On the Importance of Calibration Standards Definitions for On-Wafer Measurements up to 110 GHz

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***Abstract*—This paper reports on the follow-up evaluation of an on-wafer measurement comparison on custom-made and conventional alumina calibration substrates in the frequency range up to 110 GHz. The focus of the current investigation is on the performance of different calibration methods used for correcting device under test (DUT) measurements on the custom-made substrate. Four different calibration schemes are discussed and the results of the calibration methods are presented and compared.**

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

I. Introduction

Reliable on-wafer measurements come with the need for accurate calibration substrates and algorithms. It is well known, that up to now no standardizations exist, neither for the probes, nor the calibration substrate. It is widely accepted and common knowledge, that the probe manufacturers offer calibration substrates designed for combination with their probes. These so-called impedance standard substrates (ISS) offer the possibility to perform calibrations implemented in the firmware of most vector network analyzers (VNA) and can be performed easily by the user.

In our previous work [1], we reported on a measurement comparison on a custom-made alumina substrate which was equipped with a multi-line TRL (mTRL) calibration set and measured at different system configurations. We focussed on the highly accurate mTRL calibration algorithm [2], [3] and pointed out the influences of the chuck material, probes and the pitch size - the evaluation was only on the custom-made alumina (Al2O3) calibration substrate, which was fabricated by Rohde & Schwarz (R&S).

In many practical situations, however, the situation can be often quite different and one has to calibrate on an external calibration substrate, e.g. ISS substrate, while the DUT of interest is on a different substrate with possibly other material and coplanar waveguide (CPW) parameters. In this work we focus on four calibrations schemes to perform a reliable calibration on the DUT substrate, see Fig. 1(a-d). To this end, we used selected datasets from the measurement intercomparison [1] and evaluated the data accordingly.

II. Measurement configurations and data processing

The evaluated data was generated as part of the measurement intercomparison, reported in [1]. In most of the cases, the measurements on a custom-made alumina substrate (R&S Al2O3) and on the ISS substrate recommended by the probe

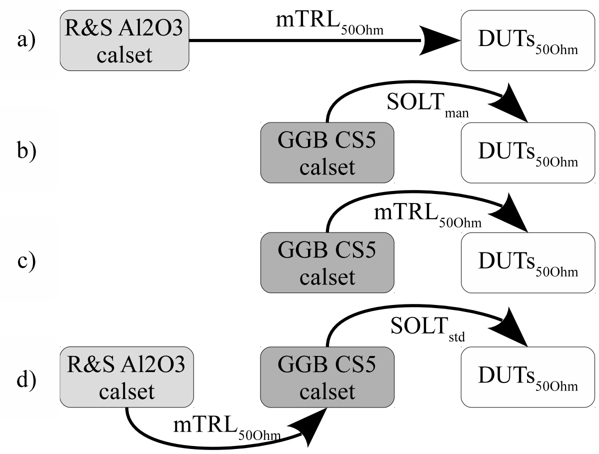

Fig. 1. Calibrations procedures: a) $\mathrm{mTRL_{Al2O3}}$ calibration from R&S Al2O3, b) $\mathrm{SOLT_{man}}$ calibration based on manufacturer settings from GGB CS5, c) $\mathrm{mTRL_{CS5}}$ calibration from GGB CS5 and d) $\mathrm{mTRL_{Al2O3}}$ corrected $\mathrm{SOLT_{std}}$ standards and calibration from GGB CS5.

manufacturer (GGB CS5) were taken shortly one after another in order to avoid significant instrument drift. In this paper we will investigate the following measurement configurations:

1) PTB: GGB Picoprobe 100 µm on ceramic chuck
2) PTB: GGB Picoprobe 150 µm on ceramic chuck
3) FBH: GGB Picoprobe 100 µm on ceramic chuck

At PTB a semi-automated SUSS MicroTec on-wafer system with an Anritsu VectorStar 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.

