In Situ De-embedding

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***Abstract*—Non-causality is often found in the S parameters of device under test (DUT) after de-embedding of vector network analyzer (VNA) measurement data. This paper presents a new de-embedding method that gives causal DUT results by construction. This method, dubbed "In Situ De-embedding" (ISD), uses a simple 2x thru test coupon as reference and arrives at the de-embedding S parameters by matching the fixture's impedance at every location. Not only are the extracted DUT results more accurate but also inexpensive test boards with large impedance variation can be used, resulting in cost saving. What is causality, why other de-embedding methods give non-causal results and why causal de-embedding is crucial for correlation and compliance testing will all be discussed.**

***Index Terms*—VNA, S parameters, de-embedding, TRL calibration, causality**

I. INTRODUCTION

Virtually all component and system manufacturers need to do fixture de-embedding to characterize the electrical performance of a component, ranging from chip to package, printed circuit board (PCB), connector and cable. Vector network analyzer (VNA) is perhaps the best equipment to use for characterization because it measures the detailed electrical behavior of a component at every frequency. A component, or device under test (DUT), does not usually lend itself for direct measurement and needs to be mounted on a fixture for connection to VNA. The effect of fixture must be removed (i.e., de-embedded) in order to get the true electrical behavior of DUT itself.

The traditional approach is to fabricate and measure test coupons that resemble the fixture's lead-ins and/or lead-outs. Information is extracted from the test coupons and de-embedded from the fixture + DUT measurement data. To collect more information, the TRL (thru-reflect-line) calibration method requires that multiple test coupons be built, taking up a fair amount of board space.

Due to the effect of fiber weave, etching and other variation, fixture and test coupons will see different impedance throughout the lead-ins/outs, so de-embedding the fixture + DUT board with information derived from test coupons is akin to subtracting C from A+B and hoping to get A, where A is DUT, B is fixture and C is the test coupon. In order to make C as close as possible to B, the conventional wisdom has been to use high-quality connectors and PCB material and tight etching tolerance, resulting in more expensive measurement. Even then, error still remains because it is impossible to make the fixture and test coupons identical in impedance at every location. In addition, the larger the fixture, the more error will accumulate.

The above de-embedding error occurs before and/or after DUT and eventually gets piled up into the extracted DUT results. Such error manifests itself as non-causality: the extracted DUT results predict that there is output signal before the input signal arrives. This non-causal behavior is apparent when one converts the extracted DUT's frequency response into time-domain transmission (TDT) or time-domain reflection (TDR) waveforms. In frequency domain, such non-causality often appears as artificial ripples in magnitude and/or counterclockwise phase angle of scattering parameters (or S parameters).

This paper introduces "In Situ De-embedding" (ISD) [1] which takes a new approach to do de-embedding. Instead of subtracting test coupons directly from the fixture + DUT, it uses the data of a simple "2x thru" test coupon only as an initial guess and arrives at the final de-embedding S parameters by matching the fixture's impedance at every location. The name "In Situ" was used to indicate that ISD identifies and de-embeds the true impedance of fixture. Many advantages arise as a result. The extracted DUT results are more accurate because they are causal by construction. The measurement vs. simulation correlation becomes easier so the design cycle time is reduced. Less expensive connectors and board material and looser etching tolerance can now be used, resulting in cost saving.

II. CAUSALITY

S parameters, often expressed in Touchstone file format, can become non-causal because of several reasons: (a) finite bandwidth, (b) simulation error and (c) measurement error. The Kramers-Kronig relations [2] require that the real and imaginary parts of an analytic function be related to each other through Hilbert transform in (1). A Touchstone file, being of finite bandwidth, is inherently non-causal because the Hilbert transform integrates to infinite frequency. Many methods, including rational function fit, have been proposed to alleviate the bandwidth limitation.

$$\begin{aligned}
\Psi(\omega) &= \Psi_R(\omega) + j\Psi_I(\omega) \\
\Psi_R(\omega) &= \frac{1}{\pi} P\int_{-\infty}^{\infty} \frac{\Psi_I(\omega')}{\omega' - \omega} d\omega' \\
\Psi_I(\omega) &= -\frac{1}{\pi} P\int_{-\infty}^{\infty} \frac{\Psi_R(\omega')}{\omega' - \omega} d\omega'
\end{aligned} \quad (1)$$

Using a field solver to simulate a structure can also give non-causal S parameters if the material property being entered is non-causal. Constant dielectric constant (DK) and dissipation factor (DF), for example, violates Kramers-Kronig relations and will lead to non-causal S parameters.

