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On the Influence of Thru- and Line-Length-Related Effects in CPW-Based Multiline TRL Calibrations

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***Abstract*—The quality of calibration standards in on-wafer measurements has a strong impact on the accuracy of the multiline Thru-Reflect Line (TRL) calibration. Especially the thru standard is one of the most critical calibration standards. For instance, it has been demonstrated recently that the probe effects are more pronounced, if the length of the thru is selected too small. In this case, the mTRL calibration is more sensitive towards probe coupling effects. Therefore, this paper reports on a systematic study on the impact of the thru length on the mTRL calibration accuracy. Additionally, the influence of the length of the calibration standards will be discussed together with the influence of probe and neighborhood effects for coplanar waveguides (CPW).**

***Index Terms*—calibration, coplanar waveguides, on-wafer, probes.**

I. INTRODUCTION

Multiline Thru-Reflect Line (mTRL) is commonly known as one of the most accurate calibration algorithms for on-wafer measurements. Its accuracy strongly relies on the quality of the calibration standards, with the thru standard being one of the most critical calibration standards. Several investigations [1], [2] and [3]) have shown that the calibrated results are strongly affected by the choice of the thru length due to probe coupling effects. More recently, this effect has been investigated by means of electromagnetic simulations in [4]. A remaining open question is whether a longer thru or in general longer lines could help to compensate for this probe effect. Starting with a measurement example, this paper presents a systematic study for two different probe types. Moreover, the benefits and risks of using longer lines as standards will be discussed.

The mTRL algorithm [5] is used for calibration of all the measured and simulated data presented in this paper. The calibration set contains an offset short with 200 µm access line length as reflect, a 400 µm long CPW for the thru standard, and several lines with lengths between 500 and 11400 µm. The CPW structures were fabricated on a fused silica substrate (ϵ_{r} = 3.78), which has been used also in [4] and [6].

The measurements were performed with probes from different vendors (GGB and MPI)[1] with a 100 µm pitch. To mitigate the propagation of surface wave and parallel plate line (PPL) modes the wafer was placed on a ceramic chuck (with a permittivity $\epsilon_{\mathrm{r,\,chuck}}$ = 6.5 larger than that of the wafer ϵ_{r} = 3.78, see [6] and [7]). For the electromagnetic simulations, CST Studio Suite from Dassault Systemes was applied [8]. The reference plane of the calibration was shifted to the probe tips for all the comparisons.

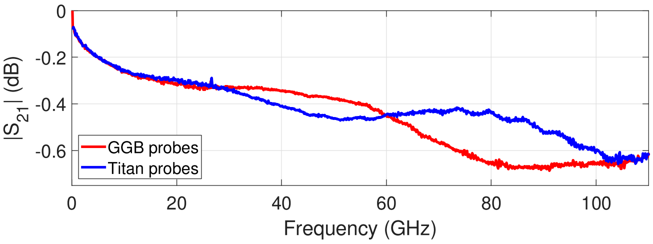

Fig. 1. Magnitude of transmission coefficient S_{21} measured with probes from different vendors for a CPW with l = 900 µm.

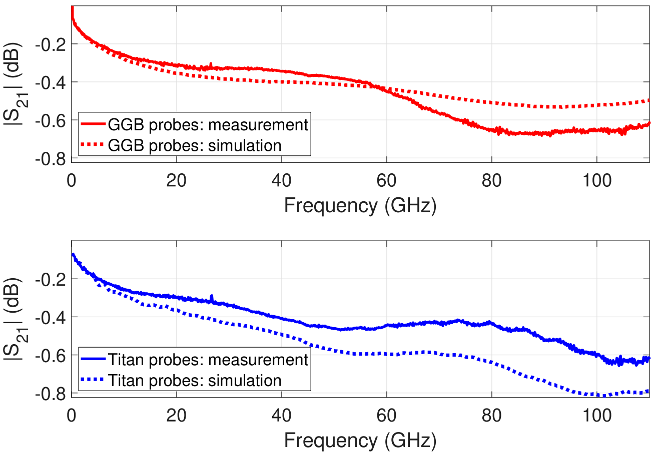

Fig. 2. Measurements and simulations of transmission coefficient S_{21} for a CPW with l = 900 µm using probes from different vendors.

