Dual Sided High Frequency Measurement of Microelectronic Packages

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Abstract—**Traditionally, validation of simulation data of microelectronic packages has been done by high frequency measurement of coplanar transmission line structures. Although this metrology has matured over the years, it is not directly applicable to product packages since they also include vertical interconnects. To address this issue, we developed a dual-sided measurement metrology, by utilizing a special fixture design and employing short-open-load-reciprocal calibration to maintain measurement stability at high frequencies. Metrology capability analysis shows that there is minimal operator and environmental condition dependency and a very good correlation with simulations up to 40 GHz for differential transmission lines.**

Keywords—dual-sided measurement, package measurement, S-parameter characterization, calibration techniques

I. INTRODUCTION

Methods for S-parameter characterization of packaged coplanar transmission line structures, using a Vector Network Analyzer (VNA) and radio frequency (RF) microprobes, are well-established. Turnkey probing solutions for test vehicles with coplanar devices, which include probe station, probe arms and manipulators, and vacuum fixtures for the device under test (DUT), are widely available from several manufacturers. In the case of a product package though, where function and cost dictate the layout of data transmission interfaces, vertical interconnects also play a fundamental role in addition to coplanar interconnects. Therefore, the ability to characterize these vertical interconnects provides valuable insight into the real performance of processor packaging for input/output interfaces such as dual data rate memory and peripheral component interconnect express links. Moreover, S-parameter data measured from the VNA can be plugged into 3D, frequency-dependent computer models to predict various parameters of an electrical system's performance.

In contrary to the coplanar high frequency measurements, measurement of top-to-bottom, through-package structures presents a unique set of physical and logistical challenges that have yet to be thoroughly addressed and quantified. A stable platform that securely supports the DUT, yet allows unimpeded probe access to both top and bottom must be implemented. Additionally, a calibration algorithm that makes use of an unknown thru standard must be used to calibrate the VNA, and must be studied to quantify the error contributions from calibration, multiple operators, and environmental factors. In the literature, there have been a few attempts to address these issues. For instance, in [1], the calibration is performed on a horizontal platform and then the structure is rotated for dual-sided measurement. This approach not only puts the quality of calibration in question, but also suffers from potential instability of the fixture during landing. Other attempts in [2-4] successfully handle the calibration and stability problems by utilizing a short-open-load-reciprocal (SOLR) calibration [5] on vacuum based horizontal platform. However, the provided data are only for single ended (SE) frequency domain measurements of vertical structures such as plated through hole (PTH) vias, pogo pins, and through silicon vias (TSV). Besides, the simulation to measurement correlation is sub-optimal, particularly for frequencies higher than 20 GHz.

In this paper, we extend the previous studies by providing a thorough metrology capability analysis (MCA) [6] for top-to-bottom measurement of differential ended (DE) product-like structures, comprised of probe pads, microvias, PTH vias, and horizontal routing. Moreover, a measurement-to-model correlation, which is supported by detailed cross-sectioning of the DUT, is performed to validate the accuracy of these dual-sided S-parameter measurements up to 40 GHz.

II. METROLOGY

A typical probe station serves as the basis of the physical measurement setup as shown in Fig. 1. The probe station has been modified to accept a bottom-mounted microscope for viewing the bottom-side probes. A probe positioner, whose nosepiece has been flipped and machined for clearance, manipulates the bottom-side probe. The top-side probe is attached to an unmodified positioner. Differential microprobes in GSGSG configuration with a pitch of 150 microns were used to probe the DUT. The measurement device is a 4-port VNA with a maximum frequency of 67 GHz. Four coaxial cables with 1.85mm connectors at each end connect the VNA ports to the probes. Commercially available software is used to calibrate the VNA and download the measured data.

The dual-sided measurement fixture shown in Fig. 2 was designed in-house and uses a combination of off-the-shelf and custom pieces. Its X-Y-Z stage attaches to the probe station with a vacuum base, and the front of the fixture is supported by mechanically-adjustable leveling feet. Spring-loaded steel bars provide stability and support for the DUT, while allowing easy adjustment and flexibility in positioning.

To ensure the most accurate measurement results, the probes and cables must remain in the same position during measurement as they were during calibration. To accomplish

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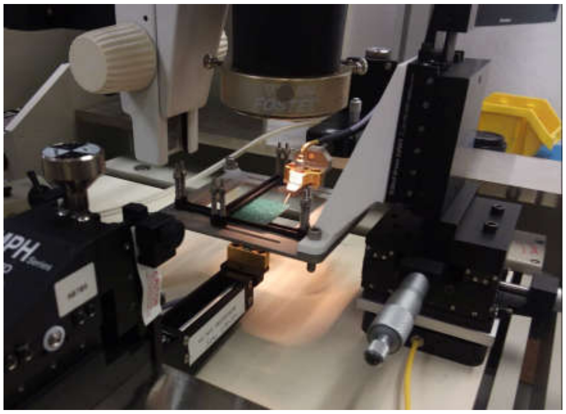

Fig. 1. Dual-sided measurement in progress.

