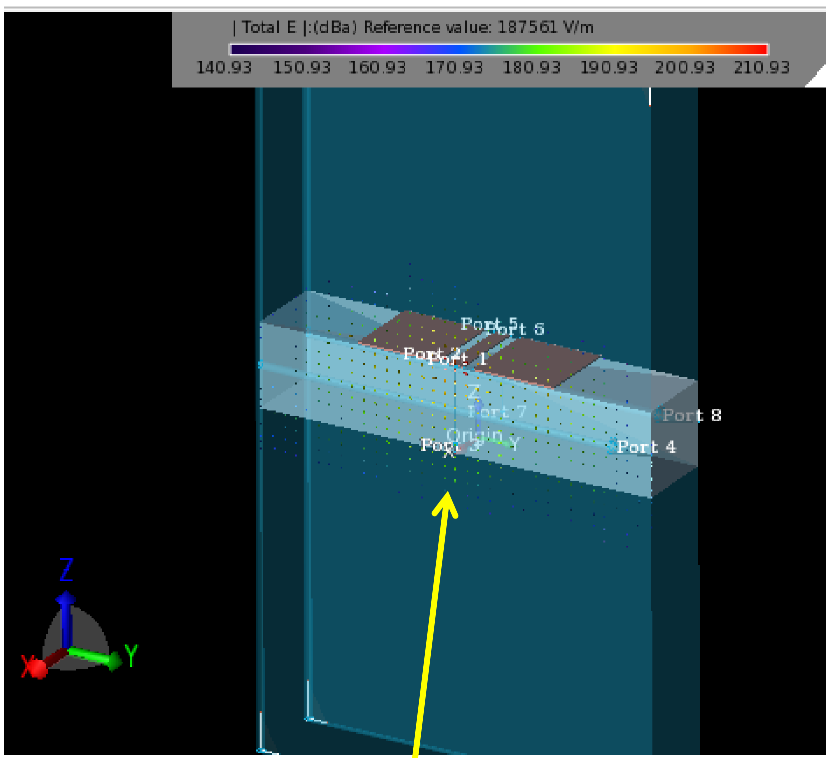




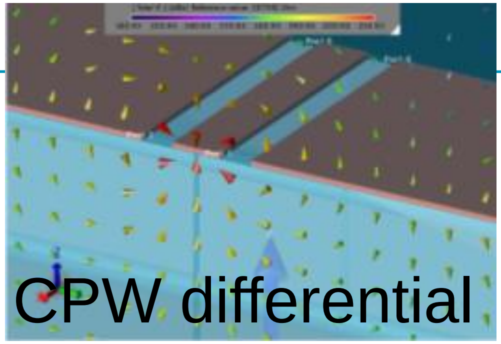
Simulation box: Air
Boundary: <u>Radiation</u> (solution region provides no edge reflection)

EM simulation - excitation

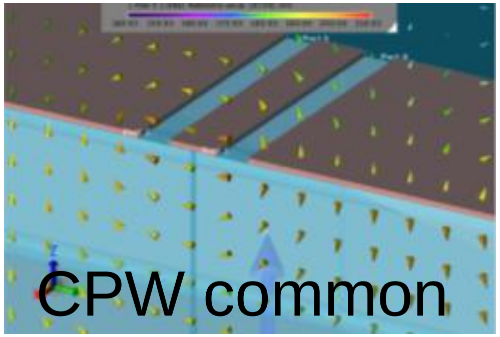
Waveguide ports are able to force and sense distinct EM waves (i.e., field distributions).



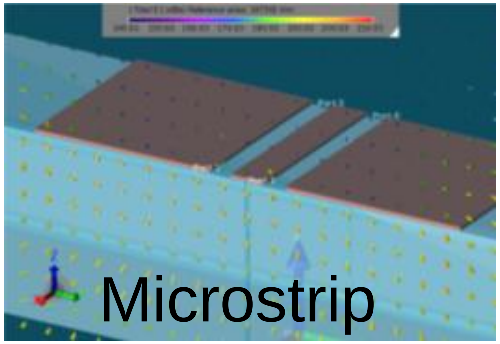
Multimode waveguide port



CPW differential



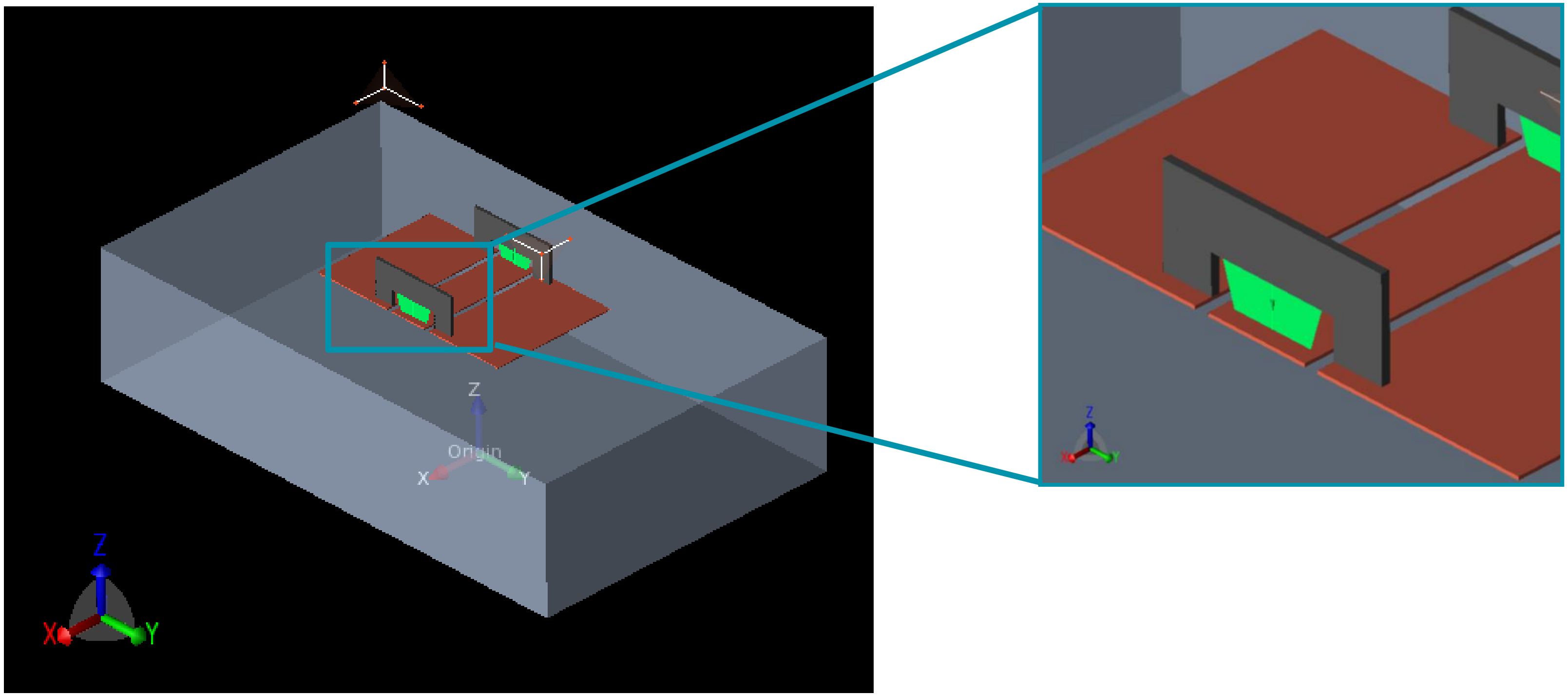
CPW common



Microstrip

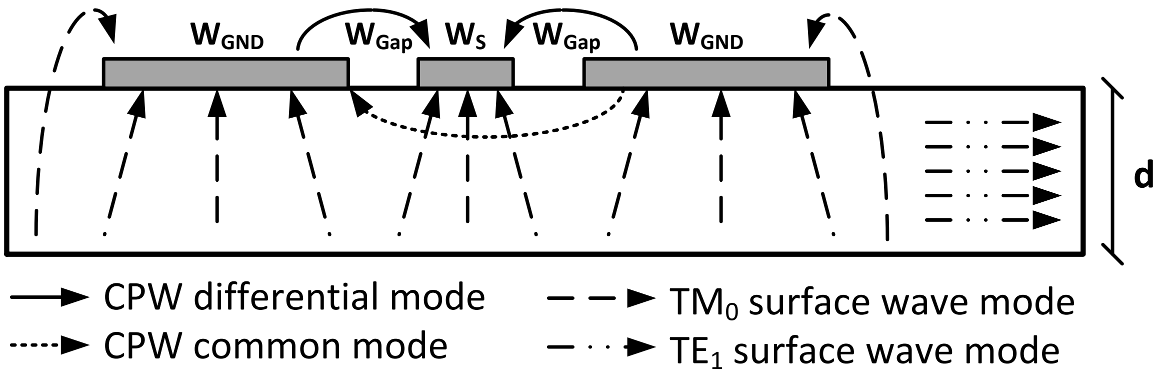
EM simulation - excitation

Lumped ports represent a point excitation and generate fields disturbance at the transition. The bridge is designed to provide low L and C.



Multi-modes in CPWs

Co-planar waveguide structures can support several modes, depending on the frequency and substrate characteristics.



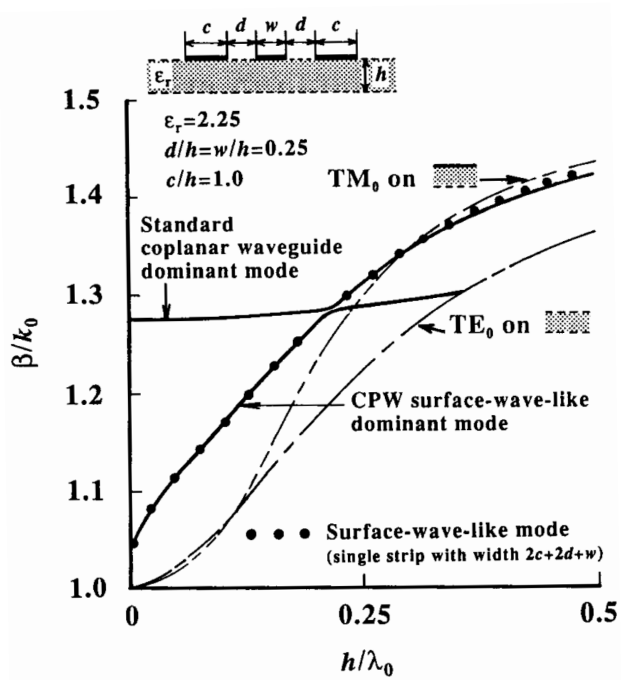
$$TM_n: \quad f_c = \frac{n \cdot c}{2 \cdot d \cdot \sqrt{\varepsilon_r - 1}} \quad n = 0, 1, 2 \ldots$$

$$TE_n: \quad f_c = \frac{(2 \cdot n - 1) \cdot c}{4 \cdot d \cdot \sqrt{\varepsilon_r - 1}} \quad n = 1, 2 \ldots$$

Parameter	W_S	W_{Gap}	W_{GND}	d	e_r
Value (in µm)	47.5	30	125	200	**9.9**
Metal: perfect electric conductor; dielectric: lossless alumina					

Multi-modes in CPWs

The various modes propagating on a given structure can be analyzed numerically by plotting the effective permittivity or the normalized wave number [Shige90].