In the following, the performance of the four calibration procedures depicted in Fig. 1 is illustrated by analyzing the results for a 3000 µm long mismatched line on the custom-made Al2O3 substrate. In all cases analyzed, the reference impedance of the calibration is set to $Z_{\mathrm{ref}} = 50\,\Omega$ and the reference plane of the calibration is located at the probe tips.

A. *mTRL_{50Ohm} calibration (custom-made standards)*

With reference to the first part of the intercomparison, we evaluated the mTRL calibration utilizing lines from 400 - 20400 µm and an offset-short as reflect according to the scheme in Fig. 1 (a). This is generally accepted as one of the

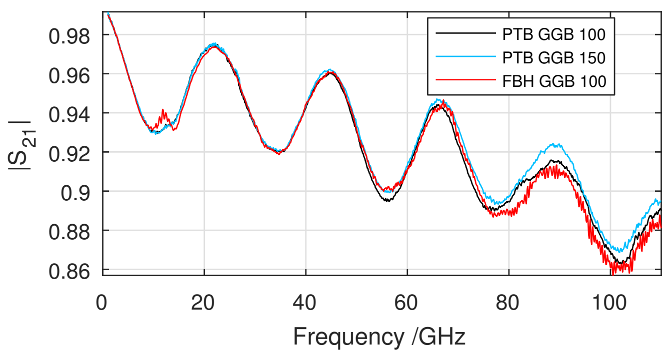

Fig. 2. Transmission of mismatched line $|S_{21}|$ in linear magnitude for calibration with $\mathrm{mTRL}_{\mathrm{Al2O3}}$.

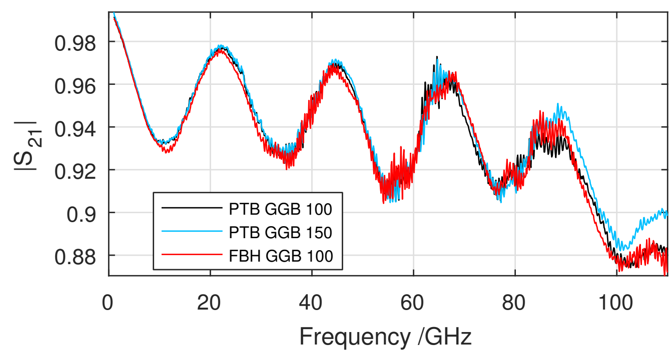

Fig. 4. Transmission of mismatched line $|S_{21}|$ in linear magnitude for calibration with $\mathrm{SOLT}_{\mathrm{man}}$.

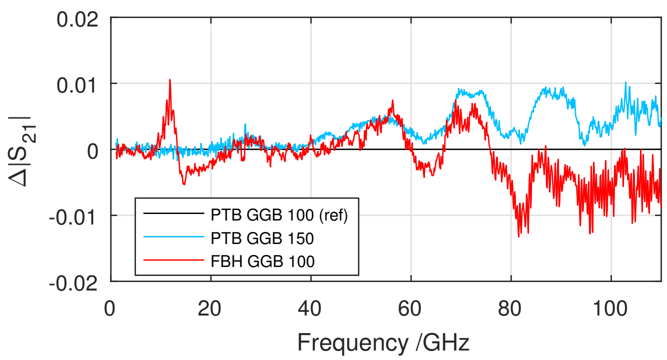

Fig. 3. Difference $\Delta|S_{21}|$ for mismatched line in linear magnitude for calibration with $\mathrm{mTRL}_{\mathrm{Al2O3}}$.

