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Tale of a Differential Pair Measurement

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Abstract

How accurately can a high frequency VNA measurement be performed when wafer probes are involved? What do we compare against? Considering the variety of VNA calibrations techniques, how do we know what is the best mechanism to use? What simulation tools do we use to correlate? How do we measure a DUT without affecting it? These are some questions SI engineers ask themselves all the time. By using a differential trace, we will show the complexities of a real differential pair, including skew, crosstalk, and losses, the pitfalls of measurements, including different types of calibration, de-embedding and simulations techniques.

Author(s) Biography

Gustavo Blando: is a Senior Principle Engineer leading the SI/PI team at Oracle Corporation. In addition to his leadership roles, he's charged with the development of new SI/PI methodologies, high speed characterization, tools and modeling in general. Gustavo has twenty plus years of experience in Signal Integrity and high speed circuits.

Eben Kunz: has worked on Oracle's SPARC systems since 2012, both on Signal and Power Integrity. Eben has been the lead SI engineer for several platforms, from architecture through to final validation. Eben also develops internal software for passive channel simulation and analysis. He has a Bachelor's and Master's degree in Electrical Engineering from the Massachusetts Institute of Technology.

Istvan Novak: is a Senior Principle Engineer at Oracle. Besides signal integrity design of high-speed serial and parallel buses, he has been engaged in the design and characterization of power-distribution networks and packages for mid-range servers. He creates simulation models, and develops measurement techniques for power distribution. Istvan has twenty plus years of experience with high-speed digital, RF, and analog circuit and system design. He is a Fellow of IEEE for his contributions to signal-integrity and RF measurement and simulation methodologies.

Introduction

How accurately can a high frequency VNA measurement be performed when wafer probes are involved? What do we compare against? Considering the vast variety of VNA calibrations techniques, how do we know what is the best mechanism to use? What simulation tools do we use to correlate? How do we measure a DUT without affecting it? These are some of the questions SI engineers ask themselves all the time.

The goal of measuring a differential-pair (DUT) without affecting it might be easier said than done. For a long time, in our lab we've used SOLT calibration and we have milled the boards down to expose a small portion of the trace directly for wafer-probe landing (no vias and minimum discontinuities). The intention is to get as close as possible to the trace without affecting its cross-section by using [**G**round-**S**ignal-**S**ignal-**G**round] probe configuration.

By looking closely at the measurement results, we have uncovered an issue with this kind of wafer probe measurement that shows up in the mixed mode S-parameters. This discovery led us to the understanding of the mechanism of the error, which ultimately resulted on a few proposed options for improved probe connections and geometry. The understanding of the issue observed will be explained with the help of a large number of VNA measurements and their corresponding simulations.

In addition, this discovery prompted us to re-explore different measurement techniques to see if we can find a better, more accurate way of taking measurements on structures with glass reinforced materials. A quick literature research shows a vast variety of calibration techniques, ranging from simple de-embedding to more complex fitting de-embedding and full TRL calibration techniques. The ultimate question is what technique would be best suited for our particular DUT considering the "sea" of methods to choose from.

By going through the measurement exercise we will show some of the inherent complexities of real-life differential traces, and how can we see the resulting side effects in measurement data. We will show that a material even with flat weave and dual ply shows intra-pair skew in the tune of 2.5ps/inch, and how the resin content and distribution on the trace will change the crosstalk behavior of the trace.

Finally we'll show correlation and issues with different simulation tools and how we try to extract "average" material properties from the measurements in spite of all the measurement uncertainties.

Measurement Techniques

The cornerstone of material characterization is accurate measurements, since bad measurements imply irrelevant correlations.
One of the main characteristics of high frequency VNA measurements is that before a measurement is taken, a calibration needs to be performed in order to negate the effect of most VNA inaccuracies, cable setup and probes connecting to the DUT.

Fundamentally, calibration is performed by measuring a known set of standards. The difference between the real measurement results and the standards known values represents the error. An error-model then is created for each port and stored in the VNA or software. When a measurement is performed the error can be automatically taken out.

Many different calibration techniques have been derived over the years to correct for the instrument setup inaccuracies, but broadly they can be divided in three main "loose" categories depending on the type of standards measured:

- SOLT and all their derivative methods: For these techniques, **S**hort, **O**pen, **L**oad and **T**hrough measurements are performed to a known standard for each probe.
- TRL and all their derivative methods: In this case a **T**hrough, **R**eflect and **L**ine is measured. This is a nice technique that under certain conditions allows you to characterize your DUT in a non-destructive way
- De-embedding: In general, this is done as a two tier calibration process. The first tier is a coaxial calibration performed at the end of the cables, and then by taking a few measurements and obtaining the probes models (second tier), de-embedding is performed to get the DUT's performance alone

In our experience:

- TRL is an excellent method, but not favorable for glass reinforced materials. The method relies on a well repeatable **Zc** (Characteristic Impedance), and that can't be guaranteed on these types of materials.
- De-embedding. We've tried this with some level of success
- SOLT has been the method of choice for us. We have been able to correlate many structures very accurately over the years.

For differential measurements using SOLT, there are many probes to choose from, with different signal-ground configurations. For practical reasons we've settled on the G-S-S-G configuration which is a pattern present on many real boards. Having a probe landing matching that pattern of the DUT is the logical configuration choice.

For differential traces, we mill the board to expose the traces, connect the grounds, and since a differential pair is naturally a G–S–S–G configuration, we can land the probe directly on the traces and take the measurement with only minimally altering the behavior of the differential line.

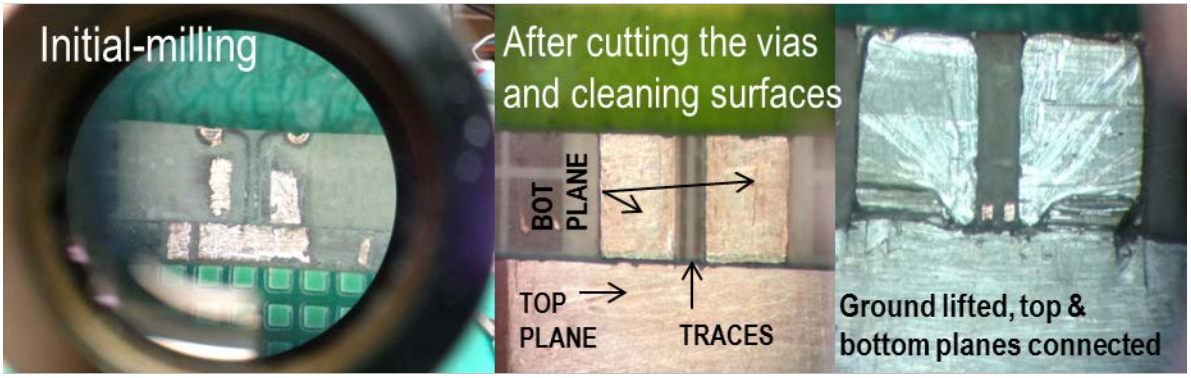

Figure 1: (left) Initial milling, exposing the traces, top and bottom planes, (center) vias cut and structure cleaned, top and bottom plane exposed, traces still with some dielectric on top, (right) final step, traces exposed and cut very short, bottom plane lifted to the same elevation as the traces and connected to the top plane.

As can be seen in Figure 1, after the structure is prepared, we are expecting only a very minimal discontinuity at the entry of the trace. In terms of measurement quality, we believe for traces there is only one other measurement method we've taken that surpasses this technique, which is measuring the DUT from the edges. For a differential stripline this requires four separate G-S-G probes, each touching down on the reference planes above and below the trace. This is possible but much more difficult to achieve.

We start with a SOLT calibration with G-S-S-G 500um or 250um probe using unknown through. When calibration is completed, we measure one of the small through pieces on the calibration standard. We are expecting a small decaying amount of loss considering there is a small amount of loss on the copper connecting the probes.

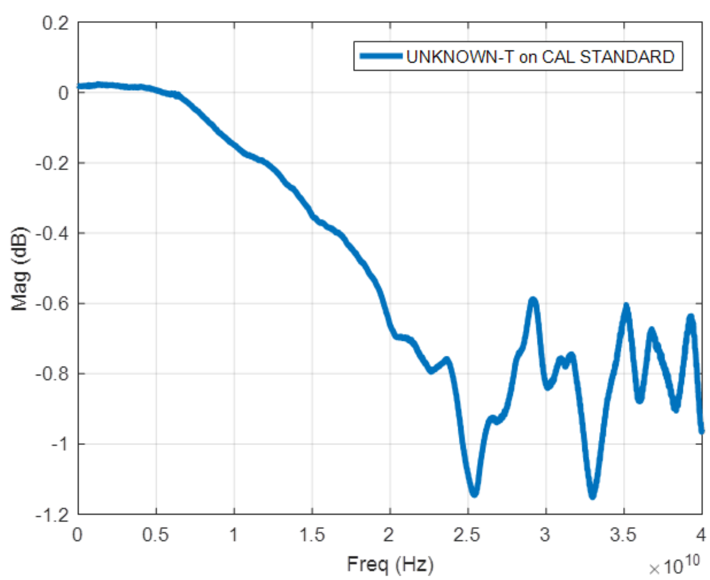

Figure 2: Unknown through Insertion loss

In Figure **2**, the thru insertion loss looks very reasonable up to about 25GHz, we can see that above that frequency the decay flattens out. We attribute this to crosstalk between the tips of the probes and it's an inherent limitation with this landing pattern (G-S-S-G). Please note, the vertical scale is very small. It's up to the user to decide how important it is for the particular application. There are other, perhaps better, probe configurations that improve the crosstalk between tips such as G-S-G-S-G, the GND blade in the middle serves as a shield between signal tips providing 10dB to 20dB better isolation. There is an extensive amount of literature about the differences between these configurations as pointed out by [1]. We will not go into that detail in this work.

Even though we know that above 25GHz the quality of the measurement is not optimal, we've chosen to keep all the data up to 40GHz, so we can see the whole frequency range of the measurement.