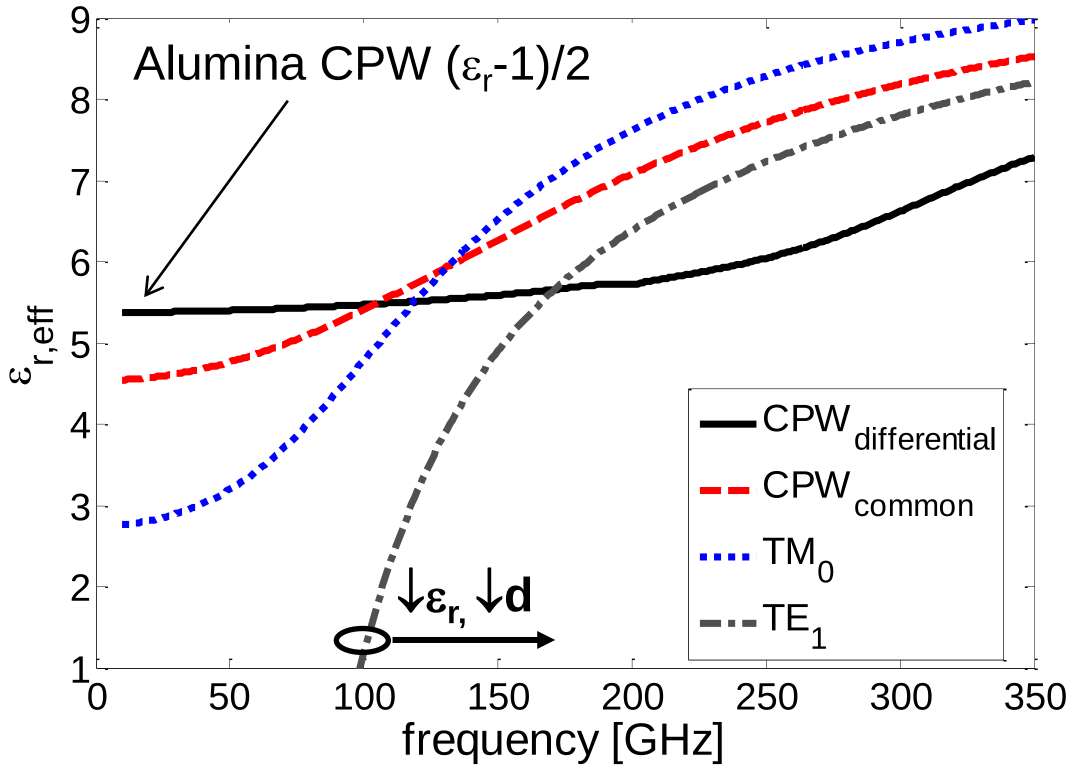


"At higher frequencies the value of β for CPW mode can become <u>lower</u> than that for the surface wave. For <u>*frequencies above that cross-over*</u> point, <u>*power will leak*</u> from the slot line mode into the surface wave and the propagation <u>*wavenumber will become complex*</u>" [Shige88]

[Shige88] H. Shigesawa, et al. IEEE MTT-S vol. 1, pp. 199-202, 1988.
[Shige90] H. Shigesawa, et al. IEEE MTT-S vol. 3, pp. 1063–1066, 1990.

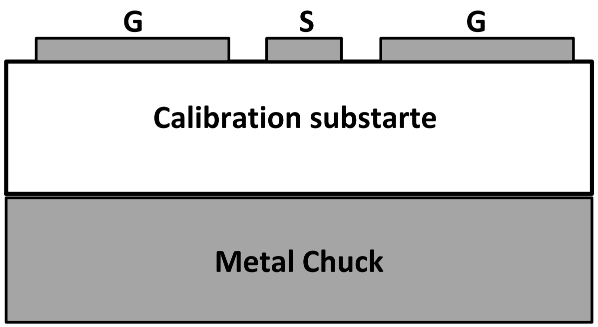
Multi-modes in CPWs

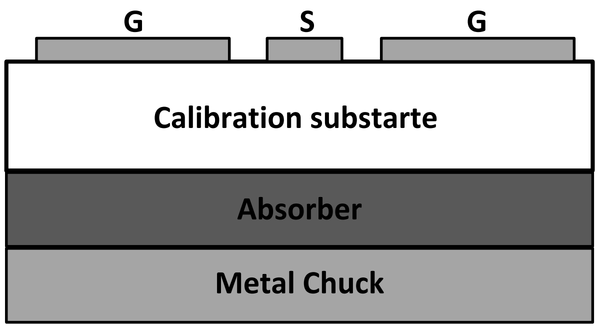
The various modes propagating on a given structures can be analyzed numerically by plotting the effective permittivity or the normalized wave number [Shige90].

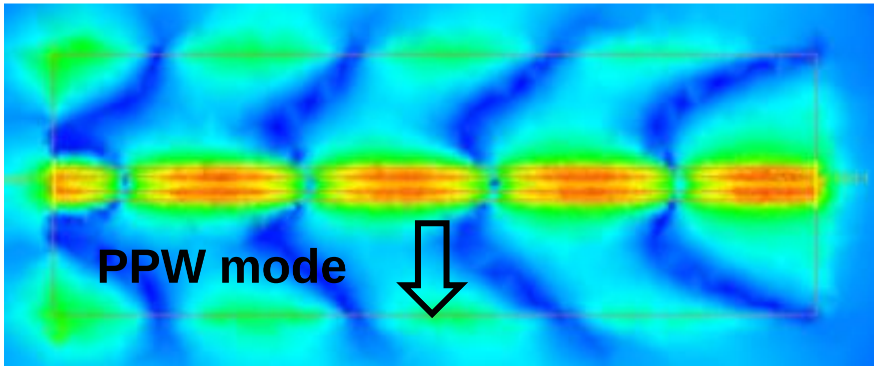


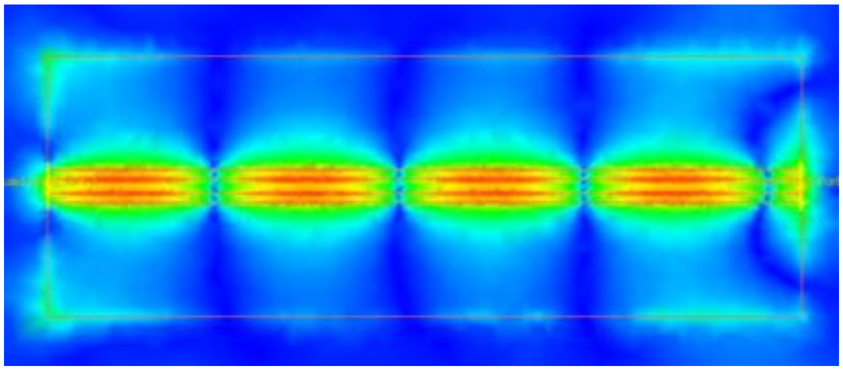
Multi-modes in CPWs - PPW

- During calibration the substrate is placed over a metallic chuck, thus supporting parallel plate waveguide (PPW) mode (CPWG).
- Absorbers can be used to suppress such mode.



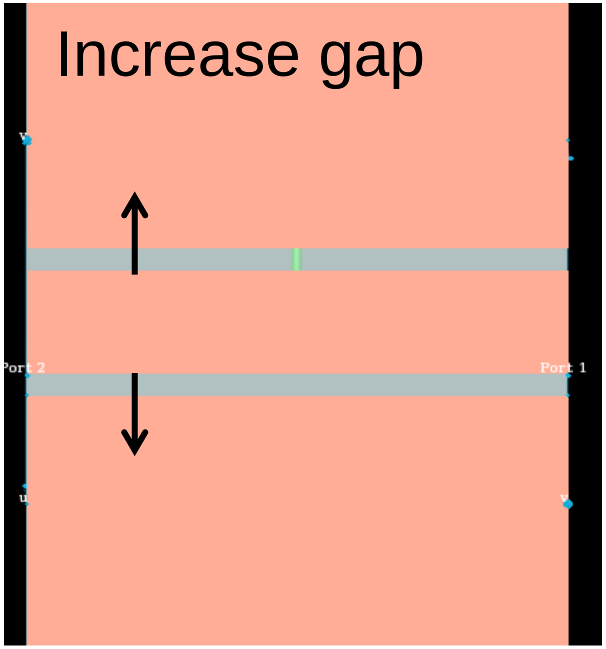


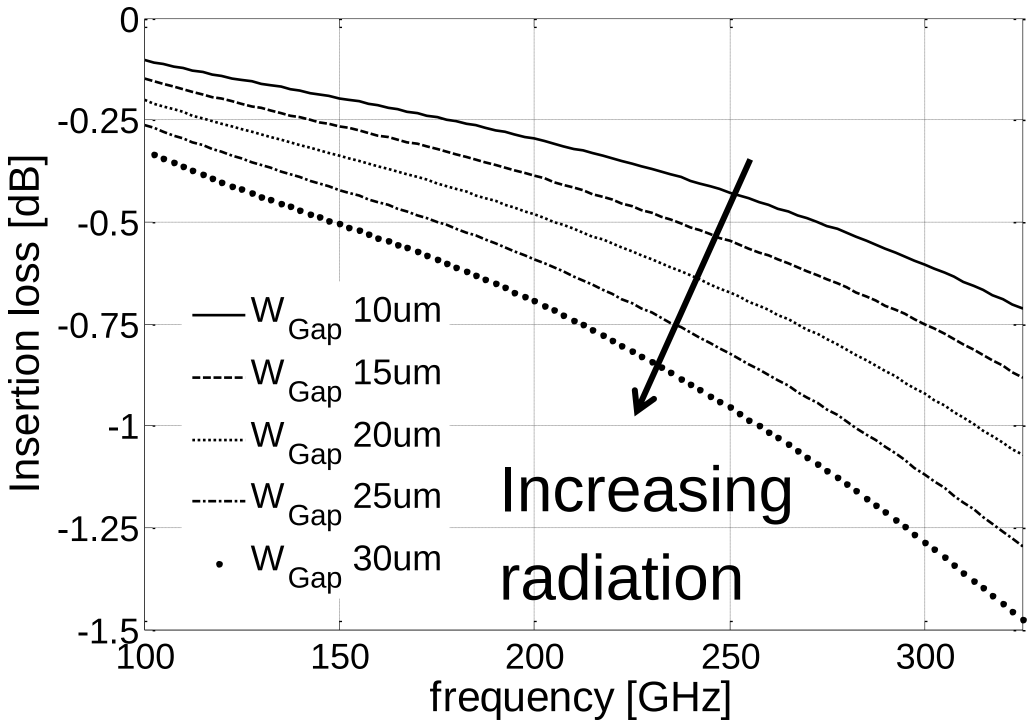




Multi-modes in CPWs – Common mode

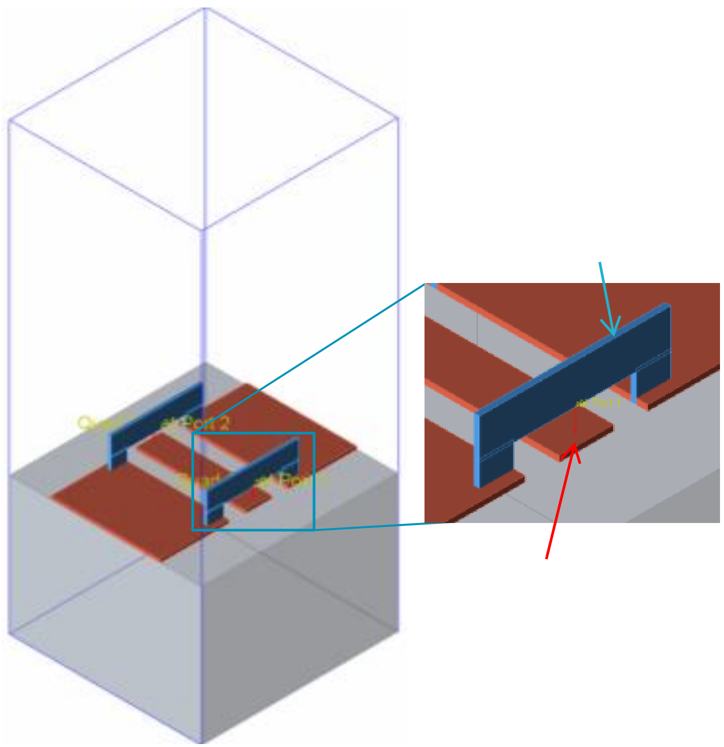
- Increasing the gap increases radiation due to the CPW common mode.
- Reducing the substrate ε_r allows to reduce the gap for a given Z_0 and W_{signal}.



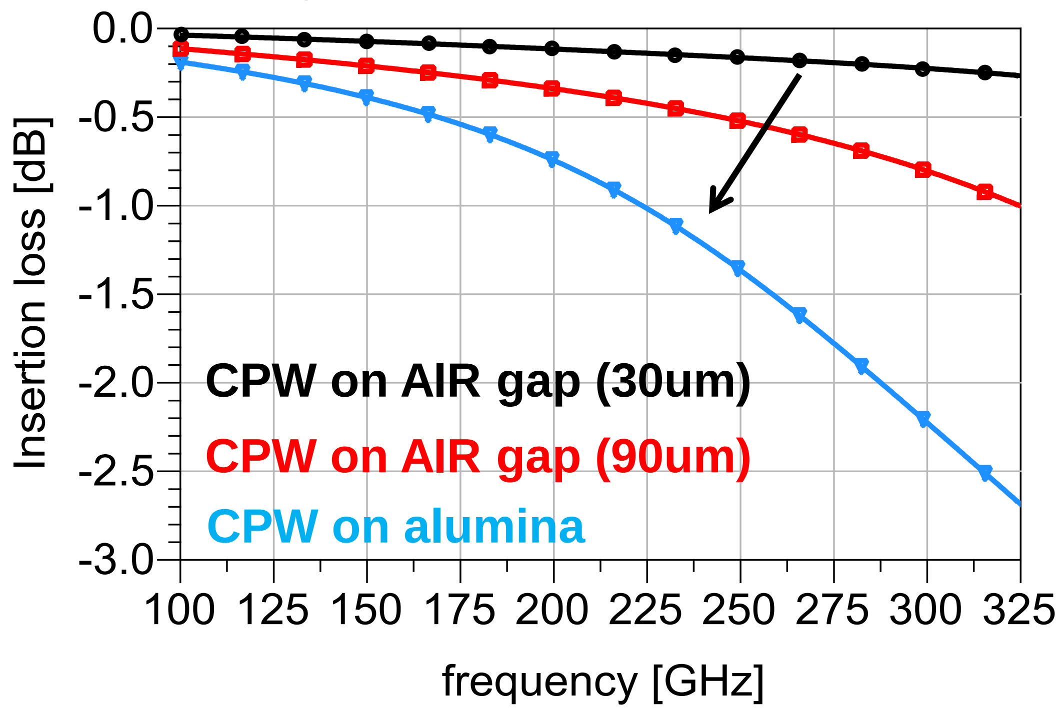


Multi-modes in CPWs - surface wave

- Surface waves modes propagate along the grounded dielectric slab.
- Losses due to surface waves can be analyzed comparing them with an ideal CPW air case.

