110 GHz On-Wafer Measurement Comparison on Alumina Substrate

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***Abstract*—This paper reports on initial results of a three-party on-wafer measurement comparison carried out on a custom-made alumina calibration substrate in the frequency range up to 110 GHz. The correction of the vector network analyzer measurement is done with the highly accurate multiline TRL (mTRL) calibration. The focus of the investigation is on the influence of the measurement system, the probe geometry and operator skills. The results of the calibrations are presented and the influence on selected devices under tests (DUT) are evaluated for different measurement configurations.**

***Index Terms*—on-wafer, calibration, substrate, probes.**

I. INTRODUCTION

On-wafer measurements have been known as ambitious and challenging compared to coaxial measurements which rely on well established standards and defined connectors. The on-wafer calibration depends on the calibration standards, but also on the substrate material, substrate metalization, probe geometry, chuck material and the operator. On-wafer probes are available for defined frequency ranges and come with a defined pitch width. There is no definition or standardization for the geometry and material of the probe tips available. Beside this, the manufacturer of the probes recommends to use their own calibration substrates with specially tailored alignment structures.

Beside the two bilateral studies [1], [2], there is, up to now - to our best knowledge - no detailed measurement comparison available, covering different measurement systems, probes (manufacturer, pitch size) and chuck materials. Therefore, as part of the PlanarCal research project [3], a measurement comparison for the frequency range up to 110 GHz has been organized with the aim to cover different measurement systems, probes, chuck materials and operators.

A custom-made calibration substrate based on alumina was produced at Rohde & Schwarz and investigated by the partners PTB, IAF and FBH. A high-precision mTRL calibration was chosen to correct the measurement data as described in [4], [5]. In the following sections we present the first results of the intercomparison.

II. INVESTIGATED LAYOUT, INTRODUCTION OF THE MEASUREMENT SYSTEMS AND EVALUATION

TABLE I
MEASUREMENT SYSTEM CONFIGURATION OF THE PARTNERS. 'C' AND 'M' DENOTE MEASUREMENTS ON CERAMIC AND METAL CHUCK, RESPECTIVELY.

Partner	Probe	Pitch	Chuck	Name
PTB	GGB PicoProbe	100 µm	ceramic	*PTB c GGB100*
PTB	GGB PicoProbe	100 µm	metal	*PTB m GGB100*
PTB	GGB PicoProbe	150 µm	ceramic	*PTB c GGB150*
PTB	GGB PicoProbe	150 µm	metal	*PTB m GGB150*
IAF	Cascade Infinity	100 µm	metal	*IAF m Cascade100*
IAF	Cascade Infinity	75 µm	metal	*IAF m Cascade75*
FBH	GGB PicoProbe	100 µm	ceramic	*FBH c Cascade100*
FBH	Cascade Infinity	100 µm	ceramic	*FBH c GGB100*
FBH	Allstron Titan	100 µm	ceramic	*FBH c Allstron100*
PTB	GGB PicoProbe	100 µm	ceramic	*PTB c GGB100 2*
PTB	GGB PicoProbe	100 µm	metal	*PTB m GGB100 2*

Based on the design used in [6], the layout of a custom calibration substrate on alumina was optimized for the purpose of this investigation. The substrate offers multiple devices under test for verification and comparison of the measurement results. The main mTRL set consists of 9 lines with lengths in the range from 400 µm to 20400 µm in combination with an offset-short as reflect. The majority of the devices, especially the main calibration set, are designed with a ground conductor width of 270 µm, but there are also devices with different ground conductor widths such as e.g. 650 µm present on the substrate to investigate the influence with respect to the calibration.

The measurement comparison involves three parties with different measurement equipment. At PTB a semi-automated SUSS MicroTec on-wafer system with an Anritsu VectorStar network analyzer (VNA) for the frequency range up to 125 GHz is available. The system allows for semi-automated measurements of devices with different lengths. A similar probe station from Cascade Microtech is utilized at FBH. The vector network analyzer is a Rohde & Schwarz ZVA for the frequency range up to 110 GHz. The system at IAF consists of a manual Cascade Microtech on-wafer system with an Anritsu VectorStar network analyzer (VNA) suitable for the frequency range up to 145 GHz.