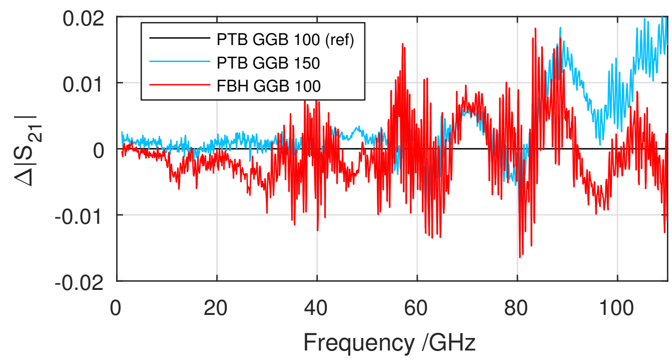

Fig. 5. Difference $\Delta|S_{21}|$ for mismatched line in linear magnitude for calibration with $\mathrm{SOLT}_{\mathrm{man}}$.

most accurate calibration approaches, because the calibration standards are embedded in the same substrate and designed to match the geometry of the DUT.

The results for each measurement configuration 1)-3) are shown in Fig. 2 as $|S_{21}|$ in linear magnitude for the mismatched line DUT on R&S Al2O3 substrate and in Fig. 3 as difference plot $\Delta|S_{21}|$with reference to the PTB GGB 100 µm case. A difference on the order of $\pm 1\%$ can be detected between the results for the configurations 1)-3).

The differences between configuration 1) (PTB GGB 100 µm) and configuration 2) are caused by the difference in the pitch size of the probes and become more pronounced at higher frequencies. The differences between configuration 1) (PTB GGB 100 µm) and configuration 3) (FBH GGB 100 µm) can most likely be attributed to the differences in the instrumentation used and to the time spent for the measurements. The results of configuration 3) show increased noise due to the longer measurement duration.

B. $SOLT_{man}$ calibration based on manufacturer settings

In practice, the most commonly used calibration approach is to follow the calibration recommendations given by the manufacturer, i.e. to use off-chip standards located on the ISS substrate and to perform a calibration which is usually implemented in the VNA firmware (see Fig. 1 (b)). Here, we focus on SOLT calibrations on the CS5 ISS manufactured by GGB.

The results shown in Figs. 4 and 5 illustrate that applying the SOLT algorithm together with manufacturer definitions of the standards leads to visibly more noise in the corrected data, starting already at moderate frequencies. Again, the influence of the increased pitch size in configuration 2) becomes evident at higher frequencies. In summary, maximum differences on the order of $\pm 2\%$ can be observed with regard to the reference configuration 1), which is almost twice as much as in Fig. 3.

C. $mTRL_{CS5}$ calibration on ISS

If custom-made standards on the DUT substrate are not available, one way to improve the results is to choose a better calibration algorithm. Here we use the reference mTRL calibration method in conjunction with the line standards fabricated on the CS5 ISS (see Fig. 1 (c)).

The resulting difference with regard to the reference configuration 1) is shown in Fig. 6. Compared to Fig. 5, the noise in the correct DUT results is significantly reduced as well as the maximum deviations with regard to the reference configuration 1).

D. $mTRL_{Al2O3}$ - corrected $SOLT_{std}$ ISS standards

In situations when users prefer to use commercial ISS substrates and easy to implement calibration procedures, such

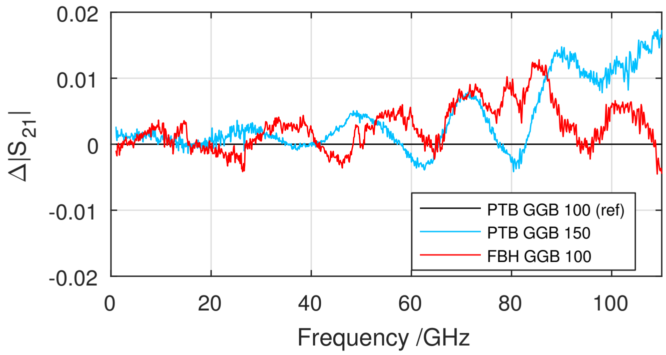

Fig. 6. Difference $\Delta|S_{21}|$ for mismatched line in linear magnitude for calibration with $\mathrm{mTRL}_{\mathrm{CS5}}$.

