New Calibration Solutions for Multi-Channel Probes using an Added Port for Thru Measurements

Kooho Jung and Michael F. Andrews*

Cascade Microtech Inc., Beaverton, OR 97008 USA, * Microsemi Co., Bend, OR 97702 USA

***Abstract* — A new method is proposed for calibrating multi-channel probes placed in multiple quadrants for wafer or chip level measurement. It uses an additional ground-signal-ground probe to enable thru measurements in a conventional calibration procedure, avoiding the need for custom calibration kits. The inherent delay inconsistencies in the proposed method are shown to be small enough to have minimal effects on the measurement uncertainties, in most practical cases.**

***Index Terms* — N+1-port, multi-channel probe, calibration, thru, SOLT, SOLR, calibration standard, calibration kit.**

I. Introduction and Overall View

Multi-channel probes are often customized probes for measuring a specific integrated circuit (IC) at the wafer or chip level. The number of channels and their pitch are customized, and each channel is configured either as ground, by-passed power, logic, or RF to match the IC's pad design. These probes are useful because they provide IC measurements before packaging, hence, can be used for engineering evaluation, as well as for production tests.

One of the biggest challenges in typical multi-channel probes is the long lead-time due to their customization [1], whereas "programmable" multi-channel probes have significantly reduced lead-time by realizing the various tip configurations (ground, by-passed power, logic, RF, etc.) by cutting or connecting traces on the probe. However, the channels formed this way typically have limited operation frequency (≤ 20 GHz) and use large tips that make them difficult to probe small pads [2]. Recently, these problems have been solved by high-performance "programmable" multi-channel probes which operate up to 110 GHz and can probe pads as small as 30 x 50 μm^2 [3]. However, an outstanding challenge still remains on their RF calibration.

Fig. 1 shows a general case of multi-channel probes used in 4 quadrants to measure an IC, which will be referred as the device under test (DUT). The blue tips are those from channels that do not need calibration, e. g., grounds, by-passed power, etc. The red tips are those from the RF channels that need calibration, which will be referred to as "S" (Signals). The red tips can be adjacent to various types of channels (of the red or blue tips), forming various configurations such as ground-signal-ground (GSG), ground-signal (GS), differential signal-signal pair without grounds (SS), etc. In some cases, the bypassed powers (P) will be used in place of grounds (G). In this work, P's used this way will be referred as G's unless stated otherwise. The network analyzer calibrates these variously configured channels, treating them individually as ports. If N is the total number of these ports, the network analyzer regards the DUT as an N-port network. Note that the differential SS pair is counted as a single port, since it is connected to a single port in the network analyzer via a balun.

When calibrating up to 4 ports, the commonly used techniques are Short Open Load Thru (SOLT) [4] and Short Open Load Reciprocal-Thru (SOLR) [5, 6]. The reflection-standards (SOL) are measured on the individual ports and the thru-standards (T or R) are measured on the selected port-pairs. From these measurements, the error-network (the paths from the network analyzer to the probes' tips) is characterized and de-embedded. These standards for various pitches and configurations are available on commercial calibration kits.

However, it is difficult to apply these calibration techniques to multi-channel probes due to the lack of available thru-standards for arbitrary port-pairs. Although the thru-standards come in various lengths and are available in straight or right-angled, they cannot cover all possible port-pairs because the port-pairs can be at any relative position. It becomes more difficult if the port-pairs are from the same probe (i.e. same quadrant), which requires "U"-shaped thru-standards which are only applicable for specific distances between the port-pairs. Since such standards are not available in commercial calibration kits, one will require custom calibration kits which can have significant costs and long lead-time.

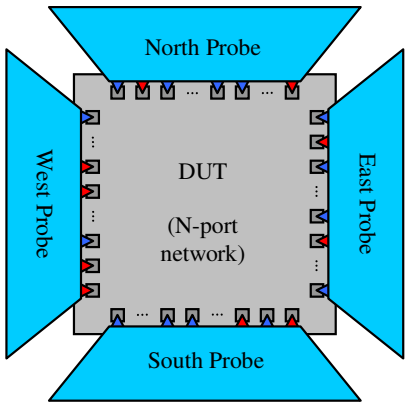


Fig. 1. DUT with 4 quadrants probes. The red tips are those of the channels that need calibration.

