

RESEARCH ARTICLE

Using a 2x-thru standard to achieve accurate de-embedding of measurements

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Abstract

The broadband measurement of interconnects and on-board devices requires the usage of test fixtures in order to connect to the measurement instrumentation. Proper assessment of the device performance requires removal of the effects of these test fixtures which is done using a de-embedding procedure. Previous de-embedding procedures such as Thru-Reflect-Line (TRL), Line-Reflect-Match (LRM) and other similar methods require the measurement of multiple standards. Alternatively, some methods such as thru de-embedding techniques require measurement of one standard with explicit computation of only two or three of the four error terms. This is justified by using the sometimes questionable assumption of fixture reciprocity. Prior art also does not include derivation of all of the required equations. Proposed and explained in detail here is the usage of a 2x-thru standard which is manipulated to derive complete fixture models without making assumptions about reciprocity or symmetry. Subsequently these models are mathematically removed from the indirect measurement, thus isolating the performance of the DUT. In contrast to prior art, this method uses only one standard instead of three, and it computes all four terms to make a complete fixture model. Several test cases are presented which illustrate the accuracy and validity of the 2x-thru method for broadband applications.

KEYWORDS

2x-thru, broadband, de-embedding, test fixtures, TRL

1 | INTRODUCTION

In the development and validation of high frequency devices, simulations are first performed to design a product so that it meets a given specification, and then measurements are performed to validate the performance of the prototyped or manufactured product. The simulations have reference planes at the beginning and end of the device which may include transitional features. Transitional features are signal-carrying conductors that transition from one medium to another. When the transitional medium is coaxial, direct measurements validate performance. A direct measurement is one where the calibrated reference planes of the test equipment are the same or very similar to the simulated reference planes. When the transitional medium is non-coaxial, (eg, microstrip printed circuit board [PCB] traces), the measurement is indirect. For an indirect measurement, the device under test (DUT) is mounted to a test fixture that has access to the component by means of a coaxial connector attached to some transitional medium.

Indirect measurements, which are those that include test fixtures, are not valuable by themselves because the test fixtures add additional losses and reflections which cloud the performance of the DUT. Hence, indirect measurements cannot be used to validate the DUT performance until after the effects of the test fixture is removed by using a process called de-embedding. De-embedding mathematically removes the behavior of the fixture and shifts the reference planes to the same location as the simulated DUT.

The mathematical method and the core problem of fixture de-embedding were recognized in Reference 1 which explained an early version of Short-Open-Load (SOL) calibration that the paper referred to as “unterminating.” The method involved making three one-port measurements of the fixture. Each individual measurement was made with a different known termination impedance. Having the reflection coefficient of each measurement and knowing the three termination impedances enabled computation of the fixture Z-parameters. Converting these Z-parameters to ABCD parameters created a fixture model that, when multiplied with the similar parameters from the indirect measurement, yielded the parameters of the DUT. This was the first attempt to characterize the fixture by creating a fixture model. Continuing the practice of computing a fixture model and removing it from an indirect measurement via ABCD parameters, the work of Reference 2 extended the technology to the measurement of 2-port devices. It recognized that the DUT could be replaced by a uniform transmission line,

and the fixture model could be solved by using two measured transmission lines of different known lengths. It recognized that large errors would occur when the difference in phase between the two transmission lines was near 180° . This was an early acknowledgement of the limitations of TRL de-embedding which is discussed below. In Reference 3, the uniform transmission line length that replaced the DUT in Reference 2 was reduced to zero. In Reference 3, time-domain gating removed the reflections of the connectors from the measured 2-port standard measurement thus simplifying both the fixture model and the original indirect measurement to only transmission terms. This practice reduced the number of standards to one, and this was the first reference to what is now ubiquitously called the “2x-Thru” standard method. The signal flow graph of the 2x-thru used to calculate the fixture model S -matrix and the method of de-embedding coupled transmission lines were both introduced in Reference 4. However, errors were introduced by assuming equivalent forward and reverse reflection terms. Subsequent literature provided equations for the reverse reflection term, S_{22} .⁵⁻⁷ However, assumptions left the theory incomplete, and adequate validation has not yet been shown. Moreover, deviation from ideal results was provided in References 5-7 which emphasized the need to complete the theory. This is where the documented prior art ended.

A complete the survey of de-embedding prior art must include Thru-Reflect-Line (TRL). TRL is a widely-known method available for test fixture de-embedding.⁸⁻¹⁰ It uses a measurement of a 2x-thru standard as defined in Reference 3, a line standard as defined in Reference 2, and a reflection standard, (ie, a transmission line of equal length as the fixture ending with an open or short) as defined in Reference 1, to create the fixture model. The TRL fixture model bandwidth is valid at frequencies where the extra phase of transmission line in the line standard is between 0° and 180° . However in practice, the valid phase is typically between 20° and 160° . Often, full characterization requires extra line standards to cover all required frequencies, and a load standard is used to calculate the lowest frequencies.¹¹ Extra lines from TRL use more PCB real estate and require more measurements than the methods of References 1-4. However, the relevance of TRL is reliant on its unique ability to solve at discrete frequencies and up to this point, solve the reverse reflection term, S_{22} , in the fixture model.