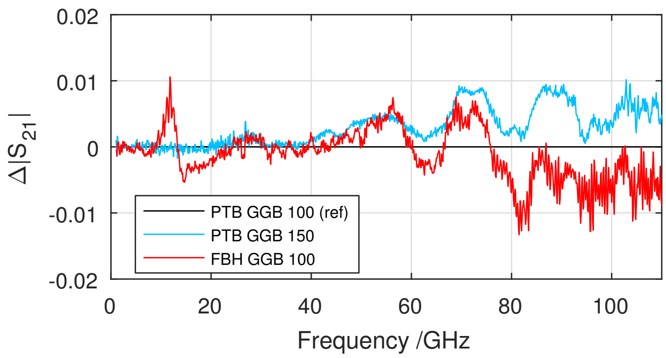

Fig. 7. Difference $\Delta|S_{21}|$ for mismatched line in linear magnitude for calibration with $\mathrm{SOLT}_{\mathrm{std}}$.

as SOLT, one can follow the scheme shown in Fig. 1 (d). Such situations can occur e.g. in high-throughput production testing, where only quick and simple algorithms together with readily available ISS substrates can be used.

The approach of Fig. 1 (d) starts with a $\mathrm{mTRL}_{\mathrm{Al2O3}}$ calibration on the DUT wafer - or on a dedicated calibration substrate which is fully compatible with the target DUT wafer. This calibration is used to correct raw measurements of the SOLT calibration standards on the ISS, thereby characterizing the SOLT calset on the ISS substrate and using it as a transfer standard. Even though the corrected SOLT standard data may look unphysical at certain frequencies, the characterization data still adequately captures the properties of the DUT target substrate.

This is illustrated in Fig. 7, which shows the resulting differences with respect to configuration 1) after applying the SOLT DUT correction with the characterized ISS standards. There is virtually no difference to Fig. 3, where we applied the best available calibration algorithm directly on the target DUT substrate together with custom-made mTRL standards.

III. Comparison and Discussion of the Results

In the previous section, the results of the four calibration approaches were used to demonstrate also the influences stemming from the different measurement configurations 1) - 3). Here we summarize the results by comparing the four calibration approaches based on the measurement configuration 1) (PTB GGB 100). We start by using the mismatch line as verification device.

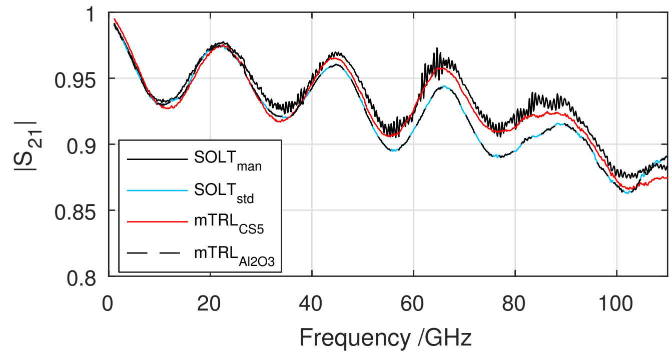

Fig. 8. Transmission of mismatched line $|S_{21}|$ in linear magnitude for different calibrations with PTB GGB 100 µm pitch.

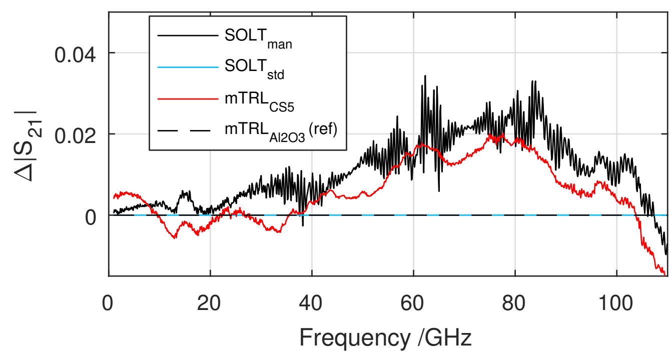

Fig. 9. Difference $\Delta|S_{21}|$ for mismatched line in linear magnitude for different calibrations with PTB GGB 100 µm pitch.