© 2013 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/ republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

II. N+1-Port SOLT/SOLR Calibration

To overcome the mentioned problems, a new calibration solution is proposed in this work. It uses an additional single-channel probe (GSG) at an added port (N+1'th port) which enables all of the required thru measurements by using a general thru-standard. Although it is shown for a case where the 4 quadrants are all occupied by multi-channeled probes, it can also be applied to single-channel probes, as well as cases where the 4 quadrants are not fully occupied.

A. Preparing GSG Probe and Thru-Standard

The proposed N+1-port SOLT/SOLR calibration requires an additional GSG probe that will be used as the N+1'th port, whose operating frequency is at least equal to that of the highest among ports 1 through N. Also, one must obtain a collection of reflection-standards and thru-standards that cover the various of pitches and configurations in the N+1 ports. The thru-standards should be configured as GSG and they must enable the thru measure between the N+1'th port and each of ports from 1 through N regardless of their configurations. For the GS configuration, only one G will be landing on the ground strips of the thru-standard, and for the differential SS configuration one of the two S's will be landing on the ground strips of the thru-standard. The thru-standards are often made with wide ground strips so only 1 or 2 thru standards are likely to be needed to cover all configurations.

B. Network Analyzer Settings

The added GSG probe is assigned to the N+1'th port and the network analyzer is set for N+1-port calibration using either SOLT or SOLR. All ports' reference impedances are defined as 50 Ω, even for the differential SS configuration. If the calibration coefficients for the SS configuration are defined for 100 Ω, they need to be scaled by a factor of 2; multiplied by 2 for parasitic capacitance of the Open (O); divided by 2 for the parasitic inductances of Short (S) and Load (L) as well as the resistance of Load (L).

The thru-pairs are selected manually so that each port from 1 through N are paired with the N+1'th port (i.e., Port 1 & Port N+1, Port 2 & Port N+1, …, Port N & Port N+1). If the firmware in the Network analyzer does not allow such manual selections but rather forces selections of thru-pairs among the ports 1 through N (e.g., Port 4 & Port 5), one must manually input the S-parameters calculated from the measurements of the previously mentioned thru-pairs (e.g., Port 4 & Port N+1 and Port 5 & Port N+1) by multiplying their T-parameter matrices and converting back to S-parameters.

The SOLT algorithm requires the user to define the precise electrical delay values of the used thru-standard. For a short 1ps thru-standard that is widely available in most commercial calibration kits, the difference in configurations (e.g. GSG vs GS) only causes ± 0.1 fs delay, which is equivalent to ± 0.1 um tip-placement error. This is far less than the actual tip-placement's repeatability. Therefore, if the thru-standard is as short as a few ps, the user only needs to define one delay value regardless of the configurations. However, if the user uses longer thru-standards, SOLR should be used as this algorithm only requires the user to define the rough estimates of the delay, such that the transmission's phase (i.e., phase of S_{21}) at the lowest frequency is within ±90°of the actual value.

C. Measurement Sequence

Fig. 2 shows the measurement sequence of calibration standards, ordered from Fig. 2(a) to Fig. 2(d). Note that the North and East probes are remounted after completing their thru measurements, which can cause variation in the electrical delays of attached cables. The amount of such variation and their effects on the calibration will be described in the next sub-section. However, one can minimize such variation by maintaining similar bending/routing of the cables, as well as using a torque wrench when reattaching the connectors. Furthermore, one can re-order the measurement sequence such that, out of the two probes facing each other (North & South or East & West), the probe that has the higher maximum frequency is measured last. For example, if the North probe's maximum frequency is 110 GHz and that of the South probe is 67 GHz, measuring the thru pairs in the North probe after those in the South probe will allow one to avoid remounting the North probe (up to 110 GHz) after the thru measurements, which is more error prone than remounting the South probe (up to 67 GHz) after the thru measurements.