The measurement system configurations are listed in Table I. The partners used an identical frequency range from 0.1-110 GHz for the comparison with a VNA bandwidth f_{IFBW}=100 Hz, which both allow for a short measurement time. The schedule for the measurement comparison consisted of a full mTRL-set (9 lines, 2 reflects), DUTs (compare devices: lines, mismatched lines, attenuators and reflects), the recommended calibration substrate of the probe manufacturer and a reduced mTRL-set (6 lines, 2 reflects) for drift characterization.

For the evaluation of the measurement campaign in this first stage, we apply the highly precise mTRL calibration

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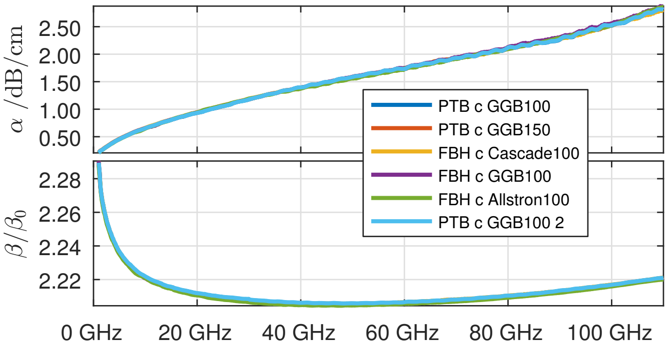

Fig. 1. α in dB/cm and β/β_0 as results of the mTRL calibrations for measurements on ceramic chuck.

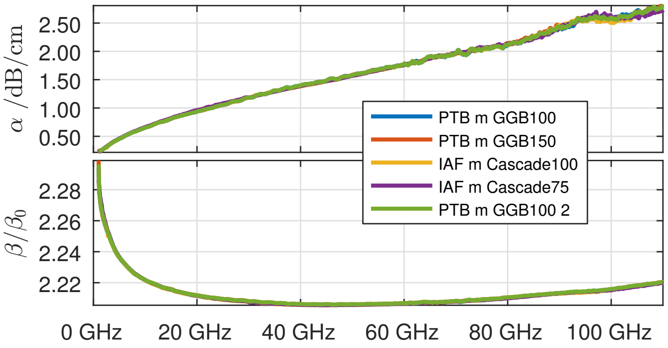

Fig. 2. α in dB/cm and β/β_0 as results of the mTRL calibrations for measurements on metal chuck.

with identical settings to the full mTRL sets and correct the remaining measurement sets. The initial calibration involves all lines and an offset short of the full mTRL set. The line impedance Z_0 was used as reference impedance Z_{ref} and the reference plane of the calibration was shifted to the probe-tip-plane. Further processing and evaluation of the measurement data will be subject of future work.

The substrate was passed on to the partners in the order indicated in Table I, ending with an integrity check measurement at PTB.

III. COMPARISON OF THE RESULTS

A. *Results of mTRL Calibration*

First, the results of the mTRL calibration, here shown as attenuation α in dB/cm and normalized phase constant β/β_0, grouped by chuck materials, indicate valid measurements for all partners, see Fig. 1 for ceramic and Fig. 2 for metal chuck. For both measurement configurations, ceramic and metal chuck, β/β_0 shows dispersion above frequencies of 50 GHz. Calibrations on the ceramic chuck show radiation losses for higher frequencies beginning at $\approx$80 GHz, see Fig. 1. In Fig. 2 the measurements on metal chuck show the occurrence of higher-order modes in the range above 70 GHz to 110 GHz. However, the results from the partners and probe configurations are in good agreement and indicate no obvious failure or anomaly.

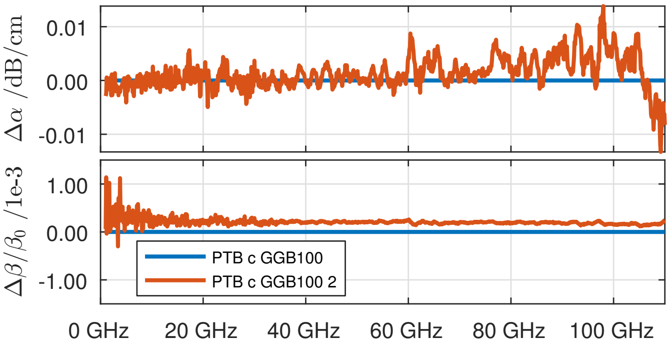

Fig. 3. α and β/β_0 Δ-plots of the first measurement and the integrity check as proof for reliability of the substrate after the run-through.