After calibration we proceeded to measure the DUT. The overall objective was to evaluate a new material and perform material correlation. We prepared a DUT as shown in Figure 1. The differential transmission line is 2.718" long and it has the following specified nominal cross section:

- Line width: 5.55mils
- Air gap: 6.45mils
- Thickness: 0.6mils
- Dielectric thickness above/below: 4mils/3.9mils
- Approximate dielectric characteristics: Dk=3.9, tand=0.001, two ply flat/spread glass
- HVLP copper

Figure **3** shows the measurement results: on the left plot we see the insertion loss of the P and N side and how it decays with frequency up until we get to the 25GHz range where things starts to deviate a little from expectations. On the right we converted the S-parameters to Mixed-Mode and plotted the even (common-mode) and odd (differential) insertion loss. Here is when we start to see something very interesting.

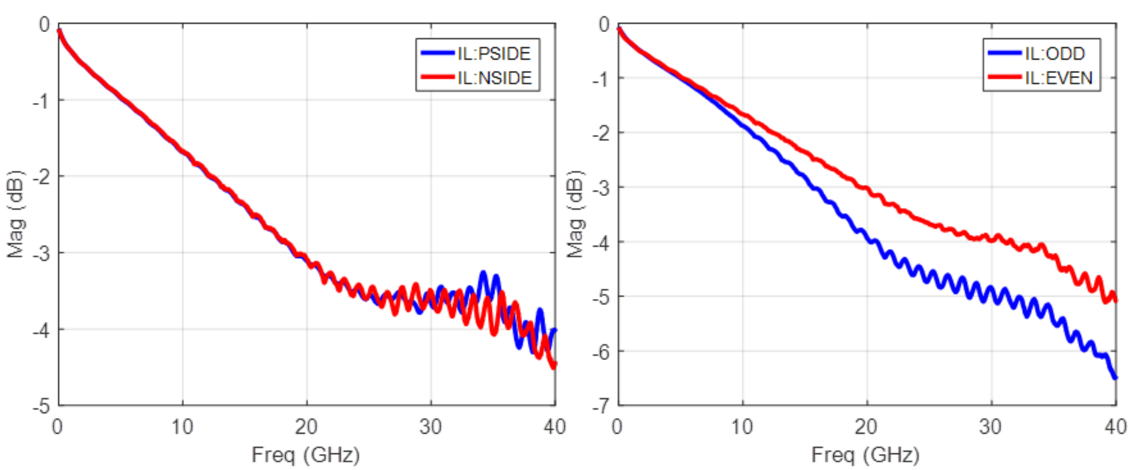

Figure 3: (left) single ended insertion loss, (right) even and odd mode insertion loss

After the mixed mode conversion, we can see the insertion loss of the odd mode has more loss than the even mode. It is interesting to pause a moment here, and ponder a little bit about this result. Some immediate questions come to mind:

1. Can we explain this? Is this real?

a. For example, we could argue this is right and it's due to proximity effect between the two traces. On differential mode, the current will tend to crowd towards the center of the diff-pair and travel over smaller cross-sectional area than the common mode, hence with more losses (this seems like a reasonable argument).

2. Can we trust the measurements 100% even after all the effort to prepare the DUT? Perhaps there are some things we don't quite yet understand on the measurements, and this is actually NOT real.

Before doing any type of measurements, it is important to have a good idea of what to expect, the measurement results have to agree with theory. The point I am trying to drive home though is if you don't know **exactly** what to expect, it's not that obvious what the real answer should be, particularly for subtle things like this, it could be something new, or it could be simply a measurement error, but it's not always easy to determine which.

Even though there are aspects of the S-parameters we don't quite understand yet, we'll continue with some additional post-processing to try to understand this DUT as much as possible.

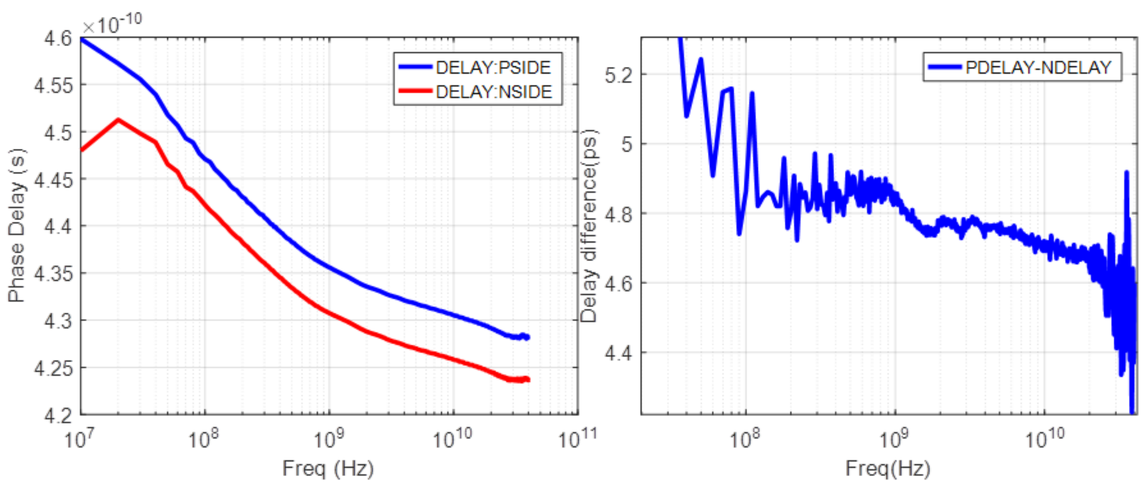

Figure 4: (left) P-side and N-side delay vs. frequency, (right) skew between P and N sides

Looking at the phase delay first, it's a bit surprising to see this much skew, considering we are dealing with only a 2.7" trace on a dual ply flat glass configuration. We are seeing approximately 5ps of skew at 1GHz as can be observed in Figure 4. This trace is not routed on an angle, so it's very possible, but nevertheless a bit unexpected.

We can also do a TDR and TDT of the traces to look at transmission, impedance and crosstalk in the time domain. Starting with the TDR on Figure 5 we can see that the odd impedance is around 44Ohms (88Ohms differential), the even impedance is 48Ohms (24Ohms common mode), and as expected the "single ended impedances" are in between the even and odd. We can also see the expected slope up on the TDR due to the copper losses of the trace, and finally how the TDR settles to an impedance value equal to the source (44Ohms in this case) + 2xDC-Loss of the traces.

We also notice on the zoomed in version, how not uniform the trace is over its length, something that is very typical on glass-reinforced materials.

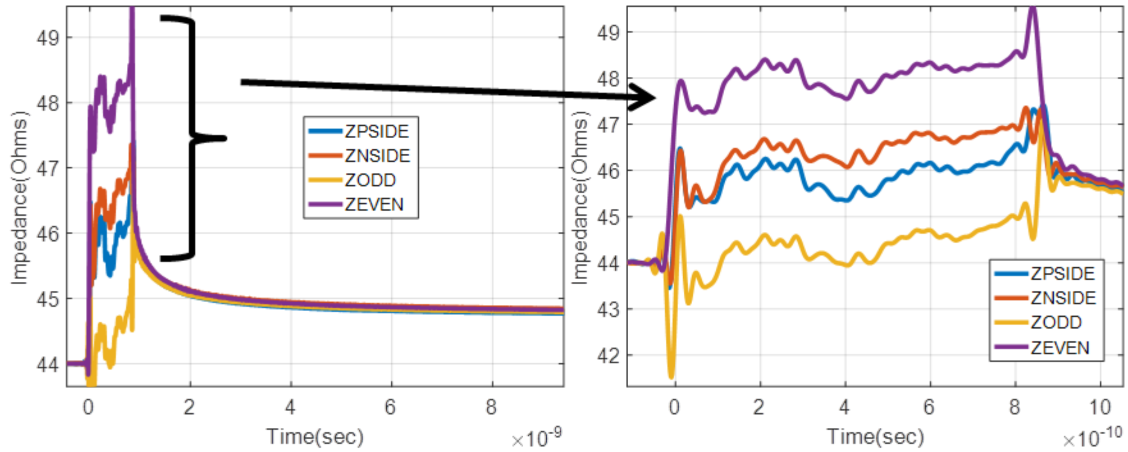

Figure 5: (left) TDR, (right) TDR zoomed in

When we perform a TDT, we observe the response with the expected 5ps of skew between the P and N sides, also the TDT of the cross-terms shows the far and near end crosstalk as shown on Figure **6**.

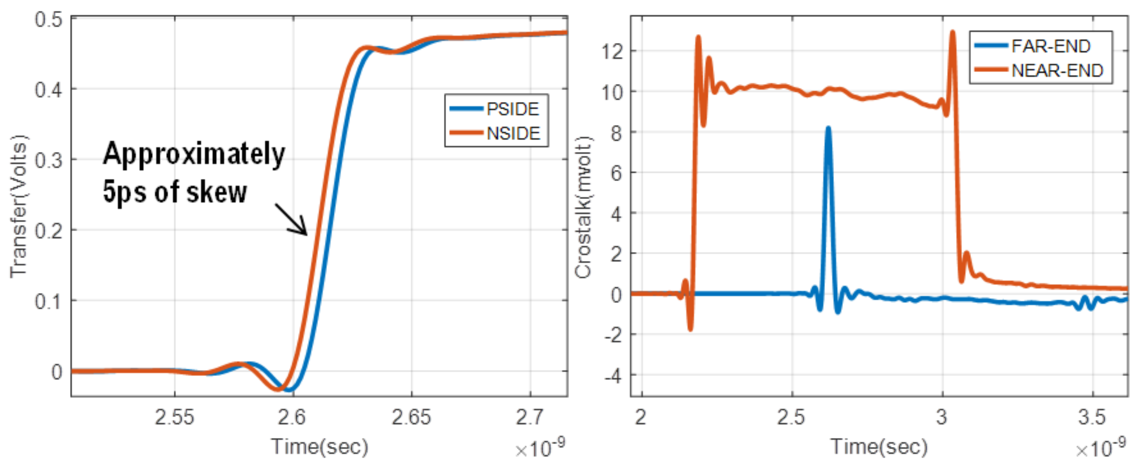

Figure 6**: (left): step response p-side and n-side showing the skew in the time domain, (right) far end and near end crosstalk**

In addition of the figures shown above, many other measurements were done, to guarantee the accuracy of the setup. As an example, to make sure the skew was real, the measurement was done at 0 degrees and flipping the structure 180 degrees to prove the delay stays with the DUT and not with the setup.