D. Delay Variations of the Error-Network

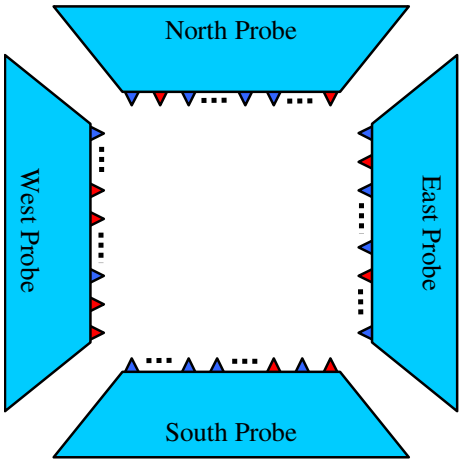
The SOLT/SOLR calibration algorithm relies on having consistent electrical delays in the error-network. Any variations in the delays may increase the measurements' uncertainties after calibration. The delays can be kept relativity consistent when calibrating the single- or dual-channel probes placed in the quadrants.

However, keeping consistent delays can become challenging in calibrating Multi-channel probes when using the proposed N+1-port SOLT/SOLR calibration, because remounting the probes can change the bending of the cables or the torque of the connectors, as shown in Table I. Furthermore, as previously mentioned for SOLT, the various configurations will cause delays in the thru-pairs to change which will manifest itself as additional delay variations in the error-network. This is because the SOLT algorithm considers the delay of the thru-standard to be the value defined by the user, hence, any difference from the actual delay will be modeled into the error-network.

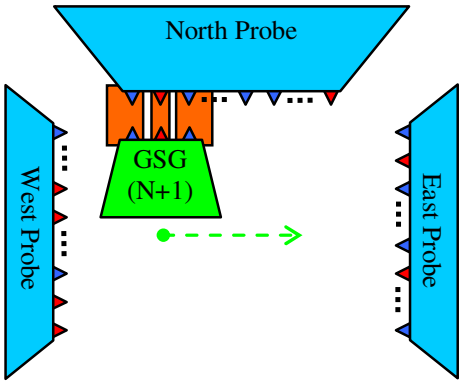
TABLE I
MEASURED DELAY CHANGES IN COMMON CABLE ASSEMBLIES

Flexible cable assembly (outer diameter / connector type)	Changes due to reattachment	Changes due to 90° bend at 6 cm radius
1.19 mm / 2.92 mm	0.05 ps	0.03 ps
3.56 mm / 2.40 mm	0.09 ps	0.10 ps
4.24 mm / 1.00 mm	0.04 ps	0.10 ps

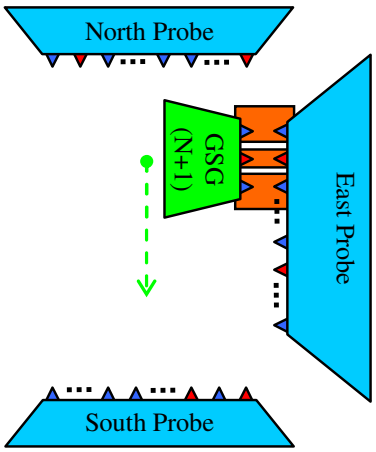
© 2013 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/ republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.



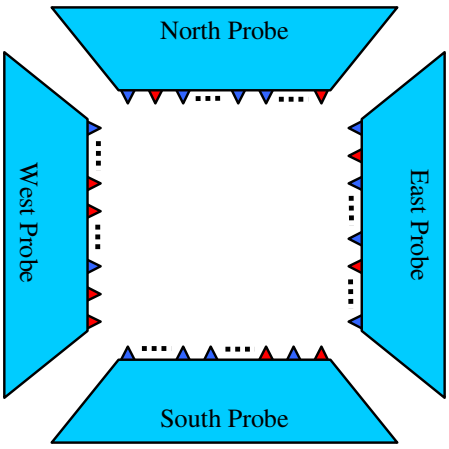
(a) Start



(b) Replace South probe with the N+1'th GSG probe and measure its SOL and all thru-pairs with the ports in North Probe. Remount South probe afterwards.