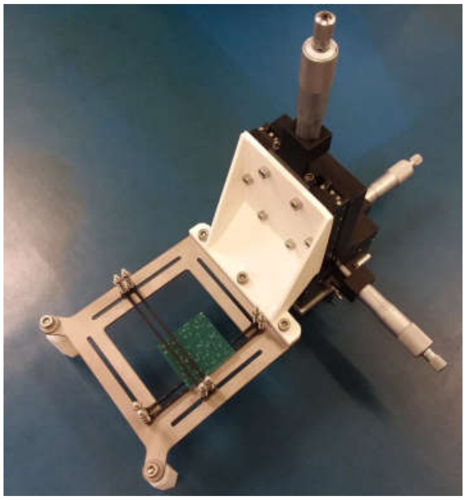

Fig. 2. Dual-sided measurement fixture detail.

this, one would need a well-defined dual-sided thru structure (which is not commonly available) and use a line-reflect-reflect-match or a short-open-load-thru algorithm. Alternatively, a calibration algorithm that does not require a well-defined thru standard can be used. SOLR algorithm allows the use of the DUT as the reciprocal standard for top-to-bottom transmission paths, while using the normal short, open, load, and loopback structures found on a calibration substrate as the remaining calibration standards. To allow full access to all of the standards on the calibration substrate, and to ensure that it was able to be supported by all 4 support bars of the fixture, the calibration substrate was mounted to a larger carrier substrate. This also allowed easy handling and flipping of the substrate throughout the calibration process.

To quantify the performance of the measurement system, an MCA was performed. The study consists of a repeatability study to explore the variability from the measurement device and the probe landing, and a reproducibility study that explores the variability due to differences between operators and environmental differences over multiple days. The repeatability study involves one operator performing a single setup and calibration of the measurement system followed by 30 dynamic measurements (land, measure, lift, repeat) on the DUT in a single session. The reproducibility study involves 3 operators, each performing his own system calibration and measurement of 3 different DUTs, for each of 3 days.

III. RESULTS AND DISCUSSIONS

Fig.3 illustrates the test structure, which is composed of horizontal and vertical interconnects as in a product package, with solder ball pads replaced by probe pads.

Analysis of the repeatability data showed very little variability due to the measurement device and the operator's probe landing technique. Viewing the differential ended insertion loss (DEIL) and differential ended return loss (DERL) plots from the repeatability study showed very little difference across the 30 measurements in the data set. This gives great confidence in the stability of the measurement system and the ability of a well-trained operator to consistently achieve the same result.

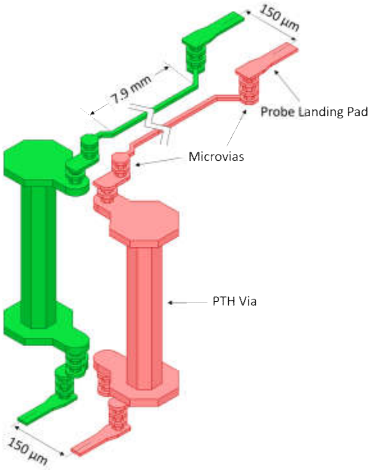

Fig. 3. Detailed geometry of the test structure.

Analysis of the reproducibility study data gives a more realistic view of the tolerance that the measurement system and a group of operators can achieve. The DERL and DEIL plots are shown in Figs. 4 and 5. Variation in the results generally increases with frequency. A post-MCA study suggests that the variation in return loss is the result of differences in probing technique between operators. Differences in initial and final probe position, and probe skate distance all seem to have a noticeable impact on DERL, but have very little impact on DEIL.

While S-parameter measurement provides a full characterization of a device from probe to probe, all aspects of the routing (probe pad, trace, PTH) are lumped into one data set, making it difficult to see the electrical contribution of each piece of the routing. Therefore, plotting the device's time domain impedance is a useful method of intuitively viewing the contributions of each piece of a device's routing. Using a commercial circuit simulator, the S-parameters from the reproducibility study were converted to a TDR impedance response using a source with a rise time of 35 ps. Fig. 6 shows the processed TDR curves. One can intuitively map the top probe pad region, horizontal routing, and PTH to the curves shown.

