Impact of Substrate Modes on mTRL-Calibrated CPW Measurements in G Band

G.N. Phung[#], F.J. Schmückle[#], R. Doerner[#], W. Heinrich[#], T. Probst[*], U. Arz[*]

[#] Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH), Gustav-Kirchhoff-Straße 4, 12489 Berlin, Germany

[*] Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany

***Abstract* —On-wafer measurements at microwave and mm-wave frequencies require reliable calibration processes to deduct unwanted effects such as the impact of probe, the wafer environment, and the instrumentation equipment itself. However, with increasing frequencies the calibrated results become more and more sensitive to parasitic effects such as radiation, multi-mode propagation, and substrate modes. This paper investigates their influence when using a typical coplanar waveguide (CPW) calibration substrate at G band. The goal of this paper is to clarify the role of substrate modes and to quantify how they affect multiline Thru-Reflect Line (mTRL) calibration.**

***Keywords* — on-wafer probes, coplanar waveguides (CPW), substrate modes, calibration.**

I. Introduction

Any on-wafer measurement requires application of a calibration procedure to deduct unwanted but unavoidable perturbation of the data due to the environment, the probes, and the instrumentation itself. This calibration process should reveal the “true” performance of the Device Under Test (DUT). However, with growing frequency the calibrated results become increasingly sensitive to parasitic effects such as radiation, multimode propagation, and substrate modes. In principle, radiation is accounted for by TRL calibration and can be eliminated if it is the same for all calibration structures as well as the DUT (which, of course, is difficult to ensure in reality [1]).

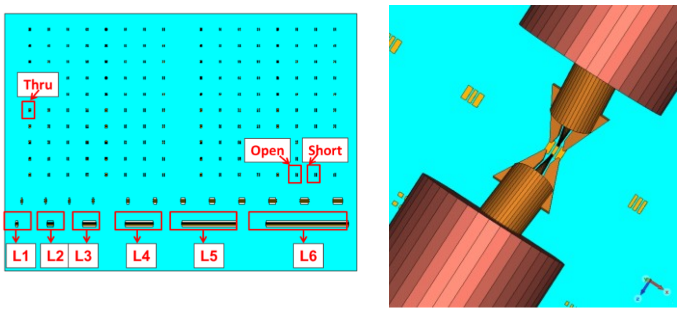

Fig. 1. Left: Layout Cal 1 of the CPW calibration substrate with marked-up calibration elements; right: Probe geometry used in simulation

More critical, however, are multi-mode propagation and substrate modes, since common calibration procedures assume only single-mode propagation and cannot compensate existence of multi-mode or multi-path scenarios. Thus, any additional mode propagating between the ports will deteriorate accuracy of the calibrated results.

Several papers have been published already investigating the impact of substrate modes for CPW structures (e.g., [2, 3, 4]), but all of them were restricted to W band frequencies and below. The CPW case is particularly challenging because one is dealing with a multi-layered substrate (e.g., when measured on a ceramic chuck material). Also, it is not easy to differentiate the effects of substrate modes from radiation effects in the measurement data.

With this motivation, the present paper concentrates on the coplanar case. Compared to previous literature, we address higher frequencies and do not only study substrate modes themselves but quantify their influence on the calibration procedure. A typical CPW calibration substrate is used, in the frequency range up to 220 GHz. We apply the mTRL algorithm [5], which is commonly accepted as one of the most accurate calibration algorithms. The investigations presented are based on measurements and electromagnetic simulations performed with Microwave Studio from CST [6].

II. Measurement Results after Calibration

A. Basic measurement setup

The investigated calibration substrate is commercially available and suggested for calibration above W band. It consists of an alumina substrate (Al_2O_3) with a thickness of 250 µm and a dielectric constant of $\varepsilon_r = 9.9$. In our measurements, the calibration substrate is placed on a ceramic chuck with a thickness of 1 cm and a dielectric constant of $\varepsilon_r = 6$. In the electromagnetic simulations, we use a thickness of 2000 µm for the chuck, followed by an open boundary which virtually extends the lower boundary to infinity.

The parameters common for all CPW lines are a signal conductor width of 35 µm, a 20 µm gap and a metalization thickness of 3 µm. Fig. 1 (left) shows the layout with the calibration elements. The set consists of the CPW lines L1… L6 with different lengths (200, 450, 900, 1800, 3500, and 5250 µm), a pair of CPW short stubs, and a CPW open. For the thru standard, a short CPW of about 135 µm +/-1 µm line length is employed, which is placed on the left-hand edge of the wafer substrate (Fig. 1, left). This calibration set is referred to as Cal 1 in the following. In a second step, we will exchange the thru standard in the calibration set Cal 1 by Thru 2f (see Fig. 2). This modified set is denoted Cal 2.