At the time of writing of this paper, several commercial tools exist which enable de-embedding after the measurement of one standard which is typically a 2x-thru. These tools use algorithms which are proprietary and hence, have not been published or reviewed by independent researchers. For academic purposes, the validity and accuracy of these tools cannot be evaluated, but they do provide a de-embedding solution which is similar to what is being described here.

In this paper, a 2x-thru is the standard. The 2x-thru is a transmission line attached to coaxial connectors, and it has the same cross-sectional geometry as the test fixture transmission line and is twice as long as the test fixture transitional medium. The 2x-thru is manipulated to derive complete fixture models, and these fixture models are simply removed from the indirect measurement to isolate the DUT. The prior art made assumptions where only three of the four terms in the fixture model were solved. Here, all four are solved. Again contrasting TRL, this method uses one standard instead of three and acquires the fixture models over the entire measurement bandwidth. Thus, the presented method is superior to TRL in broadband applications.

2 | METHODOLOGY

At a high level, Figure 1A illustrates the de-embedding challenge for a two-port setup. Specifically, the challenge is estimating the DUT performance from the indirect measurement of the test fixture plus DUT. In subsequent discussions, the indirect measurement of the structure in Figure 1A provides the contents of the matrix labeled as $FDUTF$.

The 2x-thru methodology is based on measuring both sides of the test fixture together as shown in Figure 1B.

In order to obtain the DUT S -parameters, the fixture model is removed from the indirect measurement using

$$DUT = [F_A^{-1}] [FDUTF] [F_B] \quad (1)$$

where,

F_A is the ABCD parameters of the fixture model connected to port one,

F_B is the ABCD parameters of the fixture model connected to port two,

$FDUTF$ is the ABCD parameters of the DUT mounted to a fixture or set of fixtures in the case where a separable connector is the DUT, and DUT is the ABCD parameters of the isolated DUT.

Note that for accurate de-embedding, the relationship in Equation (2) must be satisfied¹²:

$$Z_{\text{port-two}}^{\text{Fixture A}} = Z_{\text{port-one}}^{\text{Fixture B}*} \quad (2)$$

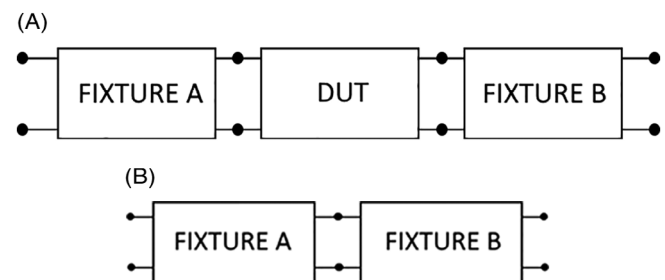


FIGURE 1 A, De-embedding challenge for a two-port system and B, the 2x-thru measurement setup

where,

$Z_{\text{port-two}}^{\text{Fixture A}}$ is the reference impedance for port two of fixture A, and $Z_{\text{port-one}}^{\text{Fixture B}*}$ is the complex conjugate of the reference impedance of port one of fixture B. This requirement was also recognized in Reference 7.

In most cases, the reference impedance is a real quantity, and thus the complex conjugate operation is ignored.

Fixture models are calculated from 2x-thru S -parameters and take the form of Equations (3)-(6).

$$S_{11} = e_{00}^1 + \frac{(e_{10}^1)^2 e_{11}^2}{1 - e_{11}^1 e_{11}^2} \quad (3)$$

$$S_{22} = e_{00}^2 + \frac{(e_{10}^2)^2 e_{11}^1}{1 - e_{11}^1 e_{11}^2} \quad (4)$$

$$S_{21} = \frac{e_{10}^1 e_{10}^2}{1 - e_{11}^1 e_{11}^2} \quad (5)$$

$$S_{12} = \frac{e_{10}^1 e_{10}^2}{1 - e_{11}^1 e_{11}^2} \quad (6)$$

These equations are the result of solving the signal flow graph for the 2x-thru in Figure 2 assuming that e_{10}^1 and e_{01}^1 are equivalent and that e_{10}^2 and e_{01}^2 are equivalent.

Ideally, e_{10}^1 and e_{01}^1 are identical. However, there are time-domain artifacts in e_{10}^1 and e_{01}^1 which are most predominantly observed in S_{21} , and S_{12} , respectively. Therefore, e_{10}^1 can replace e_{01}^1 in Equation (5), and e_{10}^2 can replace e_{01}^2 in Equation (6), resulting in

$$S_{21} = \frac{(e_{10}^1)^2}{1 - e_{11}^1 e_{11}^2} \quad (7)$$

$$S_{12} = \frac{(e_{10}^2)^2}{1 - e_{11}^1 e_{11}^2} \quad (8)$$

There are four equations and six unknowns. The amount of unknowns must be reduced to three in order to solve the error models.

