This is an author-created, un-copyedited version of the article G. N. Phung and U. Arz, "Parasitic Probe Effects in Measurements of Conductor-Backed Coplanar Waveguides," in 2021 Kleinheubach Conference, 2021, pp. 1-4, doi: 10.23919/IEEECONF54431.2021.9598396.

The definitive publisher-authenticated version is available online at: https://doi.org/10.23919/IEEECONF54431.2021.9598396.

Parasitic Probe Effects in Measurements of Conductor-Backed Coplanar Waveguides

Gia Ngoc Phung
Physikalisch-Technische Bundesanstalt
Bundesallee 100
38116 Braunschweig, Germany

Uwe Arz
Physikalisch-Technische Bundesanstalt
Bundesallee 100
38116 Braunschweig, Germany

***Abstract*—Recently, parasitic effects in on-wafer measurements have been investigated thoroughly and can be classified as stemming from probe effects, multimode propagation, crosstalk between adjacent structures and radiation effects. While a lot of investigations have been performed for conventional coplanar waveguides (CPW) measured on ceramic chucks, the parasitic effects occuring in conductor-backed CPWs (CB-CPWs) have not been fully clarified yet. Therefore, this paper demonstrates how parasitic modes and probe effects deteriorate calibrated S-parameters of CB-CPW structures.**

***Index Terms*—conductor-backed coplanar waveguides, calibration, parallel-plate-line or microstrip mode, probes, radiation.**

I. INTRODUCTION

On-wafer measurements have been known as ambitious and challenging containing a lot of parasitic effects degrading the accuracy of the calibrated results.

In recent years, a major effort has been undertaken to clarify the causes of parasitic effects on coplanar waveguides in the framework of the PlanarCal project [1] which aimed to enable the traceable measurement and electrical characterisation of integrated planar circuits and components from radio-frequency (RF) to sub-mm frequencies. It has been found that the parasitics are caused by different disturbances such as e.g. multimode propagation ([2], [3] and [4]), crosstalk effects and the influence of microwave probes during measurements ([5] and [6]).

While a number of investigations have been performed for conventional coplanar waveguides (CPW) measured on ceramic chuck, the parasitic effects occuring in conductor-backed (CB) CPWs are not yet fully understood. The CB-CPW case is of fundamental importance because it is widely used in many applications for monolithic microwave circuits (MMIC-s), hybrid integrated circuits and printed circuit boards (PCB). CB-CPWs offer several advantages with regard to improved mechanical strength and heat sinking abilities. However, the presence of a bottom ground plane allows for the propagation of an additional parallel-plate-line mode or microstrip-type mode, a transverse electromagnetic (TEM) mode which occurs without any cutoff frequency. Whenever CPWs are measured directly on a metal chuck, there are electrical potential differences between the metals residing on top of the substrate and on the bottom ground. Therefore, the PPL mode can already occur during on-wafer characterization of the CPWs and thus have an impact on the resulting measured results.

With this motivation, the goal of this paper is to investigate the underlying phenomena of the probe influences for CB-CPWs. Starting with a measurement example, this paper presents a systematic study of how the parasitic probe effects deteriorate multiline Thru-Reflect-Line (mTRL)-calibrated S-parameters of CB-CPWs.

II. MEASUREMENT AND SIMULATION RESULTS

All simulated and measured results presented here have been processed with a mTRL calibration according to [7]. The calibration set consists of a short as reflect, a 400 µm long CPW line as thru and a selection of seven additional lines with lengths between 500 and 11400 µm. The CPW structures are fabricated on a fused silica substrate (ϵ_{r} = 3.78) and have been used in [8].

All the measurements were performed with ground–signal–ground (GSG) probes from vendor (GGB Industries Inc.)[1] with a 100 µm pitch up to 110 GHz. The measurements were performed on a metal chuck to emulate the CB-CPW case and additionally on a ceramic chuck to avoid the propagation of PPL mode and surface waves (ceramic chuck with a permittivity which is larger than that of the calibration substrate $\epsilon_{\mathrm{r,chuck}}$ = 6.5 > ϵ_{r} = 3.78, see [9]). The ceramic case is therefore used in most cases as a reference for comparison.

