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## Summary

This application note outlines the process for using the WavePulser 2X Thru feature to extract high-quality 2-port and 4-port S-parameters for de-embedding electrical interconnects. It explains the assumptions made by the underlying algorithms, as well as how to connect to the WavePulser and define the inputs for 2X Thru measurements, the expected outputs, and how those outputs are used in the de-embedding process.

## Introduction

The fixture de-embedding controls in the WavePulser 40iX are designed to remove fixture effects from the signal path using customer-supplied S-parameter files, which can be measured and stored directly on the instrument.

In certain cases, it may not be feasible to measure the S-parameters of the Device Under Test (DUT) directly—typically due to connector incompatibility between the DUT and the WavePulser interface. In such cases, 2X Thru structures may be used.

For example, when testing a USB cable, direct connection to the WavePulser is not possible. Two custom fixtures are required:

- The first fixture uses a K-type connector on one end and a PCB trace terminating in a male USB connector.
- The second fixture includes a female USB connector with a PCB trace ending in a K-type connector.

These fixtures allow the USB cable to be connected at both ends, while the K-type connectors interface with the WavePulser. When the two fixtures are connected back-to-back—K-type to K-type and USB to USB—this configuration is referred to as a **2X Thru structure or fixture**.

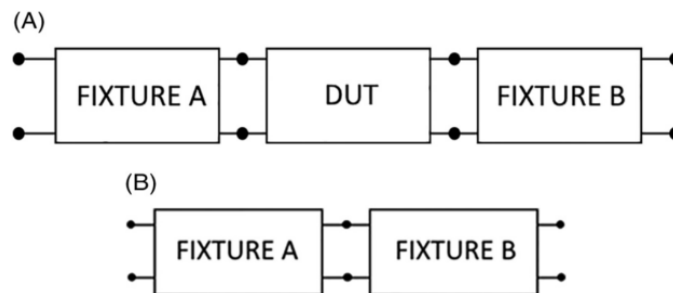


Figure 1: Typical measurement setup vs. 2X Thru structure

In Figure 1 above:

- **Configuration (A)** represents a measurement setup that includes the Device Under Test (DUT) connected through custom fixtures. This is how DUT measurements are typically made.
- **Configuration (B), the 2X Thru structure**, depicts the back-to-back fixture configuration used to characterize fixture behavior independently of the DUT.

## Types of 2X Thru De-embedding

The WavePulser **2X Thru De-embedding** feature uses the S-parameter measurement of a 2X Thru structure to compute the S-parameters of each half of the fixture. These "split" S-parameters are then applied to the de-embedding interface to isolate and remove fixture effects, enabling accurate characterization of the DUT (in the example above, the USB cable).

This application note will outline how to use the WavePulser to perform traditional 2X Thru De-embedding of 2-port and 4-port structures. The WavePulser also offers two other 2X Thru de-embedding methods which will be treated in other application notes.

In scenarios where the back-to-back fixture design described above is not possible, an alternative approach is to leave one end of the fixture open and measure it as a 1X Open. The **1X Short/Open De-embedding** method utilizes the measurement of an open structure to determine key gating parameters such as length and loss. These parameters are then used to de-embed the fixture via the WavePulser Gating feature.

The **2X Thru with Gating** (impedance corrected) method represents an advanced enhancement of the basic 2X Thru de-embedding technique. This approach incorporates impedance profile measurements used to calculate gating parameters that refine the accuracy of fixture removal. Leveraging the Time Domain Reflectometry (TDR) technology of the WavePulser, this method enables highly precise impedance characterization. As a result, the de-embedding algorithms deliver significantly improved performance and reliability, particularly in complex signal environments.

## 2X Thru De-Embedding Assumptions

The 2X Thru de-embedding feature operates by analyzing the measured S-parameters of a 2X Thru structure and mathematically dividing the structure into two symmetrical halves. When these halves are cascaded (using other S-parameter software), they should reproduce the original measured S-parameters of the complete structure.

Depending on the nature of the Device Under Test (DUT), the fixture may be configured as:

- A **2-port device** for single-ended traces
- A **4-port device** for differential traces

This method relies on several key assumptions:

- **Structural Consistency:** The 2X Thru configuration must reflect the same signal path characteristics as the actual test setup, excluding the DUT.
- **Reciprocity:** Each fixture half is assumed to be reciprocal, exhibiting identical loss characteristics and physical length. In other words,  $S_{21}$  equals  $S_{12}$  for each fixture, and both halves are considered equivalent. It is assumed that the left half of the 2X Thru structure has the same characteristics as the signal path leading up to the DUT, and the right half of the 2X Thru structure has the same characteristics as the path from the DUT to the connectors.
- **No Mode Conversion:** For differential traces, it is assumed that the fixtures do not introduce mode conversion between differential and common modes.

These assumptions are critical to ensuring accurate de-embedding and reliable extraction of the DUT's true S-parameters.

## 2X Thru De-embedding Procedure for 2-port Fixtures

This approach is specifically applicable to single-ended measurements, where the signal path is defined by a single-ended trace.

Figure 2 shows the WavePulser 2X Thru user interface (UI) for making 2-port measurements:

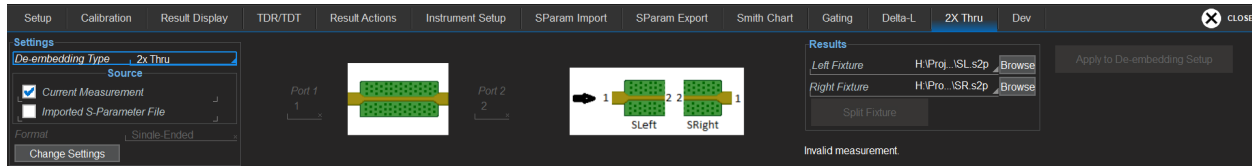


Figure 2: WavePulser 2X Thru dialog, the UI for 2X Thru de-embedding

### Connecting to WavePulser for 2-Port 2X Thru Measurements

The WavePulser 2X Thru de-embedding feature assumes that in the normal DUT+Fixture configuration for a 2-port measurement, there are two, 2-port fixtures, one connected to each side of the DUT. Port 1 of each fixture is connected to a WavePulser port and Port 2 of each fixture is connected to the DUT (Figure 1A). To create the 2X Thru structure, remove the DUT and connect the fixtures to each other (Figure 1B).

