On the Definition of Reference Planes in Probe-level Calibrations

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***Abstract* — In this contribution we analyze the definition of reference planes in probe-level calibrations. The removal of the probe type from the calibration definition is presented first analyzing the transition discontinuities and defining to which extent they have to be incorporated in the calibration error terms. Subsequently a commercial calibration, which is defined specific to a probe topology, is considered and its frequency dependent standard response are computed accurately via a 3D EM simulator. These probe independent standard definitions are then used to compare the accuracy achieved on the same structures, (i.e., CPW lines of different lengths) from two different probe topologies. Finally, the data from both probes are compared, using a worst bound metric, to the data achieved when using the probe specific calibration data showing an accuracy improvement for the probe independent approach, validating the improved identification of the reference plane proposed here.**

***Index Terms* — VNA, calibration, on-wafer, EM simulation, wafer probes, RSOL.**

I. Introduction

Traceable high frequency calibration techniques form the ‘stepping stone’ towards accurate device characterization and modeling. The accuracy of a calibration is fundamentally derived from the knowledge of the standards used in the calibration process and the consistent definition of the measurement reference plane [1]. Contrary to the connectorized measurements, where sources of uncertainty in both calibration standard and measurement reference plane definitions have been accurately identified [2], planar measurements miss this rigorous identification.

When the un-connectorized measurement can employ dedicated calibration structures employing accurate techniques such as the thru-reflect-line (TRL) [3], setting the reference plane distant from the imperfect (from an electromagnetic stand point) probe-to-pad transition, an accurate calibration with a clear definition of the reference plane can be achieved.

On the contrary, when the calibration is performed on a “general” impedance substrate and then *transferred* to the environment where the DUT is embedded a less rigorous process takes place. TRL calibrations can also be referred back to the probe tip from the knowledge of the propagation constant as was shown in [4], nevertheless this approach suffers from the usage of a pure TEM propagation (i.e., to shift the reference plane using γ) in a region where discontinuities and non-propagating modes are present.

Recently, the authors have shown [5] that accurate (pitch dependent) models of the calibration standards, present in commercially available calibration substrates, can be derived by means of electro-magnetic (EM) simulations; and coupling these standard definitions to the usage of a reciprocal SOL calibration [6] yielded improved accuracy, compared to the classical calibration flow. Nevertheless, no information on the exact location of the reference plane was provided, which is the scope of this paper.

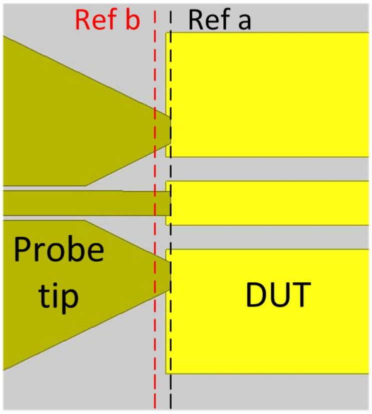

Fig. 1: Schematic top-view of a probe-to-line transition for a GSG connection. Line a (dashed black) and b (dashed red) define two possible positions for the calibration reference plane.

Up-to-date probe-level calibrations are performed using *paired* substrates probe set, where the discontinuity caused by the transition (probe-to-line/pad) is entirely embedded in the standard definition, implicitly setting the reference at plane *b* in Fig. 1. This results in two effects:

- calibration substrates cannot be used on un-paired probes,
- measured data present offsets when compared to simulated data (which are often the benchmark value in all integrated technologies), since the imperfect probe-to-pad transition is not included in the simulation.

In this contribution we propose to shift the probe-level calibration plane to *a* of Fig. 1, by embedding the imperfection of the transition in the calibration error terms, resulting in easier data benchmarking with calibration one and the ability to have probe independent calibration substrates.

The paper is structured as follows, first the effect of the probe-to-pad transition is presented using well established lumped models. Then, the commercial calibration standard is

TABLE I

STANDARD DEFINITION FOR THE CASCADE MICROTECH ISS MODEL 101-190C CONSIDERED IN THIS PAPER [9].

ACP/ FPC	C-Open fF (On substrate)	C-Open fF (in air)	L-Short pH	L-Term pH	**Infinity**	C-Open fF (On substrate)	C-Open fF (in air)	L-Short pH	L-Term pH
GSG 100	3.5	-9.3	2.4	-3.5	GSG 100	3,6	-6.5	3.3	-0.4
GSG 125	3.5	-9.5	3.6	-2.6	GSG 125	3,6	-6.6	5.7	1.6

described and the two different standard definitions are explained. The measurement comparison based on two different probe topology is then presented and the worst case bound are reported.

II. PROBE-TO-PAD TRANSITION

The probe tip of commercial probes operating up to 40/67GHz provide all a coaxial to co-planar transition, realized with different design and concepts, as shown in Fig. 2 extracted from [7].