The dimensions of the CPW structures were determined from measurements with a tolerance of +/-2.5 µm.

B. *Calibrated results of thrus at different positions*

The first step of our investigation is to both measure and simulate the calibration elements and to feed both sets of raw data into the mTRL calibration algorithm. To include all the effects of a realistic measurement, the simulations of the structures elements take into account the complete substrate and describe the probe by a sophisticated model (Fig. 1, right). As a result of the mTRL algorithm, error terms are calculated for both measurements and simulations of each set of calibrations.

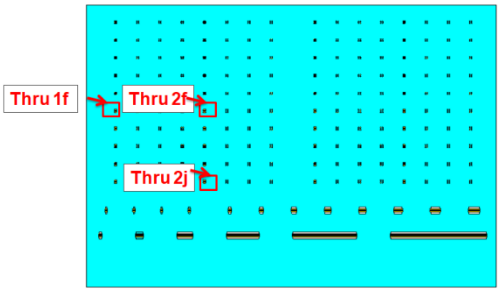

Fig. 2. The DUTs under consideration.

In the second step, the DUTs are measured and simulated, and the data is calibrated with these error terms. To allow for an easy comparison of simulations against measurements, the reference plane is shifted to the probe tips in both cases. (The data were all normalized to the characteristic impedance of the calibration lines.)

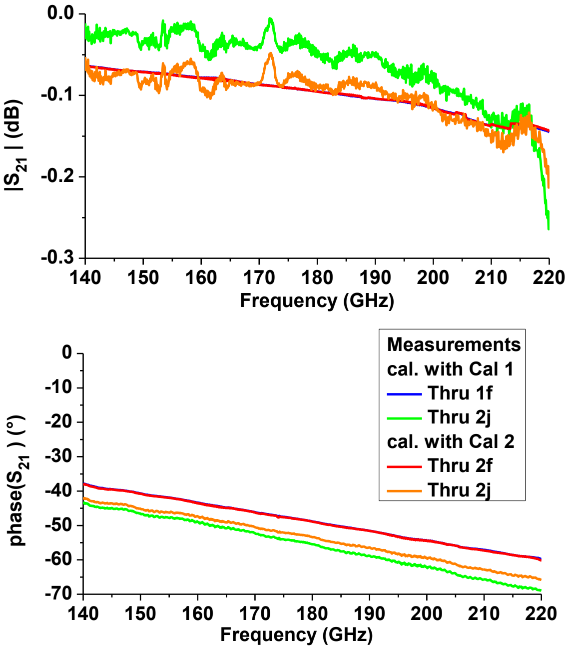

Fig. 3. G band measurements of S_{21} for three different thrus (Thru 1f, Thru 2f, Thru 2j), calibrated with Cal 1 and Cal 2; top: Magnitude of S_{21} in dB; bottom: Phase of S_{21} in °.

As can be seen in Fig. 2, there are a lot more calibration structures on the substrate, which are identical in layout but placed at different locations. Fig. 3 presents measured calibrated data in G band for a nominally identical structure, a thru, located at different positions on the substrate and calibrated using the two different set of elements Cal 1 and Cal 2. As can be seen the results for the magnitude of S_{21} vary within a range of 0.1 dB and exhibit different curve behavior, partly with clearly unphysical ripple. Only if the same thru that was used in the calibration set is measured one obtains unique and ripple-free data.

While the deviations for the magnitude of S_{21} remain relatively small, the phase of S_{21} shows more pronounced effects (Fig. 3, bottom). A maximum phase difference of 9° can be detected between Thru 2j and Thru 1f (both calibrated with Cal 1) at 220 GHz. As for the magnitude, there is only one choice to obtain unique results, independently of the calibration set: Using exactly the thru of the respective set.