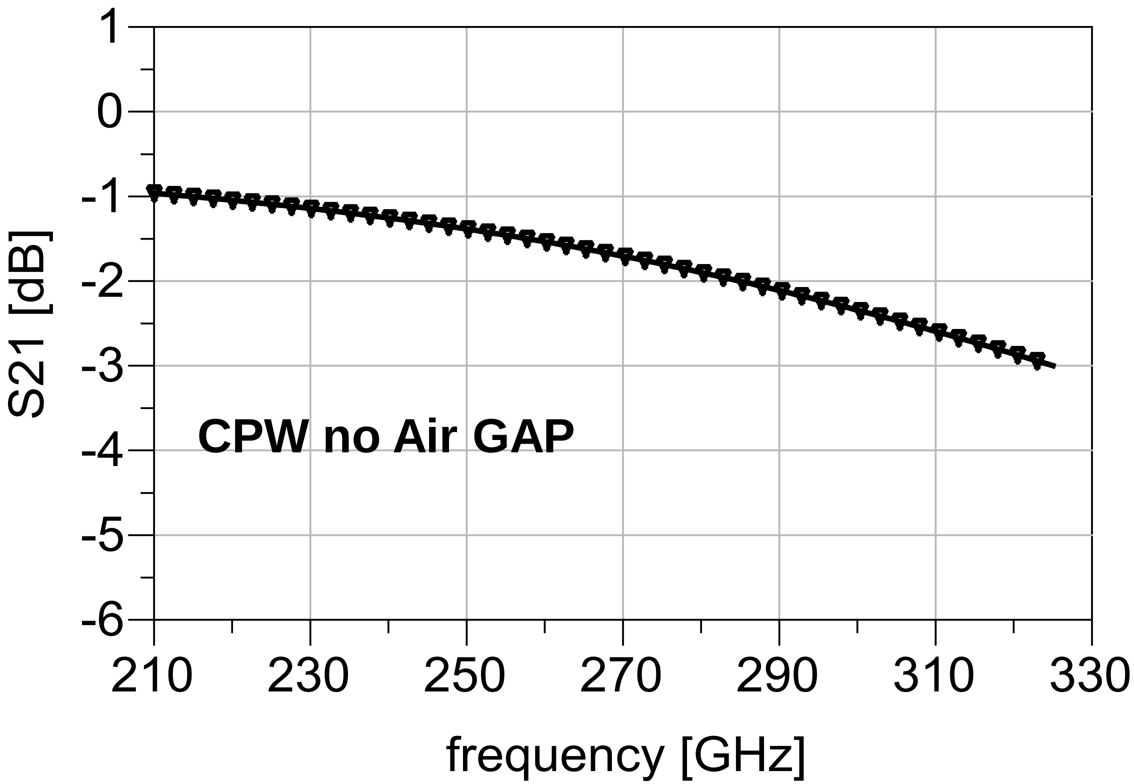


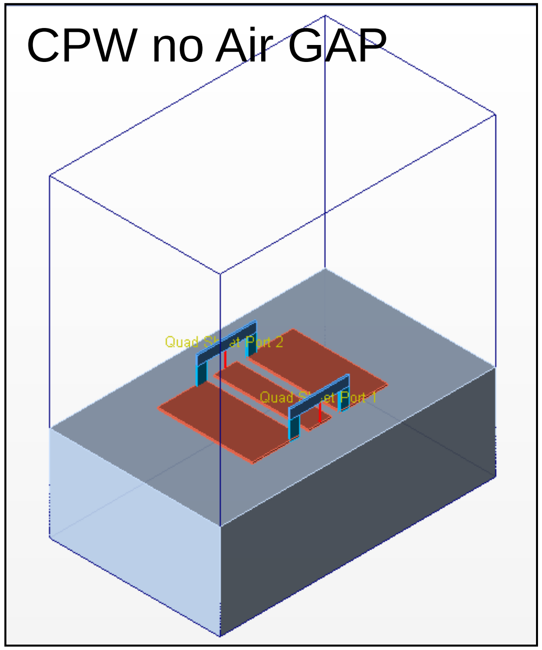
Increasing losses due to surface waves



Multi-modes in CPWs - surface wave

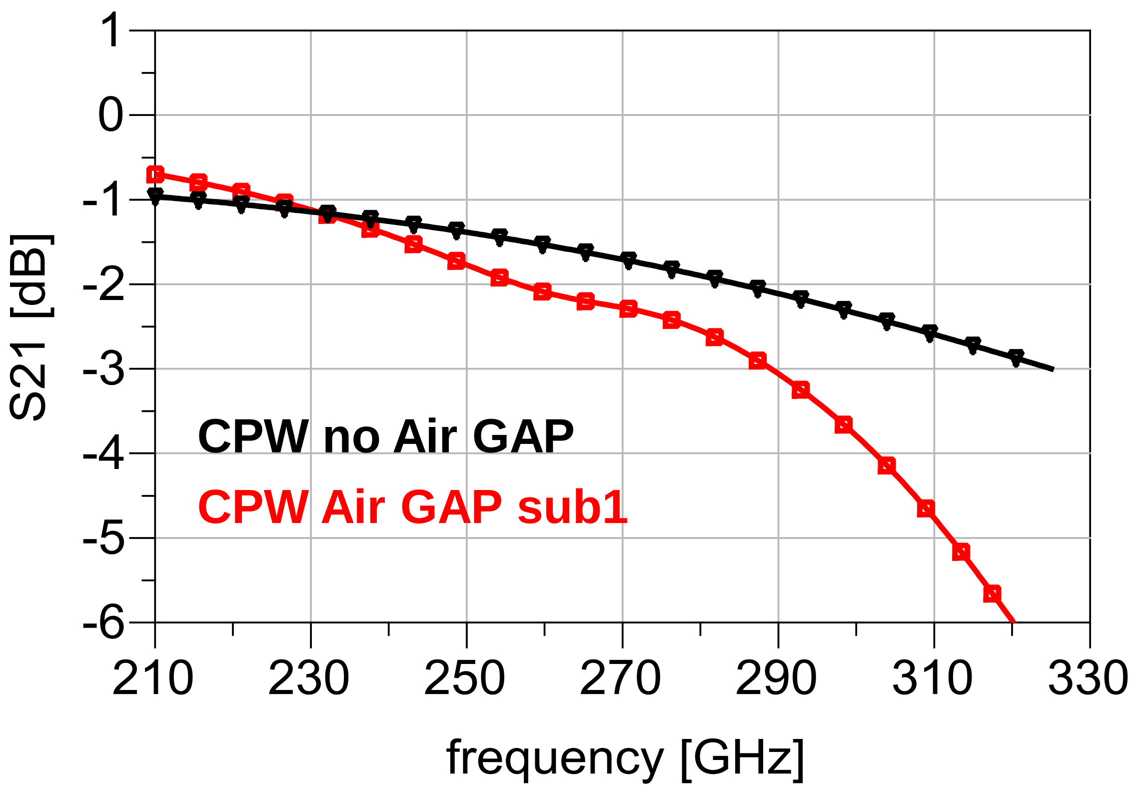
- Surface waves are reflected at dielectric discontinuities.
- Including an air gap in the simulation allows to visualize surface waves reflections from the S21 interference pattern.



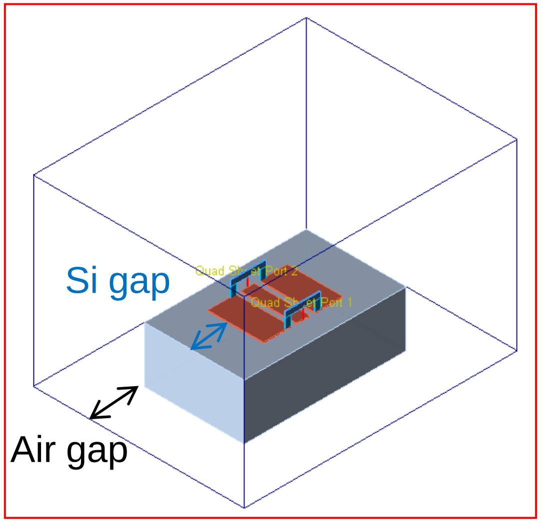


Multi-modes in CPWs - surface wave

- Surface waves are reflected at dielectric discontinuities.
- Including an air gap in the simulation allows to visualize surface waves reflections from the S21 interference pattern.

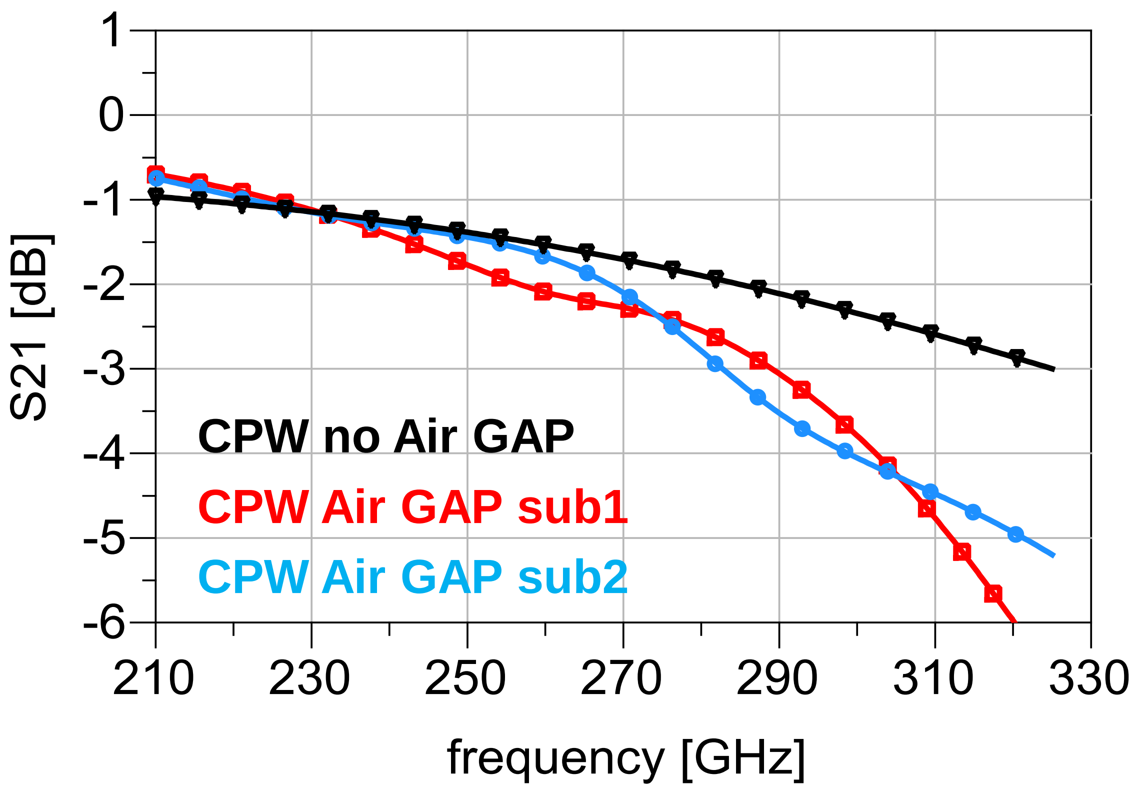


CPW Air GAP sub1

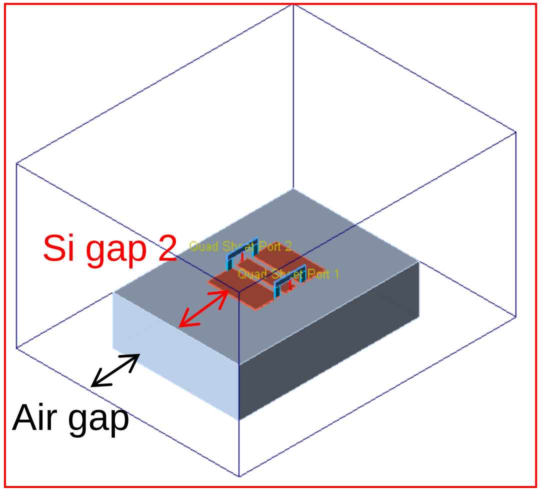


Multi-modes in CPWs - surface wave

- Surface waves are reflected at dielectric discontinuities.
- Including an air gap in the simulation allows to visualize surface waves reflections from the S21 interference pattern.