We conclude this section with a better feel for the accuracy of the measurements and the characteristics of this differential pair. In essence everything makes sense to us except for the unknown difference in IL between the odd and even mode, which we are not sure about where it is coming from “yet”.

In order to help us understand "what should be expected", we'll be relying on simulations.

Differential Transmission Line Simulations

By going through a correlation exercise, we are hoping to shed some light into this structure and some of its unknown behavior.
Based on the measurements, this structure has quite a bit of skew. To establish correlation we would have to "somehow" model that delta.

Since we dont know exactly how the dielectric is changing along the length of the board, and we don't want yet to cross-section it, we created a behavioral differential pair with all the necessary features and flexibility to match the measurements.

In order to accomplish this task, simulations were done using a Non Uniform Tline-Segment (NUT) construct with different DK on each trace.

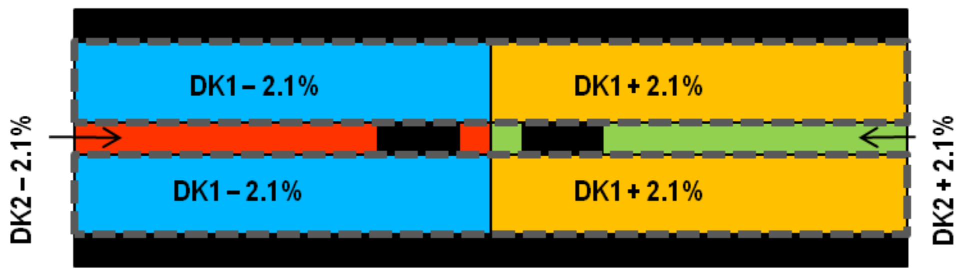

Figure 7: Behavioral transmission line model

Figure **7** shows the structure and the way NUT allows us to vary left and right dielectric properties in order to achieve the proper amount of skew.

It's important to realize that we fully understand this is a "behavioral model", we don't have nor we want to model every single nuance on the line. We are interested in creating a model that allows us to match nicely all the features of the transmission line. If we can achieve this, we then can say the line "behaves" like this.

We start by looking at the phase delay and voltage transfer in Figure 8. We can see an excellent correlation.

For the material properties we used the *Djordjevic-Sarkar* frequency extrapolation. The NUT construct allowed us to change Dk by a +/-% deviation at each side obtaining the right and different propagation delays between the P and N sides.

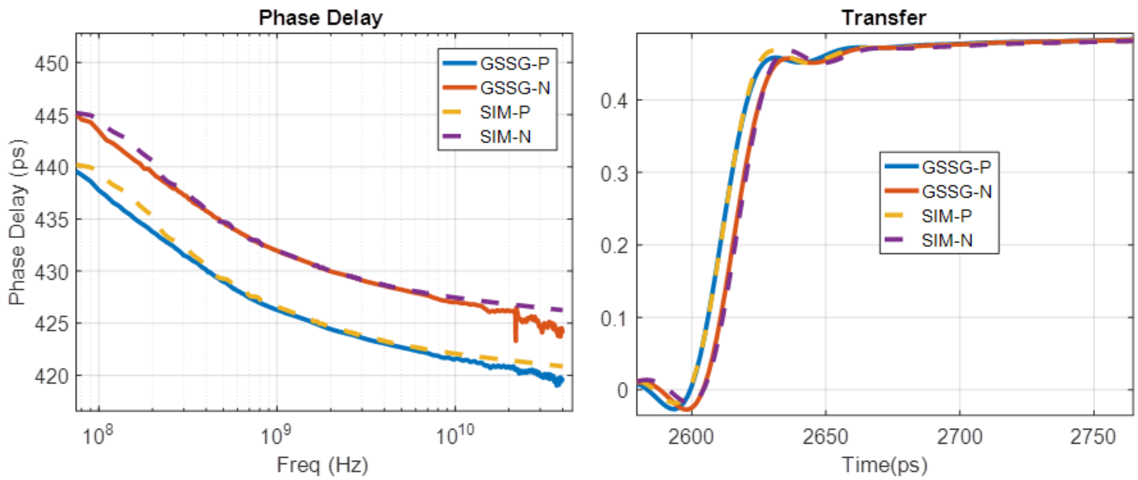

Figure 8: (left) P and N phase delay correlation, (right) P and N transfer correlation in the time domain

When looking at return loss, (Figure **9**), we observe a difference in the frequency domain that is explained by the intrinsic parasitic of the wafer probe measurement that is not being removed by the calibration. The match would become very good by simply adding a small inductance in series (not shown in here).

The time domain TDR shows very good correlation for all impedances, modal (Zodd, Zeven), and nodal (Zp and Zn). This correlation highlights the variability of impedance along the line the real structure suffers with respect to the perfect smooth simulation profile

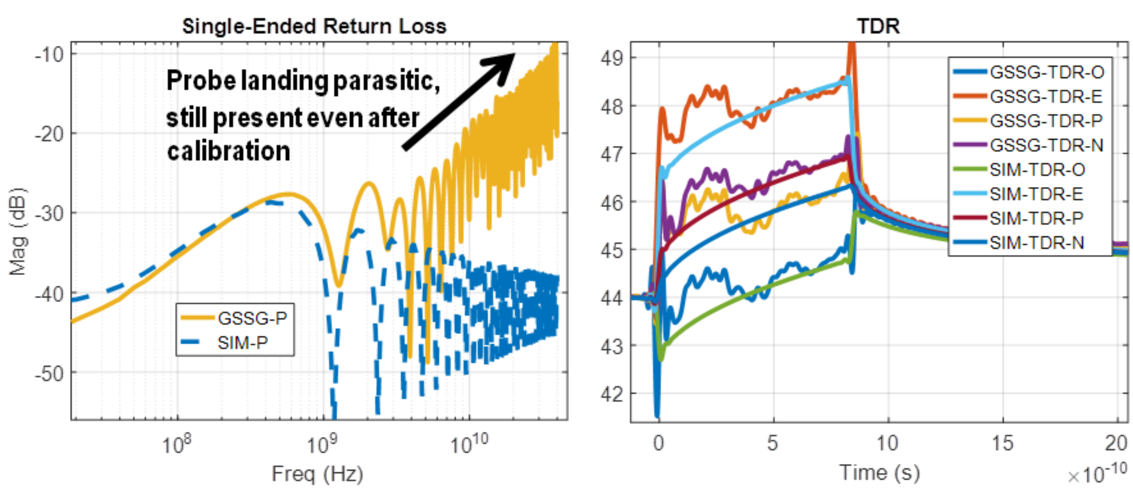

Figure 9: (left) P return loss correlation, (right) TDR correlation for P, N, odd and even modes

If we turn our attention to crosstalk, as shown in Figure 10, we can see the excellent fit both in the frequency and time domain. Even the crosstalk reflection in the sub mV level is correlating very well.

There is another interesting observation we can make in here with the level and more important, the direction of the far-end crosstalk. The positive nature of the far end crosstalk would indicate that the capacitive coupling is higher than inductive coupling. If we think about a diff pair immersed in a server grade multi layer board, we would have imagined when pressing the board resin will flow into the void in line with the traces and get squeezed in there. The interesting thing is that resin has a lower DK than the composite core laminate, in which case we would have expected the far end coupling (bulk of the fields horizontally between the traces) to be negative (inductively dominated), but "that is not the case". In the model I had to fill the section between the traces with higher DK in order to match the measurement.

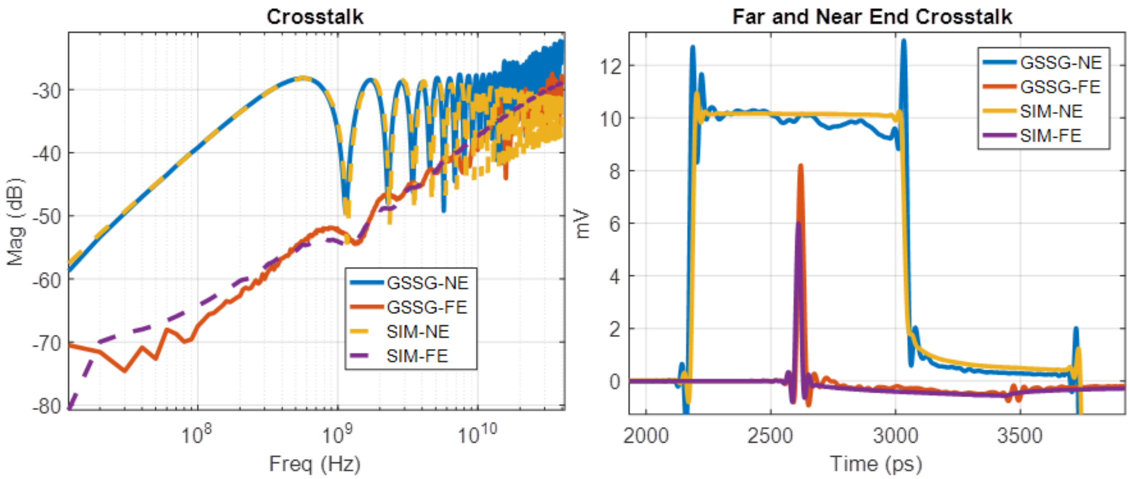

Figure 10: (left) Far and Near end crosstalk correlation in the frequency domain, (right) Far and Near end crosstalk correlation in the time domain

So far all the fitting/correlation data we've seen could be characterized as very good to excellent; we have not found anything on the measurement or simulated data to let us believe there is something wrong either in the simulations or measurement.