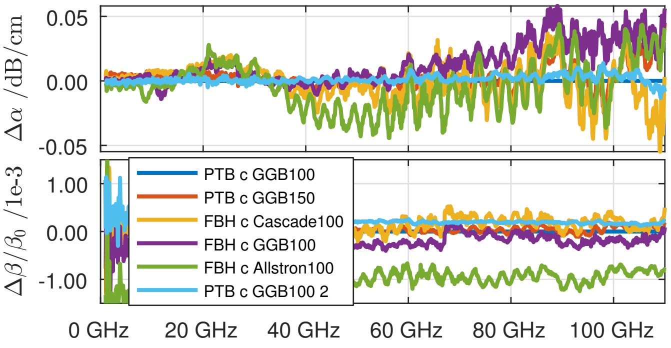

Fig. 4. α in dB/cm and β/β_0 as results of the mTRL calibrations for measurements on ceramic chuck.

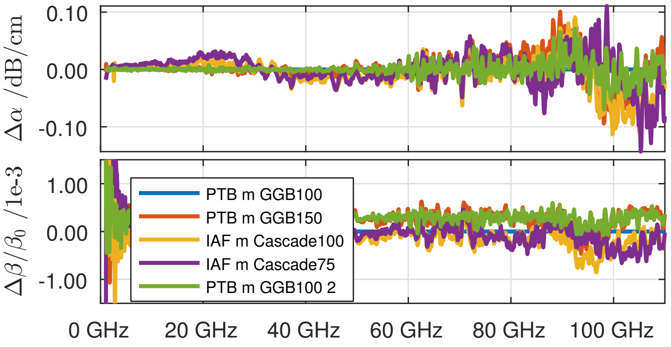

Fig. 5. α in dB/cm and β/β_0 as results of the mTRL calibrations for measurements on metal chuck.

The results of the mTRL calibration of the initial and integrity measurement (*PTB c GGB100* and *PTB c GGB100 2*) with identical probes on ceramic chuck are shown in Fig. 3 as difference-plot for α in dB/cm and for β/β_0. Both values show only small deviations in the range of $\Delta\alpha \ll 1 \cdot 10^{-2}$ and $\Delta\beta/\beta_0 \ll 1 \cdot 10^{-3}$. They are in good agreement, thus the substrate shows nearly no degradation and can be rated as still intact and usable after the measurement comparison.

To investigate further details, Fig. 4 and Fig. 5 show the difference-plots for α and β/β_0 for both chuck situations with the first measurement indicated in the legend serving as reference. This plot reveals the deviations between the

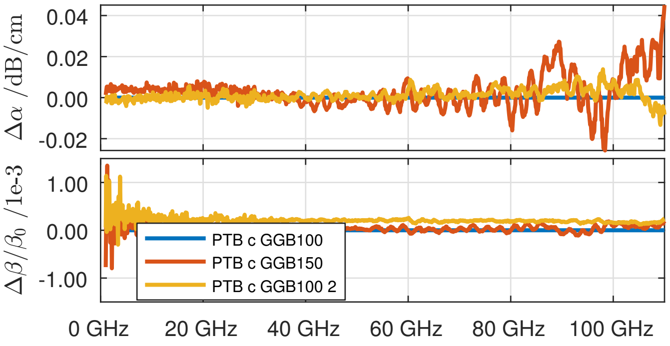

Fig. 6. α and β/β_0 Δ-plot for partner PTB on ceramic chuck.

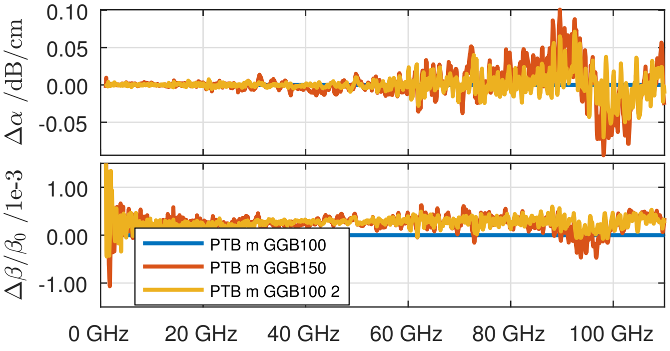

Fig. 7. α and β/β_0 Δ-plot for partner PTB on metal chuck.

calibrated results for the same chuck configuration, which may be caused by the probe configurations, the system stability, the systems operator or the system configuration. Again, all calibrations are processed with the same initial parameters. The discrepancies between the results of the partners in Fig. 4 are quite high ($\Delta\alpha \approx \pm 5 \cdot 10^{-2}$ and $\Delta\beta/\beta_0 > 1 \cdot 10^{-3}$). Also, some conspicuous behavior for $\Delta\alpha$ over the frequency can be observed (compare *FBH c GGB100* and *FBH c Cascade100* to *PTB c GGB100* for frequencies around 15-35 GHz), this issue seems to be system-related. Similar behavior can be seen in Fig. 5, where the deviation in $\Delta\alpha \approx \pm 10 \cdot 10^{-2}$ is even higher, especially for frequencies above 50 GHz.