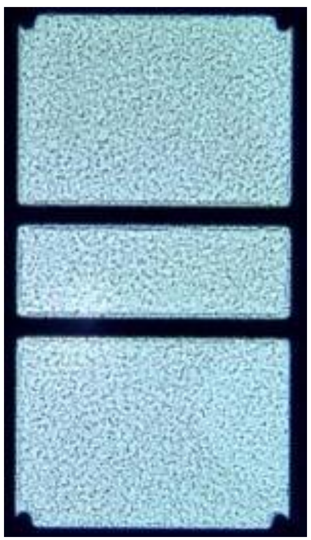


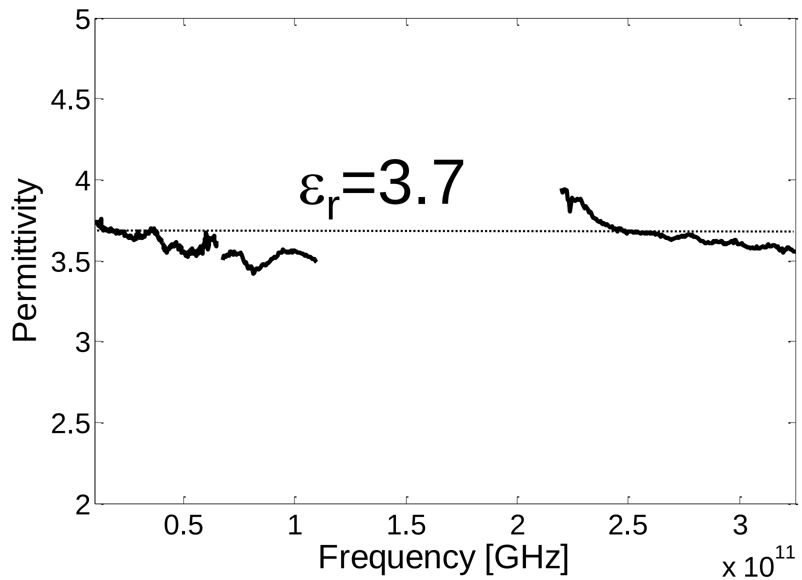
CPW Air GAP sub2



Fused silica substrate

When targeting (sub)-mm-wave calibrations high quality substrates (i.e., fused silica) with lower ε_r and low dispersion, can be used to fabricate lines for on-wafer TRL cal.

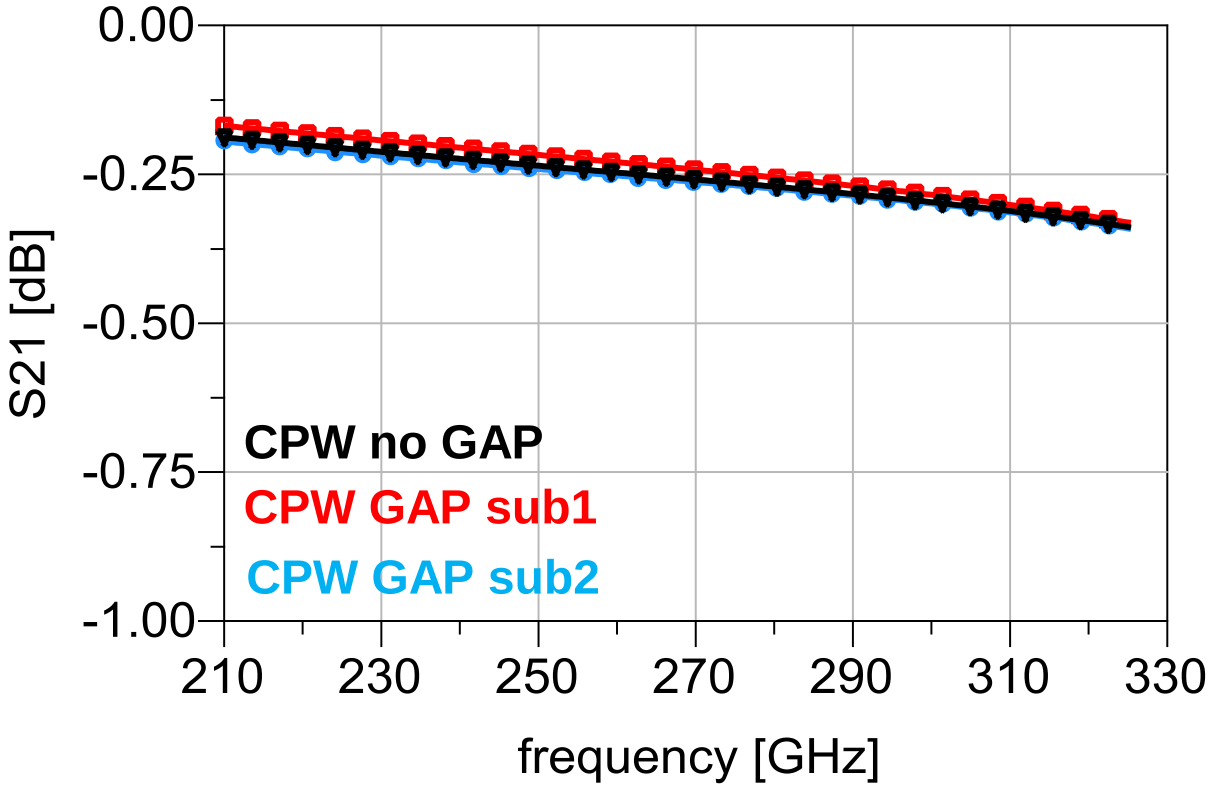




Parameter	W_S	W_{Gap}	W_{GND}	d	e_r
Value (in µm)	60	8	125	200	3.7

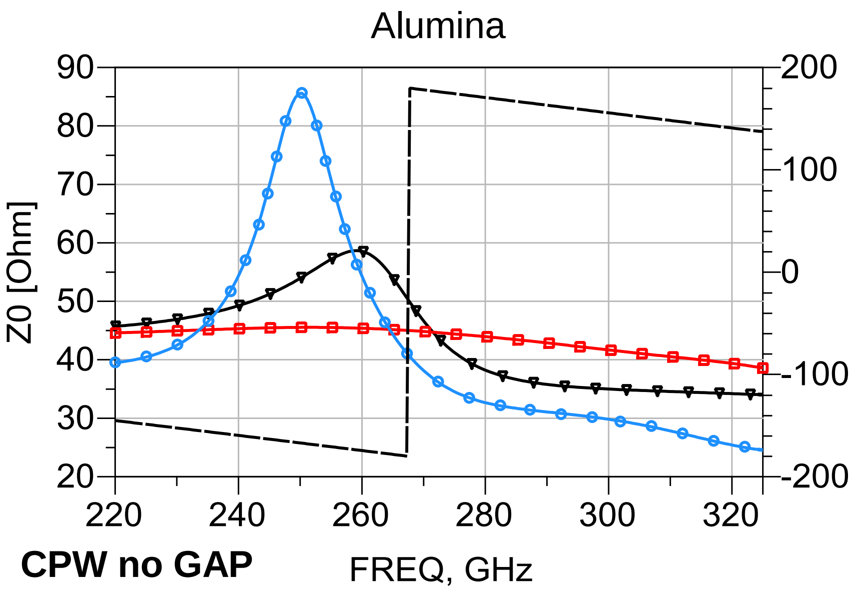
Fused silica substrate

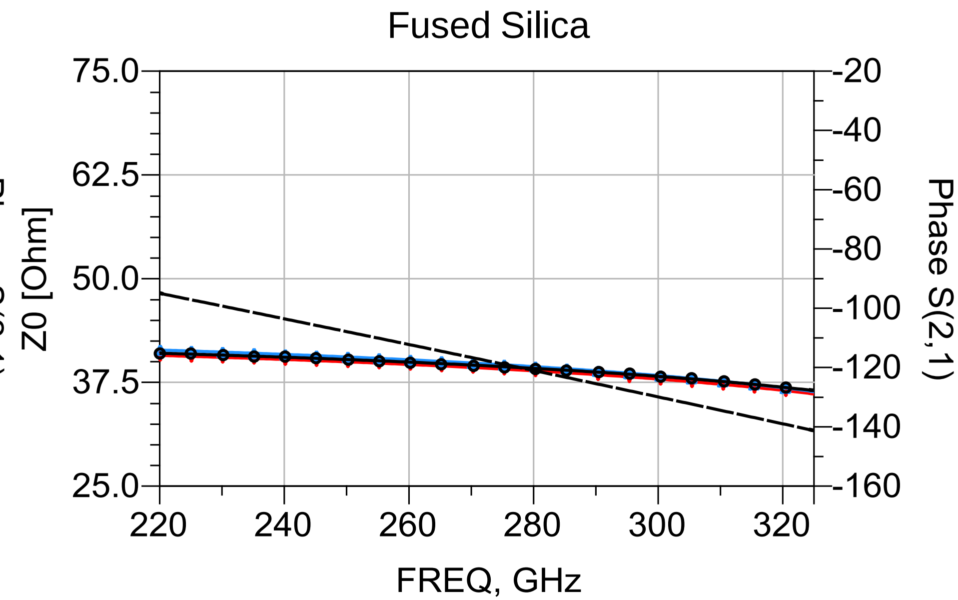
Fused silica exhibits very low losses, thanks to a small CPW gap and the higher cut-off frequency of the TE_1 mode.



Z0 extraction

The characteristic impedance is extracted using Eisenstadt approach. Fused silica substrate provides consistent values independent on the substrate terminations, i.e., energy lost in the (unwanted) substrate waves is marginal.



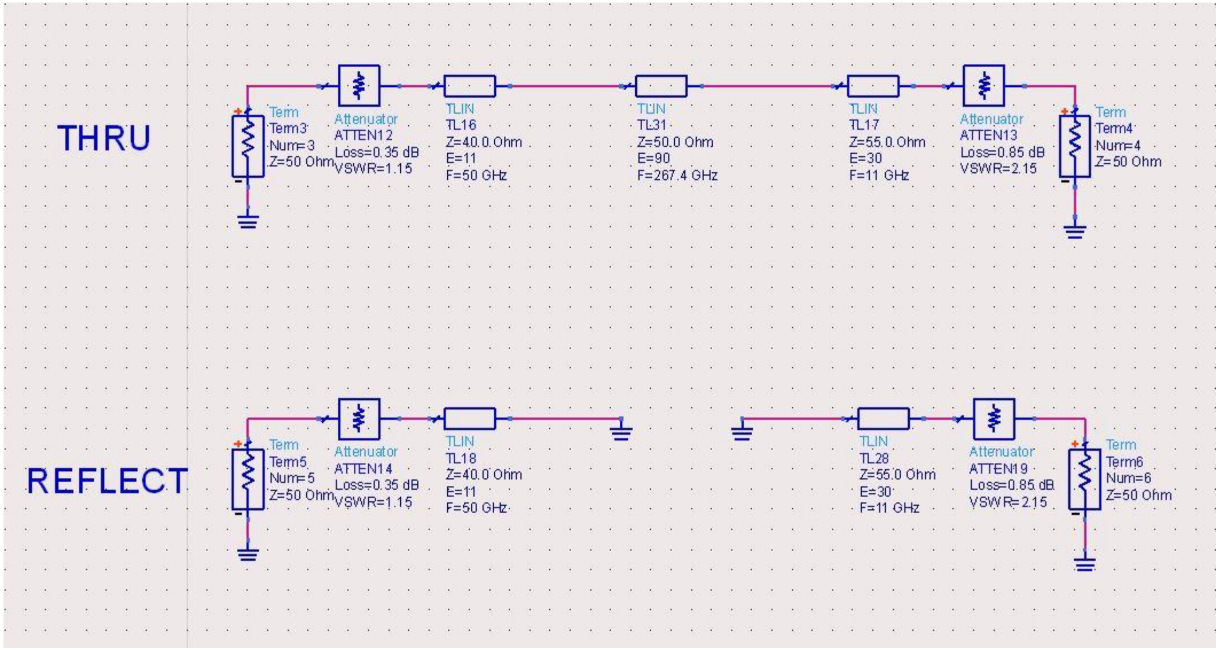


CPW no GAP
CPW GAP sub1
CPW GAP sub1

Standards design

At sub-mm-wave attention must be placed on the electrical length which occurs between the short location and the center of the thru line.

