A Novel Procedure for Characterization of Multiport High-Speed Balanced Devices

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Abstract— **Accurately measuring the frequency response of high-speed differential devices using a VNA can be exceptionally challenging for two reasons. First, instrument test ports and calibration artifacts have coaxial electrical interfaces, while typical devices needing to be measured do not. Second, differential devices generally have some amount of electrical coupling between pair halves (test ports), but all calibration algorithms assume isolation between test ports. Various approaches have been proposed and employed, but usually with unsatisfactory results. The incompatible interface issue is addressed by using test fixtures. However, the challenge of building and compensating for test fixtures becomes increasingly difficult as industry requires faster data transmission. Ideally, test fixtures are electrically transparent, but since this is not the case in practice, a method of compensating for its effects must be used to be able to obtain accurate measured data on the device of interest. The technique discussed in this paper describes a method of characterizing the test fixture that is simple and highly effective, yet requires a minimal number of assumptions. The method only requires that the input and output fixtures be mirror images, and that they be cascaded to form a THRU standard that can be measured. The THRU standard is connected directly to a traceable coaxial test port of a multiport VNA. Accuracy is extremely good because the traces on the fixture can exactly replicate the DUT test condition, there are no non-coaxial on-board standards, and traceable instrument grade coaxial connecters can be deployed on the fixture.**

Keywords-VNA, error correction, calibration, test fixture, fixture removal, deembed, SOLT, TRL, LRM, high speed, differential

I. INTRODUCTION

Generally speaking, high-speed multi-port (including differential) devices can not be connected directly to measurement instrumentation because of differences in the type of electrical interfaces. Test instrumentation typically uses industry-standard coaxial connections to facilitate calibration of the instrument using traceable calibration standards. Typical test devices may need to use application-specific electrical interfaces for which there are no calibration standards, or they may non-connectorized, requiring RF probing to interface to the instrumentation.

To establish electrical connectivity between an instrument and a device-under-test (DUT) it is common to design an interface circuit known as test fixture. Figure 1 shows schematically how the connectivity between a multiport vector network analyzer (VNA) and a two-port balanced or a four-port single-ended high-speed device is established via a test fixture.

The test fixture solves one problem while introducing another. It establishes electrical connectivity between the instrument and the DUT, but it will distort the measurement. The fixture is not electrically transparent structure, therefore, a calibrated instrument will not measure the performance of the DUT, but rather that of the DUT and test fixture together.

To characterize the DUT alone, the fixture needs to be characterized very accurately. In the case of frequency domain characterization using a Vector Network Analyzer (VNA) this means that the S-parameters of the fixture have to be accurately determined. Once the characteristics of fixture are known, its effects on the electrical behavior of the overall circuit (fixture plus the DUT) can be removed to obtain the performance of the DUT alone using a process called de-embedding. The accuracy of the resulting DUT characterization is directly related to how accurately the fixture is characterized. Unfortunately, characterizing a fixture for an application where the DUT is a high-speed balanced structure is extremely challenging because, like the DUT, the fixture also needs to have a non-

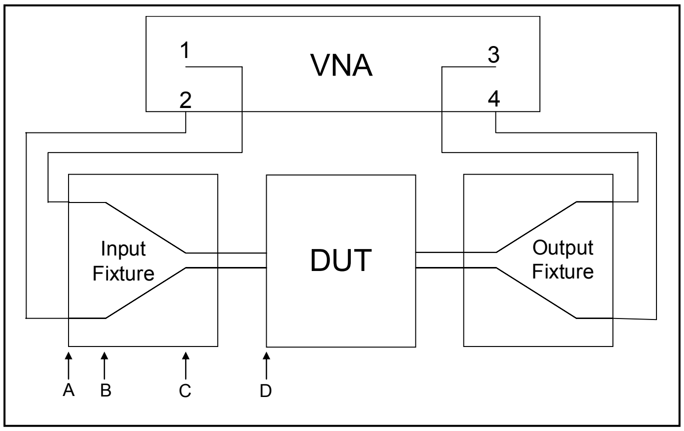

Figure 1: The connectivity between a multiport vector network analyzer (VNA) and a two-port balanced (differential) or a four-port single-ended high-speed device is established via a test fixture.

coaxial interface, unsupported by calibration standards, so that it can connect to the DUT.