Variables e_{00}^1 and e_{00}^2 are found from the time-domain information of S_{11} and S_{22} using the following procedure:

1. Determine the middle time of the 2x-thru.

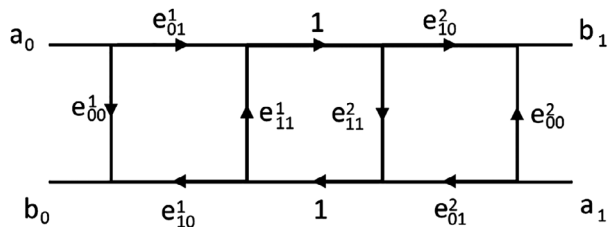


FIGURE 2 Signal flow graph of a 2x-thru

2. Extract the impedance of the 2x-thru at the middle using the TDR or S_{11} .
3. Renormalize the 2x-thru from the reference impedance of the S -parameters to the measured impedance of the transmission line from step 2 (2x-thru) to satisfy Equation (2).
4. Extrapolate the DC point of S_{11} .
5. Convert the half-spectrum domain data into full frequency domain data by enforcing symmetry.
6. Convert the symmetric information to the time domain.
7. Shift the time-domain data right by n points (where n = number of frequency points of S_{11}).
8. Make all discrete points of the resultant time-domain data zero from the middle point to the end.
9. Shift the time-domain data left by n points.
10. Convert the time-domain data to frequency domain.
11. Discard all content at negative frequencies.
12. Repeat steps 2 through 11 for S_{22} .

This leaves four equations and four unknowns remaining. Typically for high-frequency broadband testing, test boards and calibration structures are made of low-loss materials such as Megtron 6. Such materials are designed to be very isotropic in order to avoid excess loss and dispersion. Hence, the 2x-thru is assumed to be reciprocal, and e_{10}^1 and e_{10}^2 can be assumed to be equal. This assumption reduces the number of unknowns to three. The reciprocity does not, however, extend to the reflection terms S_{11} and S_{22} , (which can differ due to imperfections and asymmetry), despite their having been considered equal in prior art de-embedding methods. The remaining unknowns are determined by using the following equations:

$$e_{11}^1 = \frac{S_{11} - e_{00}^1}{S_{21}} \quad (9)$$

$$e_{11}^2 = \frac{S_{22} - e_{00}^2}{S_{12}} \quad (10)$$

$$(e_{10}^1)^2 = S_{21} (1 - e_{11}^1 e_{11}^2) \quad (11)$$

$$(e_{10}^2)^2 = S_{12} (1 - e_{11}^1 e_{11}^2) \quad (12)$$

The real and imaginary parts of e_{10} behave like decaying sine waves. By examining the real and imaginary parts of e_{10} calculated from Equation (6), a periodic discontinuity is observed. This discontinuity is shown in Figure 3 (solid lines), and it happens when the phase of e_{10} transitions from a negative to a positive number as shown in Figure 4. Note the solution of e_{10} in Equation (6) requires a square-root, and the correct solution requires choosing the proper sign in Equations (13) and (14):

$$e_{10}^1 = k^* \sqrt{S_{21} (1 - (e_{11}^1)^2)} \quad (13)$$

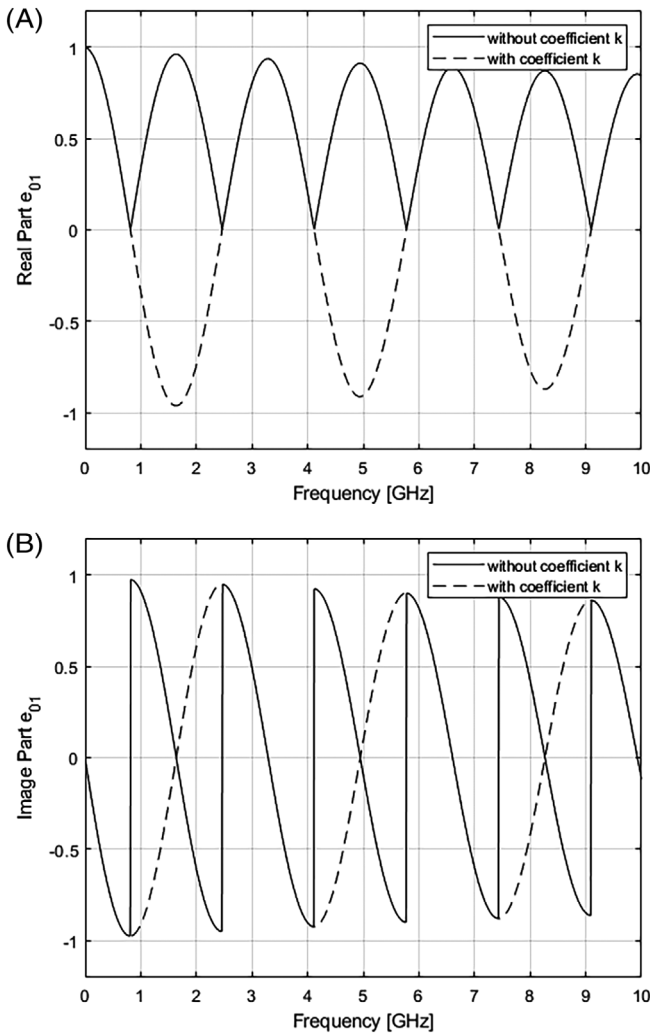


FIGURE 3 A, Real part of e_{10} and B, imaginary part of e_{10} before and after applying Equation (7)

$$e_{10}^2 = k * \sqrt{S_{12} \left(1 - (e_{11})^2 \right)} \quad (14)$$

where

$$k = \begin{cases} 1 & \text{for even number of phase transitions} \\ -1 & \text{for odd number of phase transitions} \end{cases}$$