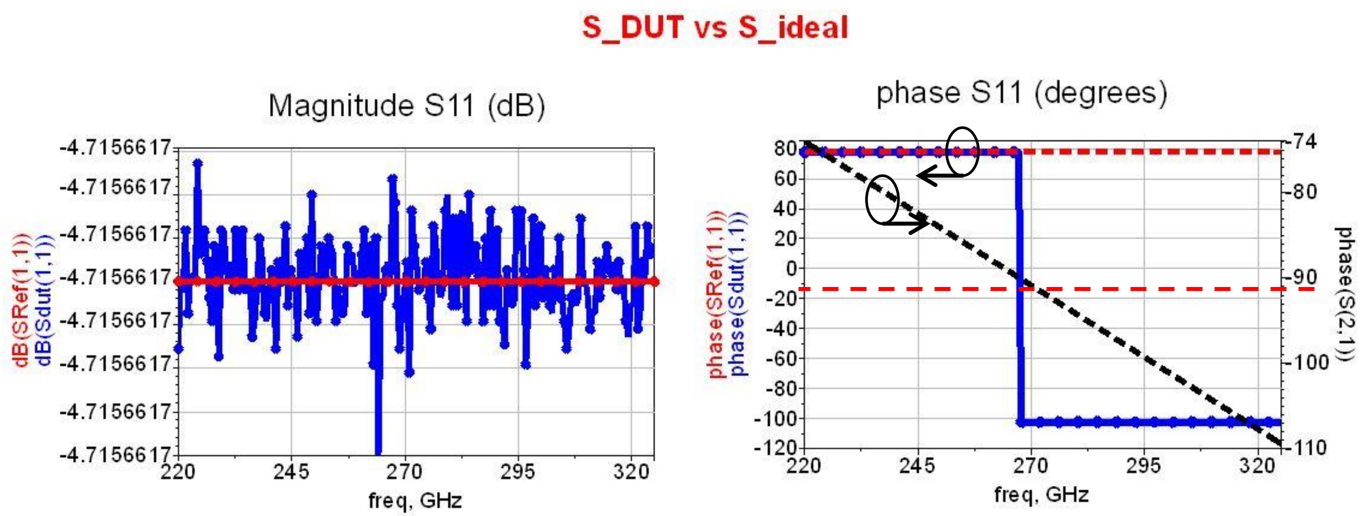
Low frequency STD design



Standards design

At sub-mm-wave attention must be placed on the electrical length which occurs between the short location and the center of the thru line.

Low frequency STD design



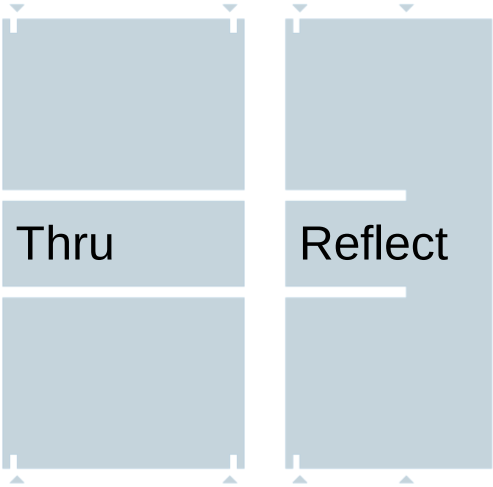
Red: correct (STD) data

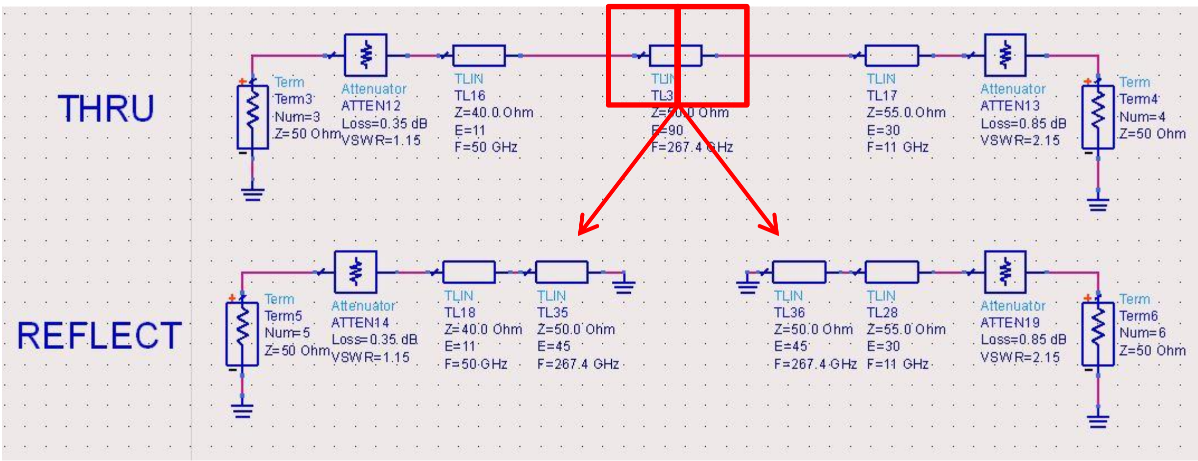
Blue: data after calibration corrupted by change of sign in the root

Cal substrate

Placing the short location at the center of the thru always avoid the change of sign of the root within the calibration bandwidth.

Mm-wave frequency STD design

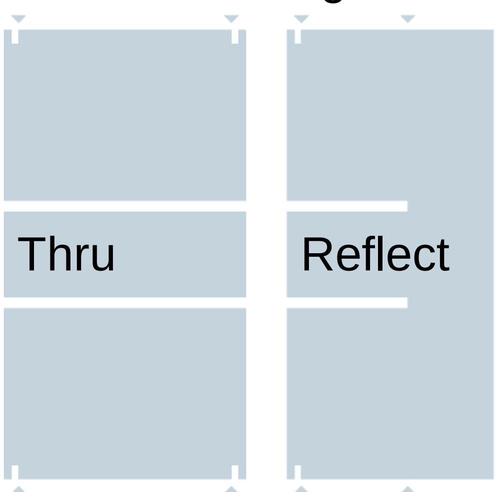




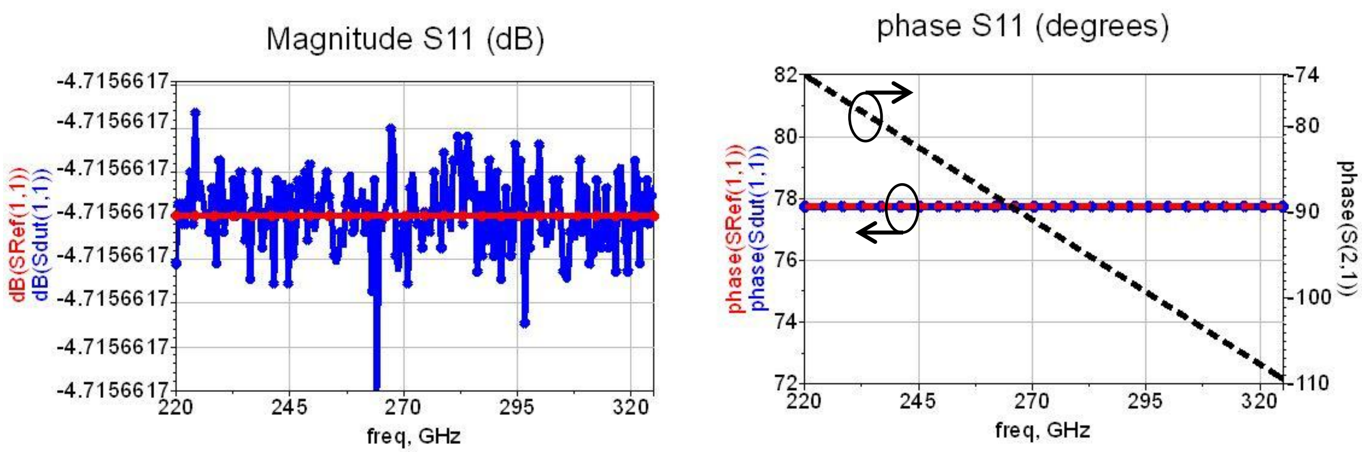
Cal substrate

Placing the short location at the center of the thru always avoid the change of sign of the root within the calibration bandwidth.

Mm-wave frequency
STD design



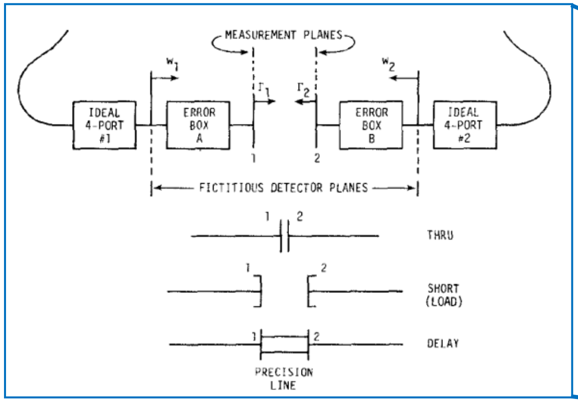
S_DUT vs S_ideal



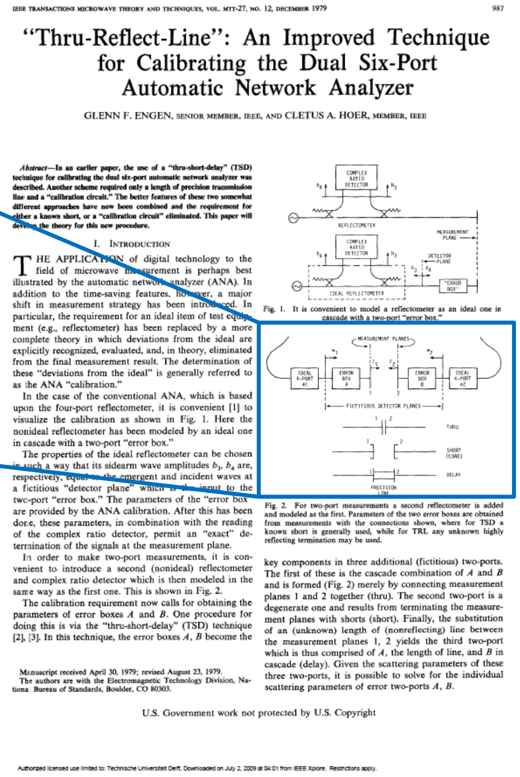
Red: correct (STD) data
Blue: data after calibration, showing proper sign of the root for all calibration band.

TRL – *a quick recall*

The thru reflect line calibration technique requires in order to calibrate a VNA only a limited number of information.



*"Instead of a collection of offset shorts, or the single short in conjunction with sliding terminations, … the only items now required to calibrate the measurement system are a section of the transmission line or waveguide in which the measurements are to be made (**which implicitly defines Z_O**), plus a termination for which a nominal value for the argument of the reflection is known."*



IEEE TRANSACTIONS MICROWAVE THEORY AND TECHNIQUES, VOL. MTT-27, NO. 12, DECEMBER 1979 987

"Thru-Reflect-Line": An Improved Technique for Calibrating the Dual Six-Port Automatic Network Analyzer

GLENN F. ENGEN, SENIOR MEMBER, IEEE, AND CLETUS A. HOER, MEMBER, IEEE

Abstract—In an earlier paper, the use of a "thru-short-delay" (TSD) technique for calibrating the dual six-port automatic network analyzer was described. Another scheme required only a length of precision transmission line and a "calibration circuit." The better features of these two somewhat different approaches have now been combined and the requirement for either a known short, or a "calibration circuit" eliminated. This paper will develop the theory for this new procedure.

I. INTRODUCTION

THE APPLICATION of digital technology to the field of microwave measurement is perhaps best illustrated by the automatic network analyzer (ANA). In addition to the time-saving features, however, a major shift in measurement strategy has been introduced. In particular, the requirement for an ideal item of test equipment (e.g., reflectometer) has been replaced by a more complete theory in which deviations from the ideal are explicitly recognized, evaluated, and, in theory, eliminated from the final measurement result. The determination of these "deviations from the ideal" is generally referred to as the ANA "calibration."