This paper's main focus is on non-causality that is caused by de-embedding and/or calibration error in measurement. Consider Figure 1 where a DUT is mounted on a fixture and, in traditional approach, data from separate test coupons are used directly for de-embedding. Due to the difference in fiber weave, etching, routing, soldering and connectors, however, the fixture and test coupons are never identical. The difference between fixture and test coupons, mainly in the form of impedance, is like "phantom limbs" [3] that contribute to non-causal S parameters after de-embedding.

Instead of using the data directly from test coupons for de-embedding, ISD adjusts their data through nonlinear optimization to match the fixture's impedance. As a result, the extracted DUT's S parameters are causal and there is no need to tighten the impedance variation between fixture and test coupons, reducing hardware cost.

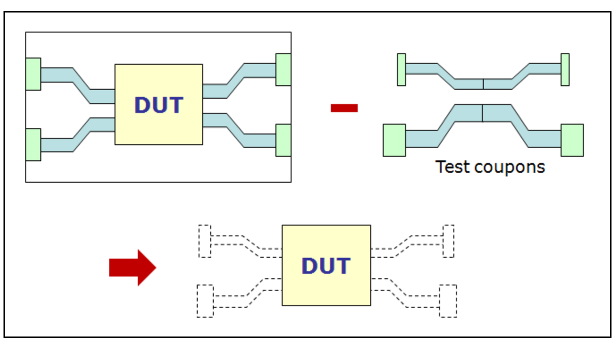

Figure 1: Non-causal de-embedding due to difference between fixture and test coupons.

III. Examples

In the first example (Figure 2), a Hirose mezzanine connector is the DUT and its electrical performance is to be characterized. Figure 3 shows the ISD vs. TRL comparison of differential insertion loss (SDD12) and return loss (SDD11). Notable difference can be seen in SDD11 where TRL gives many artificial ripples. (Note that the DUT is a small connector.) Artificial ripples in S parameters are a signature of non-causality. Converting the above SDD11 into TDR impedance at 50ps rise time (20% to 80%) in Figure 4 clearly shows the non-causal behavior of TRL results where there exists a large peak before time zero (i.e., before the input signal arrives). Figure 5 illustrates how ISD reproduces the fixture's impedance to give causal extraction in Figure 3 to Figure 4. By de-embedding the fixture's true impedance, the left-over "phantom limbs" in Figure 1 are removed.

In the second example (Figure 6), a USB Type-C connector is the DUT and its electrical performance is to be characterized. Figure 7 shows the ISD vs. Keysight AFR comparison of SDD12 and SDD11. Notable difference can again be seen in SDD11 where AFR gives many artificial ripples. (Note that the DUT is a small connector.) Converting the above SDD11 into TDR impedance at 50ps rise time (20% to 80%) in Figure 8 shows the non-causal behavior of AFR results where there are lots of "activities" before time zero (i.e., before the input signal arrives). Per USB Type-C spec. [4], ISD will give 2.4dB and 1.4dB more margins than AFR in integrated return loss (IRL) and integrated multi-reflection (IMR), respectively, in this case.

IV. Conclusions

Accurate de-embedding is crucial for component characterization and compliance testing. In Situ De-embedding (ISD) addresses the causality problem commonly found in other de-embedding methods. Most notable difference between ISD and other de-embedding methods can usually be seen in return loss. Return loss, which is related to impedance, is of utmost importance for many applications. In one application, PCB's material property is extracted from a trace's S parameters [5]. Accurate return loss must be included for extraction because it affects DK and cross section and therefore length, DF and surface roughness. ISD is able to provide far more accurate return loss than TRL and many other de-embedding methods for such applications.