The proper sign choice removes the observed discontinuities as demonstrated in Figure 3A,B (dashed lines).

At this point e_{00} , e_{11} , and e_{10} are known, and the fixture model is defined as

$$F_A = \begin{bmatrix} e_{00}^1 & e_{10}^1 \\ e_{10}^1 & e_{11}^1 \end{bmatrix} \quad (15)$$

where F_A is the S -parameter matrix of fixture model A.

If the DUT test fixture is symmetric, then fixture model B is defined as

$$F_B = \begin{bmatrix} e_{00}^2 & e_{10}^2 \\ e_{10}^2 & e_{11}^2 \end{bmatrix} \quad (16)$$

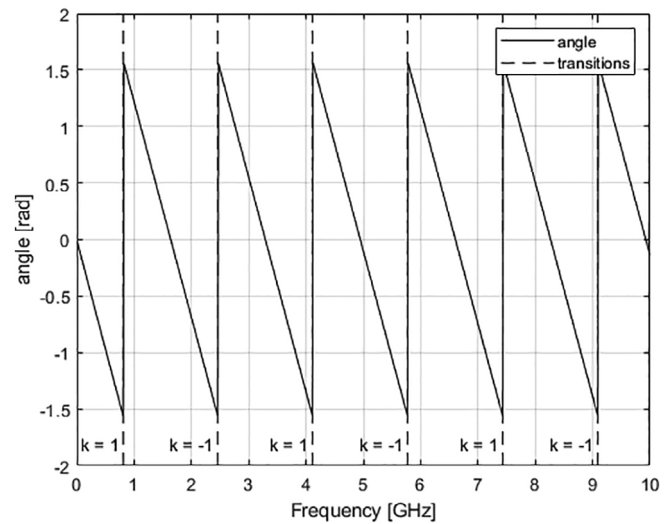


FIGURE 4 Illustration of phase changes of e_{10} and the value of k

where F_B is the S -parameter matrix of fixture model B.

The DUT is de-embedded by applying Equation (1) with F_A and F_B .

Because other methods of de-embedding such as TRL have been used with success for many years, they have a well-established user base, and any new de-embedding method should naturally be approached with skepticism until it has proven to be correct. The following section validates the new method, (and also the theory behind it), with two test cases.

3 | VALIDATION

The 2x-thru method of de-embedding was validated using both simulation and measurement as described below.

3.1 | Simulation

For validation, the de-embedding methodology is easily applied to a simulated model of a simple analytical transmission line. Later in the paper, the same procedure is performed on a measured transmission line. The simulated transmission line under test is a symmetric stripline trace of length 18 cm as modeled with the procedure described in Reference 13. The S -parameters of this transmission line are shown in Figure 5. Although all four S -parameters are plotted, S_{11} and S_{22} lie directly on top of each other as do S_{12} and S_{21} . This is a result of the perfect symmetry of the model.

To determine how well the extracted transmission line matches the reference device, two consistency tests are performed:

1. De-embedding the fixture models from the fixture. The resulting residual S -parameters will be a perfect zero-

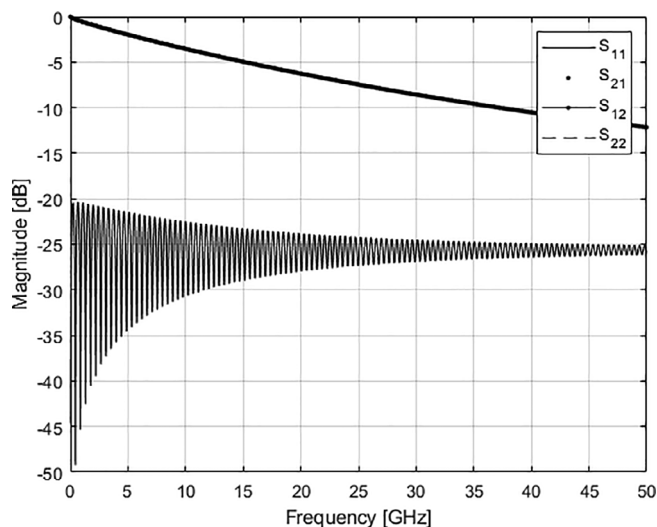


FIGURE 5 Signal flow graph of a 2x-thru

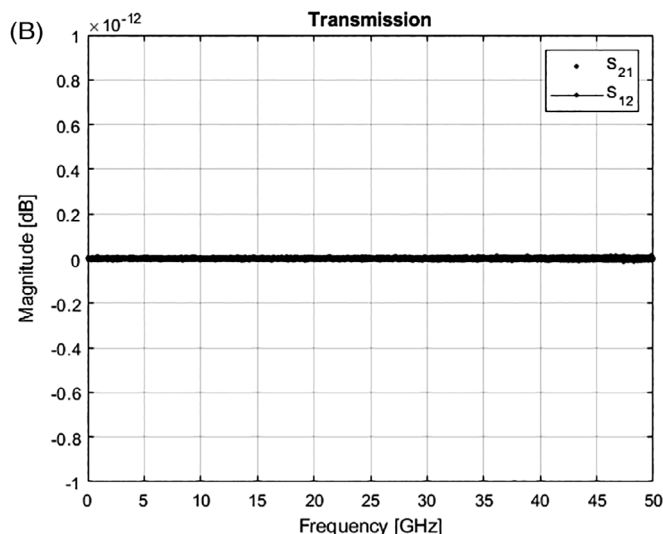
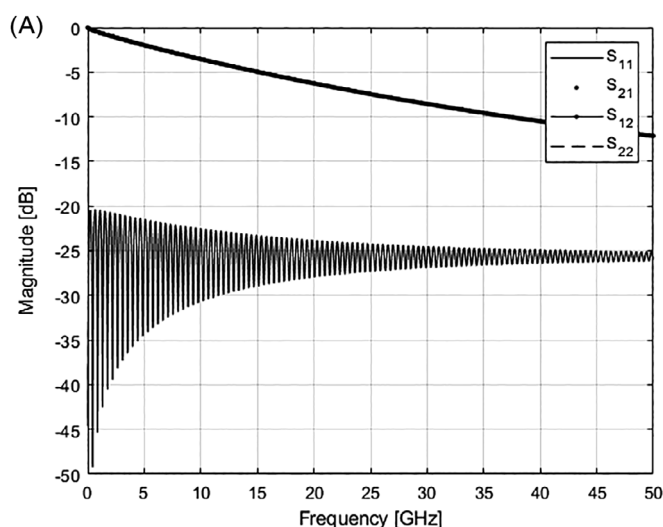


FIGURE 6 Plots of (A) the transmission and (B) the reflection residuals

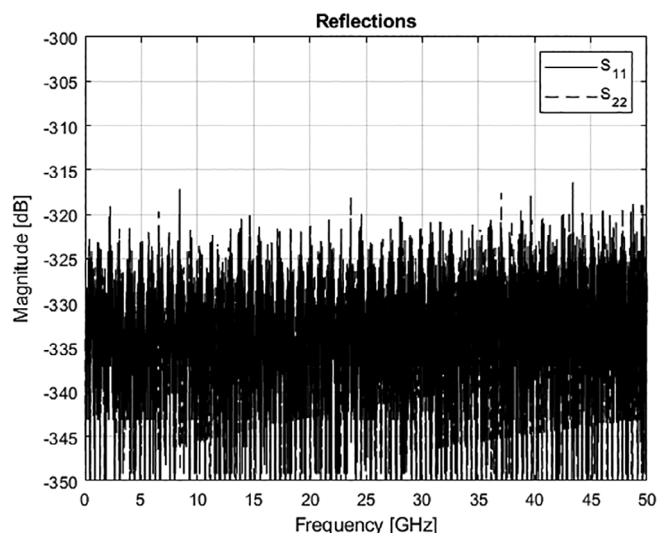


FIGURE 7 Plot of the phase after de-embedding the fixture from itself. As expected, there is no phase shift across frequency

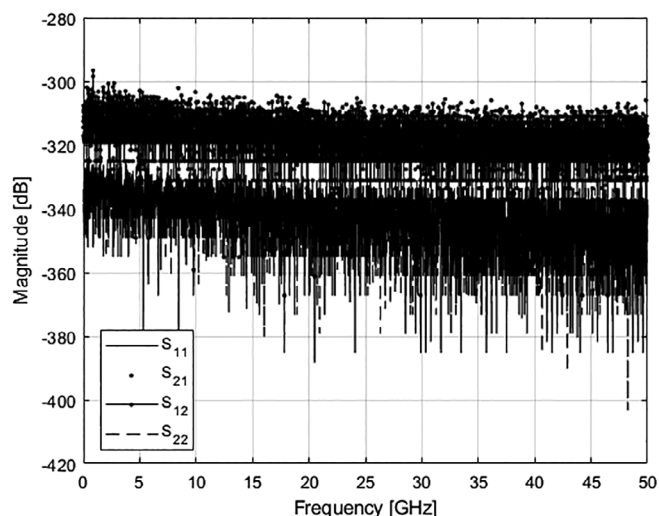


FIGURE 8 Plot showing the difference in dB between the original and the reconstructed complex S -parameters of the fixture. The result is effectively zero thus completing the validation with simulation that the de-embedding procedure works properly

loss, zero-phase, and zero-reflection matrix if the methodology is working properly.