Unfortunately, when we plot the insertion loss, as shown in Figure 11, the correlation is not as good.

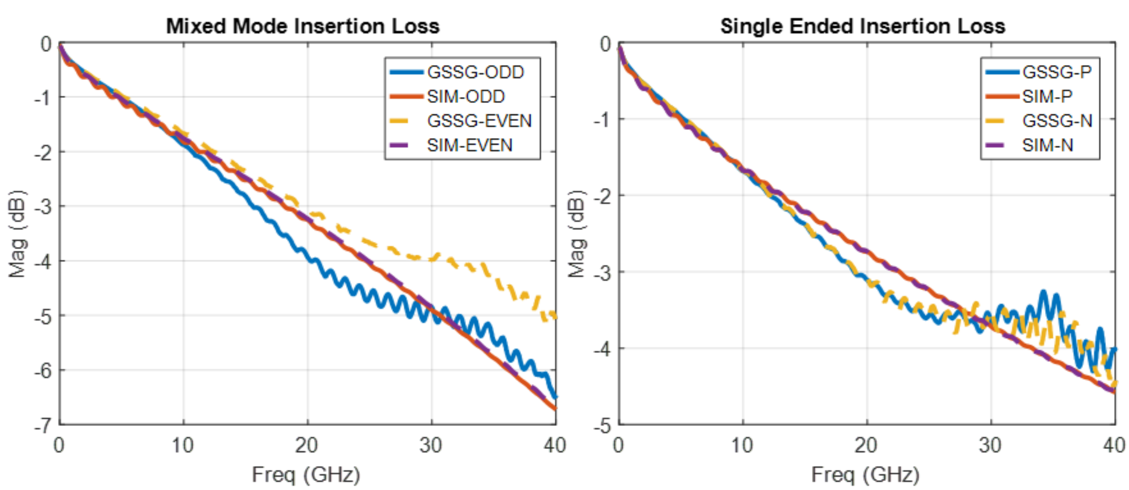

Figure 11: (left) Mix mode insertion loss correlation, (right) singled ended insertion loss correlation

Specifically for this case, we were hoping that either proximity effect, or perhaps skew would produce the difference in insertion loss between modes, but that is not the case. No matter how much we tried, the ODD and EVEN insertion loss for this small amount of coupling are on top of each other. Since we could not find what we were looking for, another structure a little longer (3.2") was measured to see if this was something that happened only once.

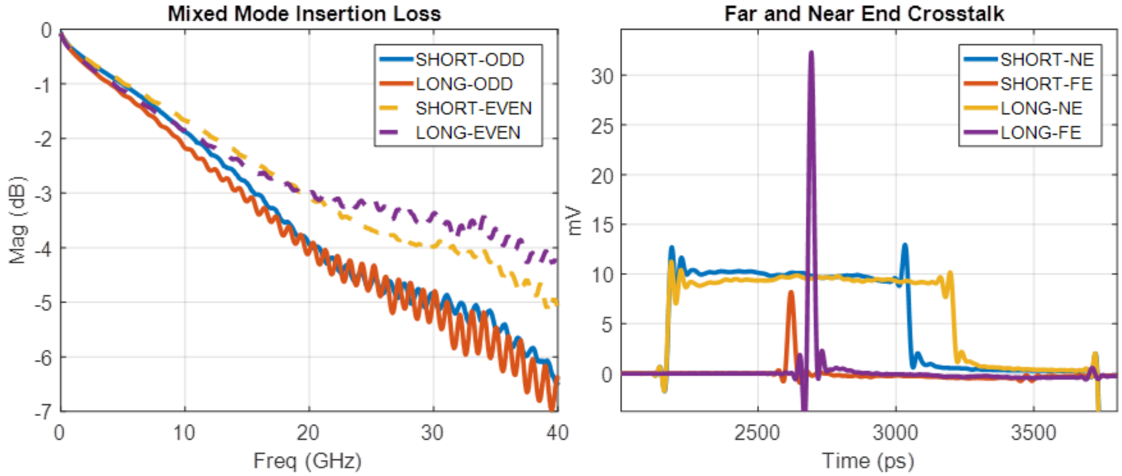

Figure 12: Insertion loss and crosstalk comparison between short and long DUT, (left) insertion loss, (right) far and near end crosstalk

As can be seen in Figure 12, both DUTs have the same observed separation between even and odd mode. In addition, when looking at crosstalk, we note the near end crosstalk is very similar, telling us that the coupling between the two DUT's is the same. On the other hand the far end crosstalk for the longer trace is disproportionally high for such small delta in length.

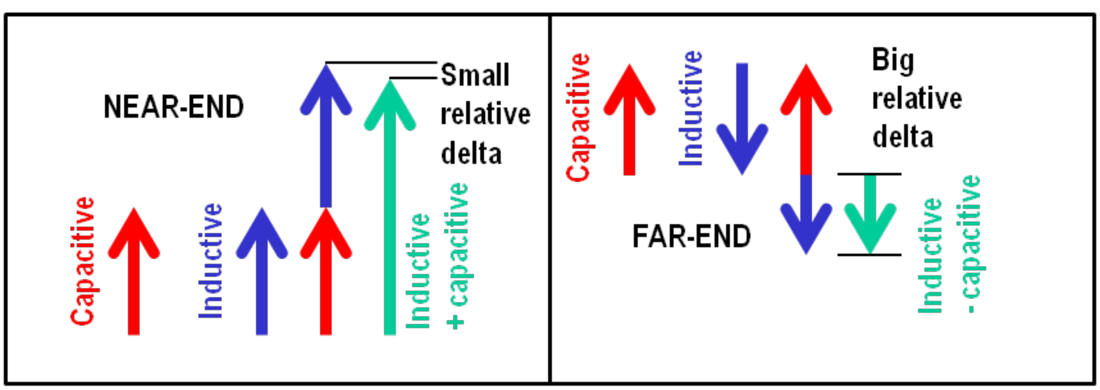

Figure 13: Sensitivity of far end and near end crosstalk

This can be explained with the help of Figure 13. Near end crosstalk can be viewed as two vectors pointing in the same direction representing the inductive and capacitive coupling. Total coupling is the sum of these two. If we have two DUT cases (two diff pairs, one a little longer than the other) and the coupling between them is a little different, that would represent a very small relative difference in near end crosstalk, concluding that near end is not a very sensitive parameter. On the other hand, far end crosstalk is the difference between the inductive and capacitive coupling vectors or the addition for two vectors that are 180 degrees out of phase as shown in the figure. In that case, a small difference between DUTs will mean a big relative difference between them, and that is why far end crosstalk is a very sensitive parameter and in our opinion dangerous to use for correlation in general and on a glass reinforced materials in particular.

In summary, at this point, we've seen the measurements are consistent, but we can't attribute the insertion loss separation between even and odd modes to the DUT. There is nothing (other than the IL separation between modes), that would suggest anything wrong either with measurements or simulations.

We conclude then, this can't be happening on the DUT and it has to be related to the probes landing. Perhaps current re-distribution, crosstalk or the combinations of both is the source of this inaccuracy.

In order to understand this behavior, other measurements with **probes only** back to back were performed in hopes to decipher the mystery.

Probe Analysis

We have established that the discrepancy is not happening in the DUT, and assuming the VNA calibration is doing its job, the only remaining piece would be the section of the probes that might not be properly calibrated.

When doing SOLT calibration, the standards are measured on a calibration substrate, but when DUT measurements are performed, the probes are landing on a structure that is different from the structure where the probes were originally calibrated. Some part of the current redistribution of the probe to the DUT will be different than on the standard substrate and hence, likely will not be calibrated out. This fact can be seen in Figure **9** (left). The up-slope of the return loss represents the landing discontinuity that remains un-calibrated. Another aspect of the probes that is not calibrated is crosstalk.
Crosstalk is a difficult parameter to calibrate for approximately the same reason. The crosstalk measured on the standard might change when the probes are landing on a different structure (DUT) than the standard. Even though 16-port VNA error models including crosstalk terms can be created [2], it's been found that the best way to mitigate this effect is to avoid crosstalk in the first place.

In order to understand the probe-only behavior, a measurement was taken by calibrating the VNA to the tips of the cables (with an Ecal), and then measuring the probes back-to-back on the open piece standard (very small piece of copper just used to facilitate the connection between the tips of the probes).

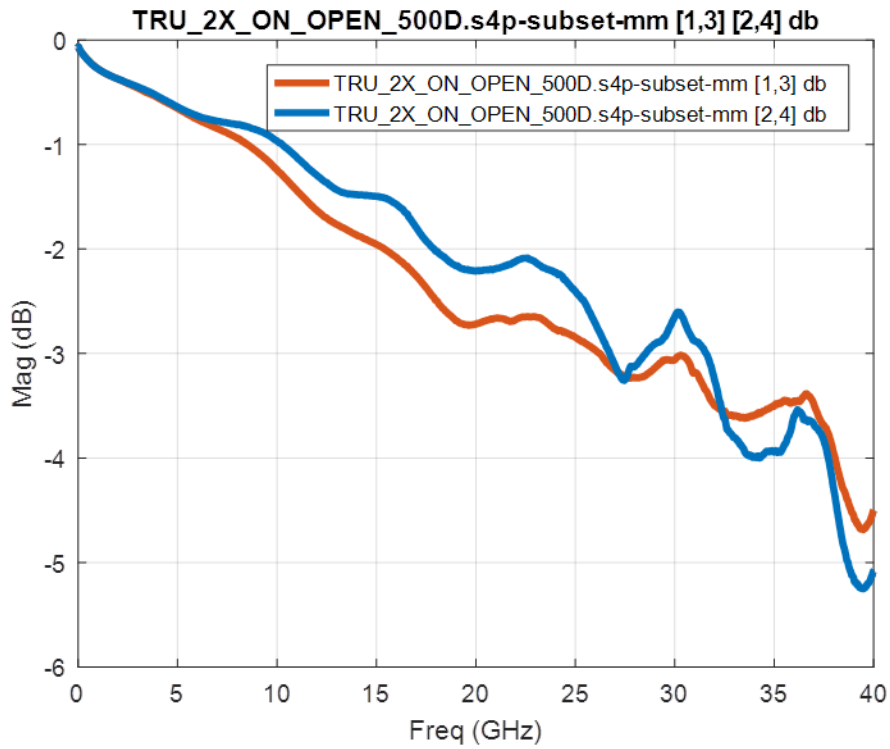

Figure 14: 500um GSSG probes back to back on a open

As can be seen in Figure **14**, when connecting the probes back to back, we also see the difference between even and odd mode. Since in this measurement the DUT is not present we can categorically say that the effect is NOT happening on the DUT, rather on the probe.