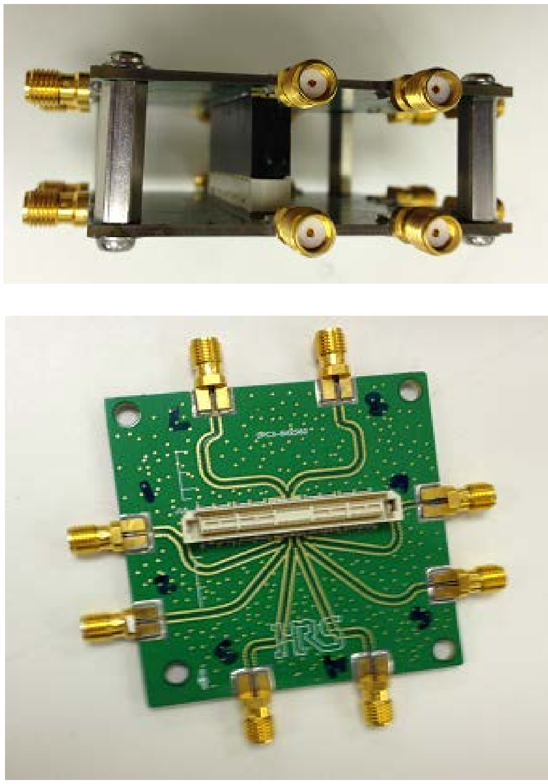

Figure 2: Mezzanine connector (DUT) and fixture.

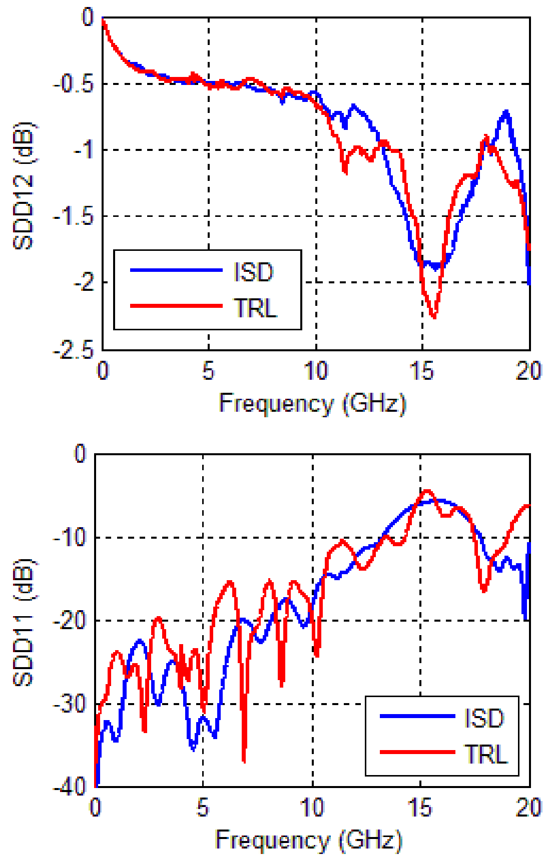

Figure 3: DUT's differential insertion and return losses.

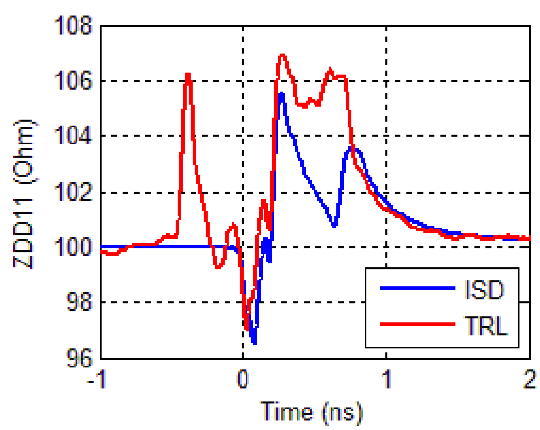

Figure 4: DUT's differential impedance.