While the previous discussion applies generally to the challenges of fixturing and fixture removal, differential devices have additional challenges. It is well known that signal lines that are in close proximity interact with each other via their fringing fields. With reference to Figure 1, just to the left of reference plane A (the position of various reference planes are shown with arrows) the VNA coaxial port cables 1 and 2 are totally uncoupled. Practically speaking this means that the coupling is less than the isolation of the VNA ports, and is typically less that -100 dB to 20 GHz in a modern VNA such as the PNA series from Agilent. From the right side of reference plane A up to the left side of reference plane B, a uniform weak coupling exists between the pairs of microstrip traces of the input fixture that is determined by the physical distance between the lines. From the right side of reference plane B up to the left side of reference plane C, a progressively tighter coupling exists between the microstrip lines of the input fixture as the physical distance between the lines get progressively closer. From the right side of reference plane C up to the left side of reference plane D, the tightest uniform coupling exists between the microstrip lines of the input fixture as the distance between the lines are at their closest. Multi-mode coupling exists in this fixture due to the physical proximity of the coupled transmission lines via their fringing fields.

The additional challenges associated with differential devices mentioned above arises from the fact that the error correction algorithm deployed in a VNA is based on single-mode transmission propagation theory and does not support multi-mode transmission propagation algorithm. Therefore, conventional VNA error correction algorithms such as SOLT, TRL, LRM, etc. will always be inadequate if there is coupling between the ports of the test fixture. The coupling between transmission lines via their fringing fields as described in Figure 1 represents an additional error term that requires an electromagnetic analysis tool that is capable of solving a multi-mode transmission propagation problem. Even with perfect calibration artifacts, the commonly practiced characterization procedures of using on-fixture SOLT or TRL are not appropriate in this application since they also support only a single-mode propagation algorithm. Nevertheless, these techniques are often erroneously applied, usually with unsatisfactory results. A novel characterization procedure is required to overcome this measurement difficulty. This procedure must address (1) the connectivity issue, (2) the fixture removal (or de-embedding) issue, and (3) the single- and multi-mode (coupled line) device issue.

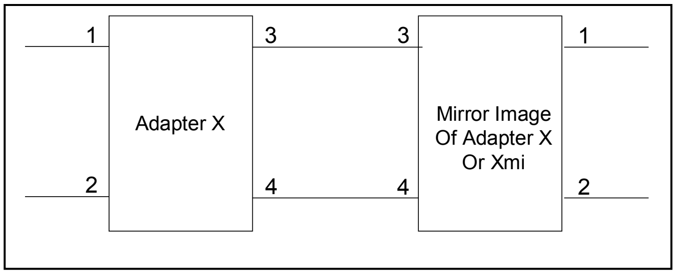

Figure 2: Differential input adapter (fixture) cascaded with a mirror image output adapter (fixture) to construct the differential THRU standard.

II. DESCRIPTION OF PROCEDURE

Figure 2 illustrates an input fixture cascaded with an output fixture to construct the THRU standard. The S-parameter of input fixture is defined by a 4-by-4 adapter matrix X and the S-parameter of output fixture is defined by the 4-by-4 adapter matrix X_{mi}. X_{mi} is the mirror image of X. Adapter X is half of the fixture and adapter X_{mi} is the other half of the fixture. The VNA ports are connected to terminals 1 & 2 of adapter X and terminals 1 & 2 of X_{mi}. If X is defined as

$$X = \begin{vmatrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ x_{31} & x_{32} & x_{33} & x_{34} \\ x_{41} & x_{42} & x_{43} & x_{44} \end{vmatrix}, \qquad (1a)$$

then,

$$X_{mi} = \begin{vmatrix} x_{33} & x_{34} & x_{31} & x_{32} \\ x_{43} & x_{44} & x_{41} & x_{42} \\ x_{13} & x_{14} & x_{11} & x_{12} \\ x_{23} & x_{24} & x_{21} & x_{22} \end{vmatrix} \qquad (1b)$$

Adapter X is a balanced structure; where the top conductor connecting terminals 1 & 3 is symmetrical with the bottom conductor connecting terminal 2 & 4. Due to top-bottom symmetry and reciprocity (passive circuit) the elements of adapter X are related by the following relationship.

$$x_{22} = x_{11} \qquad (2)$$

$$x_{12} = x_{21} \qquad (3)$$

$$x_{13} = x_{24} = x_{42} = x_{31} \qquad (4)$$

$$x_{14} = x_{32} = x_{23} = x_{41} \qquad (5)$$

$$x_{34} = x_{43} \qquad (6)$$

$$x_{44} = x_{33} \qquad (7)$$

The top input adapter X reflection coefficients described by x_{11} is equal to the bottom input reflection coefficient described by x_{22}. Also the top output adapter X reflection coefficients described by x_{33} is equal to the bottom output reflection coefficient described by x_{44}. There is no reflection symmetry between the input and output reflection coefficients of adapter X. Or,

$$x_{11} = x_{22} \neq x_{33} = x_{44} \qquad (8)$$

If the adapter X is reciprocal and perfectly top-bottom symmetrical as described above, then there are total of 6 independent elements. S-parameter matrix C is the cascade of