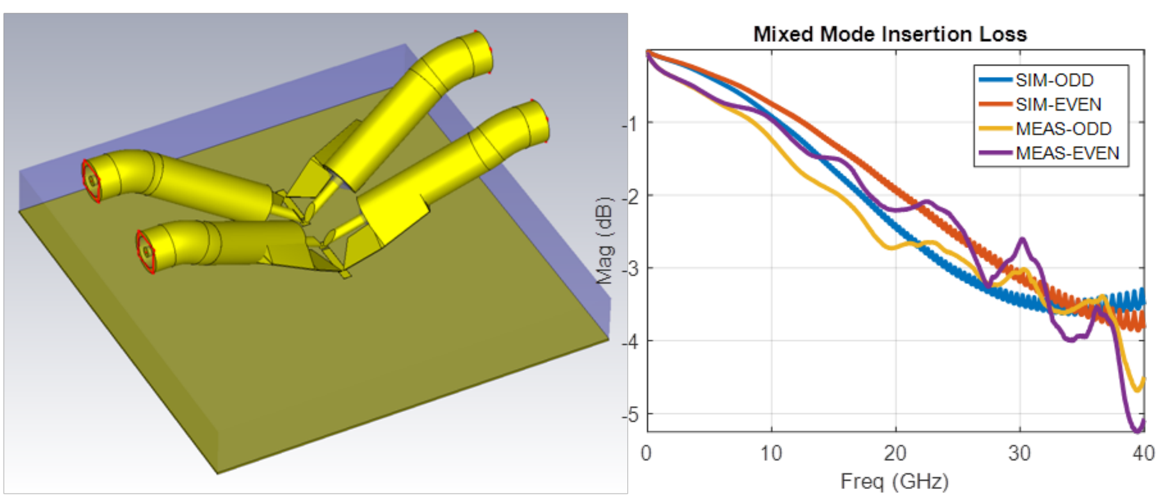

Figure 15: (left) 3D simulation model of probes back to back, (right) correlation to measurements

In addition, as shown in Figure 15, a back to back 3D model of the probes was created to see if we can capture the effect in simulations. It's important to note that we did our best to derive measurements and material characteristics for the probe with some help from our vendors, but we can't guarantee the 3-D modeled probe is identical to the real physical probe. We can show though, that even though the probe might not be identical, the fundamental behavior of the model and the physical probe correlate very well in relative value.

After this correlation we concluded that to a great extent, this effect is happening because of probe current redistribution dependent of the relative location of the ground blades with respect to the signal tips. We know modal return currents (fields) concentrate differently depending on the mode. In odd mode the fields will be located mostly between the differential traces. In even mode, the fields will be concentrated toward the outside of the traces with less fields in between. Our intuition tells us that a G-S-S-G probe configuration have the ground blades in a favorable location for the even mode return currents as compared to the odd mode, hence odd mode experiences a bit more losses.

In order to prove this through measurements, another test was performed. Instead of measuring the signals with a typical G-S-S-G diff-probe, the DUT was measured with four independent single ended probes as shown in Figure 16.

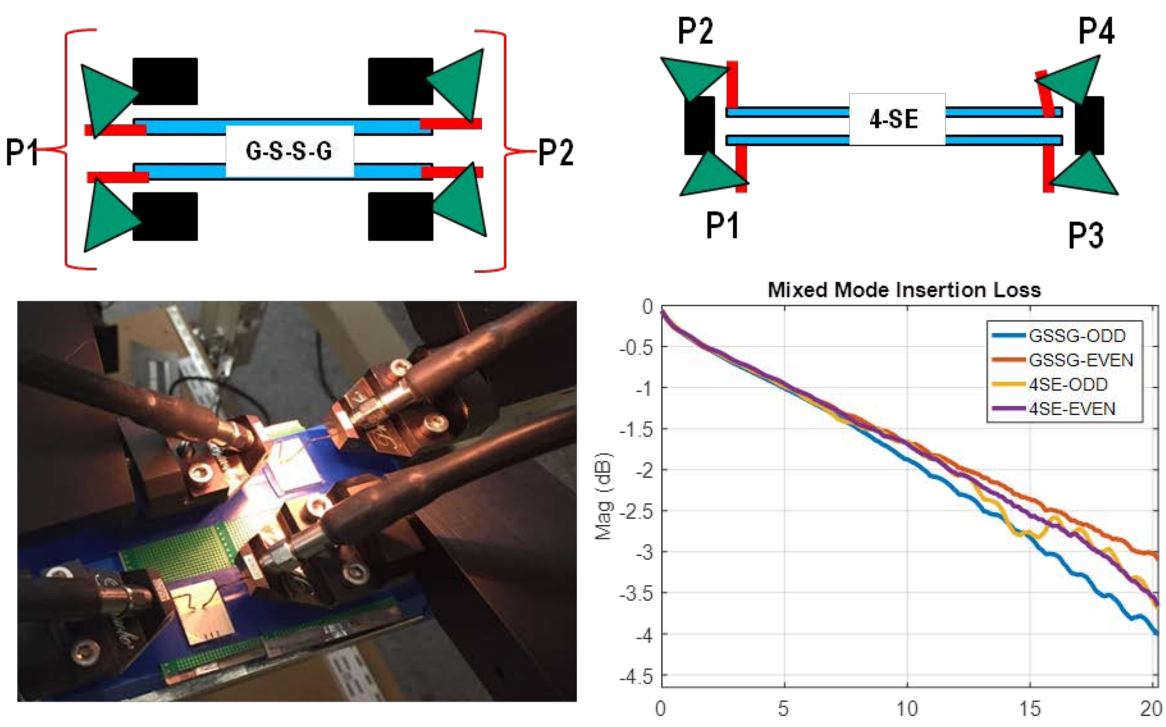

Figure 16:(top left), typical GSSG probe configuration, (top right) with 4 independent single ended probes, (bottom left) picture of the calibration set-up for the single ended probes, (bottom right) correlation between two different type of measurements

By doing this, we can see that the blades location are more symmetrical with respect to the traces, on the back, not the sides, as shown on the top-right of Figure 16. The measurement correlation can be seen on the bottom right, and it shows that now, the odd and even mode when the measurement is taken with four independent probes, are on top of each other (this is a difficult measurement to make, that is why one of the side deviates from the ideal trajectory, but the trend is clear)

This to some extent proves the point. The GND blade location in relation to the DUT has a noticeable effect between the mixed modes of propagation.

Before we move away from this section, let's now do a relative comparison of the complete structure including the DUT in the middle.

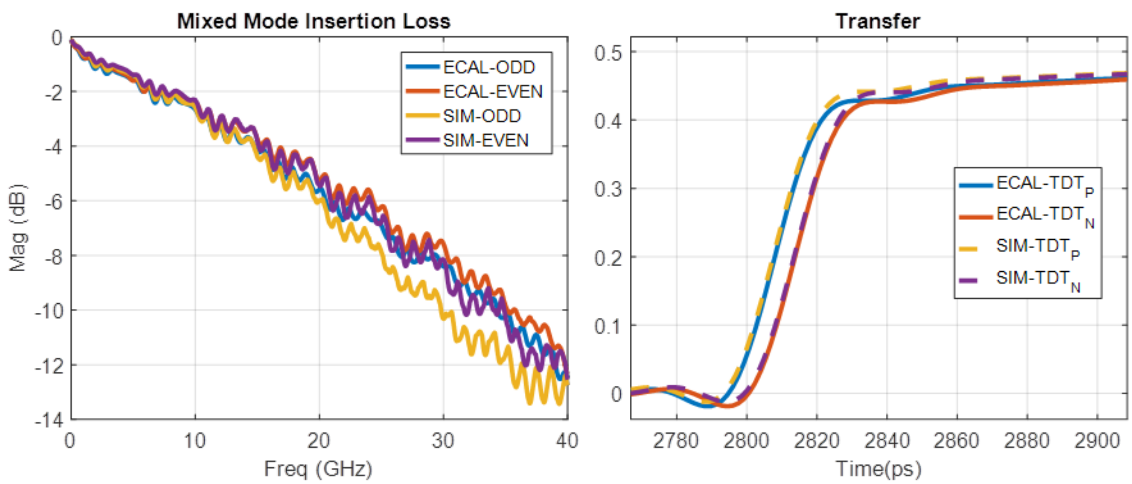

Figure 17: (left) mixed mode insertion loss correlation, (right) TDT correlation

We can see both insertion loss and transfer correlates well between measurements (E-Cal to the end of the cables), and simulation including the probes with approximate mechanical parameters.