In the electromagnetic (em) simulations, CST Studio Suite was used [10]. In order to realistically emulate the given scenarios, the layout of the complete wafer with all neighboring effects was modeled [5]. For the excitation, the sophisticated probe model of [5] (emulating the geometry measured for real probes) was applied. The reference plane of the calibration for both chuck conditions was shifted to the probe tips to enable comparisons between simulations and measurements. The measured and simulated magnitudes of the transmission coefficient S_{21} of CPWs of different line lengths for both chuck conditions are presented in Figs. 1−3. For comparison purposes the relative difference $\Delta|S_{21}|$ is plotted, which is defined as follows:

$$\Delta|S_{21}|_{dB} = |S_{21,metal}|_{dB} - |S_{21,ceramic}|_{dB} \qquad (1)$$

[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.

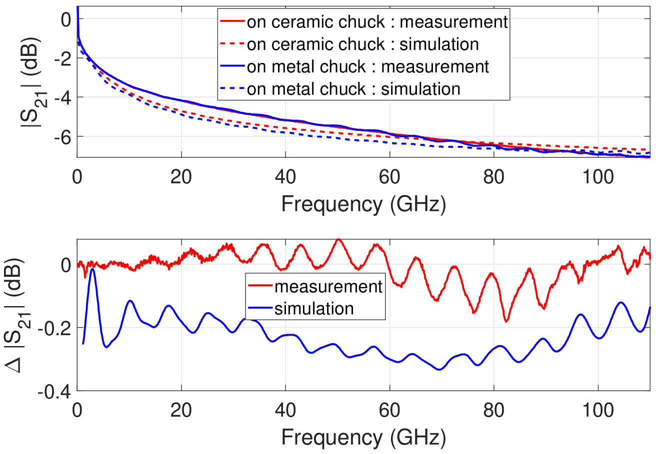

Fig. 1. Measurement and em simulation of the CPW with l = 11400 µm on different chuck materials: Transmission coefficient $|S_{21}|$ and difference $\Delta|S_{21}|$ between transmission on metal and ceramic chuck.

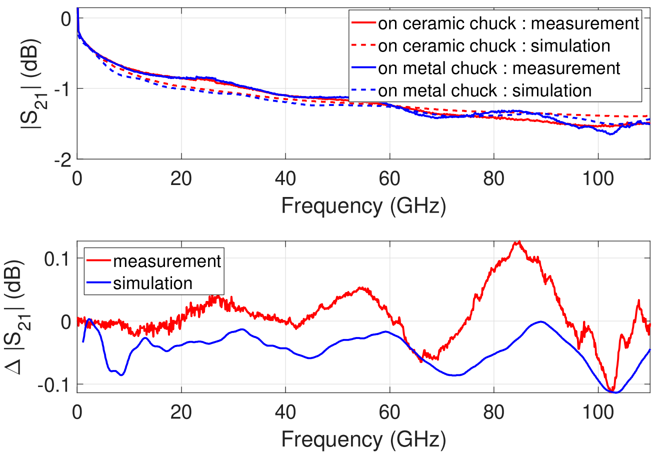

Fig. 2. Measurement and em simulation of the CPW with l = 2400 µm on different chuck materials: Transmission coefficient $|S_{21}|$ and difference $\Delta|S_{21}|$ between transmission on metal and ceramic chuck.