A detailed view of the differences in mTRL calibration for each partner and chuck configuration is given in Figs. 6-9. At all partners' sites, the results show a smooth behavior and only small deviations between the configurations of each partner occur. However, in Fig. 7 a bigger peak-to-peak deviation $\Delta\alpha \approx 15 \cdot 10^{-2}$ on metal chuck can be noted compared to $\Delta\alpha \approx 6 \cdot 10^{-2}$ for the ceramic chuck in Fig. 6. This is consistent with the observations made in [7] and [8]. In Fig. 6, a more pronounced deviation in α can be observed at higher frequencies for the larger pitch width of 150 µm.

The peak-to-peak deviations shown in Figs. 8-9 (where the reference value for calculating the deviations was measured by the respective partner), are on the same order of magnitude as in Figs. 6-7.

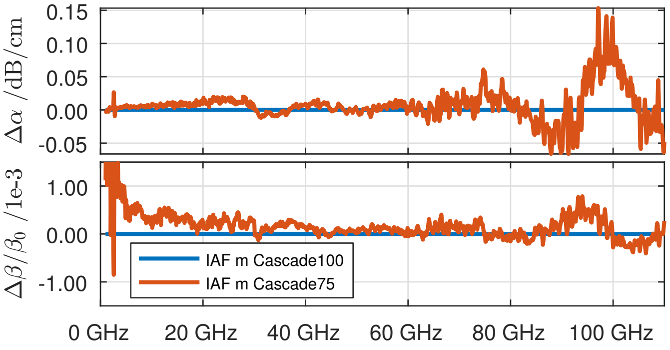

Fig. 8. α and β/β_0 Δ-plot for partner IAF on metal chuck.

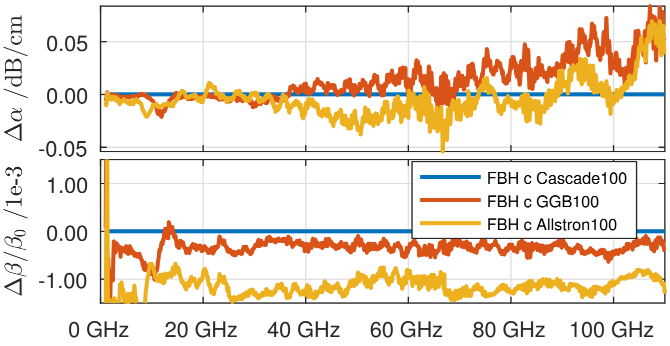

Fig. 9. α and β/β_0 Δ-plot for partner FBH on ceramic chuck.

B. *Comparison of Device Under Test*

The comparisons of the partners results are shown exemplarily with the DUT line_7400_650, which is a 7400 µm line with nominal coplanar wave guide (CPW) dimension from the mTRL-set, but with larger ground metalization to facilitate the occurrence of higher-order modes. The measurements were corrected with the mTRL calibration. The magnitude of S_{12} for ceramic and metal chuck is shown in Fig. 10 and Fig. 11. These graphs already reveal the deviation between the individual measurement configurations of the partners. A more detailed view with Δ-plots is given in Fig. 12 and Fig. 13 for ceramic and metal chucks; both configurations differ in the worst case by $\Delta|S_{12}| \approx \pm 3 \cdot 10^{-2}$, which is significant. It can be seen from the graphs, that the results on metal chuck comprise stronger ripples than on ceramic chuck.