In the case of the conventional ANA, which is based upon the four-port reflectometer, it is convenient [1] to visualize the calibration as shown in Fig. 1. Here the nonideal reflectometer has been modeled by an ideal one in cascade with a two-port "error box."

The properties of the ideal reflectometer can be chosen in such a way that its sidearm wave amplitudes b_3, b_4 are, respectively, equal to the emergent and incident waves at a fictitious "detector plane" which is the input to the two-port "error box." The parameters of the "error box" are provided by the ANA calibration. After this has been done, these parameters, in combination with the reading of the complex ratio detector, permit an "exact" determination of the signals at the measurement plane.

In order to make two-port measurements, it is convenient to introduce a second (nonideal) reflectometer and complex ratio detector which is then modeled in the same way as the first one. This is shown in Fig. 2.

The calibration requirement now calls for obtaining the parameters of error boxes A and B. One procedure for doing this is via the "thru-short-delay" (TSD) technique [2], [3]. In this technique, the error boxes A, B become the key components in three additional (fictitious) two-ports. The first of these is the cascade combination of A and B and is formed (Fig. 2) merely by connecting measurement planes 1 and 2 together (thru). The second two-port is a degenerate one and results from terminating the measurement planes with shorts (short). Finally, the substitution of an (unknown) length of (nonreflecting) line between the measurement planes 1, 2 yields the third two-port which is thus comprised of A, the length of line, and B in cascade (delay). Given the scattering parameters of these three two-ports, it is possible to solve for the individual scattering parameters of error two-ports A, B.

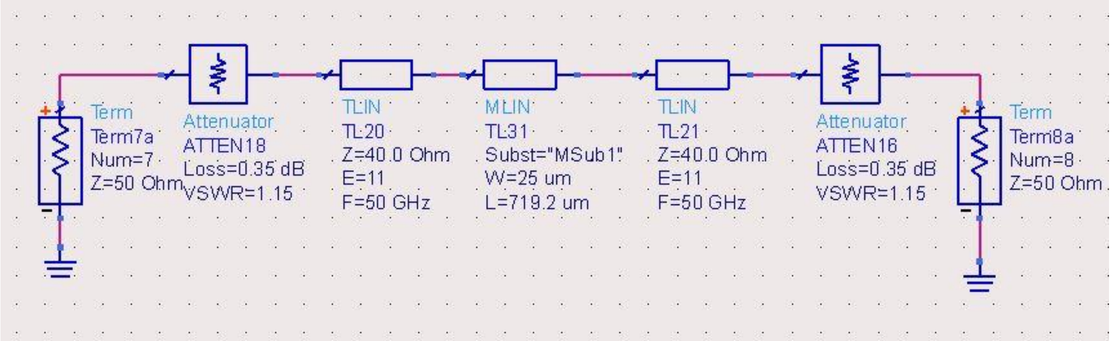
Fig. 1. It is convenient to model a reflectometer as an ideal one in cascade with a two-port "error box."

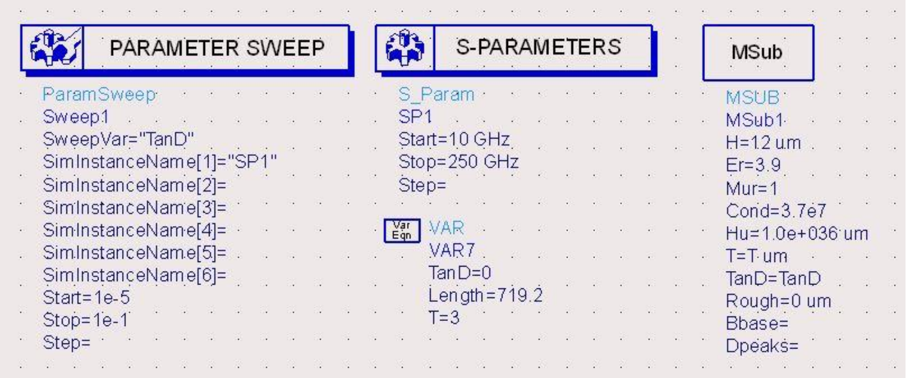
Fig. 2. For two-port measurements a second reflectometer is added and modeled as the first. Parameters of the two error boxes are obtained from measurements with the connections shown, where for TSD a known short is generally used, while for TRL any unknown highly reflecting termination may be used.

Manuscript received April 30, 1979; revised August 23, 1979.
The authors are with the Electromagnetic Technology Division, National Bureau of Standards, Boulder, CO 80303.

TRL – *a quick recall (cont.)*

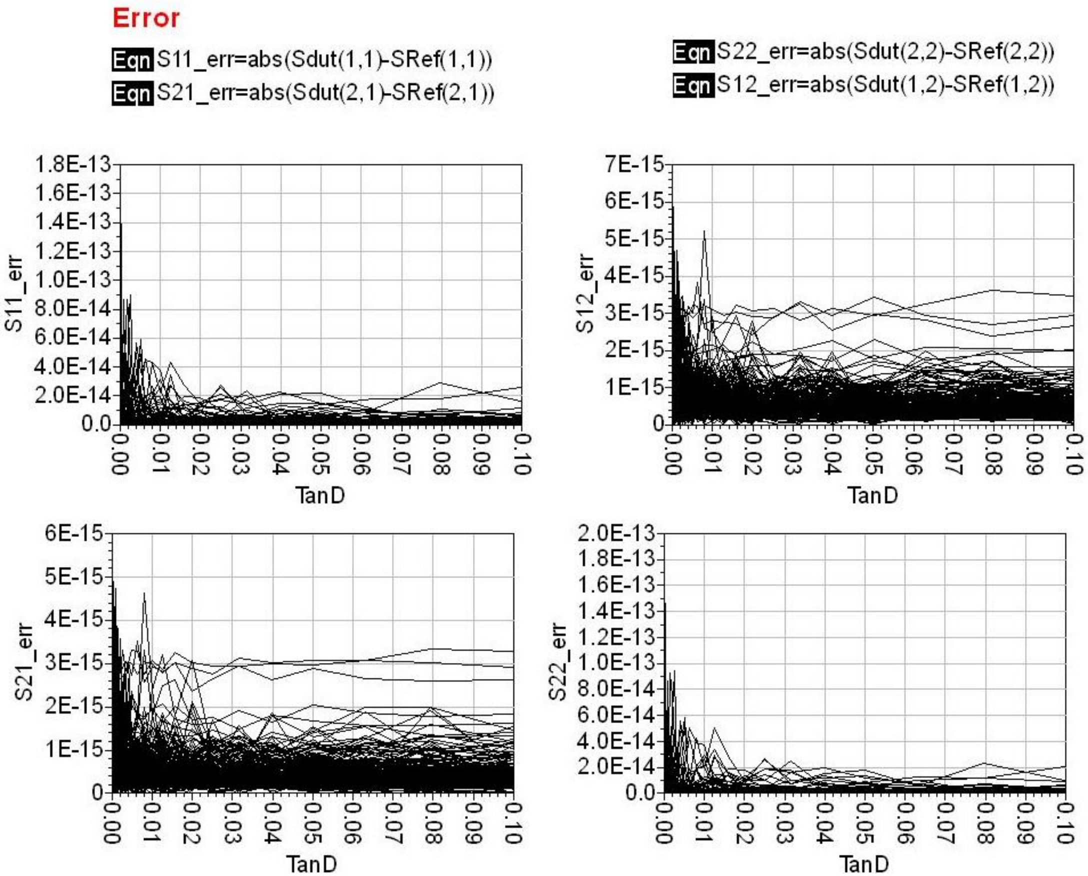
Calibrations equations and “residual” errors can be easily investigated employing circuit simulator, and making use of the extended analysis tools which are now embedded in the data displays, i.e., Agilent ADS.

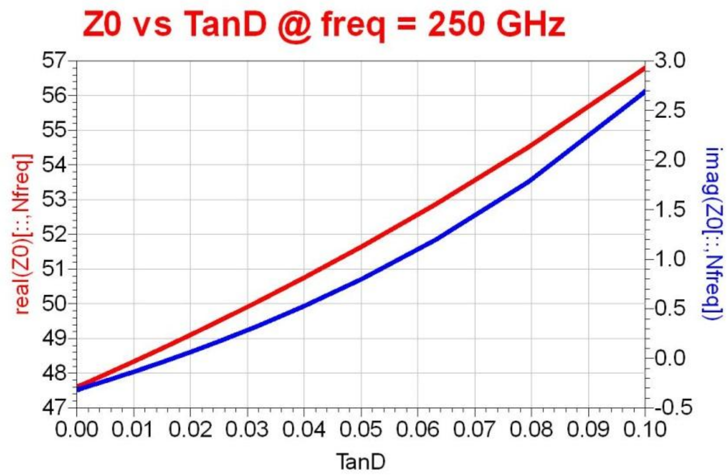




TRL – *a quick recall (cont.)*

After applying proper renormalization (on a well-behaved TEM line) effect of high tanδ provides no additional error to the calibration.



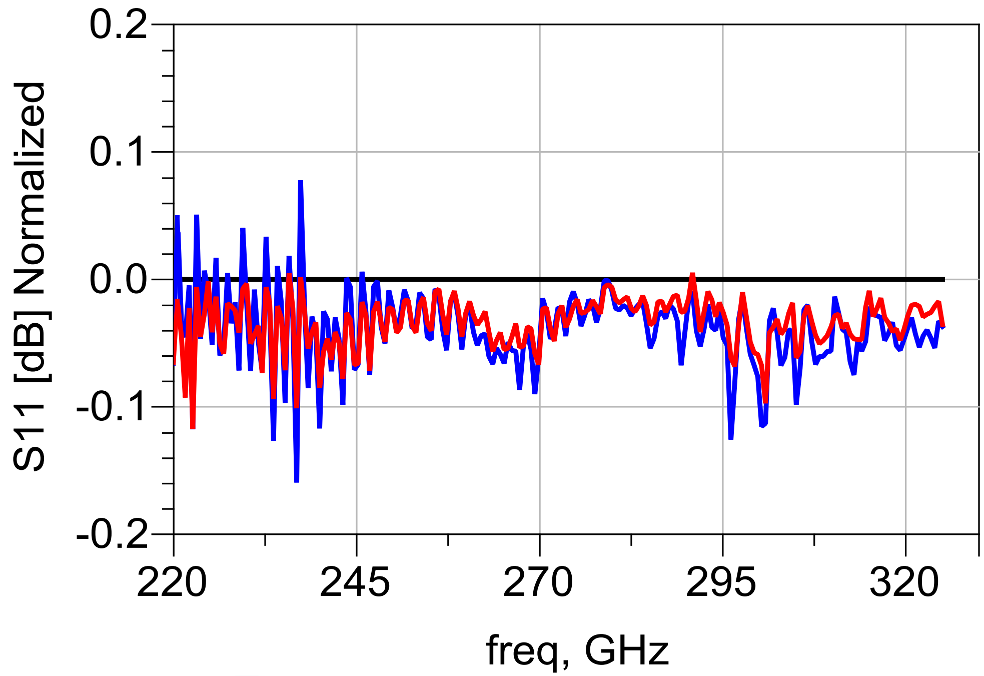


$$[ABCD] = \begin{bmatrix} \cosh \gamma l & Z \sinh \gamma l \\ \frac{\sinh \gamma l}{Z} & \cosh \gamma l \end{bmatrix}$$

[Eis92] W. Eisenstadt, Y. Eo, *IEEE Transactions on Components, Hybrids, and Manufacturing Technology,* vol.15, no.4, pp.483,490, Aug 1992.

Probe-substrate coupling

First (qualitative) measurements show limited impact of probe capacitive (coupling) versus the substrate. This indicates the possibility of calibration transfer also at sub-mm-wave.