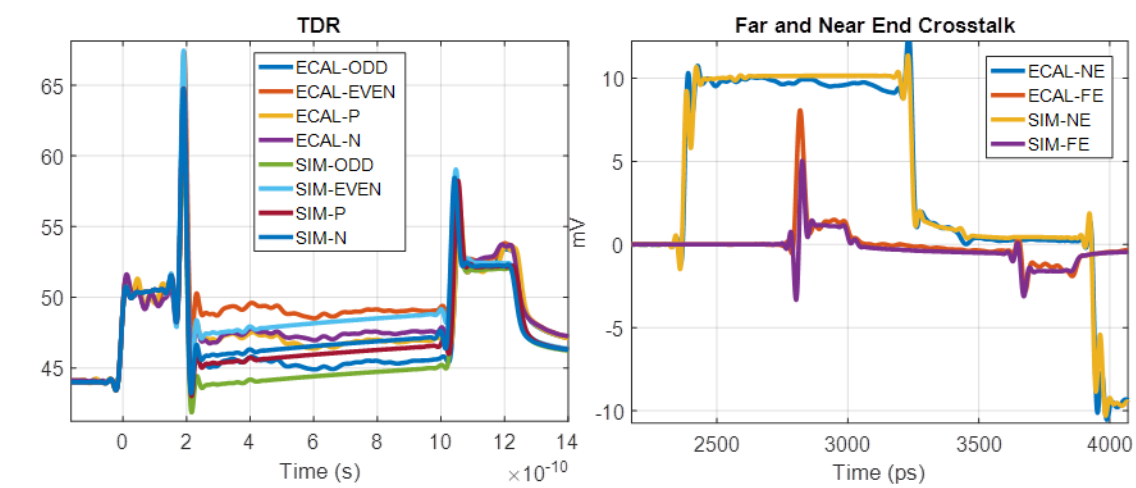

Figure 18: (left) TDR correlation, (right) near and far end crosstalk correlation

Finally we can see in Figure 18 a good correlation of the TDR and far and near end crosstalk. In the TDR we can clearly see the big discontinuity peak at the DUT entry and exit, as well as the length of the probe and DUT.

New Probe Design

It's obvious from the previous discussion that changing the location of the GND blade with respect to the probe tip changes the relation of loss between even and odd modes. Hence the probe model was changed by placing the blades on the back of the tips as shown in Figure **19**

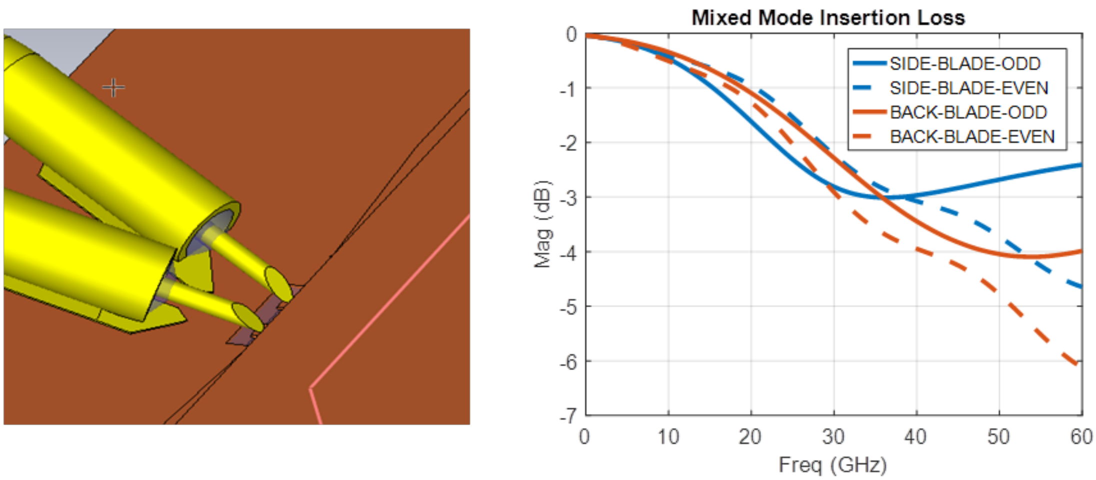

Figure 19: New probe with blades on the back, (left) 3D model, (right) mixed mode insertion loss comparison against traditional probe with blades on the sides.

When we compare the new probe with the old probe, we can certainly see a difference in the loss profile. In the original case, even mode has less loss than odd mode. On the probe with the blades on the back, we see not only the difference being smaller, but the trend reversing. These results led us to believe that we might find an optimal GND blade location to minimize the difference between even and odd mode. Trying a few angles, we found that with a blade at an angle of forty five degrees approximately, the delta between modes is almost zero.

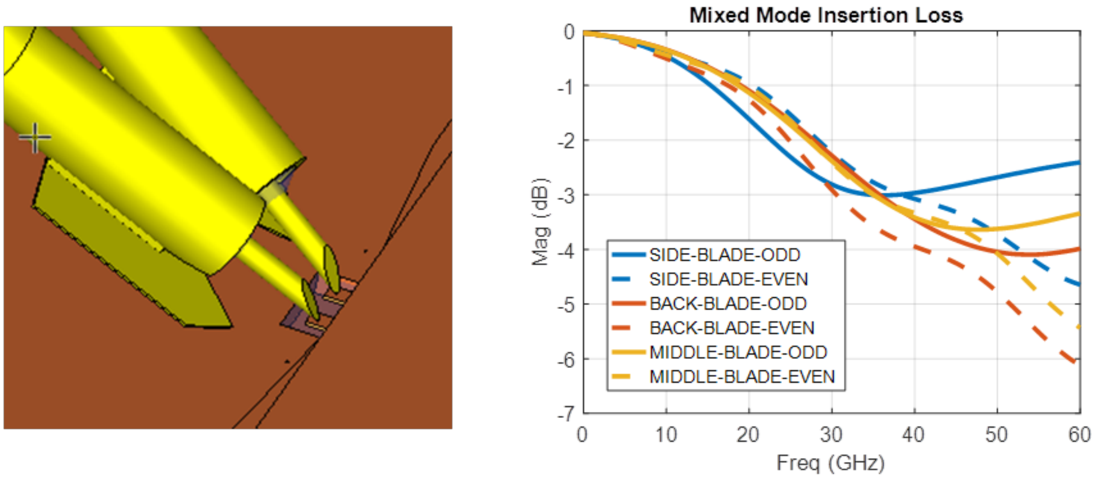

Figure 20: Blades at forty five degrees, (left) 3D models, (right) mixed mode IL comparison

As shown on Figure 20, when trying different angles we can observe that the IL is changing as we rotate the probe. Another important aspect for the angles is crosstalk. We can see that there are certain probe configurations were crosstalk is reduced by approximately 15dB, these configurations are of great interest since, as mentioned previously, the best solution against probe to probe crosstalk, is to try to avoid it.

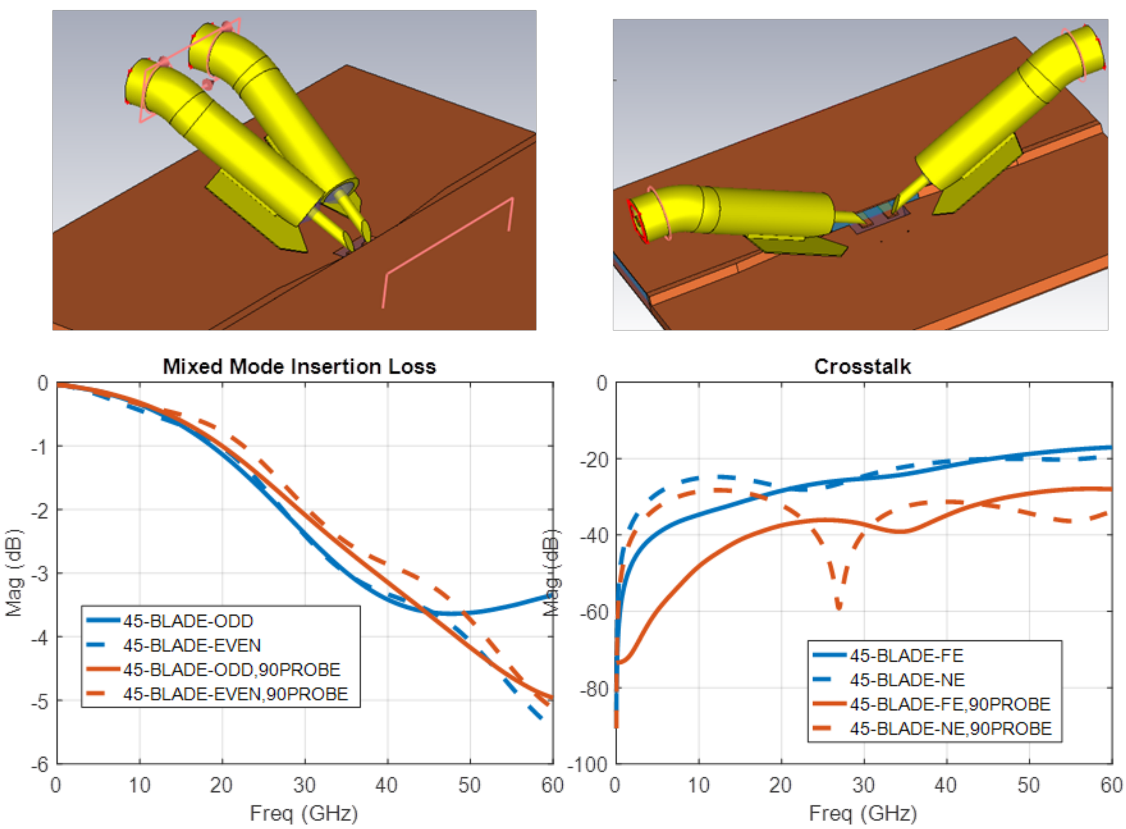

Figure 21: Forty five degrees blades, (top left), parallel probe orientation, (top right) opposing probe orientation, (bottom left) Mixed mode insertion loss comparison, (bottom right) far and near end crosstalk comparison

In Figure 21, we can see, when we position the probes facing each other (top-right figure), the crosstalk levels are greatly reduced, while the IL difference is still very small between the cases. At the time this seems to be the best solution to improve both crosstalk and ground current redistribution on the probes

We've shown, there are some inherent errors we have and can't calibrate out when using a typical G-S-S-G probe, but with some design modification is possible to correct, "to some extent" the error by changing the location of the GND blades.

When we started the discussion, we mentioned the big effort to prepare the DUT to have access to only what we want to measure, yet, even after all this work, we find ourselves in a situation with a measurement with some issues. We've shown that with some probe modifications, the situation can be improved.

In addition, and to complete this work, we wanted to experiment with other measurements and calibration techniques to see if perhaps other approaches would help minimize this problem.