Fig. 1 shows the mTRL-calibrated transmission coefficient S_{21} for a CPW with l = 900 µm measured with the probes from GGB and MPI. The overall losses of the CPW do not differ significantly between the probes. However, the curves of the same DUT measured with two different probes show a very different behavior over frequency with different waviness.

In order to reproduce this behavior, em simulations of the DUT and the entire calibration set including the complete wafer with different probes were performed. Fig. 2 plots a comparison between em simulation and measurement of the corresponding probe results. The measured peculiarities occurring when using the different probe types can be reproduced reasonably well by em simulation. The overall shift between em simulation and measurement can be attributed to

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[1] We use brand names only to better specify the experimental conditions. PTB does not endorse commercial products. Other products may work as well or better.

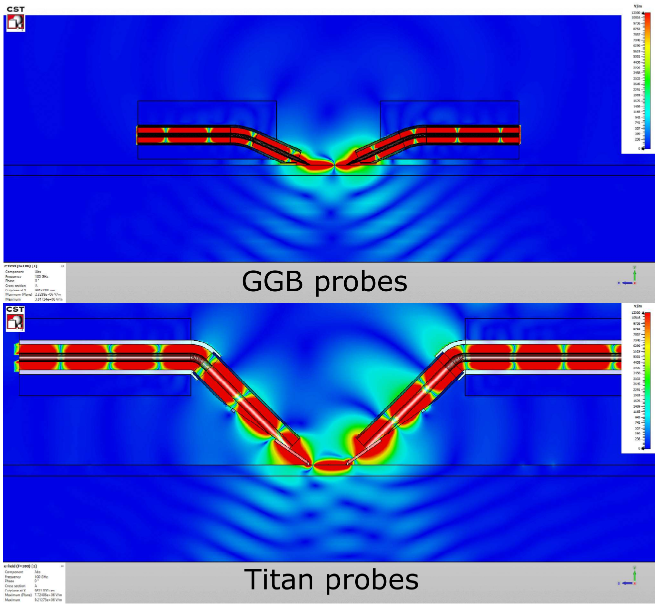

Fig. 3. Cross-sectional view of electric fields at $f = 100$ GHz of the investigated CPW excited by different probes

the limited knowledge of the material properties and exact probe geometries.

The field plots in Fig. 3 clearly demonstrate where the divergent behavior of the mTRL-calibrated results measured with different probes comes from. Not only the fields in the close vicinity of the CPW and the probe tips differ, but also the fields in the air region between the probes. The different field distributions caused by the different probe excitations lead to the deviations observed in both the simulated and measured results. Therefore, the unphysical curve behavior in Fig. 1 can be attributed to the probes, in combination with the calibration process due to the relatively short CPW length. In order to investigate the effect of the thru length, a systematic study via em simulations will be presented in the following.

II. SYSTEMATIC STUDY

The first step of the study is to simplify the DUTs by using single CPWs to exclude any disturbances caused by multimode propagation, crosstalk and neighborhood effects. For the excitation, two different probes are applied. The length of the shortest CPW (thru) is made longer with all the CPWs of the calibration set extended by the same amount. Therefore, the line differences are not changing. For the reflect standard an offset short is used with an access line length equal to the half length of the thru. Table I shows the length variation of the calibration standards. Three different calkits are defined and denoted as calkit 1, 2 and 3.

The selected DUT is a CPW 100 µm longer than the corresponding thru of the calkits. The reference plane of the DUT is placed such that the remaining CPW length is 450 µm for the calkits $1-3$ and for the standard case. Fig. 4 and Fig. 5 illustrate the shifting of the reference plane for the two different probes using calkits $1-3$.