2. Cascading the fixture models to recreate the original fixture. The differences between the original and reconstructed complex fixture S -parameters are observed. The result will be zero if the method is working.

The S -parameters are compared using a technique detailed in Reference 14. All the residual S -parameters are shown in Figure 6. Figure 6A shows the transmission residual, and Figure 6B shows the reflection residual.

These results are consistent with perfect transmission and perfect reflection. The phase is plotted in Figure 7. Again, this shows perfect transmission with a zero phase shift over the entire frequency spectrum.

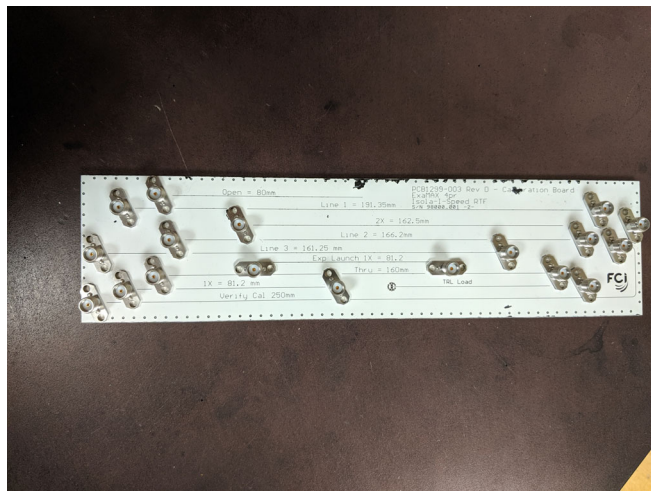


FIGURE 9 Photograph of a calibration PCB that includes the specific stripline trace of length 81.2 mm that was measured for the purpose of validating the new de-embedding methodology [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/mop.32098)]

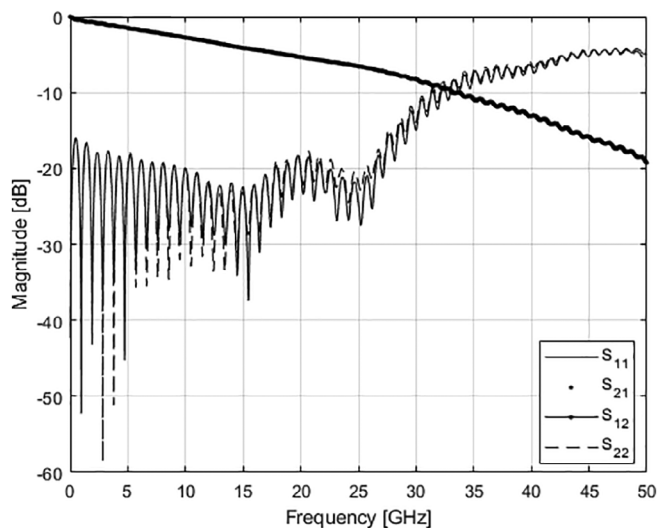


FIGURE 10 Measured insertion and return loss for a stripline trace of length 81.2 mm

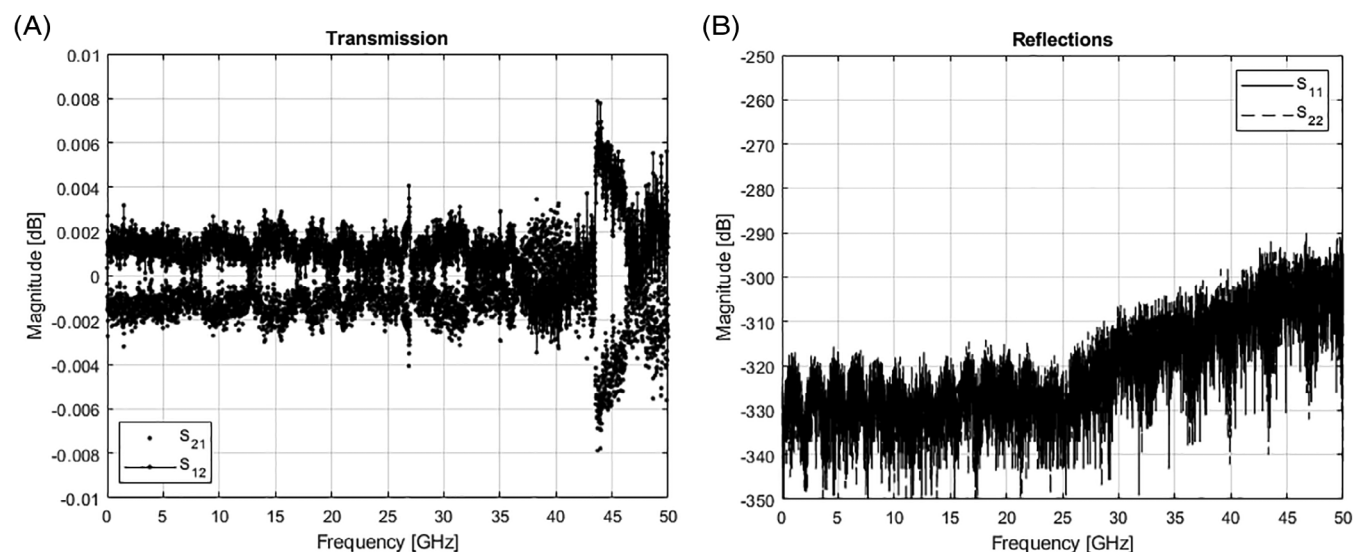


FIGURE 11 Plots of (A) residual insertion loss and (B) residual return loss. Both are almost zero