On the WavePulser Main Setup dialog, make all the usual settings required for a 2-port measurement, except for the De-embedding selection, which you do not need to make at this time.

### Input Settings

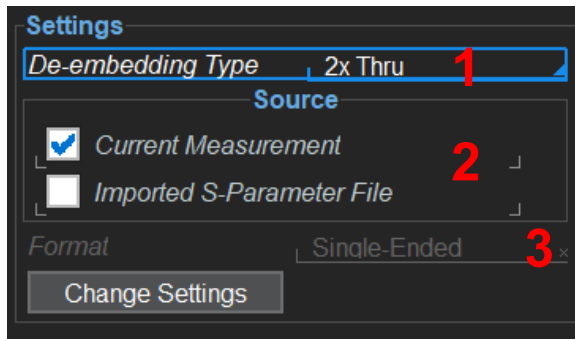


Figure 3: Input section of 2X Thru dialog

On the WavePulser 2X Thru dialog, the first selection is the **De-embedding Type (1)** (described on p.1), in this case **2X Thru**.

The **Source (2)** for the 2X Thru measurement can be either the **Current Measurement** (most recent measurement in the WavePulser buffer) or else an **Imported S-parameter File**. Use Current Measurement when you have the structure connected to the WavePulser and are ready to measure S-parameters or have just done so. In case you have the S-parameters (either from a simulation

or older measurement), you can import the S-parameter file into the WavePulser software and use that as the Source. The WavePulser will calculate the S-parameters for each half of the structure and split the file into the two halves for use in future de-embedding.

If the Source is an imported file, the software should be able to determine whether the **Format (3)** (here shown grayed out) is single-ended or mixed mode, provided the file was measured on a WavePulser, which stores that information with the S-parameters. If the S-parameters were measured using a different method, the Format field will be activated and you must provide the format. In the case of a WavePulser "Current Measurement", the Format field is always grayed out because this information is known.

### Port Configuration and S-parameter Format

When performing 2X Thru de-embedding of 2-port structures, the input format must be single-ended. This implies that the structure is configured as single transmission line connecting the input and output ports. The objective of 2X Thru de-embedding is to extract the S-parameters of each half of the structure.

The block diagrams used on the 2X Thru dialog illustrate the fundamental concepts of 2X Thru de-embedding, highlighting the configuration and signal flow used to isolate fixture characteristics and enable accurate de-embedding of the DUT.

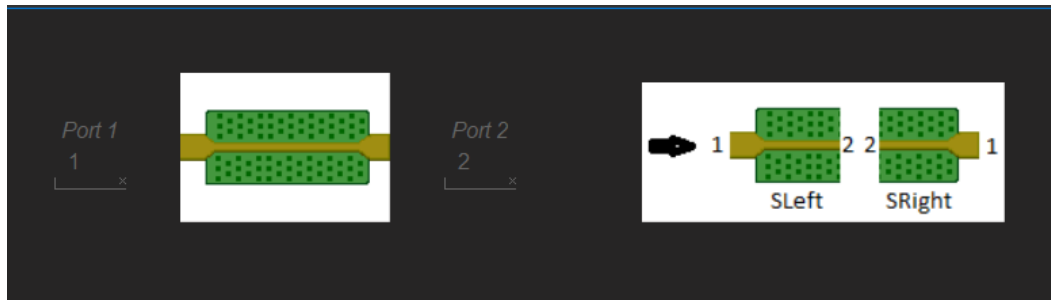


Figure 4: Block diagrams of generic 2-port fixture (left) and 2X Thru structure (right)

The schematic on the left of Figure 4 shows the input, in this case, a 2-port measurement. The right shows the 2X Thru output—the two halves (SLeft and SRight) that are computed from the 2-port measurement. The port numbering for both the input and output portions are fixed and cannot be changed. The assumption is that both halves will be removed from the DUT+Fixture measurement.

SLeft and SRight are the S-parameters of the left and the right halves of the complete 2X Thru structure. The original DUT+Fixture is a measured or simulated .s2p file that is comprised of the DUT connected to the WavePulser via the two fixtures. What the de-embedding algorithm needs to figure out are the unknown, DUT-only S-parameters. Everything else is known—either as a measurement or an estimate made by the 2X Thru algorithm.

### Output Results

The third portion of the 2X Thru dialog is related to the SLeft and SRight outputs:

