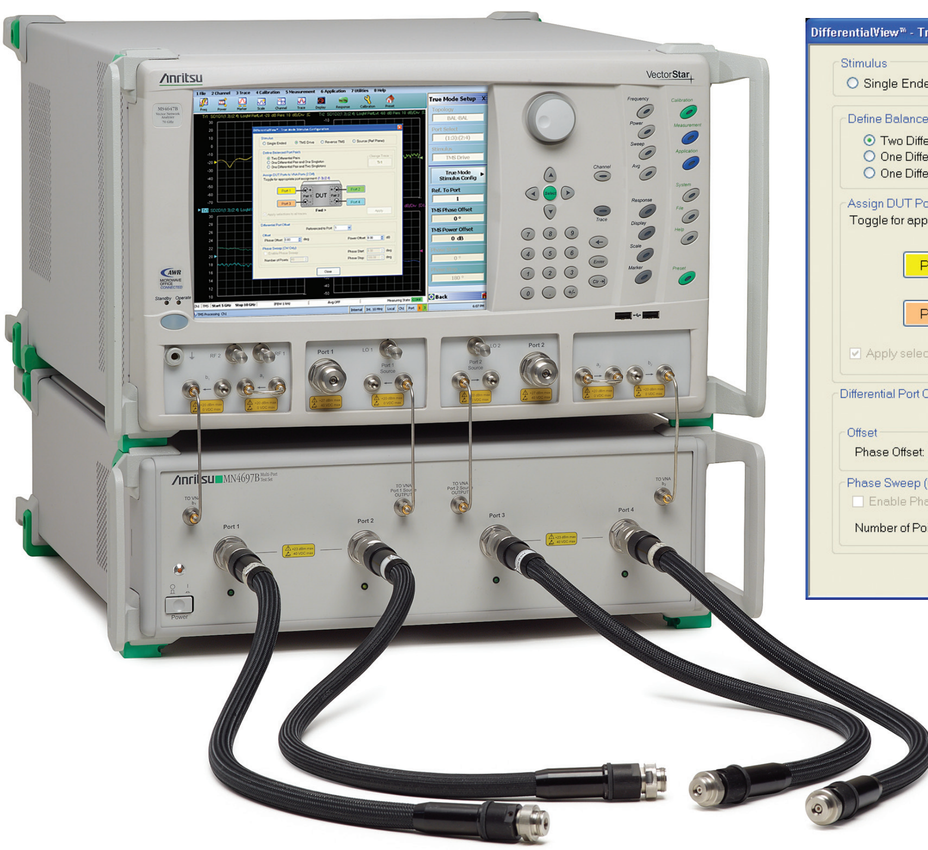
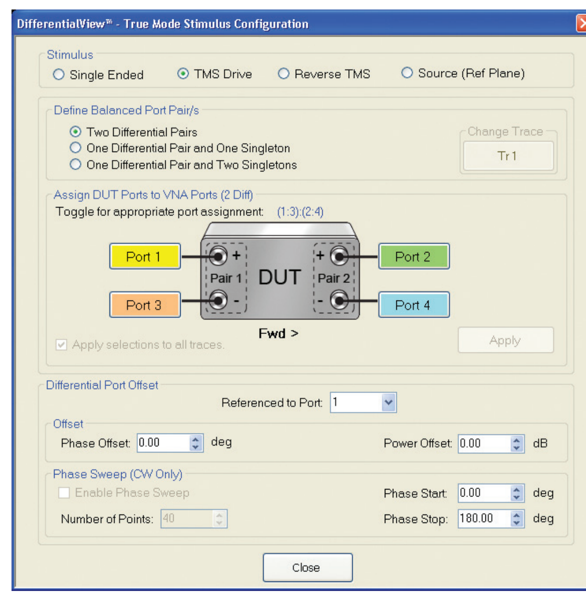
Application Note

True Mode Stimulus Measurements

For VectorStar® VNAs with DifferentialView™ Option 43 and Dual Source Option 31

MS4640B Series Vector Network Analyzer





Introduction

With the proliferation of differential devices in today's electronics industry, there is a need for accurate characterization of these devices. Traditionally, Vector Network Analyzers (VNA) have been used to characterize each port of these differential devices individually with single ended stimulus and then mathematically transform the results to produce "mixed-mode" S-parameters that attempt to characterize the differential behavior (differential and common-mode, see Figure 1) of the devices. For passive devices or active devices operating in their linear region, this method is sufficient. However, this technique will not work for devices operating in their non-linear region. For example, let's consider the case when one may want to characterize an amplifier operating near its compression point. In order for engineers to make these kinds of measurements, it is necessary to drive the device under test (DUT) with true differential signals.