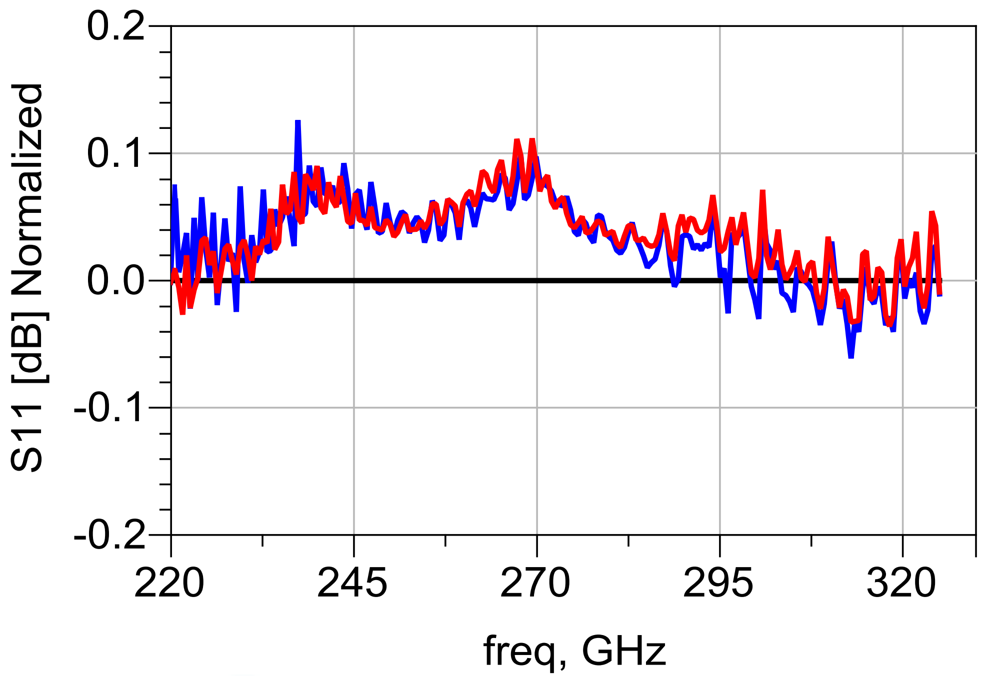
Fused Silica Normalization

Silicon Normalized

BiCMOS Normalized

Probe-substrate coupling

First (qualitative) measurements show limited impact of probe capacitive (coupling) versus the substrate. This indicates the possibility of calibration transfer also at sub-mm-wave.



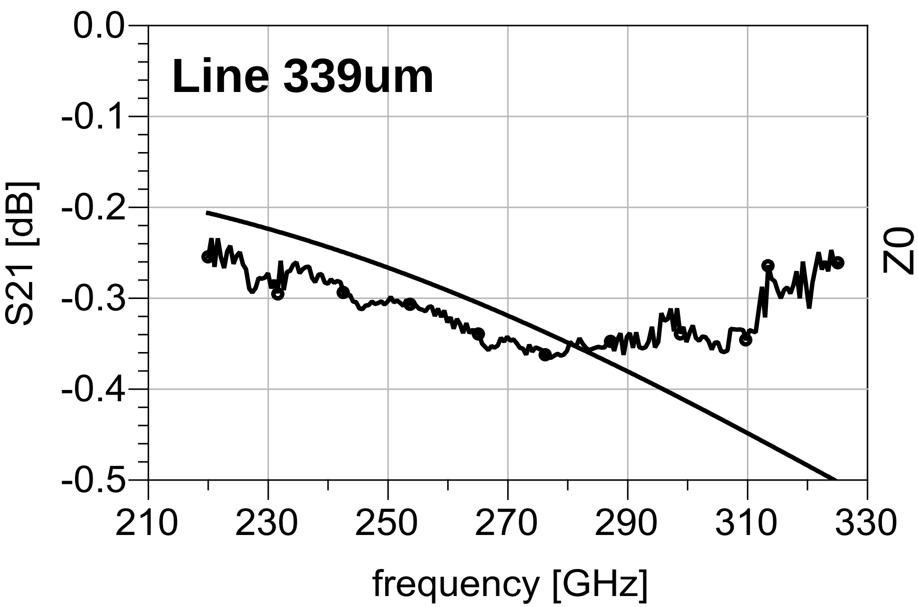
Alumina Normalization

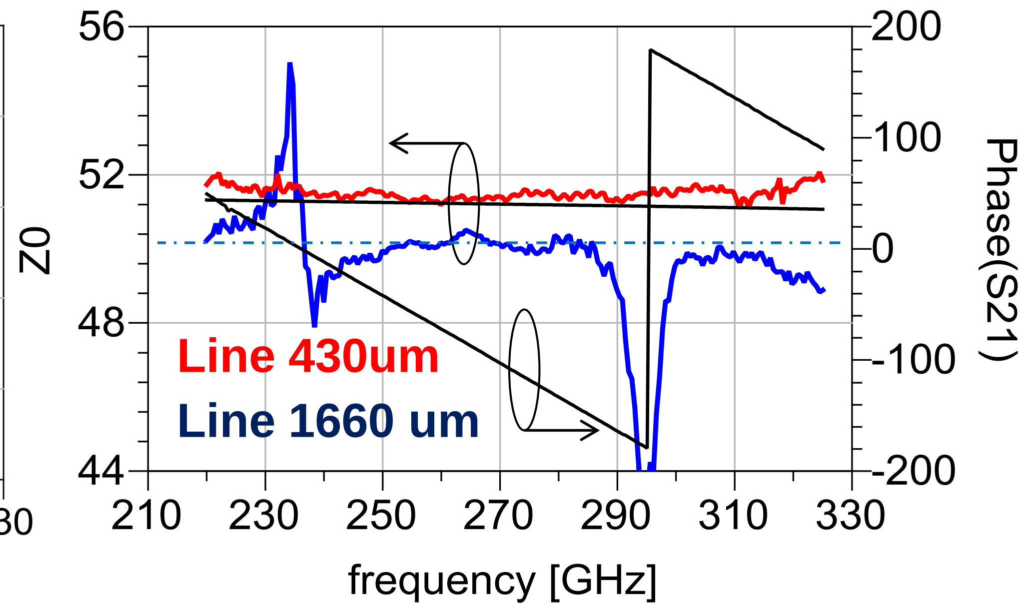
Silicon Normalized

BiCMOS Normalized

Meas. results - *Fused Silica*

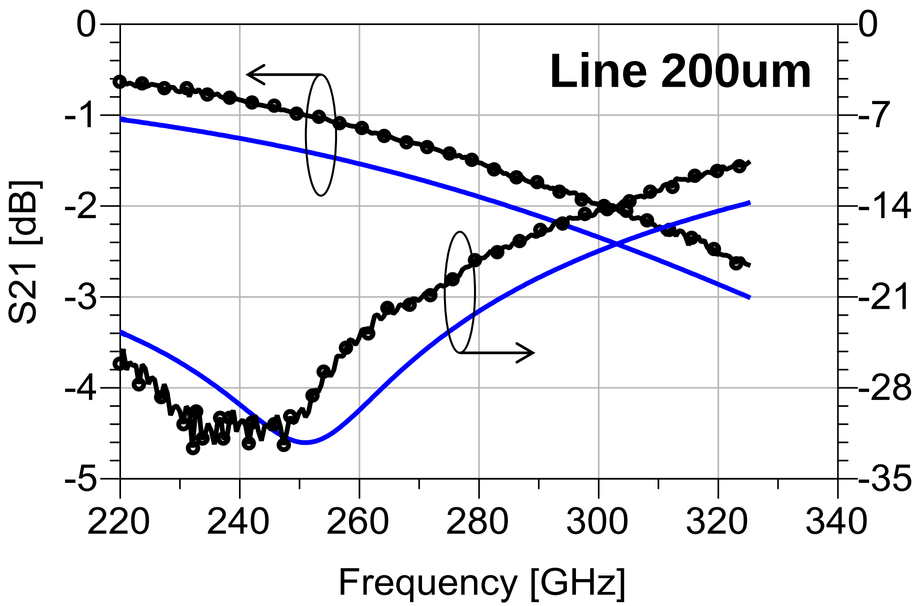
- Probe level TRL calibration performed on fused silica structures.
- Measured data correlates well with simulation predictions
- Measured characteristic impedance for short and long lines is consistent.

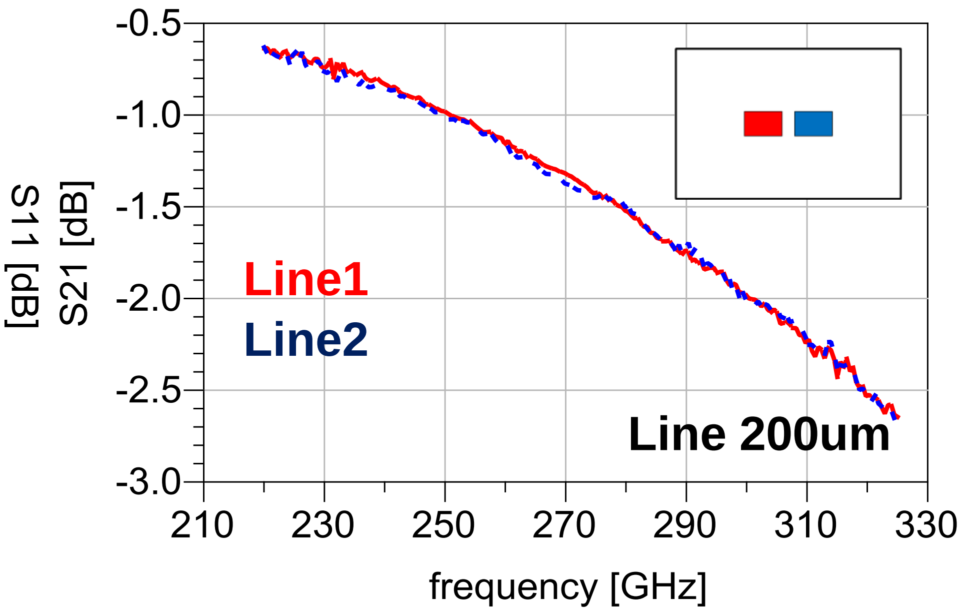




Meas. results - *Alumina*

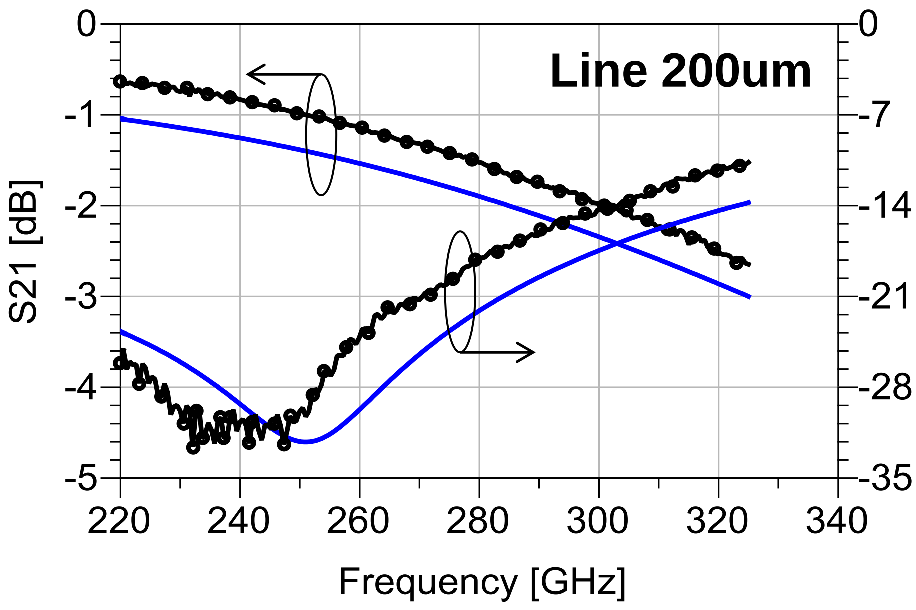
- Alumina lines (after TRL using fused silica), correlate well with simulation, exhibiting the expected high loss due to radiation modes.
- Alumina lines measured over different locations show interference patterns, as seen in simulations.

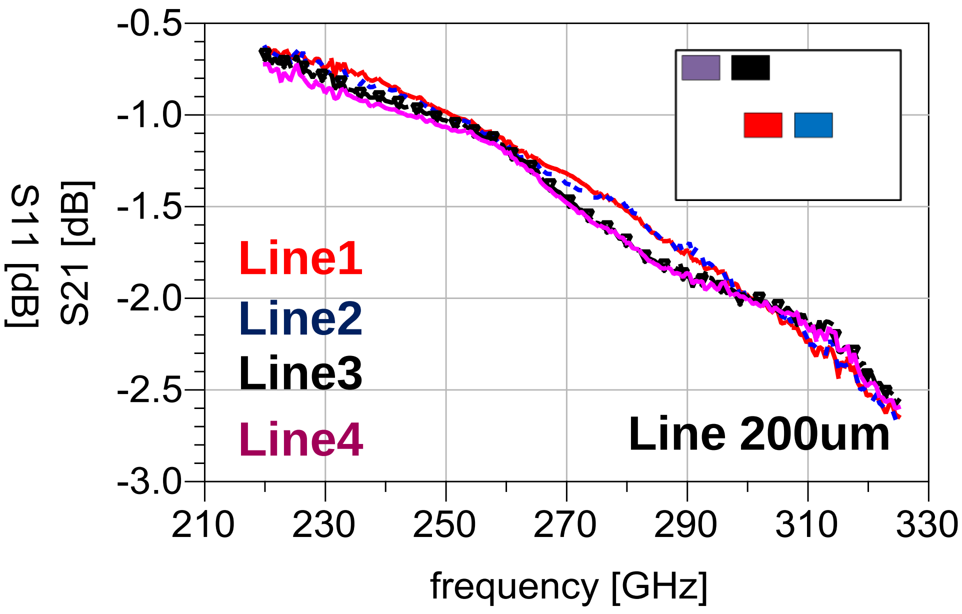




Meas. results - *Alumina*

- Alumina lines (after TRL using fused silica), correlate well with simulation, exhibiting the expected high loss due to radiation modes.
- Alumina lines measured over different locations show interference patterns, as seen in simulations.