From the vast sea of options we selected two, which up front we considered could be the most effective:

1. AFR Calibration technique: **A**utomatic **F**ixture **R**emoval, is a technique developed by a leading VNA vendor by which they characterize the probes by taken a few measurements and then de-embed the probes from the measurements. Similar methods are offered on stand-alone software packages.
2. Trying a different probe configuration that would force a difference current redistribution. We selected a G-S-G-S-G probe. This probe has an extra ground in the middle that will serve two purposes, one, it will force a different GND current redistribution from the probe to the DUT, and second it'll isolate the probes reducing crosstalk.

AFR Calibration Process and results

This is a two tier calibration process. The first tier is to calibrate to the end of the cables. The second tier is to take measurements of the probes alone and then derive a model. To obtain the probe model, it's required either/or a short, open and back-2-back troughs between the probes (2X tru). The tool will do a TDR/TDT of some of these measurements, and determine where the probe starts and end, and then it'll generate a probe model to match the time-domain waveform.

After that, a measurement of the probes + DUT is taken, but since the probes models have been generated, they can be de-embedded leaving only the DUT data.
We thought this would be useful, since in order to get the probe models, we need to measure a 2XTru, and we know from before that this configuration contains the error. So perhaps the model will include the uncertainty and solve our measurement issue.

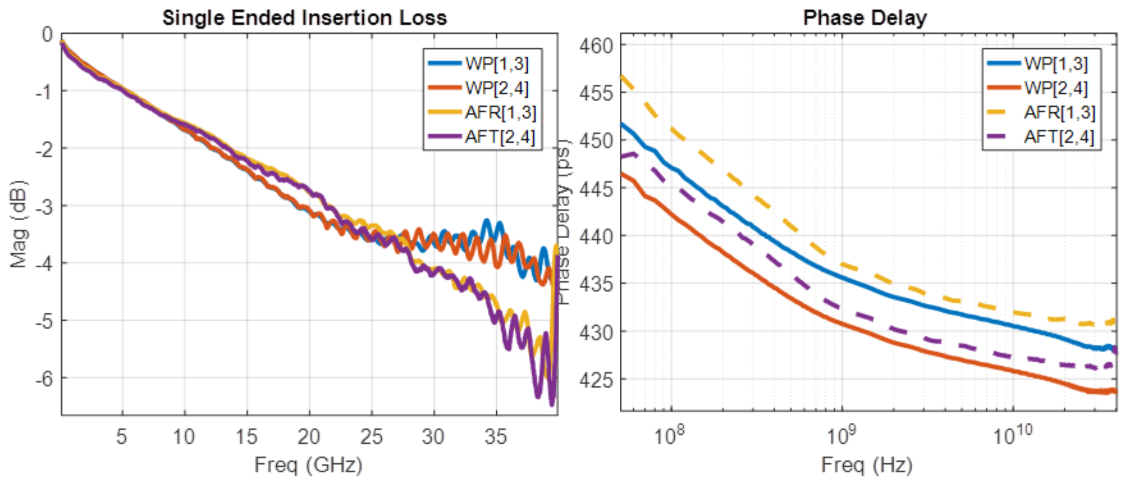

Figure 22: (left) Single ended insertion loss after AFR, (right), single ended phase delay after AFR. Both cases compared to SOLT calibrations

Let's start by looking at the single ended S-parameters as shown in Figure 22. What we see is very promising. The single ended insertion loss, looks straight, and the tilt that we used to have for the SOLT wafer calibration is gone. Perhaps part of the crosstalk in properly included in the model of the probe and is removed when de-embedded. The phase delay is also very good, the shape is virtually identical, there is a minor difference of less than 0.8ps of skew. Please note this structure has been used to take a lot of measurements, so it's entirely possible, the tip of the trace has been wearing off, and simple small variations of probe landing positioning can create this small level of difference. But remember that the main objective of this exercise is to see if the even and odd modes Insertion Loss are not separated.

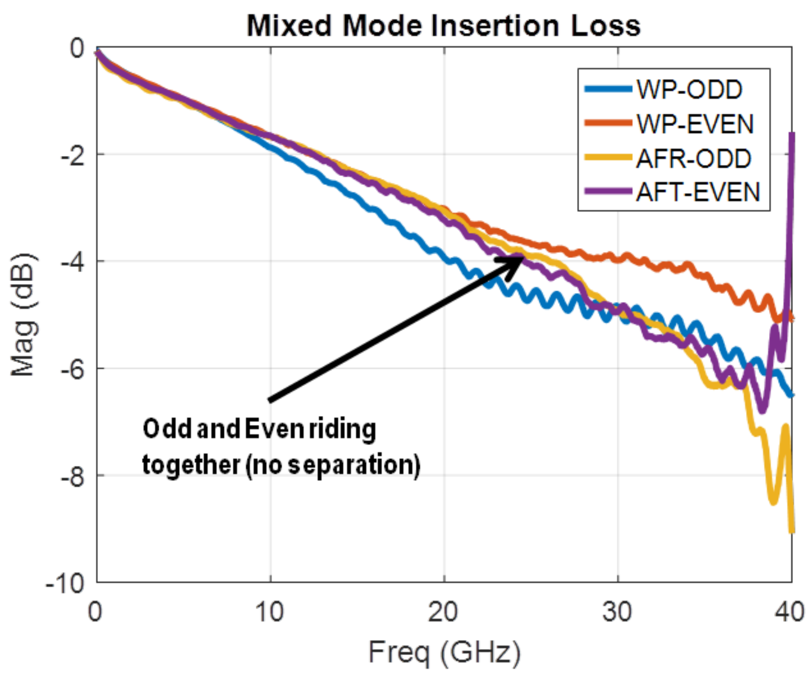

Figure 23: Mixed mode insertion loss after AFR

Figure 23 results are very encouraging. We can see now the modes riding on top of each other. Particularly when compared to the SOLT wafer probe calibration, we can see a vast improvement.

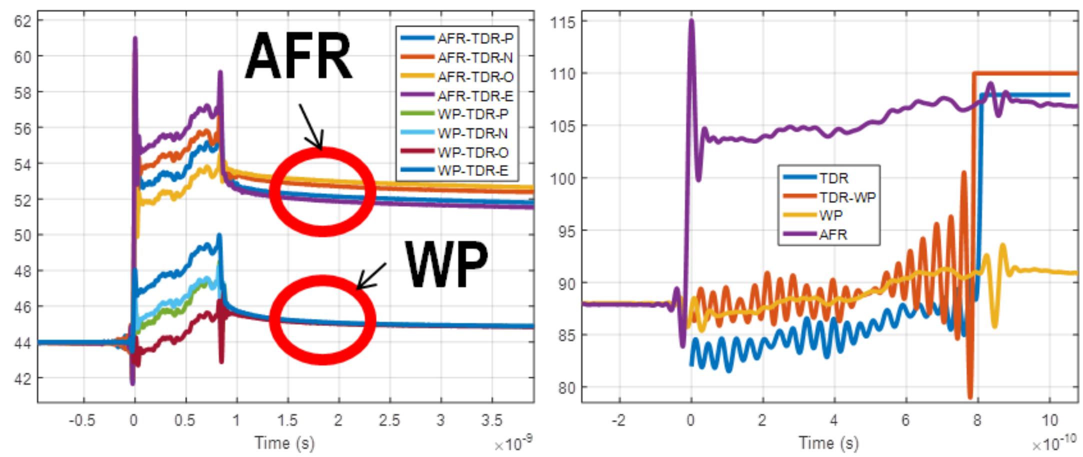

Figure 24: (left) TDR of SOLT and AFR computed from VNA data, (right) SOLT and AFR TDR compared to real time domain TDR measurements

Unfortunately the TDR shown in Figure 24 (left), shows a big impedance difference between the computed TDR after SOLT and AFR. The difference is substantial. To make sure of what is the real impedance of the trace, a time domain direct measurement was performed with two different calibration on the TDR, (red) to the tips of the probes using the calibration substrate and (blue) to the end of the cables (probes included). We can see that indeed the physical time domain measurement align very well with the SOLT VNA calibration, and proves that the AFR is off.

When the AFR algorithm is extracting the probe models (required for de-embeding) based on the probe measurements, it needs to decide where the probes begin and end. This is a key element of the process. In all the figures above, I purposively kept the values to the tool's defaults. For this application, the probes are too short and nearly lossless, and the algorithm is getting a little bit into the DUT.

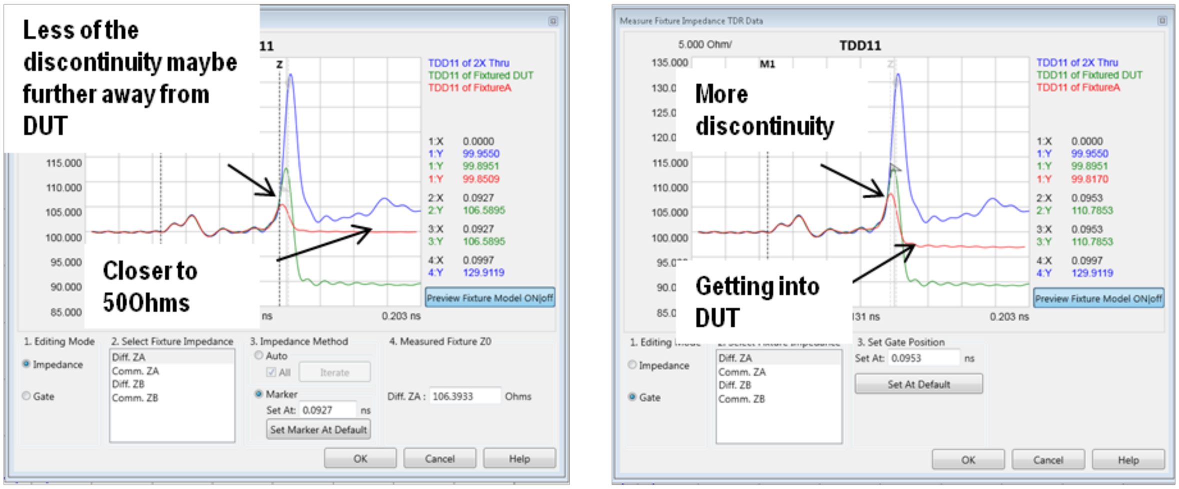

Figure 25: (left) moving gate to the left (away from the end of the probe), (right), moving gate to the right, into the DUT

Figure 25 shows the window used to manually adjust where the probe begins and ends.