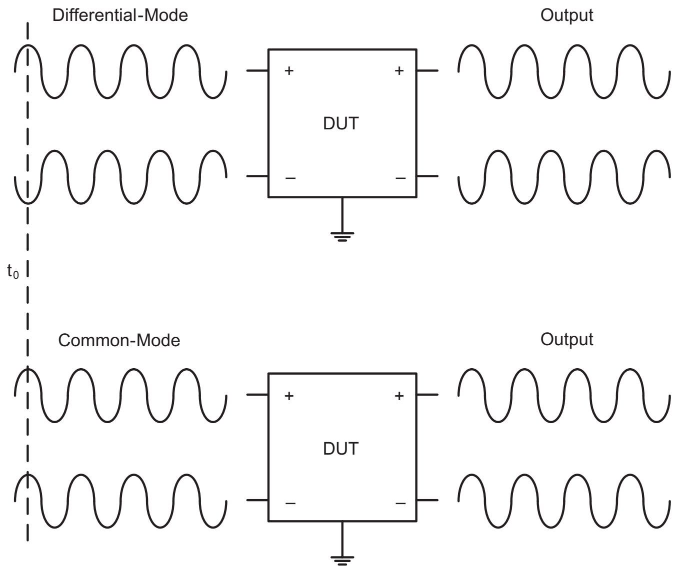


Figure 1. *Two types of differential signals are shown above: Common-Mode signals have 0° phase difference; Differential-mode signals have 180° phase difference*

The Anritsu VectorStar™ series of VNAs with DifferentialView™ (Option 043), working with the dual sources of Option 031, provides phase-calibrated stimuli when true differential stimulus is needed. Anritsu's True-Mode Stimulus capability allows the user to control the phases and amplitudes of two internal sources to provide the user with true differential or true common mode stimulus (e.g., two signals with balanced or equal amplitude, but with phase that is 180 or 0 degrees apart, respectively). For imbalanced measurements, VectorStar™ also allows users to specify arbitrary amplitude and phase parameters for the two signals.

This application note will discuss how to use the Anritsu VectorStar™ VNA to measure differential devices that require true Differential/Common Mode Stimulus.

Background

Single-ended and Differential Signaling

When transmitting a signal over a transmission medium, such as copper wires or traces on a printed circuit board, the two most commonly used methods are single-ended signaling and differential signaling. Single-ended signaling is the simplest and most commonly used method of transmitting electrical signals due to lower cost and smaller footprint (e.g., fewer wires, less traces, smaller devices, etc.). However, in today's electronics industry, the trend for lower voltage and higher speed signaling means that in many instances, single-ended designs are not feasible. This is mainly due to electromagnetic interference (EMI) or noise. Differential signaling has become increasingly popular because of its greater immunity to noise. As compared to single-ended signaling, differential signaling gives twice the noise immunity for a given supply voltage.

Consider the single-ended and differential digital systems shown in Figure 2. For the case of the single-ended digital system with supply voltage Vs and a common reference at ground (0 V) transmitting on one wire, both the High and Low logic levels are referenced to ground. Suppose the High logic level is Vs, and the Low logic level is 0 V. The difference between the two levels is therefore Vs – 0 V = Vs. Now consider the differential system with differential sources with the same voltage Vs, and the signals transmitted on two separate wires (+ and –). The High and Low logic levels on each wire are no longer referenced to a common ground, instead they are referenced to each other. Furthermore, the High and Low logic levels on each wire are always the complement of each, where one wire(+) is at Vs and the other wire(–) is in the Low state, –Vs. The difference between High and low Logic levels is therefore Vs - (–Vs) = 2Vs. This is twice the difference of the single-ended system.

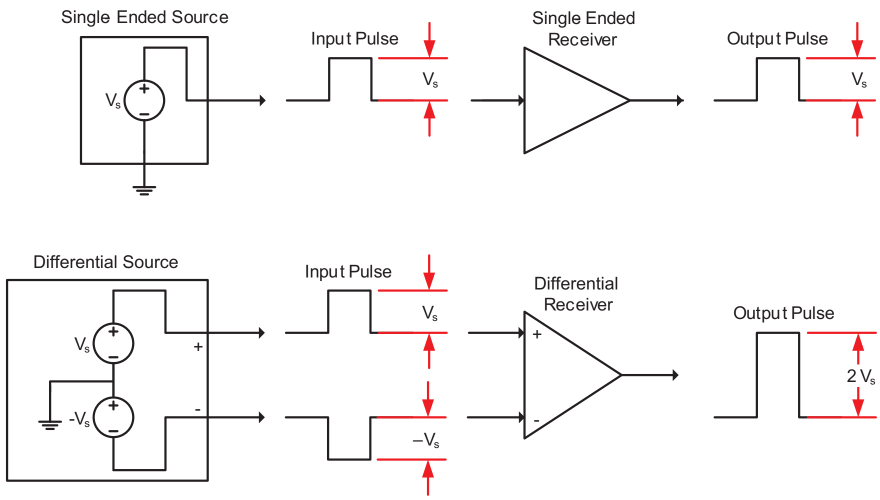


Figure 2. *Single-Ended and Differential Systems*

Suppose that the voltage noise on one wire is uncorrelated to the noise on the other one, the result is that it takes twice as much noise to cause an error with the differential system as with the single-ended system. In other words, the noise immunity is doubled. See Figure 3.