The line lengths selected for the comparison are l = 11400, 2400 and 900 µm. At first sight, one can observe a relatively good agreement between the em simulation and measurement for all the results (Figs. 1−3). Overall, there is a slight shift between the measurements and em simulation due to not fully known material properties and lack of knowledge of the exact probe geometry. When comparing the different chuck conditions, the metal and ceramic chuck, an interesting behavior can be observed. The metal chuck case shows strong ripples in $|S_{21}|$. The ceramic chuck case shows an ideal smooth curve within the investigated frequency range especially for the longer CPWs. Fig. 1 shows the results for the CPW with l = 11400 µm. Ripples are not only pronounced in S_{21} but also in the difference $\Delta|S_{21}|$ calculated according to eq. (1) with the ceramic chuck as reference. Obviously, the differences $\Delta|S_{21}|$ of both simulations and measurements show a similar curve behavior. The ripples are also visible when the CPW

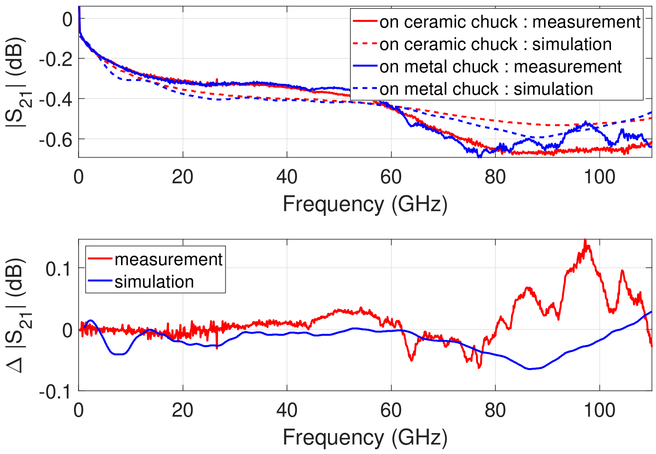

Fig. 3. Measurement and em simulation of the CPW with l = 900 µm on different chuck materials: Transmission coefficient $|S_{21}|$ and difference $\Delta|S_{21}|$ between transmission on metal and ceramic chuck.

length is decreased (l = 2400 µm (Fig. 2). Here, the same statement holds. The metal chuck represents the worst case with strong ripples and the CPWs on ceramic chuck reveal the expected smooth behavior. The periodicity of the ripples also changes when the CPW length is decreased. This behavior can be detected for both measured and simulated results.

The situation changes when comparing the curves corresponding to the CPW with l = 900 µm (Fig. 3). Here, the CPW on the ceramic chuck shows a wavy curve behavior instead of the expected smooth curve behavior. Thus, the ceramic chuck does not represent the ideal case with least parasitics. The peculiarities of the wavy behavior can be attributed to the interaction of parasitic probe effects. The mTRL calibration cannot fully compensate for the influence of the probes when the CPW length is below 2000 µm [11]. Therefore, the ripple behavior occuring in longer CPWs is different from that of shorter CPWs (e.g. l = 900 µm).

III. Field Plots

So far, the CPW measurements and em simulations demonstrate ripples for the metal chuck case and a smooth curve behavior for the ceramic chuck. In this section, the underlying reasons will be investigated by means of thorough field analysis. Figs. 4 and 5 show the cross-sectional and top view of the em-simulated vertical electric field component for the longest CPW with l = 11400 µm. The scaling of the vertical electric field is exaggerated in order to see pronounced effects. When comparing the vertical electric field component of the CPW placed on the ceramic chuck against that on the metal chuck at cross-sectional view (Fig. 4), one can clearly detect an undisturbed CPW mode propagation for the ceramic chuck. The field plots for the metal chuck show the propagation and superposition of two modes. The CPW mode on the ceramic chuck propagates with a constant phase velocity, whereas on the metal chuck, two modes, the CPW and the PPL mode, are propagating with two different phase velocities. The divergent

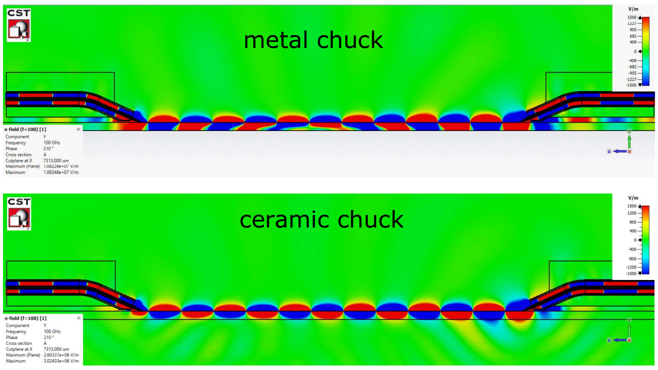

Fig. 4. Cross-sectional view: simulated vertical electric field component of the CPW with l = 11400 µm excited with port 1 (right port) on different chucks at f = 100 GHz.