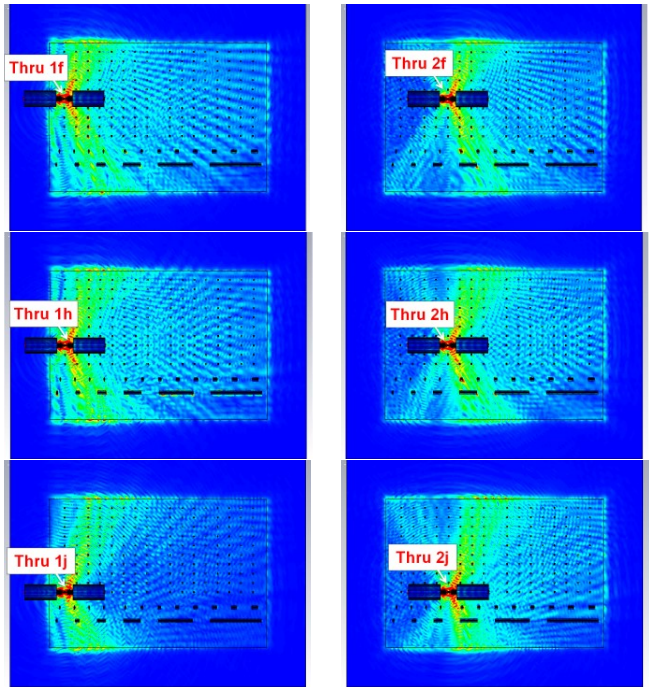

Fig. 4. Magnitude of the electric field at 196.9 GHz (top view on the substrate) when measuring the thru at different positions, as specified.

In order to clarify this behavior, we simulated the electric field for the differently positioned thrus at 196.9 GHz (see Fig. 4). Obviously, the electric fields spread over the whole substrate and the patterns for the thrus differ. The observed phenomena can be explained only by the propagation of substrate modes. This is detailed in the following section.

III. Influence of Substrate Modes

A. *Impact of wafer size*

For the following investigations, we extend the wafer substrate four times larger in area (Fig. 5 left). We repeat the simulation of the calibration set Cal 1 on this extended wafer and rerun the calibration algorithm (Cal 2 is not considered in this section).

The calibrated results for the phase of S_{21} for Thru 1f and Thru 2f are compared in Fig. 5 (right), where the phase difference is plotted. Clearly, the extended substrate size leads to a significant improvement regarding the phase deviations. This is supported by the data for the relative deviation in Fig. 6 which shows a reduction from 13% (standard substrate) to 2% (extended substrate size).

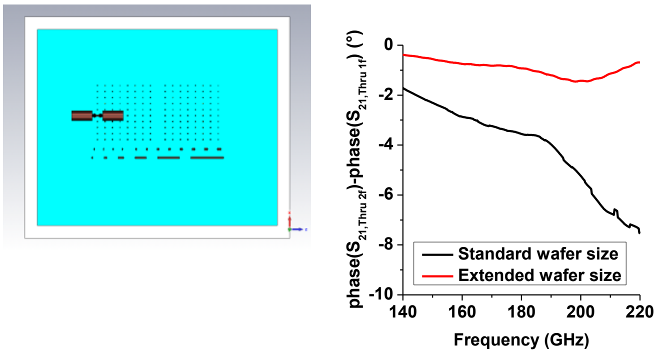

Fig. 5. Substrate with extended dimensions, left: Layout; right: Calibrated results of the phase difference of S_{21} in ° between Thru 1f and Thru 2f

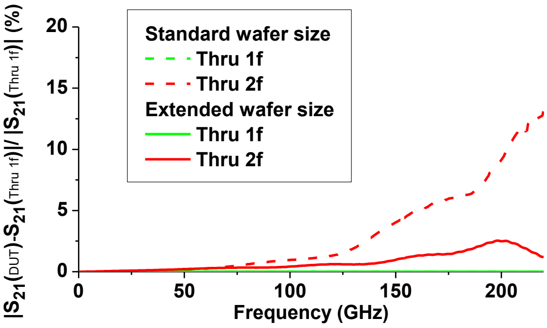

Fig. 6. Complex difference of S_{21} between Thru 1f and Thru 2f on standard and extended substrate (magnitude of relative difference in %).

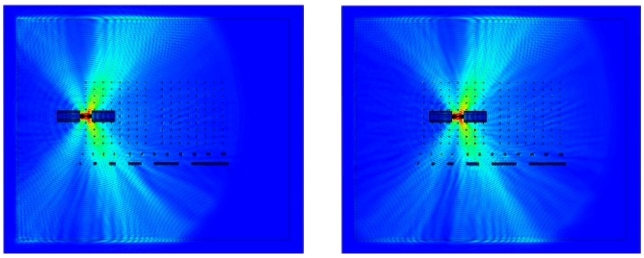

Fig. 7. Magnitude of electric fields at 196.9 GHz for Thru 1f (left) and Thru 2f (right) on extended wafer

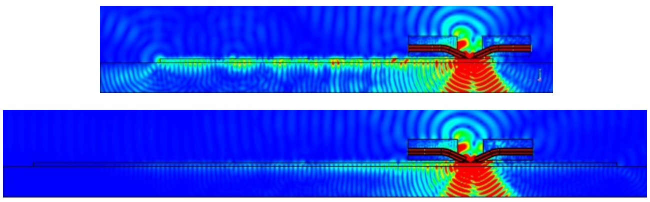

Fig. 8. Magnitude of electric field at 196.9 GHz (cross-section in the centre of the probe for Thru 1f); comparison between standard (top) and extended wafer size (bottom)).