Standards	calkit std	calkit 1	calkit 2	calkit 3
Thru	400 µm	600 µm	1200 µm	2000 µm
Line	2400 µm	2600 µm	3200 µm	4000 µm
Line	5400 µm	5600 µm	6200 µm	7000 µm
Line	7400 µm	7600 µm	8200 µm	9000 µm
Line	11400 µm	11600 µm	12200 µm	13000 µm
Offset short	200 µm	300 µm	600 µm	1000 µm
DUT	500 µm	700 µm	1300 µm	2100 µm

TABLE I
DEFINITION OF CALIBRATION KITS

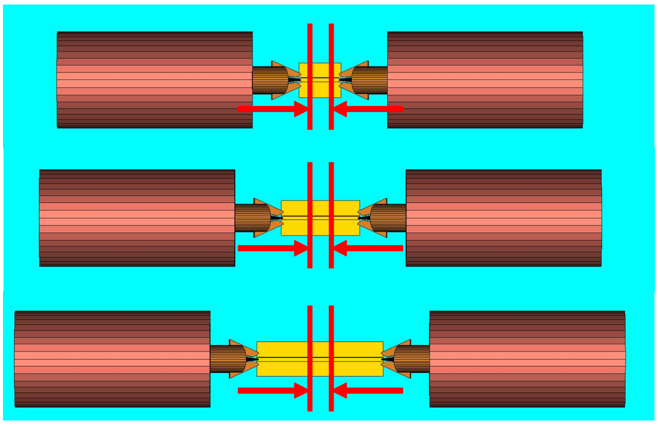

Fig. 4. Shifting of reference plane for GGB probes.

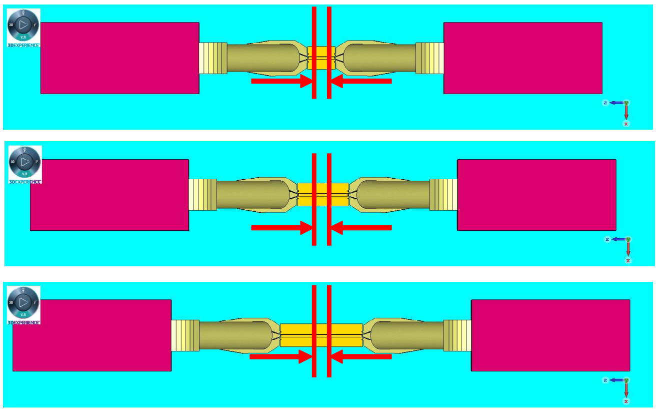

Fig. 5. Shifting of reference plane for Titan probes.

In Fig. 6 the calibrated results S_{ij} are plotted for the simulations with the GGB probes. Obviously, not only the transmission values but also the reflection coefficients are affected by the lengths defined in the calkits. Calkit 1 and the standard case (std) show the most pronounced waviness in S_{21} and the highest reflection coefficient S_{11} of approximately 0.01. With longer lengths, a slight improvement can be obtained. The waviness in S_{21} can be reduced with longer thru lengths (see calkit 3 in Fig. 6). However, some waviness still remains and cannot be fully reduced even with a relative long thru length of 2 mm. This indicates that longer calibration standards help to reduce probe coupling but the discontinuities of the coaxial transition to the probe needles and from the needles to the CPW are still causing reflections and waviness in S_{21}. This effect cannot be removed fully by the mTRL

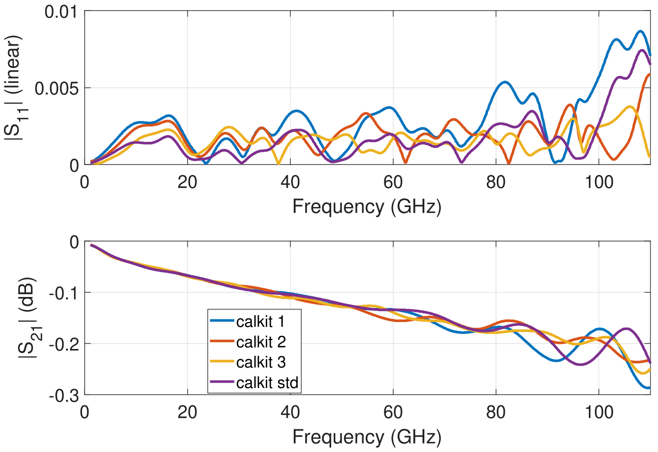

Fig. 6. Simulated magnitudes of S_{ij} for a DUT with l = 450 µm using GGB probes and different calkits according to Table I.