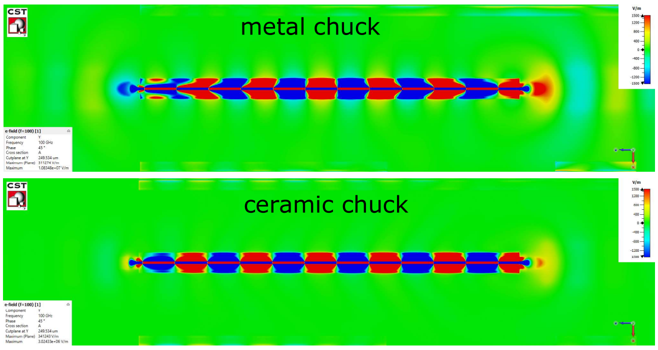

Fig. 5. Top view: simulated vertical electric field component of the CPW with l = 11400 µm excited with port 1 (right port) on different chucks at f = 100 GHz.

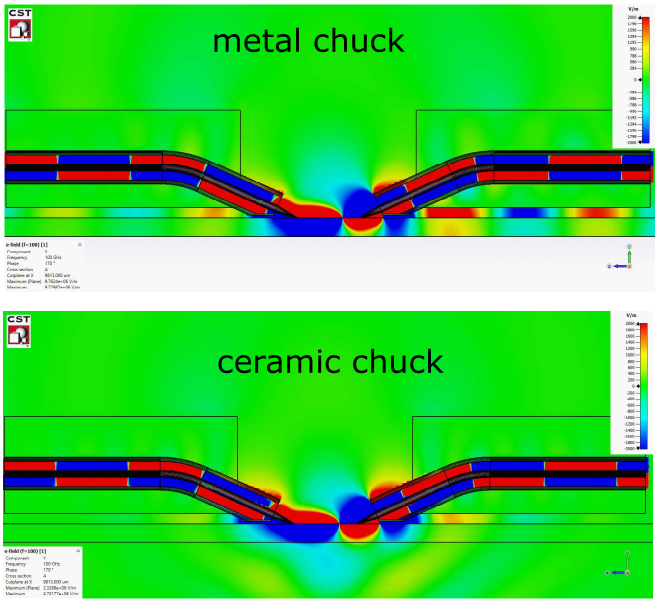

Fig. 6. Cross-sectional view: simulated vertical electric field component of the CPW with l = 900 µm excited with port 1 (right port) on different chucks at f = 100 GHz.

phase velocities can be traced back to different effective permittivities. The PPL mode has a larger phase constant $\beta_{\mathrm{PPL}} > \beta_{\mathrm{CPW}}$, thus leakage behavior is unavoidable. The larger phase constant (or effective permittivity) of the PPL mode can be traced back to the stronger field concentration of the PPL mode inside the substrate whereas the fields of the CPW mode are mainly concentrated inside the gap region.

Additionally, one can observe that the PPL mode is not only propagating along the CPW line, but is also supported by the probe needles and transferred into the air region surrounded by the absorber enclosing the coaxial line of the probe and the calibration substrate. The superposition of the CPW with the PPL mode leads to constructive and destructive interference of the electric fields which result in phase distortions along the CPW (see Fig. 4). Thus, the destructive interference of the two modes in turn leads to the resonance effects which document themselves in ripples detected in the measurement results (Figs. 1−3).

The fields in the top view of Fig. 5 also confirm this statement. For the ceramic chuck the electric fields of the CPW are mainly concentrated in the gap region and show a regular field pattern. Therefore, whenever the vertical electric field component at the signal conductor reaches its maximum field strength (red), the vertical electric field component at the two CPW grounds reaches the minimum field strength (blue) and vice versa. This consistent field pattern is clear evidence of a pure CPW mode propagation.