(c) Replace West probe with the N+1'th GSG probe and measure all thru-pairs with ports in East Probe. Remount West probe afterwards. Repeat for reaming other 2 quadrants.



(d) Measure-reflection standards (SOL) for ports 1 through N in the 4 quadrant probes.

Fig. 2. Calibration standard measurement for N+1-port SOLT/SOLR calibration; ordered from (a) to (d).

Fortunately, as shown in the next section, these delay variations are likely to be small enough so that they don't cause significant measurement uncertainties in most practical cases.

III. Measurement Results

The proposed calibrations method was applied to a 2-port case (Port 1 and Port 2) with the added GSG probe on the 3rd port (Port 3), and had used a 1 ps GSG thru-standard. To illustrate the effects of having inconsistent delays, the cables were bent by 90° after remounting the probes, and the thru-standard was purposely defined to be 2 ps more from its correct values. Furthermore, a conventional 2-port SOLR calibration was performed using the correct delay values, which will be considered as the ideal case.

The comparison is done by the calibrated measurement of a lossy transmission-line, as shown in Fig. 3, where the S_{22} and the S_{12} were omitted due to their symmetry. In order to eliminate any additional measurement uncertainties caused by the variation in the probe-tips' placements, each calibration standard was measured only once and manually input to the calibration processes to create the plots in Fig. 3.

The results show that the delay's inconsistencies had almost no effect when using N+1-port SOLR calibration. This is because the defined delay of the thru-standard is within in the valid range, i.e. its transmission's phase at the lowest frequency is within ±90°. The only delay variations are due to re-connecting the connectors and bending the cables, all of which are 0.1ps or less.

When using N+1-port SOLT calibration where the total delay variation had significantly increased by incorrectly

© 2013 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/ republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