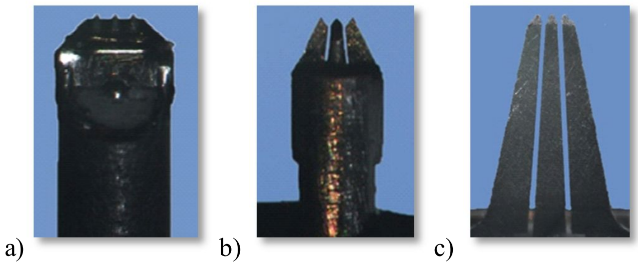

Fig. 2: Photograph of various Ground-Signal-Ground probe tips, bottom: a) Infinity Probe, b) Picoprobe, c) |Z| Probe, extracted from [7].

Nevertheless, all the different probe tip implementations end with a tip providing a contact point in the order of 10-20µm in order to easily contact pads and lines having a width of 50µm, as shown in Fig. 3 a).

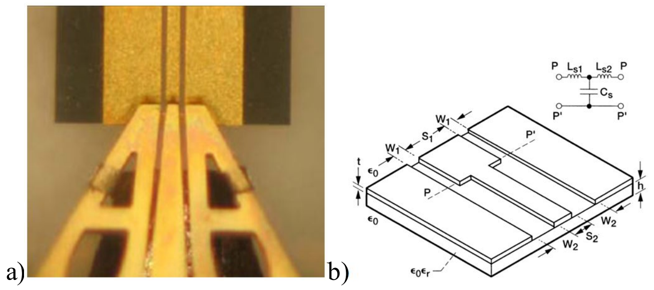

Fig. 3: a) Probe-to-line transition for a |Z| probe on a CPW transmission line. b) Equivalent model for a step change in signal line width for a CPW transmission line, as derived from [8].

This width step, between the probe tip and the line/pad, can be modelled (in first approximation) as a step change in the width of the signal line of a CPW, as shown in Fig. 3 b), from [8]. As can be seen from the inset in Fig. 3 b), this step discontinuity can be modelled as a T-network with a shunt capacitor. In order to move to the reference plane of the probe-level calibration to plane *b* (Fig. 1) this capacitance is removed (becoming of negative sign) and embedded in the standard definition, as can be seen from Table I. In the Table the values from commercial probes paired with a calibration substrate are shown. As can be seen by the Table, the different capacitance realized by the different (probe specific transition) are removed making the standard definitions (for the same substrate) probe specific. In this paper we propose to embed the parasitic components arising from the probe specific transition into the calibration error set, thus setting the reference plane at *a*, (Fig. 1).

III. STANDARD DEFINITIONS ON ISS

Commercially available calibration kits are typically provided with simple, purely reactive standard models, in order to maintain the required compatibility with old network analyzer firmware. To perform our study, we used a Cascade Microtech ISS model 101-190C as calibration substrate. For this, probe-paired standard models are provided by the manufacturer, as reported in TABLE I, for two probe types, ACP/FPC [10] and Infinity [11], and different probe pitch. No model is instead provided for un-paired probes. For the same calibration substrate, an alternative model has been developed, as reported in [5]. For each calibration standard, dimensions have been accurately determined by means of precision measurements using a Dektak 8 profilometer. Using this information, the standards have been then drawn and simulated, for different probe pitches, in a 2.5D full-wave EM environment (i.e., Keysight Momentum), as depicted in Fig. 4.

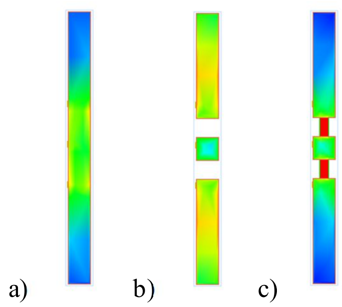

Fig. 4: 3D models of the short (a), open (b) and load (c) terminations from the ISS 101-190C calibration substrate, after

Keysight Momentum simulation, indicating field intensity over the conductor and resistive layer surfaces.

The s-parameters extracted from simulations have been then used as models for the calibration kit. Note that, in this case, the model is only dependent upon the probe pitch, while no further information on the probe type is required. For this reason, the model is in principle applicable to any GSG probe.