Fig. 8 shows the results from the four calibration approaches $\mathrm{SOLT}_{\mathrm{man}}$, $\mathrm{SOLT}_{\mathrm{std}}$, $\mathrm{mTRL}_{\mathrm{CS5}}$ and $\mathrm{mTRL}_{\mathrm{Al2O3}}$ for the magnitude of S_{21}. $\mathrm{mTRL}_{\mathrm{Al2O3}}$ and $\mathrm{SOLT}_{\mathrm{std}}$, which correspond to Figs. 1 (a) and 1 (d), are virtually indistuingishable, which proofs that characterized standards (here: SOLT) built on an impedance standard substrate can be used as transfer standards.

This is consistent with the findings in [4], where the properties of microwave probes were determined with different procedures. In [4], it was also shown that the probe characteristics depend on the substrate material used in the target application. Even though, in our current investigation, we have alumina as a substrate material and gold as a metallization for both the custom wafer and the ISS, there are still differences in the material properties, and, equally important, in the cross-sectional dimensions of the planar waveguides involved.

Fig. 9 shows the differences between the curves of Fig. 8 with respect to the reference calibration $\mathrm{mTRL}_{\mathrm{Al2O3}}$. Again, the difference between $\mathrm{mTRL}_{\mathrm{Al2O3}}$ and $\mathrm{SOLT}_{\mathrm{std}}$ is by orders of magnitude less than the respective differences of $\mathrm{mTRL}_{\mathrm{CS5}}$ or, even worse, $\mathrm{SOLT}_{\mathrm{man}}$.

Finally, we verify our findings based on the mismatched-line

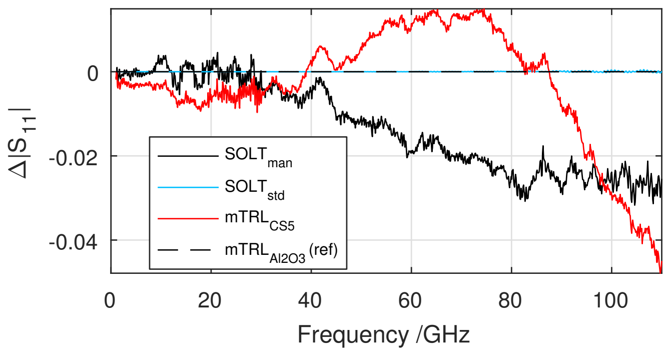

Fig. 10. Difference $\Delta|\mathrm{S}_{11}|$ for open in linear magnitude for different calibrations with PTB GGB 100 µm pitch.

DUT with an offset-open DUT, which was also custom-made on the Al2O3 substrate by R&S.

If we compare the behavior of the different calibrations shown in Fig. 9 for transmission of the mismatched line $\Delta|\mathrm{S}_{21}|$ to the results of the high-reflect in Fig. 10, we can observe different behavior between the CS-5 based calibratiions $\mathrm{mTRL}_{\mathrm{CS5}}$ and $\mathrm{SOLT}_{\mathrm{man}}$. The two other calibration approaches $\mathrm{mTRL}_{\mathrm{Al2O3}}$ and $\mathrm{SOLT}_{\mathrm{std}}$, however, again yield virtually identical results.

IV. Conclusion

Using three different measurement configurations, we have investigated the performance of four different calibration procedures on the basis of error-corrected measurements of verification devices built on a custom-made alumina wafer. While the results using the procedures recommended by the manufacturer of the ISS and probes are less satisfactory, the results of a reference mTRL calibration using custom standards can be in essence duplicated with the aid of characterized ISS standards and a much simpler calibration, in this case SOLT. This demonstrates that properly characterized standards can be used to account for differences between the ISS and the target DUT measurement situation.

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