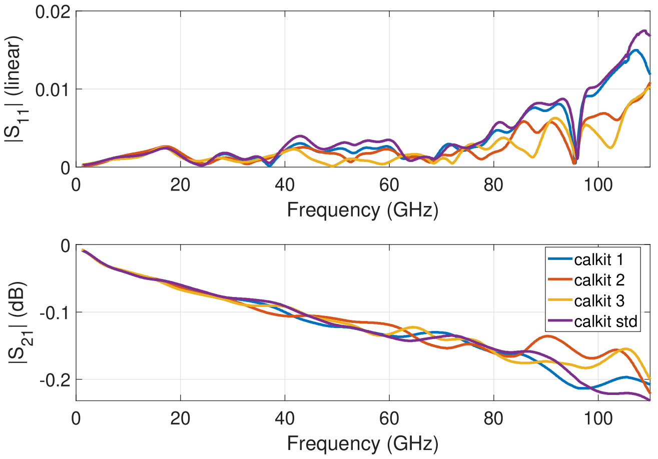

Fig. 7. Simulated magnitudes of S_{ij} for a DUT with l = 450 µm using Titan probes from MPI and different calkits (see Table I).

calibration.

Complementing the results of Fig. 6, we performed additional em simulations using the Titan probes which are plotted in Fig. 7. It can be seen that a different curve behavior over frequency due to the differences in probe geometry can be observed. Here, a similar observation as in Fig. 6 can be made. Calkit 1 and the standard case (std) represent the worst case due to the relatively short thru length. With increasing thru length, the reflections S_{11} especially at higher frequencies can be reduced. However, again the waviness remains. Fig. 8 illustrates this effect for the two different probe types investigated.

Analyzing the above results, one can state that the measurement quality is determined by the lengths of the thru and calibration standards. The shortest thru length reveals the highest coupling between the probe needles. With increasing lengths, probe coupling effects can be reduced. This might lead one to conclude that one should use longer lines for the calibration in general. However, this is not fully true. In the next section, the risks of using longer CPWs are presented.

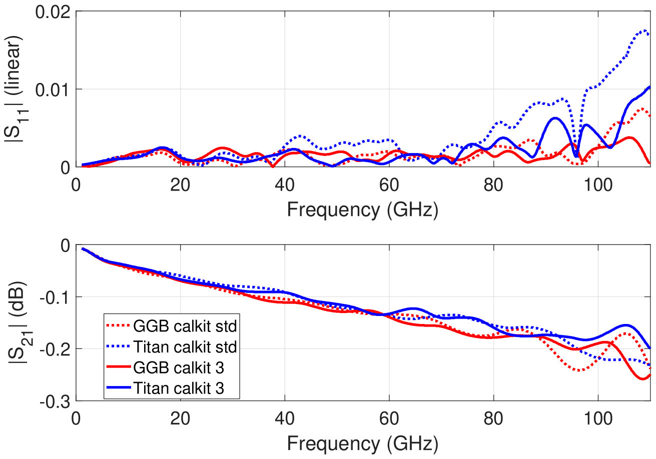

Fig. 8. Comparison of simulated magnitudes of S_{ij} using GGB and Titan probes.