The electric field plots in Fig. 7 help to explain why the deviations have decreased. Due to the extended substrate the distance of Thru 1f to the substrate edge is so large that the electric fields are similar to those of Thru 2f. In other words, the parasitic substrate mode is still excited and propagates through the substrate but what makes it critical are reflections at discontinuities located in close distance, which cause strong reflections that coupled back into the measured structure. For the enlarged substrate, the substrate edges are further away and thus the influence of the reflections is lower. The field plot in Fig. 8 illustrates this. The substrate mode travels away laterally from the probe location but its amplitude decreases with distance, due to its circular characteristics.

B. Impact of the dielectric constant of the chuck material

The existence and the general behavior of the substrate modes follow the classical theory of surface waves [7]. The structure under consideration here is a 3-layered one, comprising the air region above the substrate, the substrate itself, and the chuck below, in our case: air, Al_2O_3, and ceramics with $\varepsilon_{r,chuck} = 6$. The air region and the chuck can be approximated to be infinite at the top and bottom level, respectively. Thus, the behavior of substrate modes is governed by the dielectric constants of the three layers and the thickness of the intermediate one, the substrate.

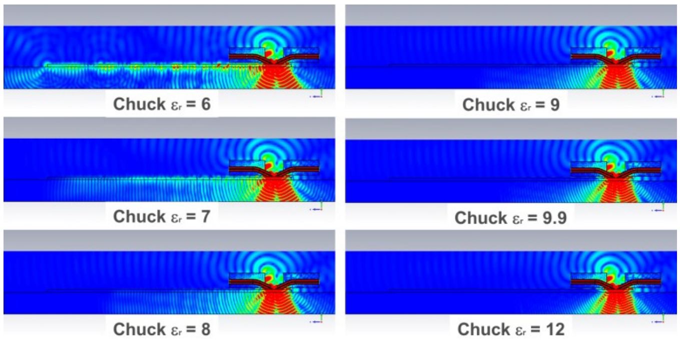

Fig. 9. Magnitude of electric field at 196.9 GHz at a cross-section in the centre of the probe, varying the permittivity of the chuck below the substrate.

In particular, substrate modes can be suppressed under three conditions:

- If the substrate is thin enough so that the cutoff frequency for the lowest surface wave mode is above the highest frequency of interest.
- If the dielectric constant of the chuck material is similar to that one of the substrate. Then substrate and chuck form more or less a homogeneous medium and one has a two-layer structure, which does not support any surface waves.
- If the dielectric constant of the chuck is larger than that of the substrate. This type of three-layer structure also does not support surface waves.

The field plots in Fig. 9 support these statements, studying the effects when varying the chuck permittivity. As can be seen, one has always a superposition of two effects, the propagation of the substrate mode and the radiation from the probe tips into the substrate and the chuck material. For $\varepsilon_{r,chuck}$

values up to 8, one observes propagation of the substrate modes, since at 196.9 GHz the 250 µm thick Al_2O_3 substrate ($\varepsilon_{r,wafer} = 9.9$) supports a substrate mode. If the dielectric constant comes close to the value of the wafer substrate $\varepsilon_{r,chuck} = \varepsilon_{r,wafer}$, the substrate mode vanishes and only radiation fields generated by the probe tips are observed which travel further and disappear in the (infinitely thick) chuck layer. For higher $\varepsilon_{r,chuck}$ values, the substrate mode is suppressed as well.

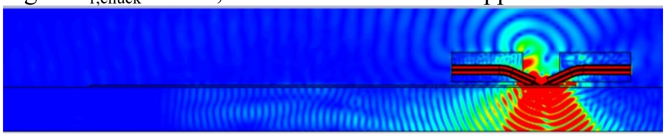

Fig. 10. Magnitude of electric field at 196.9 GHz at the cross-section in the centre of the probe, for $\varepsilon_{r,chuck}$ but a thinner substrate of 100 µm.

Similarly, this can be achieved when choosing substrate thickness thin enough (see Fig. 10, with 100 µm thick substrate). Therefore, one should use a material for the chuck which has a similar (about +/- 1) or higher permittivity than the substrate, or the thickness of the substrate needs to be chosen small enough to increase the cut-off frequency to values higher than the maximum frequency of operation. Radiation into the chuck is unavoidable, but it does not cause back-reflections and thus a second path between the probes which would corrupt the mTRL approach is avoided.