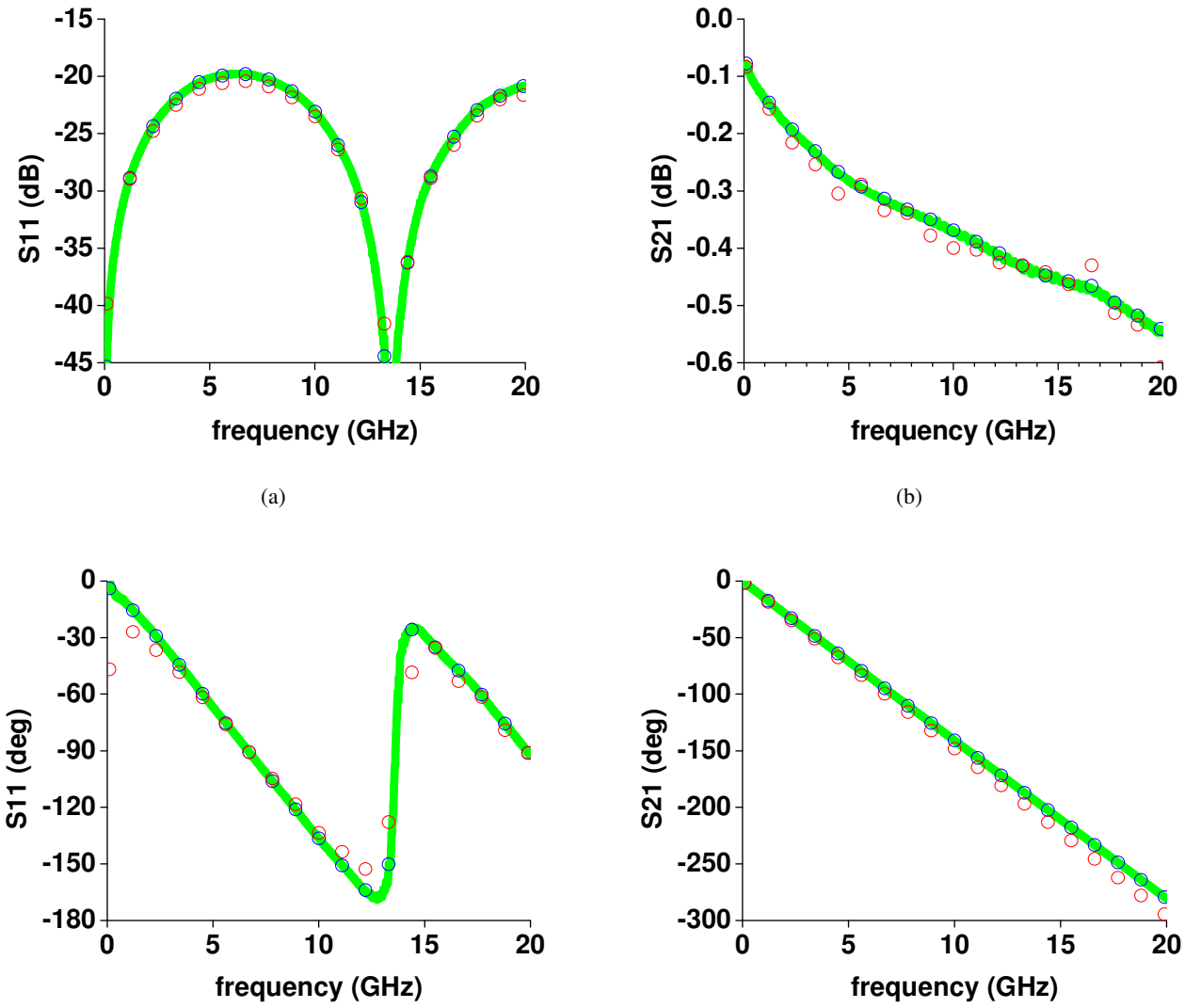


Fig. 3. Post-calibration measurements of a symmetric lossy transmission-line; using conventional 2-port SOLR calibration (**thick green line**) and using the presented N+1-port SOLT (**red circle**) / SOLR (**blue circle**) calibration.

defining the thru-standard's delays (off by 2 ps), the effects are still minimal except for the S_{21}'s phase. The change in the S_{21}'s phase (~ 15 deg at 20 GHz) is directly caused by the total delay variation (~ 2 ps) which can be expressed as $\Delta\phi = \Delta t \cdot f \cdot 360°$, where $\Delta\phi$, Δt, and f are the change in phase, total delay variations, and frequency, respectively. Note that the phase differences in S_{11} near DC and 14 GHz are insignificant due their low magnitudes (< -40 dB).

ACKNOWLEDGEMENT

The authors would like to thank Leonard A. Hayden at LeCroy for teaching the basics in various calibrations algorithms and John Ebner at Cascade Microtech for his help editing the manuscript.

REFERENCES

[1] "Multi-Contact Wedge," GGB Industries, Inc., May 2000.
[2] "Unity: High-Performance, Multi-Contact RF Probe," Cascade Microtech, Inc., Tech. Rep., Feb. 2009.
[3] "Addressing the Challenges of Small Pad Probing," Cascade Microtech, Inc., Tech. Rep., Oct. 2011.
[4] D. Rytting, "An Analysis of Vector Measurement Accuracy Enhancement Techniques," *Hewlett-Packard RF & Microwave Measurement Symposium and Exhibition*, Mar 1982.
[5] A. Ferrero, *et al.*, "Two-Port Network Analyzer Calibration Using an Unknown 'Thru'," *IEEE Microw. Guided Wave Lett.*, vol. 2, No. 12, pp. 505-507. Dec 1992.
[6] S. Basu, *et al.*, "An SOLR Calibration for Accurate Measurement of Orthogonal On-Wafer DUTs," *IEEE MTT-S Int. Microw. Symp. Digest,* vol. 3, pp. 1335-1338, Jun. 1997.

© 2013 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/ republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.