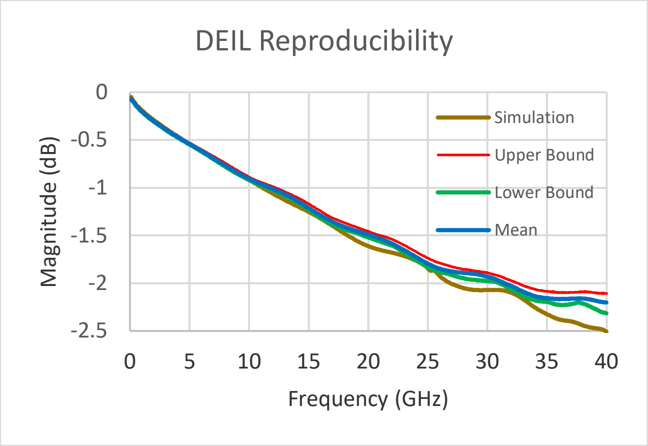

Fig. 4. DEIL reproducibility results.

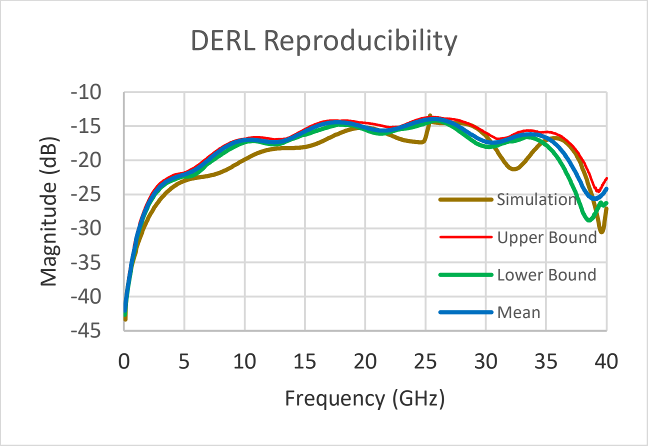

Fig. 5. DERL reproducibility results.

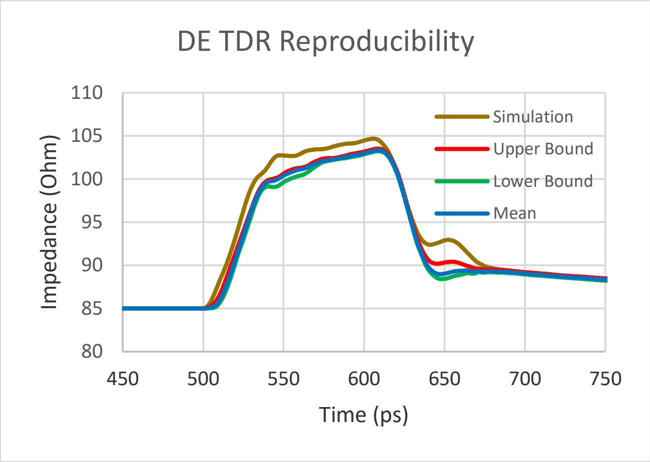

Fig. 6. DE TDR reproducibility results.

Figs. 4-6 also show the comparison of the measurements with simulations where cross-section images were utilized for accurate dimensioning of the design features. The measured dimensions are then loaded into a 3D model of the package, and a high-frequency solver simulates the S-parameters of the model. The simulated S-parameters are then compared to the measured S-parameters. It can be seen that the simulation slightly overpredicts IL compared to the measurements. This is desired to cover the worst case scenario in the performance estimations. The measured and simulated RL are also in a good agreement. Finally, the TDR impedance comparison between simulations and measurements show less than 2 Ω difference for the horizontal routing part.

IV. CONCLUSIONS

It is possible to characterize top-to-bottom packaged interfaces by performing modifications to commercially available probe stations and probe positioners, and designing a custom fixture to allow dual-sided probing of the DUT. A VNA calibration algorithm that uses an unknown thru standard (SOLR) is well-suited to allow the probes to remain in the same position during calibration and measurement, ensuring that the VNA calibration remains accurate throughout the measurement process. Results of an MCA study show that the measurement system is capable of excellent measurement repeatability. Examining the reproducibility results of the MCA, it can be seen that DEIL variation is very small and not influenced by operator or environmental factors, while DERL shows more variation due mostly to operator probing technique. Measurement-to-model agreement for DEIL, DERL, and TDR impedance is achieved, further supporting the quality of measurement with the dual-sided probing system.

ACKNOWLEDGMENT

The authors would like to thank Kuang Liu, Raul Marquez, Leigh Wojewoda, and Gaurang Choksi for their contributions.

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA) under CHIPS program (Contract Number: HR00111790020). The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

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