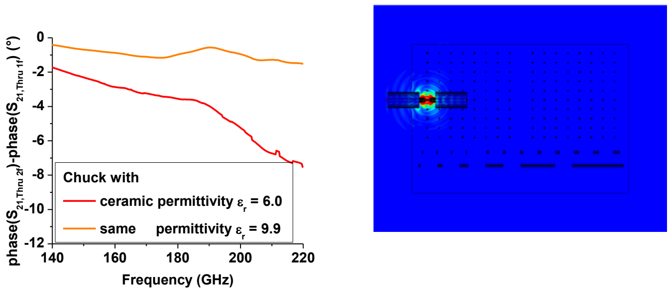

Fig. 11. Calibrated results of the phase difference of S_{21} in ° for Thru 1f and Thru 2f (left); right: Magnitude of electric fields at 196.9 GHz for Thru 1f on chuck with same permittivity as substrate ($\varepsilon_{r,chuck} = 9.9$).

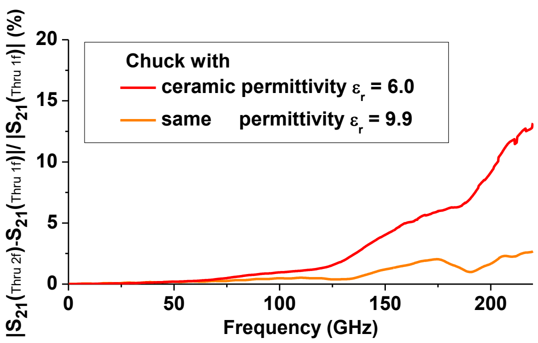

Fig. 12. Complex difference of calibrated S_{21} for Thru 1f and Thru 2f on different chuck material (magnitude of relative difference in %)

Fig. 11 illustrates the situation for the case with a chuck of exactly the same permittivity as the substrate. The laterally spreading fields, caused by the substrate modes, have completely disappeared and, as a result, the deviations between the different DUT positions are significantly reduced. The phase difference remains below 1.5° up to 220 GHz (Fig. 11 left) and one finds that the maximum complex deviations between the calibrated data for the thru at the different locations decrease from 13 to 2 % (see Fig. 12). This proves the correlation between substrate modes and mTRL errors: Applying the same material as the wafer substrate for the chuck material not only suppresses the parasitic substrate mode but also improves the accuracy of the calibrated results.

IV. Conclusions

Propagation of substrate modes is shown to degrade accuracy of mTRL calibration in on-wafer measurements of coplanar structures in G band. A set-up with thick ceramic chuck is assumed, the presently most preferable solution for high-frequency coplanar characterization. The substrate modes are reflected at wafer edges and similar discontinuities, bounce back and couple back to the excitation point, thus providing a parasitic parallel path to the ports of the DUT. Suppression of substrate modes can be achieved by choosing the substrate thin enough or by using a chuck with a permittivity of about the same value as the substrate or above.

Acknowledgment

The authors acknowledge support by the European Metrology Programme for Innovation and Research (EMPIR) Project 14IND02 "Microwave measurements for planar circuits and components". The EMPIR program is co-financed by the participating states and from the European Union's Horizon 2020 research and innovation program. The authors would like to thank Marco Spirito from TUD, and Chong Li and Nick Ridler from NPL for support and fruitful discussions.

References

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

[2] A. Tessmann, W. H. Haydl, T. v. Kerssenbrock, P. Heide and S. Kudszus, "Suppression of parasitic substrate modes in flip-chip packaged coplanar W-band amplifier MMICs," *in 2001 IEEE MTT-S Int. Microwave Symp. Dig.*, Phoenix, AZ, USA, May 2001, pp. 543–546.

[3] E. M. Godshalk, "Surface wave phenomenon in wafer probing environments," *in 40th ARFTG Microwave Conf. Dig.*, Orlando, FL, USA, Fall 1992, pp. 10–19.

[4] F. J. Schmückle, T. Probst, U. Arz, G. N. Phung, R. Doerner, W. Heinrich, "Mutual Interference in Calibration Line Configurations," *in 89th ARFTG Microwave Measurement Conference Digest*, Honolulu, HI, USA, Jun. 2017.

[5] R. B. Marks, "A Multiline Method of Network Analyzer Calibration," *IEEE Trans. Microwave Theory & Tech.*, vol. 39, pp. 1205–1215, Jul. 2015.

[6] Microwave Studio (MWS) of CST, Darmstadt, Germany.

[7] R. E. Collin, *Field Theory of Guided Waves*, 2nd ed., New York, NY, USA: McGraw-Hill, 1960, pp.712–716.