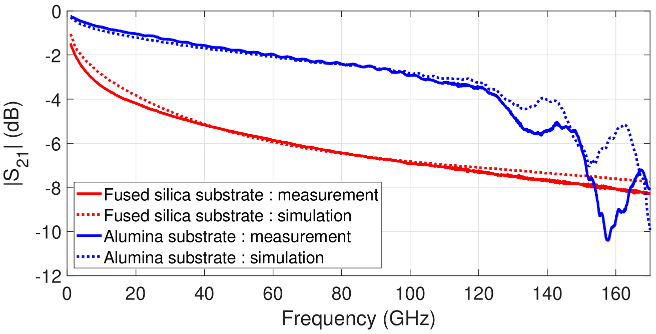

Fig. 9. Measurements and simulations of magnitude of S_{21} for CPWs with l = 11400 µm fabricated on fused silica and alumina substrate.

III. DISCUSSION AND ANALYSIS OF EVANESCENT MODES IN LONGER CPWS AT HIGHER FREQUENCIES

So far, we have performed the systematic study based on the simulations by using an ideal case on fused silica without the interference of neighborhood effects and evanescent modes. However, in other measurement situations, longer CPWs can support standing wave pattern in presence of evanescent modes [9]. We have chosen an example which supports surface wave propagation to discuss this effect. To this end, CPWs manufactured on an alumina substrate (ϵ_{r} = 9.7) are used for investigation. Measurements were performed with GGB probes on a ceramic chuck (ϵ_{r} = 6.5) up to 170 GHz.

In order to demonstrate the interaction of the surface wave with the neighborhood, a CPW with l = 11400 µm, which is laterally surrounded by two longer CPWs (l = 20400 µm and 7400 µm), is selected for the investigation. The same CPW length is also available on the fused silica wafer. Due to the chosen length of l = 11400 µm the probe coupling between the needles is negligible.

Fig. 9 shows the comparison between the measured and simulated transmission coefficient S_{21} after mTRL calibration

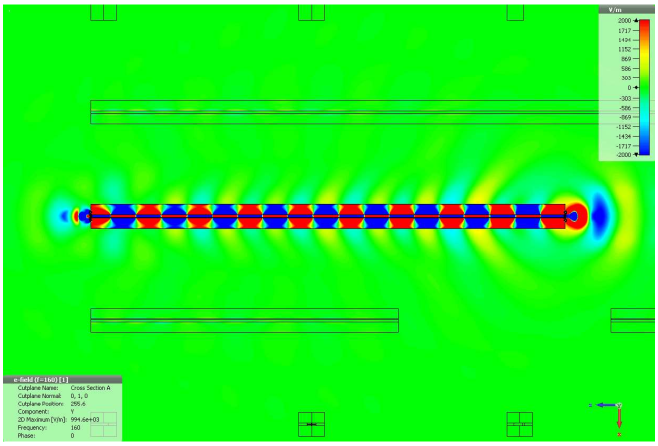

Fig. 10. Top view of the simulated vertical electric field component for a CPW with l = 11400 µm on fused silica substrate at f = 160 GHz.

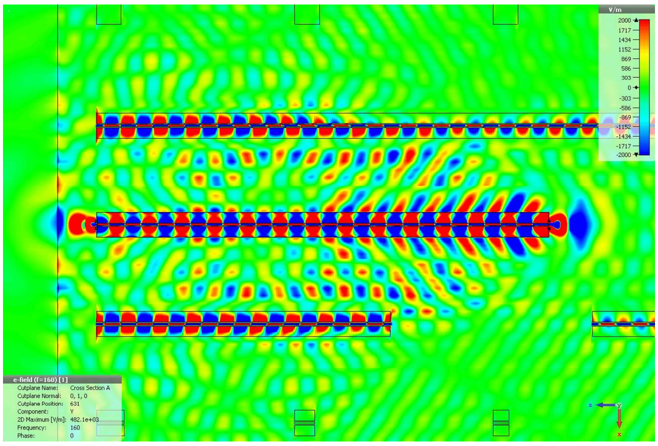

Fig. 11. Top view of the simulated vertical electric field component for a CPW on alumina substrate with l = 11400 µm at f = 160 GHz.

for the CPW with l = 11400 µm on the two different substrate materials. Obviously, the CPW on fused silica substrate shows a much smoother transmission behavior. The CPW on alumina substrate on the other hand shows more peculiarities and a strong resonance near 160 GHz.