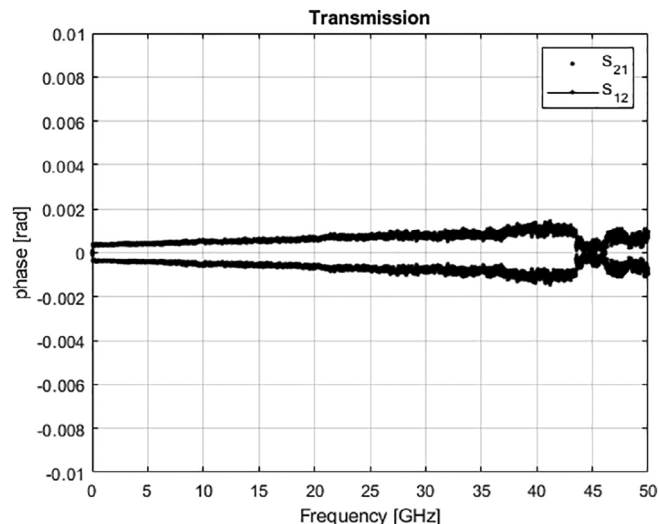


FIGURE 12 Plot of the phase of the residual data, and as before, there is practically zero phase shift over the entire frequency range

Next, the fixture models are cascaded, and the difference between the original and recreated complex S -parameters are plotted in decibels in Figure 8. This takes both the magnitude and the phase into account. Therefore, the difference is clearly practically zero.

These results show the methodology working well with a simulated transmission line. Thus, the confidence in the methodology is high. In the next section, the same experiment is performed on a measured transmission line.

3.2 | Measurement

The procedure described in the Methodology section was applied to a measured stripline trace of length 81.2 mm. The transmission line was attached to coaxial connectors at each end so that it could be measured with a VNA. Figure 9 is a photograph of the test board that includes the test trace.

Figure 10 shows the measured S -parameters of the test trace transmission line.

Slight asymmetry was observed between S_{11} and S_{22} which corroborated the idea of treating these terms as unique entities rather than equals as has been assumed in prior art. The separate treatment of these terms was central to the theory behind Equations (9) through (12).

The fixture models are removed from the measurement of the stripline trace, and the resulting residual S -parameters are plotted in Figure 11.

The residual transmission and reflection magnitudes exhibit practically zero-loss and zero-reflection. The phase is plotted below in Figure 12, and again there is practically zero-phase shift exhibited over the entire frequency range thus further signifying that the structure has been successfully de-embedded.

Next, the fixture, (ie, 2x-thru), is reconstructed by cascading the fixture models, and the differences between the reconstructed and the original measured S -parameters are plotted in Figure 13. In agreement with the results of the previous consistency test,