X with its mirror image Xmi. Matrix C is the THRU standard that is measured prior to the DUT measurement. Matrix C is given by

$$C = \begin{vmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ c_{31} & c_{32} & c_{33} & c_{34} \\ c_{41} & c_{42} & c_{43} & c_{44} \end{vmatrix} \qquad (9)$$

A perfectly reciprocal cascaded matrix C has both top-bottom symmetry as well as reflection symmetry. There are only 4 independent elements to the cascaded matrix C. Or,

$$c_{11} = c_{22} = c_{33} = c_{44} \qquad (10)$$

$$c_{21} = c_{12} = c_{34} = c_{43} \qquad (11)$$

$$c_{32} = c_{13} = c_{24} = c_{42} \qquad (12)$$

$$c_{41} = c_{14} = c_{32} = c_{23} \qquad (13)$$

The THRU standard must be designed such that it has a very little mode conversion from a differential propagation to common mode propagation and vise versa. The best accuracy is achieved when the THRU standard circuit and the embedded DUT between the input/output fixture have exactly the same footprint, material content and assembly procedure. It is critical that both the THRU standard as well as the embedded DUT utilize the same dielectric constant, connector type and all other parts that make up their final construction.

The measured S-parameters of C matrix is transformed into Mixed-Mode S-parameters (MMSP) [1]-[3]. The 2-by-2 differential mode quadrant of MMSP described by C_{dd} is symmetrical as well as reciprocal. Or,

$$C_{dd11} = C_{dd22} \qquad (14)$$

$$C_{dd21} = C_{dd12} \qquad (15)$$

The C_{dd21} frequency domain transmission coefficient is converted to a corresponding time domain impulse transmission response [4]. The peak value of impulse transmission response provides the total electrical length of the THRU circuit in the differential mode. This delay corresponds to the combined delays of the first and the second halves of the fixture. Exactly half of the delay belongs to the first fixture because Xmi matrix is the mirror image of X matrix. The C_{dd11} frequency domain reflection coefficient is converted to a corresponding time domain impulse reflection response. Then time domain impulse reflection response is gated by the half of electrical length determined by time domain impulse transmission response as described before. The modified time domain impulse reflection response is then transformed back into frequency domain. The transformed frequency domain response is the X_{dd11} of the X matrix. X_{dd11} is the forward reflection coefficient of the input fixture. The remaining X_{dd} parameters of the input fixture are given by

$$X_{dd22} = \frac{C_{dd11} - X_{dd11}}{C_{dd21}} \qquad (16)$$

$$X_{dd21} = X_{dd12} = \sqrt{C_{dd21} - \frac{\left(X_{dd11} - C_{dd11}\right)^2}{C_{dd21}}} \qquad (17)$$

X_{dd21} has two solutions; the correct solution is the one where phase approaches zero degrees at DC.

The calculations of the input fixture for X_{cc} is determined by the same procedure as described for X_{dd}, and the X_{dc} and X_{cd} quadrants are set to zero. The 4-by-4 input fixture MMSP can be constructed from X_{dd}, X_{dc}, X_{cd} and X_{cc}. Let's define as the MMSP of the input fixture X. Then X can be calculated from

$$X = M^{-1} X_{mm} M \qquad (18)$$

where, matrix M is given by

$$M = \begin{bmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \qquad (19)$$

and, M^{-1} is the inverse of matrix M. Once the input fixture S-

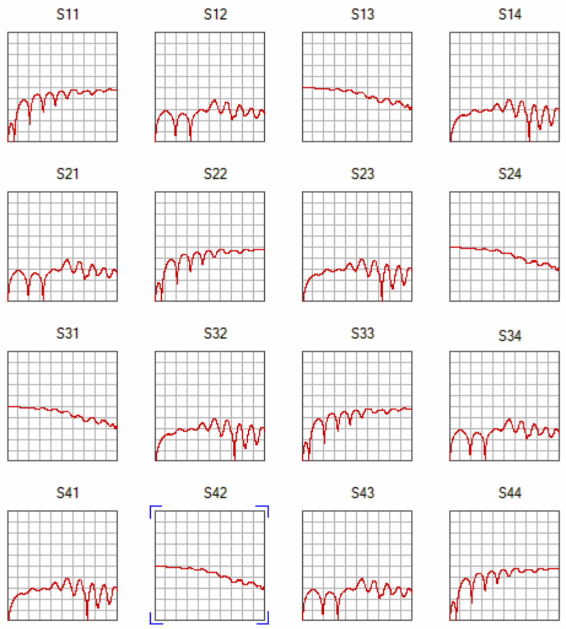

Figure 3: Single-ended S-parameters of measured differential THRU standard.