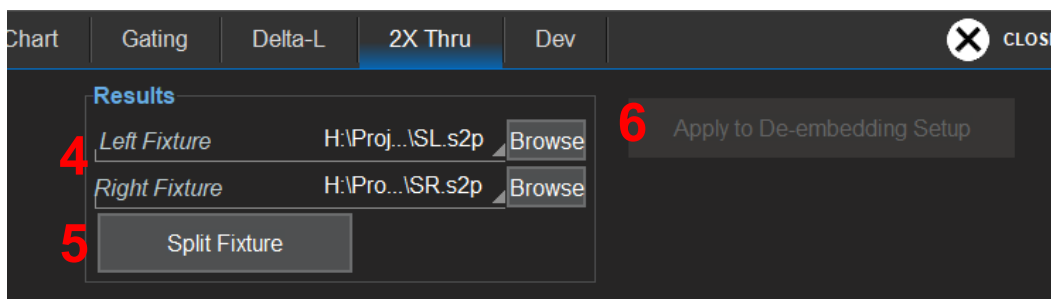


Figure 5: Output section of 2X Thru dialog

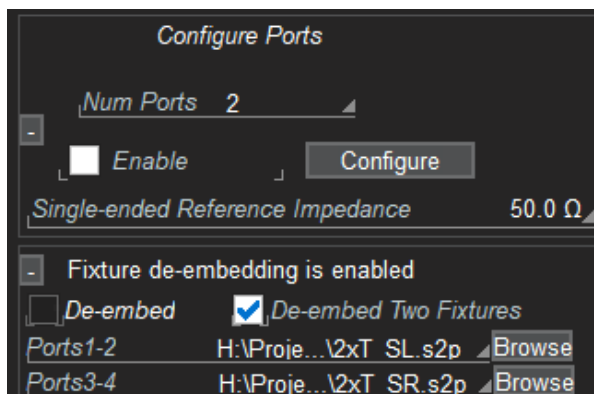


Figure 6: De-embedding setup on Main Setup dialog

**Left Fixture** and **Right Fixture (4)** allow you to set the paths to the resulting SLeft and SRight S-parameter files. When you click **Split Fixture (5)**, the software takes the selected input and creates the two files. Once you split the fixture, the **Apply to De-embedding Setup (6)** button is ungrayed. When you click it, the de-embedding section of the WavePulser Main Setup dialog is modified to reflect that two-fixture de-embedding is enabled with the specified files (Figure 6). The next DUT+Fixture measurement will be calculated using the new de-embedding setup.

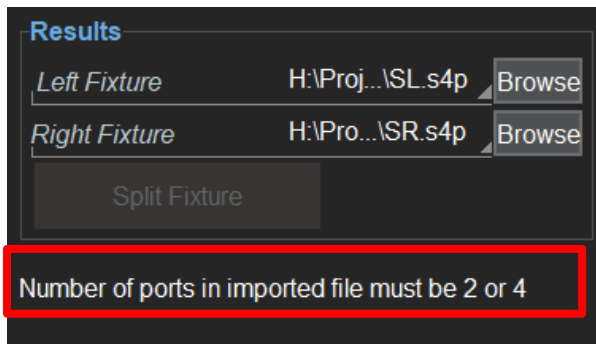


Figure 7: Status message on 2X Thru dialog

There is an area below the Split Fixture button that displays a status message when the two, half-fixture files are created or when the setup is not valid. For example, in Figure 7, the Source was an imported .s1p file. Since this file cannot be used to describe a 2-port fixture, the software displays the error message shown.

### Verifying 2-Port 2X Thru S-parameters

When SLeft and SRight are de-embedded from the 2X Thru structure measurement, you should be left with an Ideal Thru, as shown in Figure 8.

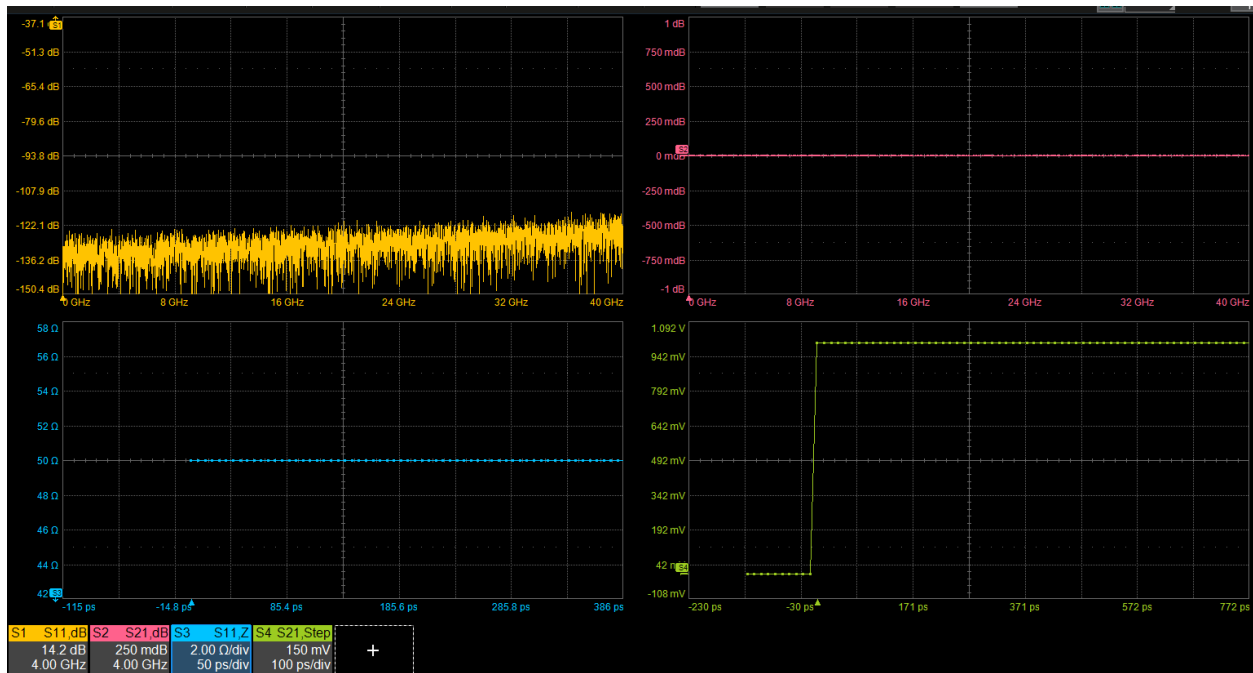


Figure 8: 2X Thru files de-embedded from 2X Thru structure measurement result in an Ideal Thru