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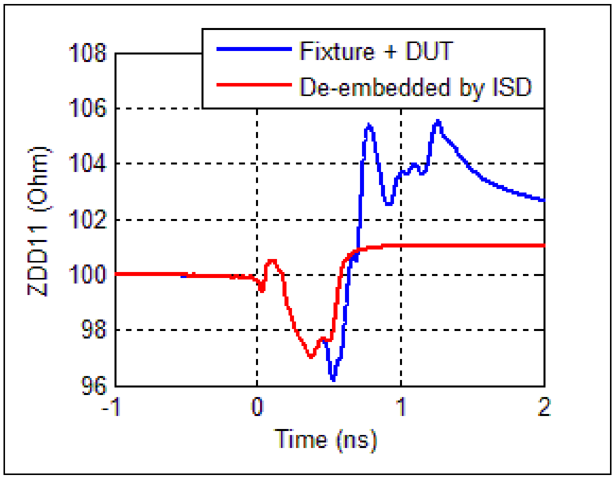

Figure 5: Fixture's impedance vs. impedance de-embedded by ISD.

Figure 6: USB Type-C connector (DUT) and fixture.

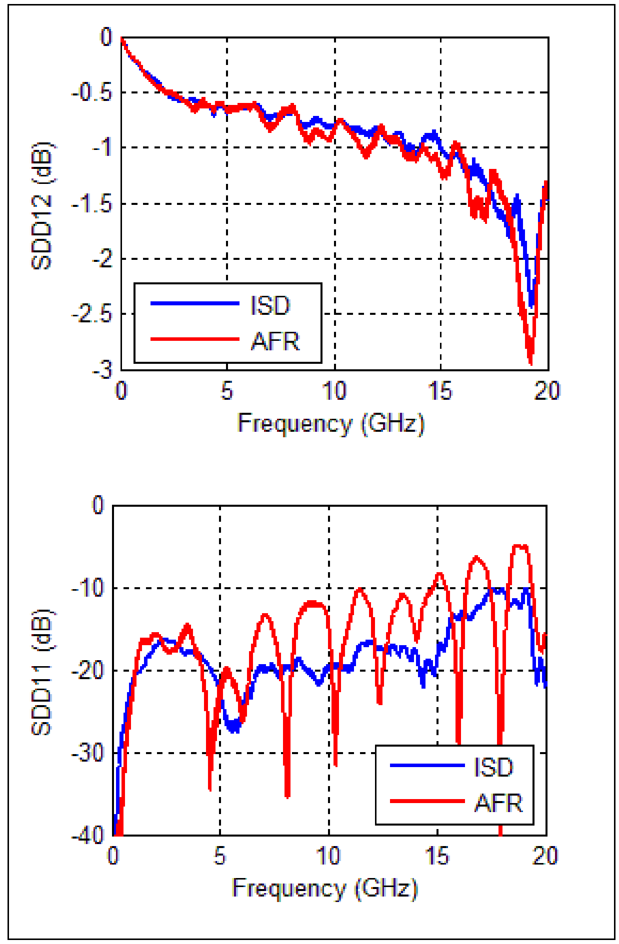

Figure 7: DUT's differential IL and RL.

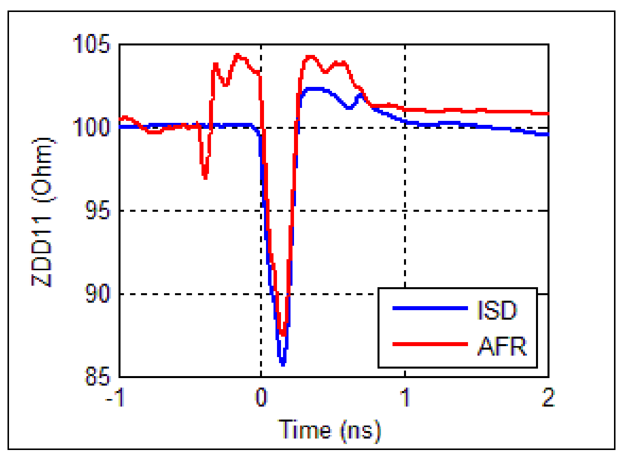

Figure 8: DUT's differential impedance.