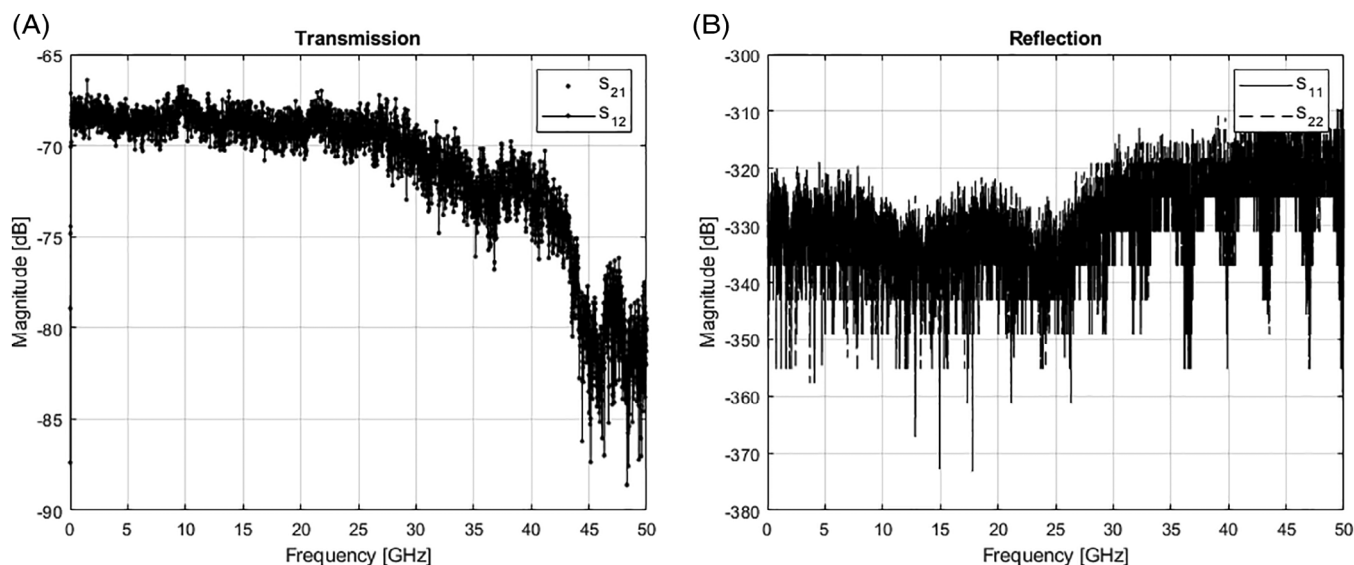


FIGURE 13 Plots of the differences between the original and reconstructed (A) insertion loss and (B) return loss

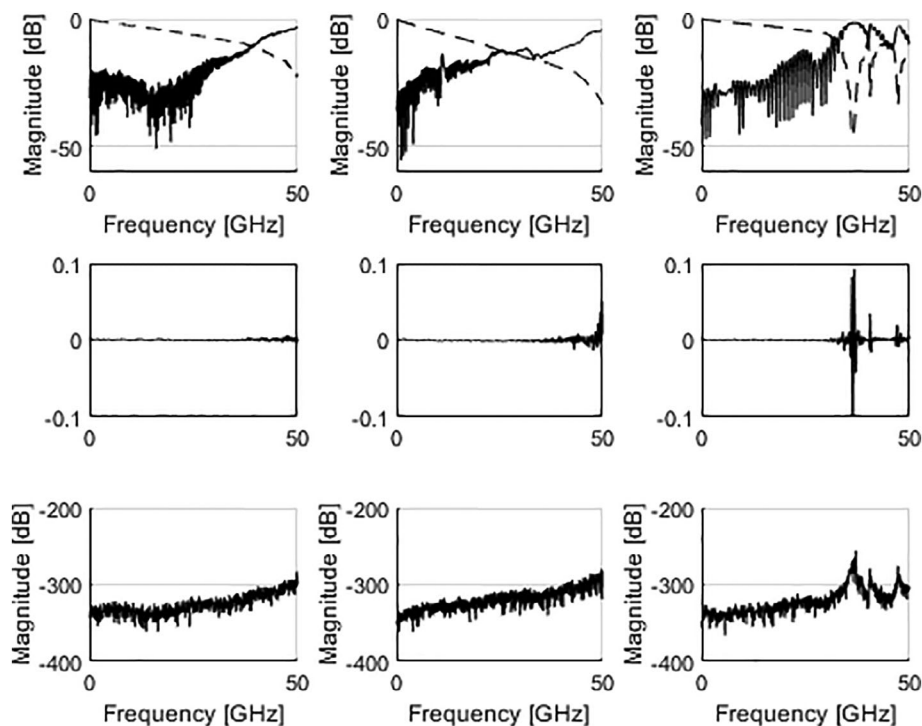


FIGURE 14 Shown here are measurements taken of the three additional 2x-thru standards. Plots of the insertion loss and return loss are in the first row. The second row shows the residual insertion loss after de-embedding, and the third row shows the residual return loss

the residual data is very close to zero for both quantities thus demonstrating very effective removal of the structure.

To further test the method, three additional 2x-thru standards were measured and de-embedded from themselves yielding similarly low values for the residuals. Figure 14 shows the results for these additional tests. The first row of plots shows the insertion and return losses of each of the three fixtures. The second row shows the residual insertion loss after de-embedding, and the third row shows the residual return loss.

Interestingly, for each of the fixture measurements shown in Figure 14, the residual values increase at the same frequencies at which the insertion loss and return loss fail.

The residual results from each of the measurements are farther from zero than they are for the simulated results. However, as with any measurement, calibration error and measurement noise are to be expected. Hence, these results are considered sufficiently low to give high confidence to the methodology.

4 | CONCLUSION

This paper presented a detailed methodology for de-embedding a test fixture using a 2x-thru standard. To extend prior art, it included a complete exposition of the necessary equations as well as their derivations. The method completely defined the center of the test fixture by explicitly determining all of the S -parameters rather than relying on the sometimes dubious assumption of fixture symmetry and reciprocity. Additionally, it was shown how the correct assignment of the sign to the real and imaginary parts of the transmission parameter, e_{10} , removed the discontinuities that occurred when the phase transitioned from negative to positive. Following all of these steps and equations made it possible to create a very accurate model of the test fixture which could be removed from the indirect measurement, thus yielding very accurate S -parameters characterizing the DUT.

To demonstrate the efficacy of the proposed de-embedding procedure, the method was tested by using it to remove both a simulated and several measured 2x-thru standards from themselves. In each case, the residual Insertion and Return Losses were either zero or extremely close to zero. This was even true for the measurement data which included additional complicating factors such as measurement noise. The low residuals in each of the tests showed that the method is accurate across the entire available bandwidth.

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