The metal chuck, however, reveals a different electric field pattern. The total CPW width (which is two times the CPW ground width plus the spacing) forms the upper metal plate and the backside forms the bottom plate which enables the propagation of the PPL mode. The PPL mode is concentrated inside the substrate supported by the two metal plates. Thus its expected field pattern is characterized by vertical electric field components which are oriented perpendicularly to the CPW surface. The vertical electric field component on the upper plate (CPW total width) either reaches its maximum (red) or its minimum (blue). The superposition of the CPW mode with the PPL mode distorts the field pattern (see metal chuck case in Fig. 5).

So far, the propagation of the PPL mode has been presented for longer CB-CPWs. The probe effects are more evident in the field plots of the CPW with shorter line length l = 900 µm (Fig. 6) and thus have a larger impact on the resulting S-parameters (Fig. 3). For the metal chuck case a strong interaction of the PPL mode with the parasitic probe effects can be found. The PPL mode is transferred to the regions around the probe needles, the transition to coaxial extensions and between the absorber of probe and calibration substrate.

IV. Conclusion

Summarizing the above results, this paper demonstrates how probe effects deteriorate mTRL-calibrated S-parameter measurements of CB-CPW structures. This paper presents a thorough study of CB-CPWs through field analysis and demonstrates the interaction of the parasitic PPL mode and probe effects. Currently, research is in progress for developing analytical expressions which will help to better predict the occurrence of ripples in CB-CPWs including the parasitic probe effects.

Acknowledgment

The authors acknowledge support by the European Metrology Programme for Innovation and Research (EMPIR) Project 14IND02 "Microwave measurements for planar circuits and components". Furthermore, this work was supported in part by 18SIB09 "Traceability for electrical measurements at millimetre-wave and terahertz frequencies for communications and electronics technologies". Both projects (14IND02 and 18SIB09) have received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

The authors are also grateful to Rohde & Schwarz for manufacturing the calibration substrate used in this study. The authors also thank D. Schubert from PTB for their expert technical assistance.

References

[1] European Metrology Programme for Innovation and Research JRP Number 14IND02, "Microwave Measurements for Planar Circuits and Components." https://planarcal.ptb.de.

[2] M. Spirito, C. De Martino, and L. Galatro, "On the Impact of Radiation Losses in TRL Calibrations," in *2018 91st ARFTG Microwave Measurement Conference (ARFTG)*, 2018, pp. 1–3.

[3] M. Tsuji, H. Shigesawa, and A. A. Oliner, "New Surface-Wave-Like Mode on CPWs of Infinite Width and its Role in Explaining the Leakage Cancellation Effect," in *1992 IEEE MTT-S Microwave Symposium Digest*, 1992, pp. 495–498 vol.1.

[4] H. Shigesawa, M. Tsuji, and A. A. Oliner, "A New Mode-Coupling Effect on Coplanar Waveguides of Finite Width," in *IEEE International Digest on Microwave Symposium*, 1990, pp. 1063–1066 vol.3.

[5] G. N. Phung, F. J. Schmückle, R. Doerner, B. Kähne, T. Fritzsch, U. Arz, and W. Heinrich, "Influence of Microwave Probes on Calibrated On-Wafer Measurements," *IEEE Transactions on Microwave Theory and Techniques*, vol. 67, no. 5, pp. 1892–1900, 2019.

[6] S. Fregonese, M. De matos, M. Deng, M. Potereau, C. Ayela, K. Aufinger, and T. Zimmer, "On-Wafer Characterization of Silicon Transistors Up To 500 GHz and Analysis of Measurement Discontinuities Between the Frequency Bands," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 7, pp. 3332–3341, 2018.

[7] 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.

[8] 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.

[9] 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.

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

[11] G. N. Phung and U. Arz, "Anomalies in Multiline-TRL-corrected Measurements of Short CPW Lines," in *2021 96th ARFTG Microwave Measurement Conference (ARFTG)*, 2021, pp. 1–4.