### 2X Thru De-embedding Procedure for 4-port Fixtures

The general procedure for splitting 4-port measurements is largely the same as for 2-port measurements, except that when the input is a 4-port measurement, the Source S-parameter **Format** can be either **Single-Ended** or **Mixed Mode**. If single-ended, the WavePulser converts the S-parameters to mixed mode internally. For it to do so, you must supply the correct thru paths. Figure 9 shows the 2X Thru dialog schematic for 4-port S-parameters:



Figure 9: 2X Thru dialog schematic for 4-port S-parameters

### Port Mapping for 4-Port Measurements

The software assumes that the thru paths are Port 1 to Port 3 and Port 2 to Port 4, as shown on the schematic. If your fixtures are configured differently, you can use the **Port** fields on the 2X Thru dialog to specify which two ports make a thru path—or which two ports form the differential input, and which two ports form the differential output. In Figure 9, Port 1 and Port 2 are the differential input pair (with 1 being + and 2 being -), while Port 3 and Port 4 are the differential output pair (with 3 being + and 4 being -).

Internally, the algorithm converts the single-ended S-parameters into mixed mode S-parameters and works with the 2-port differential S-parameters and 2-port common mode S-parameters separately. It splits the differential S-parameters into two halves and the common mode S-parameters into two halves. Mode conversion, if any, is ignored. The two left halves (from differential and common mode) are then combined to make a single-ended fixture as shown in Figure 10:

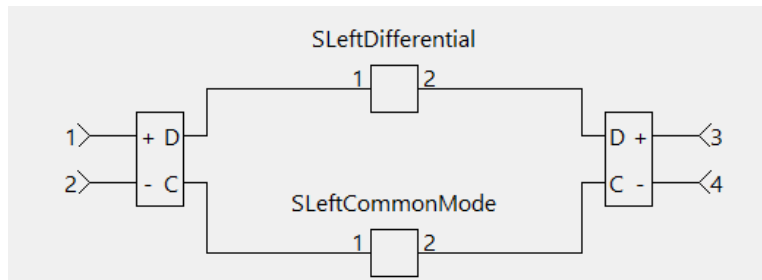


Figure 10: 4-port conversion to mixed mode S-parameters

Similarly, a single-ended fixture is created from the right-half differential and common mode measurements.

### Connecting to WavePulser for 4-port Measurements

Note that you cannot choose the port numbering of the resulting output files. This means that when measuring DUT+Fixture, Ports 1 and 2 of the fixture on the left must be connected to WavePulser Ports 1 and 2, while Ports 1 and 2 of the fixture on the right must be connected to WavePulser Ports 3 and 4. Ports 3 and 4 of both fixtures connect to the DUT.

### Verifying 4-port 2X Thru S-parameters

By design, the two halves are equal to the complete 2X Thru structure, so when you de-embed the two halves from the structure measurement, you should be left with an Ideal Thru. This was indeed shown to be the case with the single-ended, 2-port measurement (Figure 8).

For 4-port measurements, depending on the design of the fixtures, you might see some difference from an Ideal Thru. The main cause would be mode conversion. Since our algorithm ignores mode conversion,

when you de-embed the halves created by the 2X Thru algorithm, you will be left with some residual. Figure 11 shows a 2X Thru structure measurement in mixed mode:

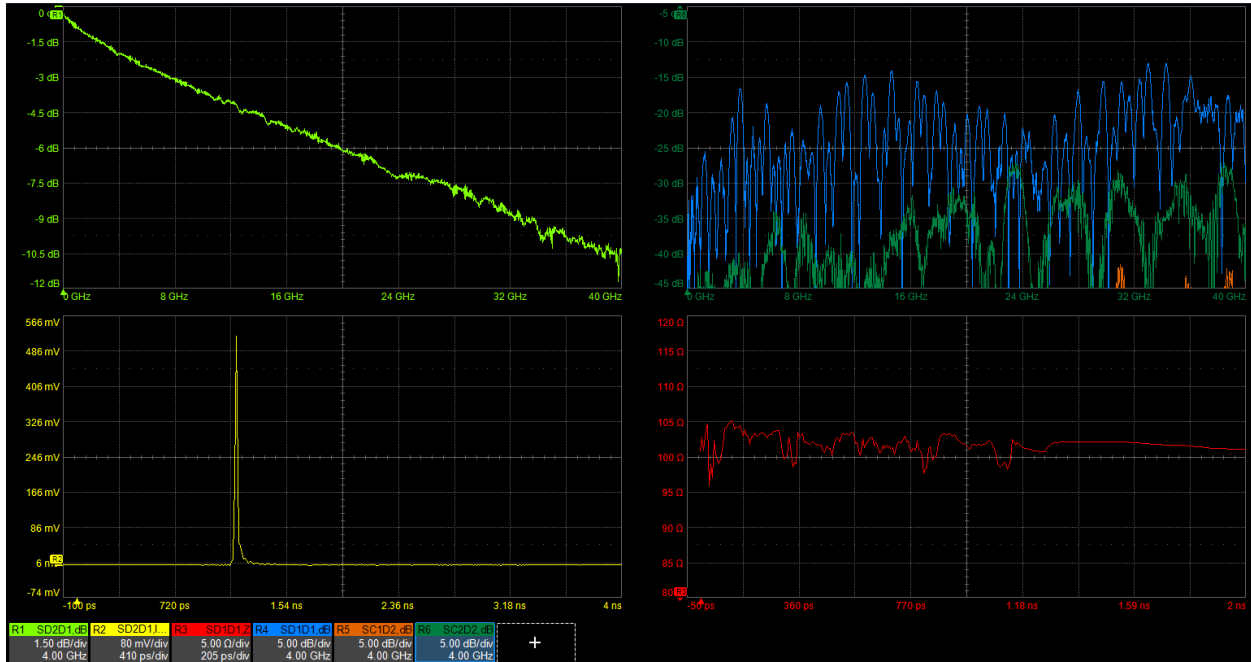


Figure 11: Mixed mode 4-port S-parameters

SC1D2 is quite small (orange plot) but SC2D2 does come up after 25 GHz. After splitting the S-parameters and de-embedding the two halves, the residual in mixed mode is shown in Figure 12:

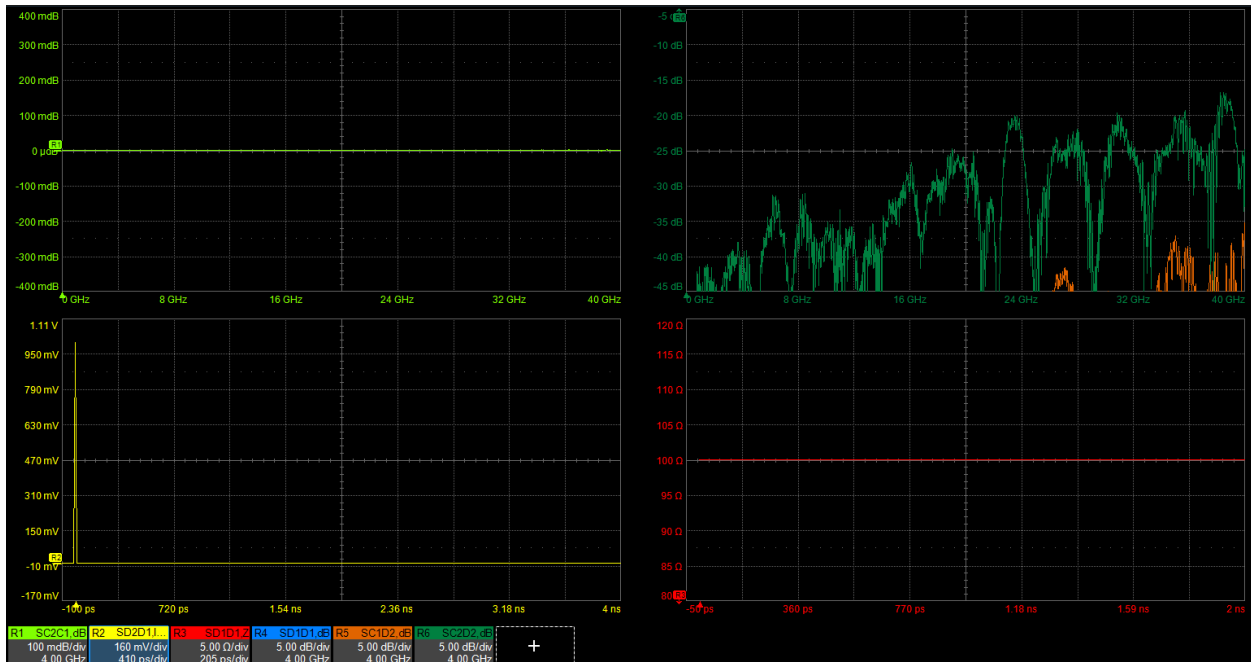


Figure 12: Residual on mixed mode S-parameters

As can be seen, the differential S-parameters are that of an Ideal Thru. However, the SC2D2 mode conversion has increased after de-embedding due to the incorrect assumption of zero mode conversion.

Figure 13 and Figure 14 show a DUT+Fixture measurement of a 4-port differential trace with a stub in the middle. When comparing the de-embedded result to a direct measurement of the DUT, the differential and common mode S-parameters show a good match:

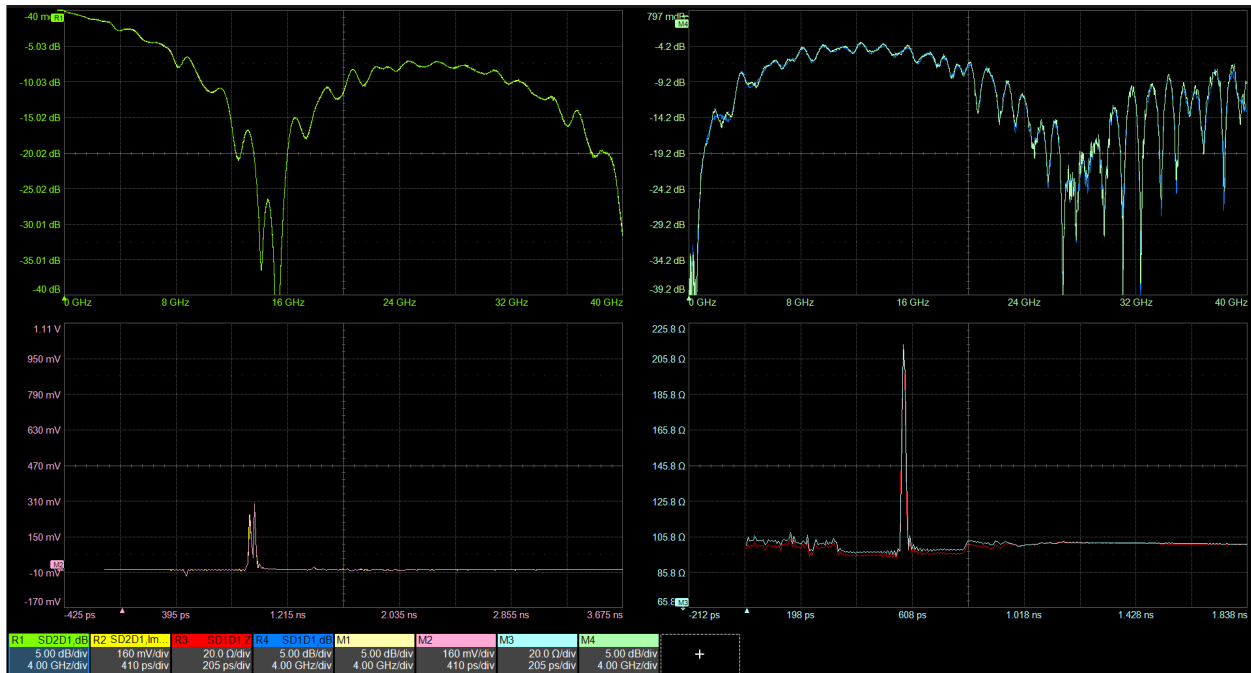


Figure 13: De-embedded differential S-parameters compared to DUT

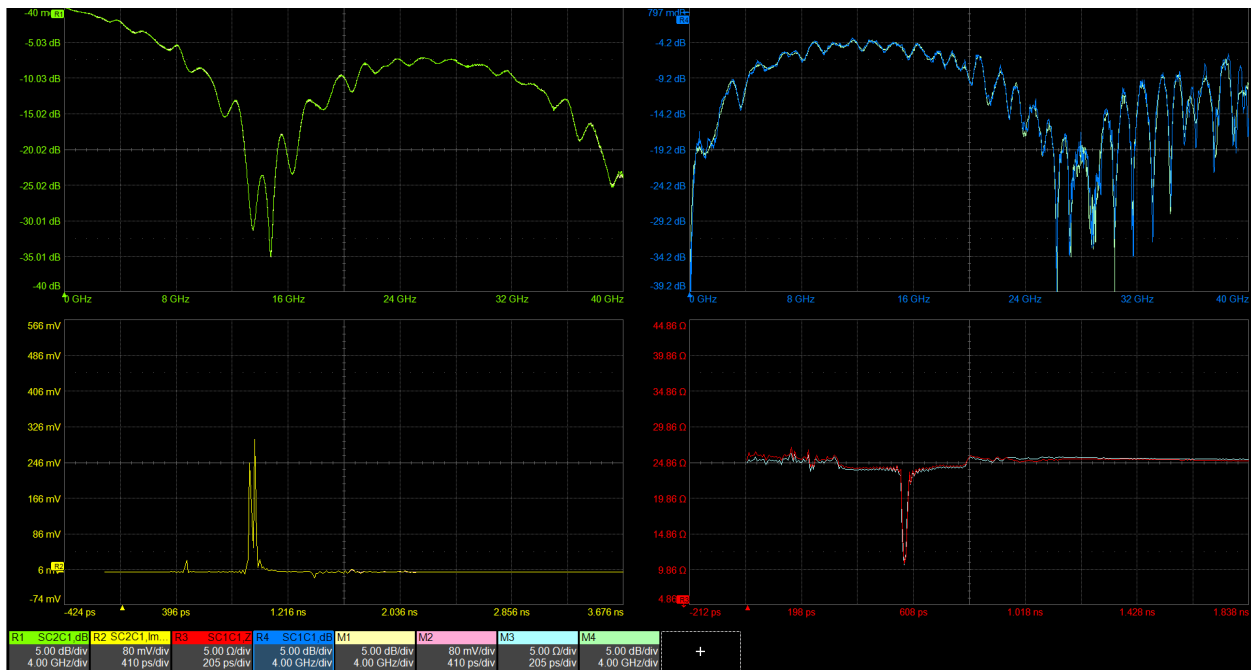


Figure 14: De-embedded common mode S-parameters compared to DUT

The mode conversion S-parameters are shown in Figure 15. SC1D2 is a good match given that the DUT is more than 35 dB down. SC2D2 shows some discrepancy beyond 16 GHz but that should not be much of a concern given that it is 25 dB down.