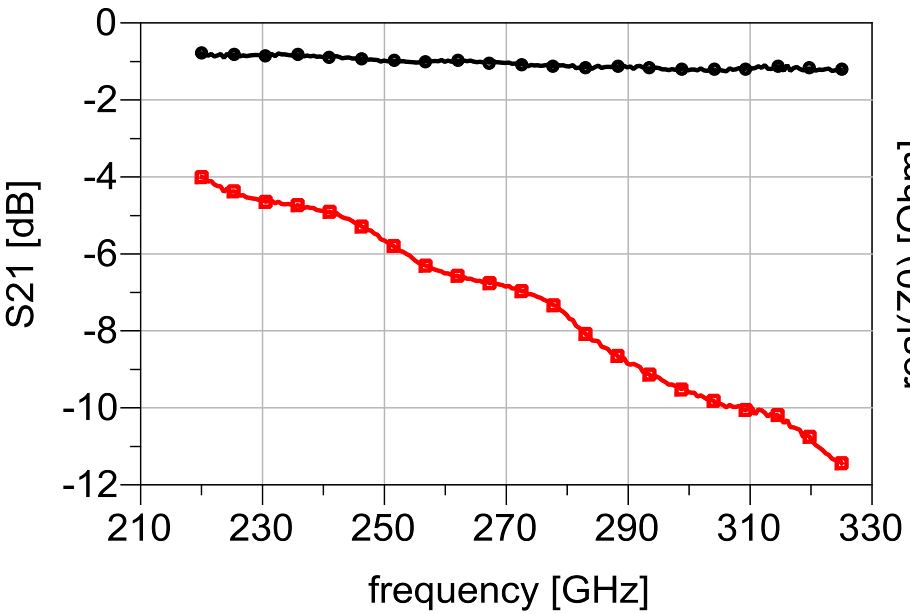


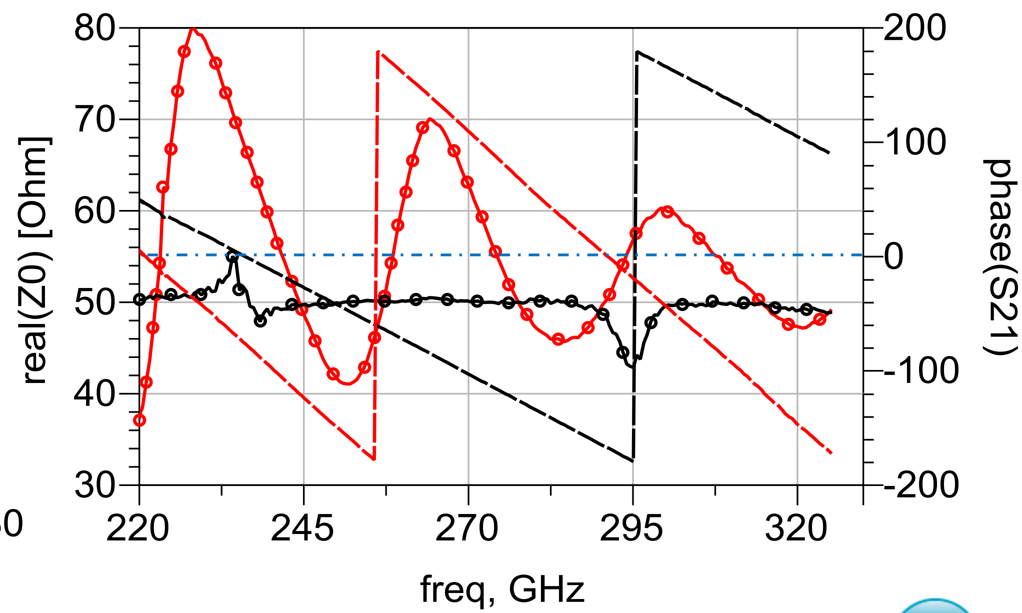
Meas. results - *comparison*

Fused silica lines, exhibit low losses arising from mode coupling, thus providing a good base for (sub)mm-wave probe level calibration.

1.8mm alumina

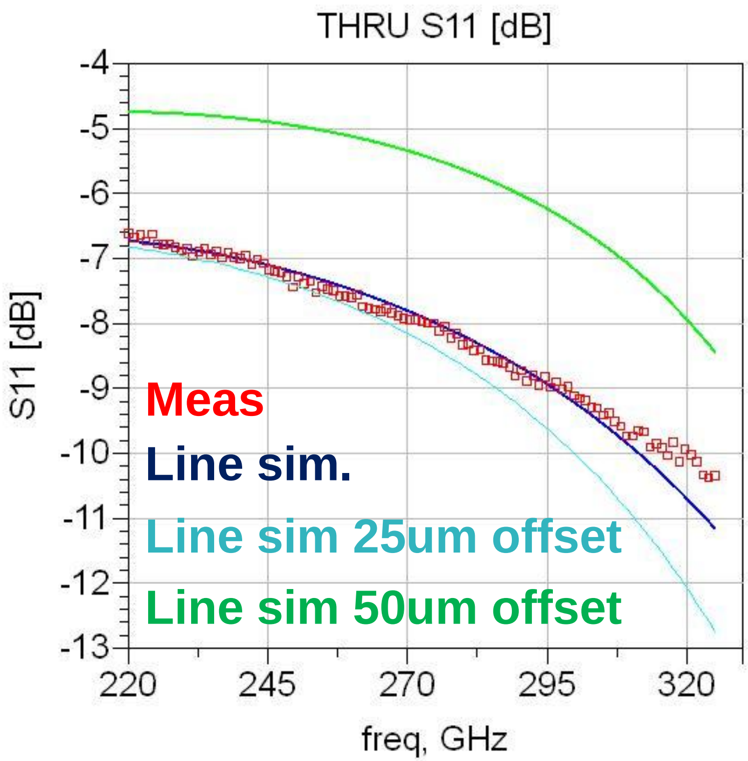
1.66mm fused silica

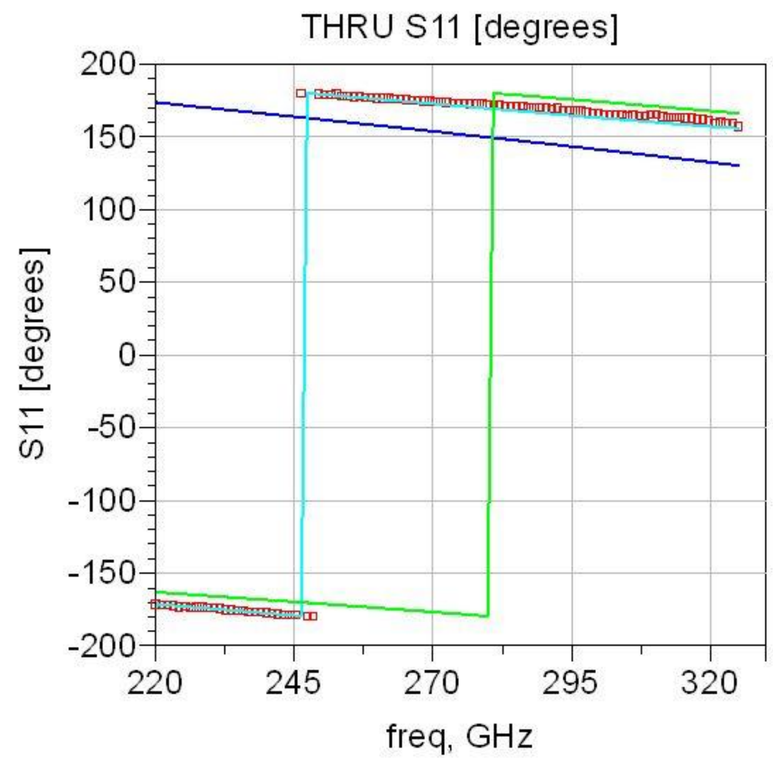




Meas. results - *BiCMOS*

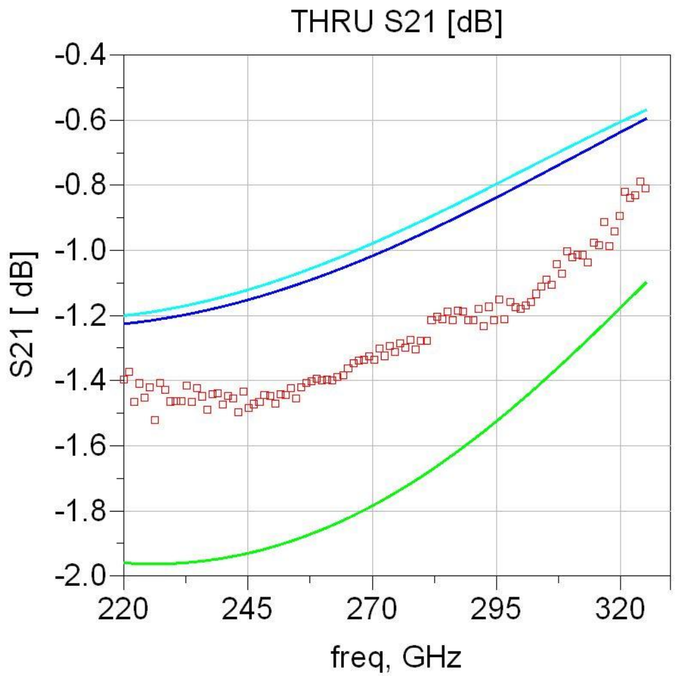
Lines implemented in BiCMOS back end, measured after fused silica calibration, show high correlation with 3D simulation (EM Pro).

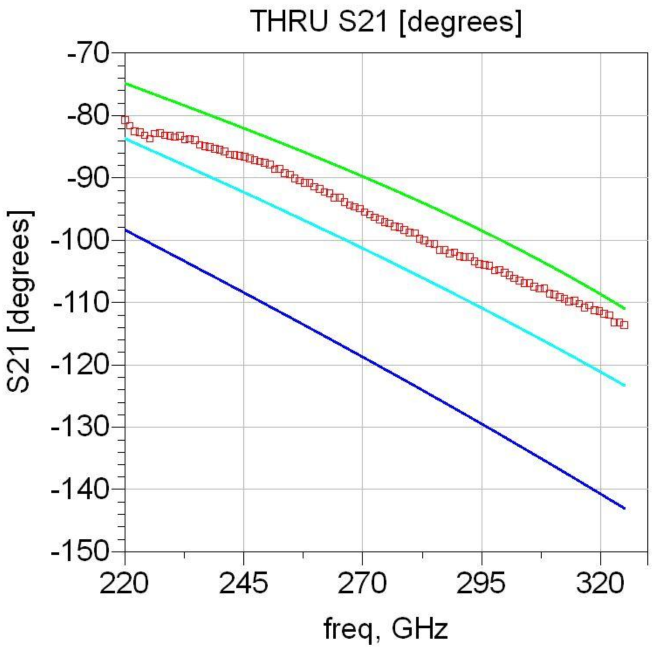




Meas. results - *BiCMOS*

Lines implemented in BiCMOS back end, measured after fused silica calibration, show high correlation with 3D simulation (EM Pro).





Meas

Line sim.

Line sim 25um offset

Line sim 50um offset

Conclusions

- A detailed analysis, based on 3D EM simulations, of the effect of multimode propagation occurring on CPW structures was presented.
- The limitations on the predictions of the electrical behavior of CPWs integrated on electrically thick substrates were discussed.
- A fused silica substrates was proposed and fabricated to perform accurate (sub)mm-wave calibration.
- Experimental data of CPW lines on both fused silica as well as alumina (after a TRL calibration using fused silica) were performed and show high correlation with their simulations.
- Experimental data on BiCMOS lines, after fused silica calibration, shows high correlation with 3D EM simulations, validating the calibration transferring assumption.

Acknowledgement

- The authors would like to thank Giuseppe Fiorentino from the Delft Institute of Microelectronics and Submicron Technology for fabricating the fused silica structures.

- *This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No 316755*