The ripples in 4 curves of Fig. 12 appear nearly in the same almost sinusoidal shape. This behavior is described by a mode which is similar to a substrate mode below the CPW. In Fig. 13 other parasitic modes superpose. The magnitude of the deviations in the curves of Fig. 12 and 13 come from the different shapes and geometries of the probes. At the present state it is difficult to assign certain artifacts in the measurements to certain properties of the probe. The main influences stem from the extension of the probe, the extension of any absorber around the probe and the extension and geometry of the needles. An important role plays also the region of the transition from the coaxial line to the needles

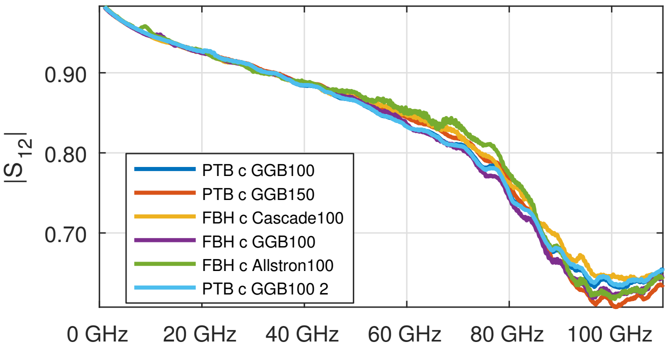

Fig. 10. $|S_{12}|$ plot for line_7400_650 on ceramic chuck.

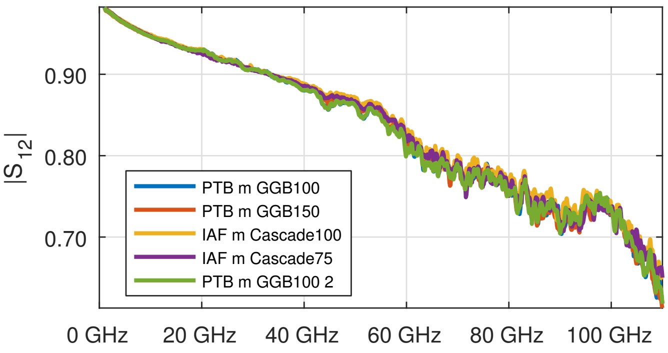

Fig. 11. $|S_{12}|$ plot for line_7400_650 on metal chuck.

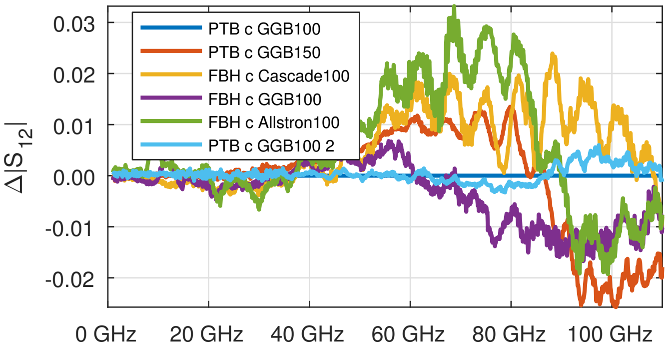

Fig. 12. $\Delta|S_{12}|$ plot for line_7400_650 on ceramic chuck.

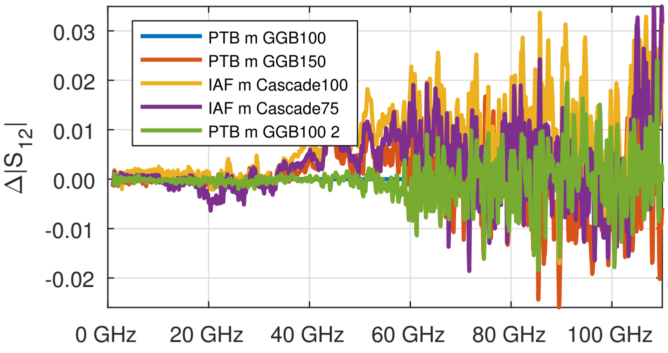

Fig. 13. $\Delta|S_{12}|$ plot for line_7400_650 on metal chuck.

(size, width of coax opening, distance to DUT and substrate).

C. *Discussion*

The first results of the comparison show that many factors have to be considered for the evaluation of on-wafer measurements. However, it is very difficult to isolate the factors leading to the differences observed between the different configurations.

IV. CONCLUSION

This paper reports on the first part of an intercomparison of on-wafer measurements in the frequency range up to 110 GHz. Reliable and comparable on-wafer measurements are still challenging and rely strongly on the measurement equipment, e.g. chuck material, probe geometry, but also on the art of measurement and the operators skills. Impact of the environment and system stability can be seen in the drift behavior (not shown here), which strongly depends on the over-all measurement duration.

First observations relating to the different measurement setups and probe properties could be made, but there is still more work to do to get reliable and reproducible measurements across different on-wafer systems.

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