IV. Experimental data comparison

In order to compare the two different standard models described in Section III, we considered two different set of probes with the same probe pitch, i.e., 100µm. In particular, one set of Cascade Microtech Infinity i40 and one set of Cascade Microtech 40 GHz |Z| [12] probes have been employed. Two calibration sets from the same ISS model 101-190C substrate have been considered, and on each one raw measurements of all the calibration standards have been performed with both sets of probes, in the frequency range from 1GHz to 40GHz, using a semi-automated probe-station to reduce probe misplacement. Afterwards, the raw data have been used to derive the error set for RSOL calibration, using the manufacturer provided standard definition of Table I for the Infinity, and EM derived standard models for both Infinity and |Z| probes, obtaining a total of six different error sets. All the data acquisition, generation of the calibration terms, and data correction was performed using Cascade Microetch Wincal XE ver. 4.5 [13]. Raw measurements of two 220µm lines and two 450µm lines, on the same calibration substrate, have been performed, and the six error sets mentioned above have been applied, obtaining twenty-four independent measurements. In order to compare the different probe-tips calibrations, the method of [4] has been employed, using simulation data of the two verification lines as reference, and defining the worst case error bound (WCB) as:

$$WCB = \max\left|S_{ij,n}^{k} - S_{ij}^{Ref_k}\right| \quad (1)$$

Where S^{Ref} is the s-parameter associated to the reference data (i.e., simulation of the 220µm and 450µm, respectively) with $k \in [1,2]$, $S^{k}ij_{,n}$ is the n[th] s-parameter measured with $n \in [1 \div 6]$ being the considered error set, and $i,j \in [1,2]$.

The results of the comparison are shown in Fig. 5. The comparison highlights how, when EM models for the calibration standards are employed (see, Fig. 5, full squares for Infinity, empty circles for |Z|), different probes provide similar values for the error bounds, making the calibration in principle insensitive of the probe type. Furthermore, when probe-paired standard definitions are employed (see, Fig. 5, star symbols), the resulting error bound is up to two times higher than the error associated to any EM model based calibration, irrespectively of the probe. Note, that in this analysis the higher error bound is not to be interpreted as a worse calibration, but as a wrong association of the reference plane, when compared with a clearly defined plane in the simulation environment. This result can also be highlighted by comparing the phase response of the 450µm line of the two different probes employing the EM models (see, Fig. 6, full squares for Infinity, empty circles for |Z|), showing an high agreement with the simulated data (see, Fig. 6, solid line), and the result using the probe dependant model provided by the manufacturer (see, Fig. 6, star symbols).

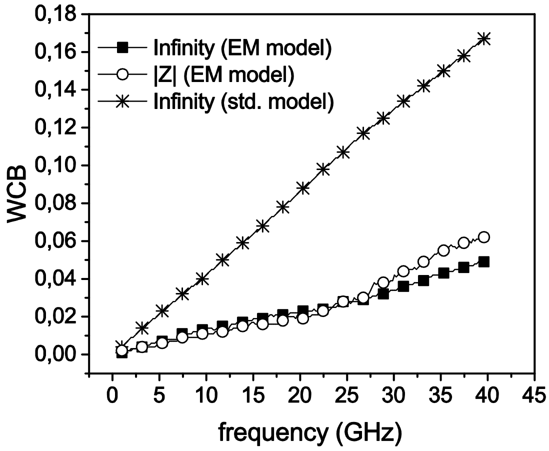

Fig. 5: Worst case error bound defined by the two different sets of probes, employing EM derived calibration standard model for Infinity (full squares) and |Z| probes (empty circles) and the standard probe-paired model for the Infinity (stars) probes, when calibrating using a Cascade Microtech ISS 101-190C. Calibrations have been performed on two different calibration kits on the same substrate, and verified on four different lines. The WCB is computed using simulation data of the verification line as reference.

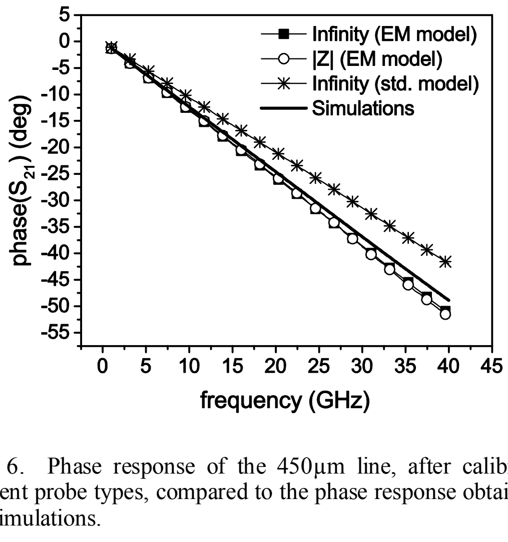

Fig. 6. Phase response of the 450µm line, after calibration for different probe types, compared to the phase response obtained using EM simulations.

V. CONCLUSIONS

In this paper we analyzed the impact associated to the choice of the reference plane in probe-tips calibration on the accuracy of S-parameter during on-wafer measurements. Using a commercially available calibration substrate, a probe-paired standard definition and a probe-independent standard modeling, based upon EM simulations of the standards, have been employed and benchmarked on independent transmission lines, using simulation data as comparison. The results of the experiment show how a probe-independent definition of the calibration standards allows to properly define the measurement reference plane, embedding the probe-dependent contact point transition in the calibration error terms, and improves the measurement accuracy when compared to probe-paired standard definitions.

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