To understand this behavior, the vertical electric fields are shown in Fig. 10 and Fig. 11 for the CPW on fused silica and alumina substrate. Comparing the field plots of Fig. 10 and Fig. 11, one can clearly state that the fused silica substrate represents a case with much less parasitics, which explains the smooth measured curve behavior in Fig. 9. By contrast, the CPW on alumina substrate shows more parasitics due to the presence of surface waves (Fig. 11).

One can observe a superposition of multiple parasitic effects. Radiated fields are caused by the CPW itself which leaks energy to the surroundings along the line. Surface waves are excited due to the violation of the recommendation in the guideline [7] and couple into the neighboring CPWs. In these adjacent CPWs unwanted slotline and CPW modes are excited and propagate along the entire CPW lengths. The parasitic modes from the adjacent CPWs in turn couple back to the measured DUT and cause a standing wave pattern leading to the resonance effects shown in the measurement of Fig. 9.

IV. CONCLUSION

Summarizing the above results, one can state that the measurement quality is influenced by the choice of the length of the calibration standards. On one hand, coupling effects between the probe needles can be reduced by using longer line lengths. On the other hand, longer lines can support additional parasitics when evanescent modes (e.g. surface waves) are present. Therefore, the choice of the line lengths needs to be properly considered in conjunction with the em boundary conditions especially in the design of MMICs and for high-precision calibration purposes.

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REFERENCES

[1] C. Yadav, M. Deng, S. Fregonese, M. Cabbia, M. De Matos, B. Plano, and T. Zimmer, "Importance and Requirement of Frequency Band Specific RF Probes EM Models in Sub-THz and THz Measurements up to 500 GHz," *IEEE Transactions on Terahertz Science and Technology*, vol. 10, no. 5, pp. 558–563, 2020.

[2] S. Amakawa, A. Orii, K. Katayama, K. Takano, M. Motoyoshi, T. Yoshida, and M. Fujishima, "Design of Well-behaved Low-loss Millimetre-wave CMOS Transmission Lines," in *2014 IEEE 18th Workshop on Signal and Power Integrity (SPI)*, 2014, pp. 1–4.

[3] A. Orii, M. Suizu, S. Amakawa, K. Katayama, K. Takano, M. Motoyoshi, T. Yoshida, and M. Fujishima, "On the Length of Thru Standard for TRL De-embedding on Si Substrate above 110 GHz," in *2013 IEEE International Conference on Microelectronic Test Structures (ICMTS)*, 2013, pp. 81–86.

[4] G. N. Phung and U. Arz, "Anomalies in Multiline-TRL-corrected Measurements of Short CPW Lines," to appear in 2021 96th ARFTG Microwave Measurement Conference (ARFTG), 2021.

[5] 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.

[6] U. Arz, K. Kuhlmann, T. Dziomba, G. Hechtfischer, G. N. Phung, F. J. Schmückle, and W. Heinrich, "Traceable Coplanar Waveguide Calibrations on Fused Silica Substrates up to 110 GHz," *IEEE Transactions on Microwave Theory and Techniques*, vol. 67, no. 6, pp. 2423–2432, 2019.

[7] M. Spirito, U. Arz, G. N. Phung, F. J. Schmückle, W. Heinrich, and R. Lozar, "Guidelines for the Design of Calibration Substrates, including the Suppression of Parasitic Modes for Frequencies up to and including 325 GHz," *EMPIR 14IND02 – PlanarCal, 2018, Physikalisch-Technische Bundesanstalt (PTB)*, 2018.

[8] "CST Studio Suite," 2020. [Online]. Available: https://www.3ds.com/products-services/simulia/products/cst-studio-suite/

[9] D. F. Williams, F. Schmückle, R. Doerner, G. N. Phung, U. Arz, and W. Heinrich, "Crosstalk Corrections for Coplanar-Waveguide Scattering-Parameter Calibrations," *IEEE Transactions on Microwave Theory and Techniques*, vol. 62, no. 8, pp. 1748–1761, 2014.