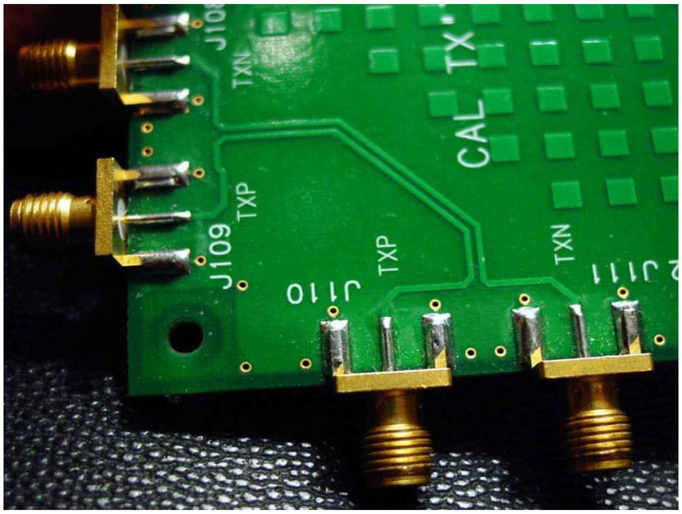

Figure 4: A photograph of the actual differential THRU standard

parameters, X, is calculated then the output fixture X_{mi} is determined from equation 1. Referring to Figure 1, the DUT S-parameters can be calculated by de-embedding the input and output fixture S-parameters from the overall cascaded measurement.

III. VALIDATION PROCEDURE

Figure 3 shows the measured S-parameters of an input/output test fixture THRU standard measured from 10 MHz to 13 GHz in 10 MHz steps. A photograph of the actual cascaded THRU structure is shown in Figure 4. This is matrix C as presented by equations 9-13. The input fixture S-parameters defined by X matrix is calculated from the THRU measurement as described above. The output fixture is calculated from the input fixture S-parameters using equation 1. The input and output fixture are then cascaded so the results can be compared with the direct THRU measurement for the purpose of validating the data. Figure 5 shows an overlay of two representative S–parameters (S11 and S42) in magnitude and phase to show the quality of the agreement between the actual measured fixture and the mathematically cascaded data on the individual fixture halves. Agreement of the other parameters is equally good. The excellent agreement validates the approach to accurately characterizing a differential test fixture so that its effects can be removed from a device measurement.

IV. CONCLUSIONS

There are several challenges associated with accurately measuring high-speed differential devices. Among these are that non-coaxial calibration standards are not sufficiently precise, calibration techniques are commonly misapplied, and direct test fixture measurement is very difficult. This paper has illustrated a method of removing the effects of test fixtures in a way that is accurate, relatively simple to perform, and employs a minimal number of assumptions. Some of this work is protected by patent pending status.

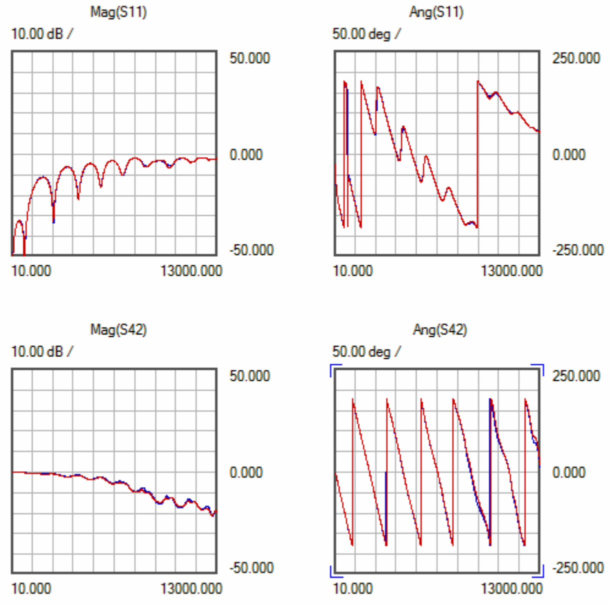

Figure 5: Comparison of measured S-parameter magnitude (Blue) with the mathematically cascaded input & output fixtures (Red). Two (of sixteen) representative parameters are shown (S11 and S42) in both magnitude and phase.

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