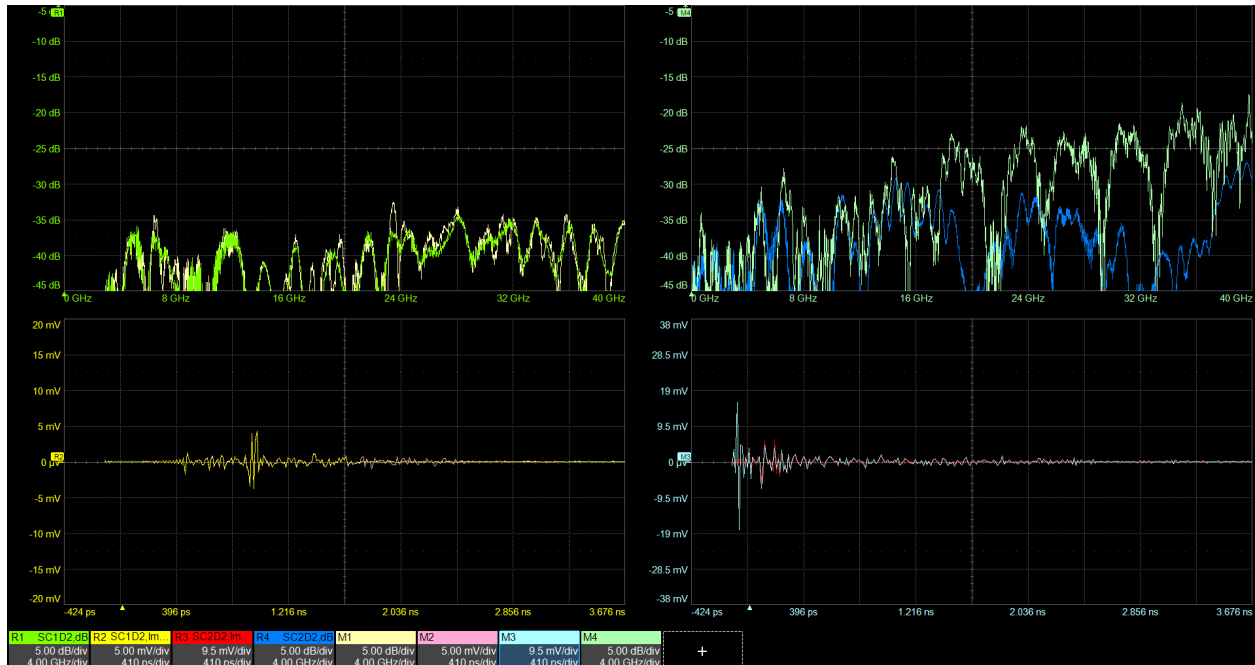


Figure 15: De-embedded mode conversion S-parameters compared to DUT

### Use Case: Creating and Verifying 2-port 2X Thru S-Parameters

Figure 16 shows a method for 2X Thru de-embedding algorithm verification described in IEEE Standard 370 (Standards Development Committee of the IEEE Electromagnetic Compatibility Society, 2021).

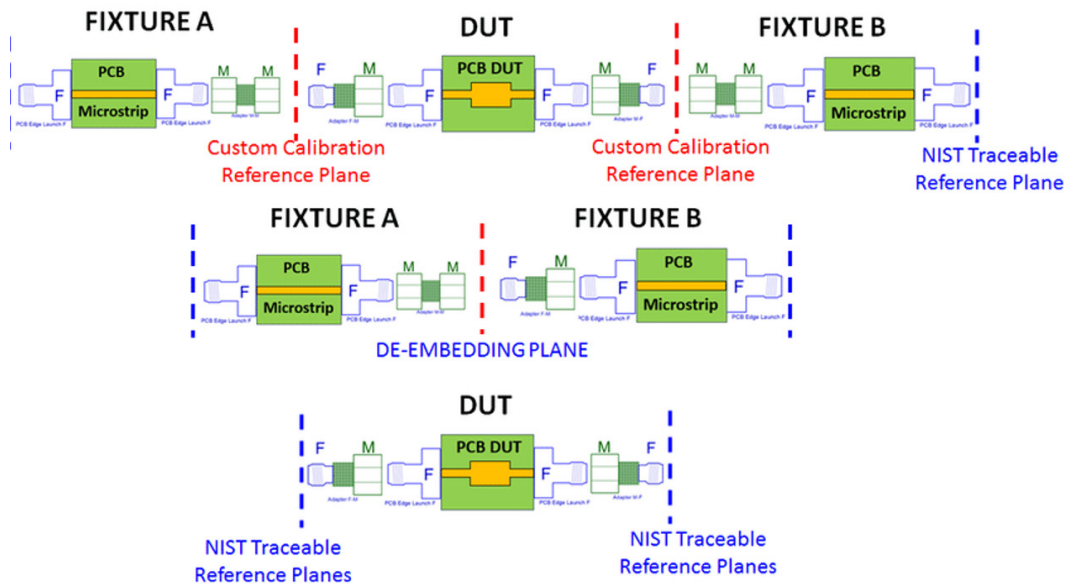


Figure 16: De-embedding algorithm verification concept for a 2X Thru de-embedding approach

The method involves the successive measurement and comparison of the structures represented by each row of the diagram: DUT+Fixture (top), 2X Thru structure (middle) and DUT only (bottom).

To apply this method, you would measure the structures using the procedure on p.3, then use the WavePulser Result Display to compare the results and assess their accuracy:

1. Connect Fixture A (with M-M connector) to Fixture B (with F-M connector) to create the 2X Thru structure (middle row of Figure 16).
2. Connect the WavePulser to the two open ports of the 2X Thru structure and measure the S-parameters. This is now the "current measurement".
3. On the WavePulser 2X Thru dialog, select De-embedding Type 2X Thru and Source Current Measurement, then Split Fixture.
4. Apply to De-embedding Setup the resulting Left Fixture and Right Fixture .s2p files.

You should get an Ideal Thru, as shown in Figure 8.

5. With the 2X Thru de-embedding setup applied, measure the DUT+Fixture shown in the top row of Figure 16.

Note that the connector on the Fixture B side is changed to M-M connector type. The assumption here is that one can change the connector without affecting the S-parameters of Fixture B.

Since 2X Thru de-embedding was turned on, the measurement made in Step 5 should give the de-embedded DUT.

6. Save the de-embedded DUT+Fixture result as an S-parameter file.
7. Connect the DUT directly to the WavePulser and measure the DUT S-parameters.
8. Import the de-embedded DUT+Fixture measurement from Step 5 and compare it to the direct DUT measurement from Step 7. They should be reasonably matched, as in Figure 18.

The S-parameters of a 2X Thru structure are shown in Figure 17. The loss (amber S1) is around 12 dB at 40 GHz, which is a bit excessive, but in this case, we had connected two, lossy fixtures to generate the 2X Thru structure. The impedance profile (blue S3) shows the two regions clearly. The structure is about 1.1 ns in length and as can be seen from the impedance profile, it's not symmetric (i.e., you cannot expect the left half to be exactly the same as the right half). The software splitting algorithm uses the S11 measurement to generate the left half and the S22 measurement to generate the right half, so there is no expectation that the two will be exactly the same. The loss, however, is attributed equally to both.