Three traces can be observed: (blue) two probes back to back, (green), two probes with the DUT in between and (red), the derived probe models based on the cursors to tell the tool where the probe begins and ends.

On the left plot, I moved the cursor (indicating the end of the probe) to the left. When doing that we can observe the peak of the discontinuity between the probes becomes smaller, and after it, the TDR settles to 50Ohms.

This picture attempts to highlight one of the issues, how do I know where the probe ends? On the left, the same was done, but now the probe was moved towards the right. A growing peak discontinuity can clearly be seen, but notice how after the impedance of the model goes bellow 50Ohms indicating, I am getting into the DUT.

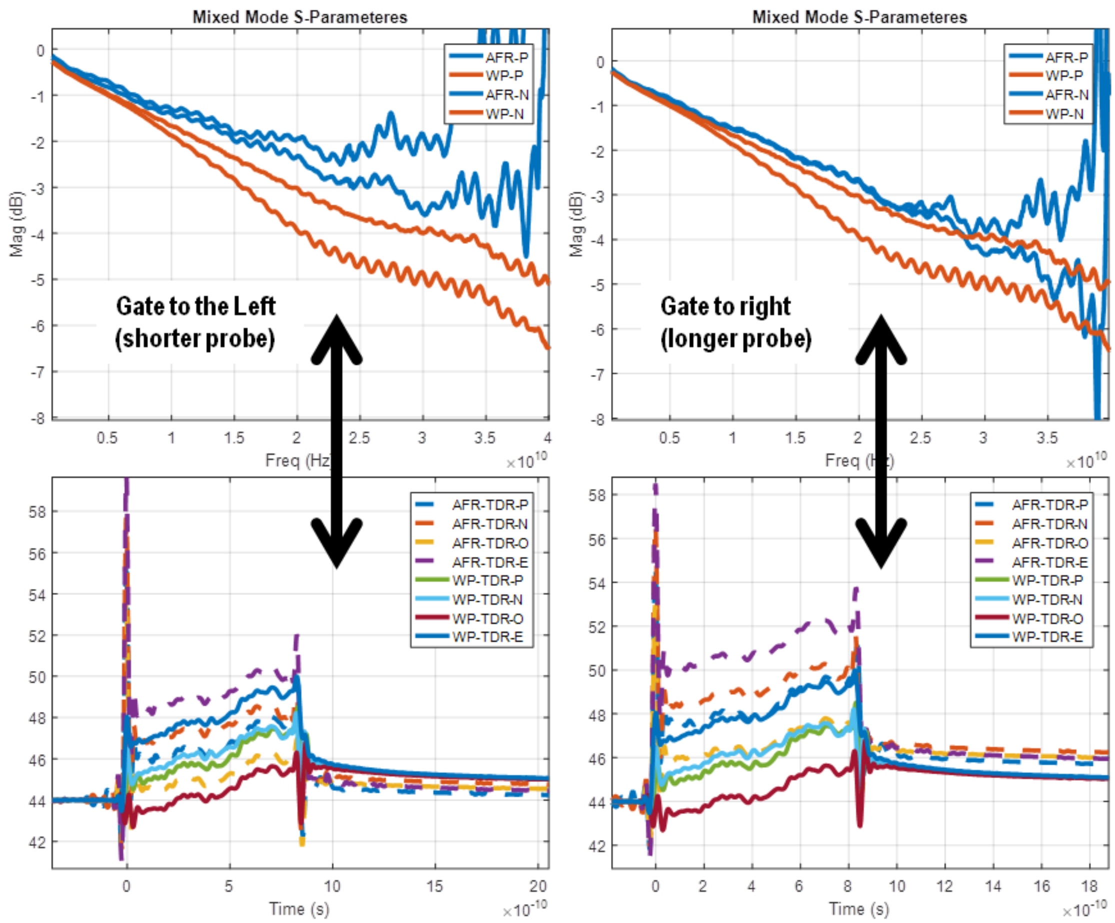

Figure 26: Comparison between SOLT on wafer probe directly, to AFR, (left) placing the gate of the probe on AFR towards the left, (shorter probe), (right), placing the end of the probe to the right and perhaps getting into the DUT

If we refer back to Figure 24 (left) we see a big difference in the TDR between SOLT at the tips of the probe and AFR. This was generated using the default gate (probe end positioning by default for this short structure is way to the right). If now refer to Figure 26 (right), in this case from the default value I moved the probe to the left as shown on Figure 25 (right), still a little bit into the DUT. We can notice that the TDR is matching better, and that actually the impedance settles now to a value just a bit higher than SOLT case. On the other hand, we observe now that the insertion loss is off and not in between the ODD and EVEN as expected and desired. If now on Figure 26 I keep moving the probe end to the left, we see the TDR getting even closer, with the impedance settling to even a lower value than the SOLT, but the mixed mode insertion loss less and less lossy (less of the probe modeled).

Many more cases have been tried, based on measurements and also pure simulations, and ultimately the conclusion is that **for the structures that we are trying to measure and the level of accuracy we are intending to achieve**, this is not an appropriate methodology and even after a lot of manual intervention the results are not accurate enough. The case on this study is a specific case for wafer probes and should not be generalized. There might be many other cases, perhaps in application with connectors on PCB, in which this methodology might work very well.

Wafer Probe G-S-G-S-G

The other test we wanted to do, was to try a GSGSG probe configuration, since we know it should definitely outperform our typical G-S-S-G probe. Before we go into the results, we would like to provide a few thoughts for the advantages and disadvantages that we see with this configuration.

- Advantage:
  - Less crosstalk (isolation between signal traces)
  - Better ground current re-distribution
  - The probe we use has a better 50Ohm match almost to the tip end
- Disadvantage (mostly practical)
  - The DUT would have to be modified in order to be measured (not enough space for the GND in between)
  - In general for differential vias on boards the topology is G-S-S-G, so a probe with a GND in between, even though better, can't really be used unless some modification is done on the board.

The main issue (also for this paper), is that the structure we have measured, can NOT be modified to be measured with this type of probe. So in order to test the probe, I'll just measure the probe on a standard and compare it's behavior to the G-S-S-G probe.

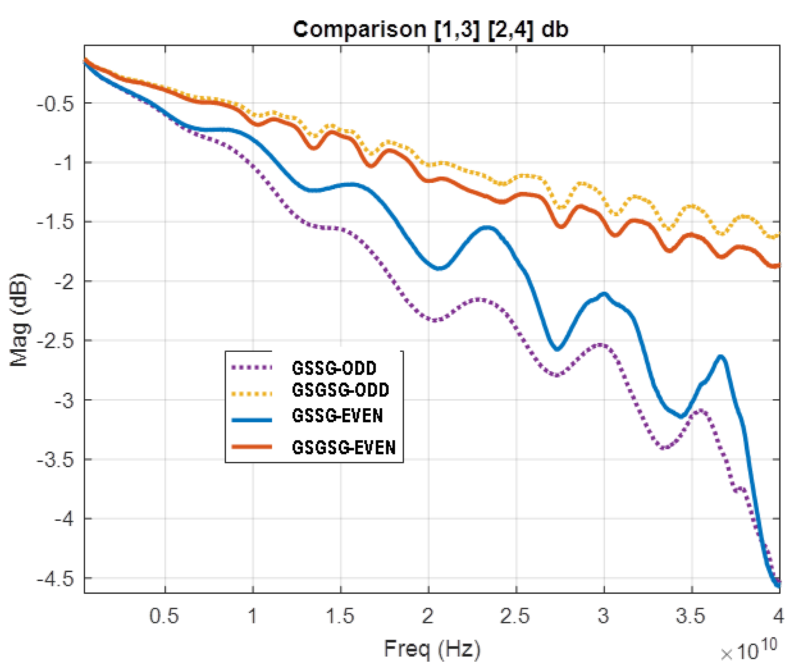

Figure 27: GSSG vs GSGSG probe back to back measurement

Specifically just to the issue at hand, we can see in Figure 27 that the GSGSG probe behaves much better than the GSSG one. Even though there is still a difference between modes, it's much smaller. Another interesting aspect is that in the new probe configuration, the odd mode is a bit less lossy than the even mode, as compared to the original configuration. It's likely that the extra GND in the middle is slightly favoring the odd mode.

Conclusion

This paper is a good example of what we can call the snowball effect in Signal Integrity. Originally, we simply wanted to perform material correlation on a new material, but then an issue we found on measurements led us to simulations, where we found many more issues, not shown here and outside the scope of this papere. In turn that led us to try different calibration mechanism and found all other kind of issues, finally leading to a new probe landing design. Like a snowball, it keeps getting bigger and bigger…..

For this study, we have uncovered and shown, some of the "hidden" inaccuracies of wafer probes measurements and the reason they are happening. We've shown interesting features of a transmission line experiencing a lot of skew on flat glass and dual ply, we've shown how the far-end crosstalk is very sensitive and it's magnitude and polarity is counter intuitive (in this DUT) to expectations.

In addition we've shown some of the pitfalls of other types of calibration and proposed guidelines of when it should or should not be used. We've shown the advantages of different probes, and finally we've proposed a new probe landing design that will help alleviate the measurement error on GSSG probes.

References

[1] A High Isolation Dual Signal Probe Technology (Tim Lesher, Leonard Hayden)
[2] Network Analyzer Error Models and Calibration Methods (Doug Rytting)
[3] Agilent, Stripline TRL Calibration Fixtures for 10-Gigabit Interconnect Analysis
[4] Fixture S-parameter model from 2x Fixture Physical Test Structures (Mike Reso)