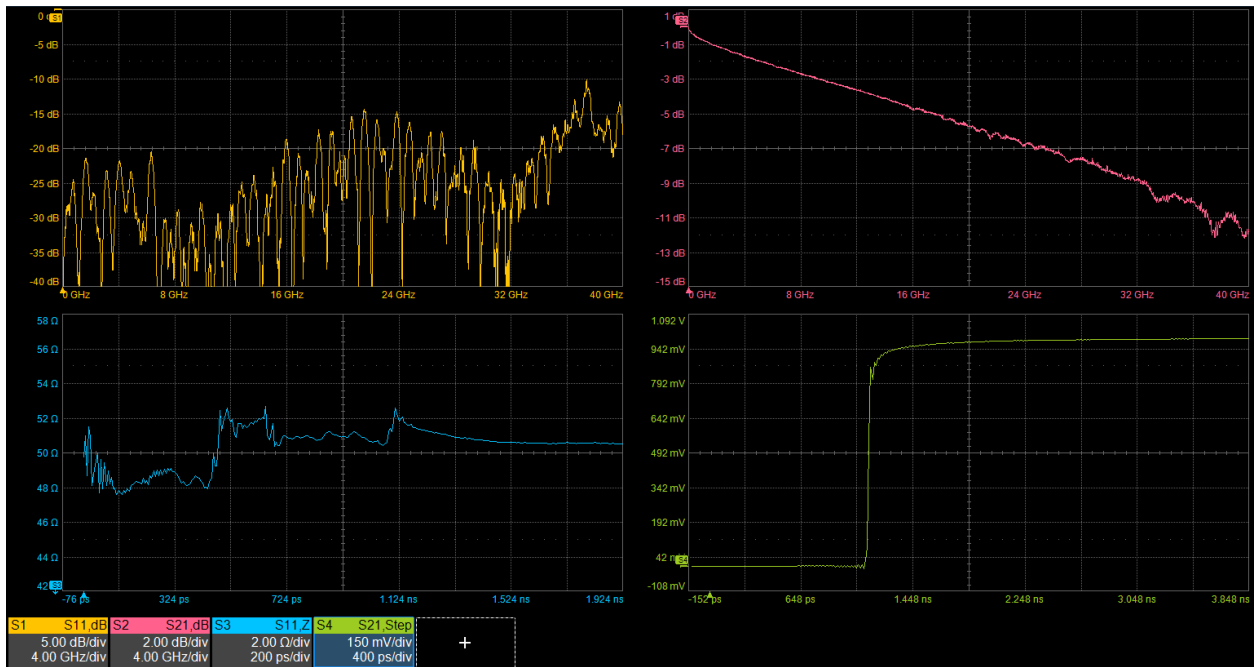


Figure 17: 2-port 2X Thru structure S-parameters

Figure 18 shows the de-embedded DUT measurements compared to the direct DUT measurements. The S-traces are those of the de-embedded DUT, and the R-traces are those of the direct DUT measurement.

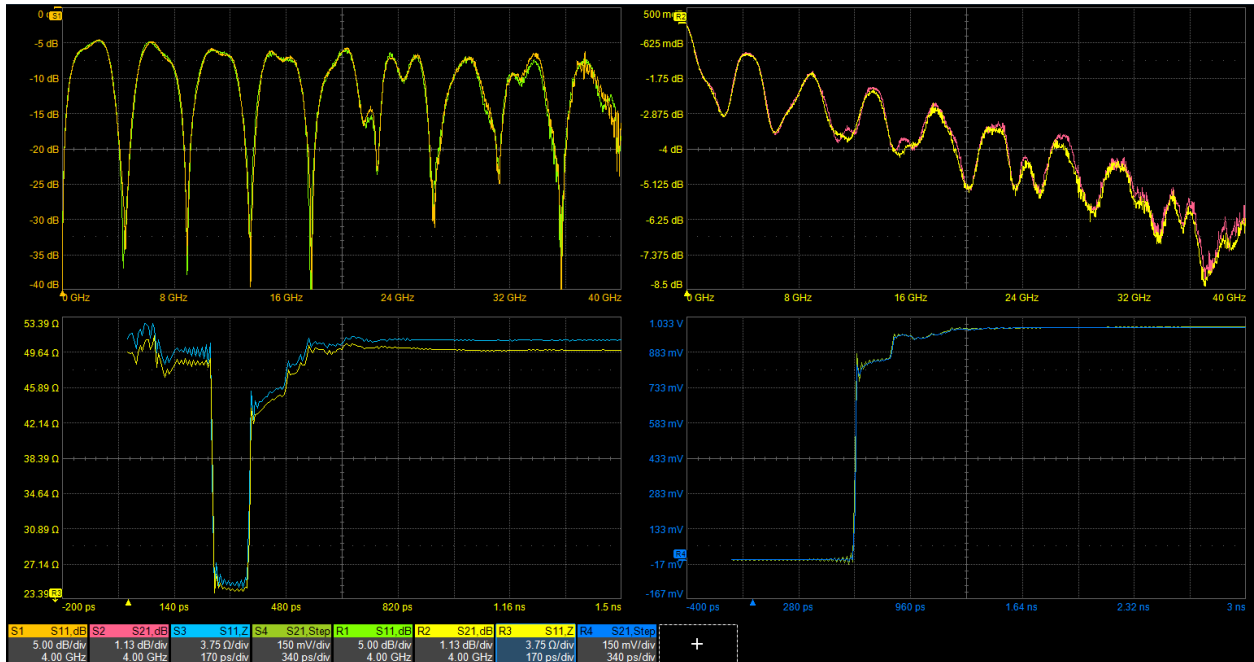


Figure 18: De-embedded DUT vs. expected DUT

## Recommendations for Making 2X Thru Measurements

- The 2X Thru structure is a passive, reciprocal and causal device. Therefore, choose to Enforce Passivity, Enforce Reciprocity and Enforce Causality on the WavePulser Main Setup dialog when setting up the structure measurement.
- For 4-port fixtures, mode conversion is ignored. Designing fixtures that meet this criterion will help with accuracy.

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