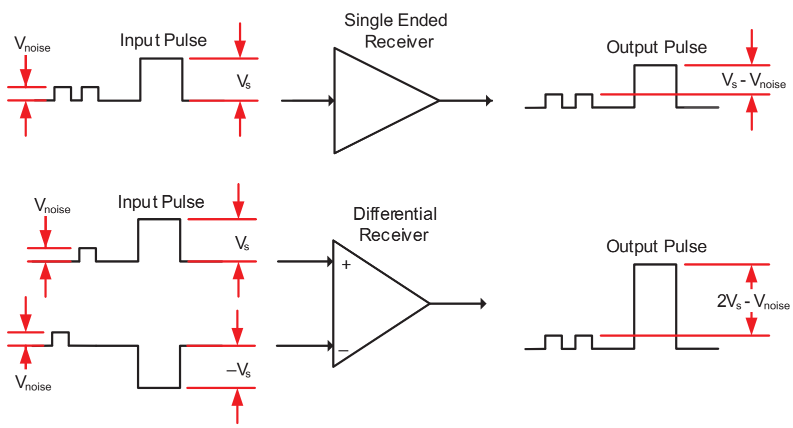


Figure 3. *Uncorrelated Noise*

An additional benefit of differential signaling is common mode rejection. Common mode rejection is the rejection by the differential device of unwanted input signals common to both inputs (+ and –). To illustrate this, consider the drawing in Figure 4. In this example, there is unwanted noise that is present on both the + and – input ports to the differential receiver. Because the output is the difference of the + input to the – input, the unwanted noise signal is effectively rejected by the differential receiver.

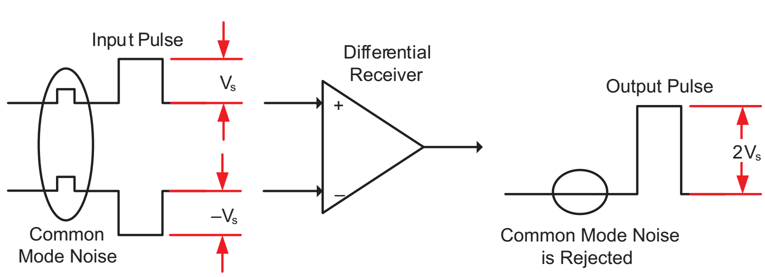


Figure 4. *Common Mode Noise is rejected*

The advantages discussed above are not entirely due to differential signaling itself, but also to the common practice of transmitting differential signals on balanced lines. A balanced line or balanced signal pair is a transmission line consisting of two conductors of the same type, each of which have equal impedances along their lengths and equal impedances to ground and to other circuits.

Balanced Devices

An unbalanced, or single-ended, device has all of its signals referenced to a common ground potential. A balanced device, by comparison, is composed of two nominally identical halves. The signals on each side of the device can have any relative amplitude and phase relationship, but they can be decomposed into a differential-mode (out of phase) component, and a common-mode (in-phase) component.

Single-ended and Differential S-Parameters

For the case where passive or active devices are operating in their linear region, at relatively low frequencies, these devices can be analyzed using lumped-element models and techniques. However, with the frequency of operation of many of today's devices increasing beyond 1GHz, the lumped-element approach is no longer valid because the size of the circuit approaches the size of the wavelength. The lumped element model is only valid whenever $L_c \ll \lambda$, where L_c denotes the circuit's characteristic length, and λ denotes the circuit's operating wavelength. Otherwise, when the circuit length is on the order of a wavelength, we must consider more general models, such as the distributed element model (including transmission lines), whose dynamic behavior is described by Maxwell's equations. Scattering parameters, or S-parameters, have been developed for this purpose. These S-parameters are defined for single-ended networks. S-parameters can be used to describe differential networks, but a strict definition was not developed until Bockelman[1] and others addressed this issue. Bockelman's work also included a study on how to adapt single-ended S-parameters for use with differential circuits. This adaptation is called "mixed-mode S-parameters", which addresses differential and common-mode operation as well as the conversion between the two modes of operation.

As previously discussed, for passive devices or active devices operating in their linear region, it is sufficient to measure the individual single-ended responses from a balanced device and then combine the results mathematically to obtain the differential or balanced response. A device is said to be in its linear region when the signals are small enough such that the device behavior does not change with signal level. However, many active devices do not follow such a model for their behavior. For example, an amplifier might change its bias current between large signals and small signals. For such devices, it is necessary to drive them with separate signals at each of their inputs that present the proper amplitude and phase relationships. These drive signals must be presented at the differential input ports (+ and –) of the DUT with the same amplitude and 180 degrees of phase difference, to be true differential signals. The Anritsu VectorStar™ VNA provides True Mode Stimulus (TMS) measurements for this situation. The TMS application ensures the stimulus signals to the differential device are calibrated and accurate for differential or common-mode operation.

[1] D.E. Bockelman and W.R. Eisenstadt, "Combined Differential and Common-Mode Scattering Parameters: Theory and Simulation," IEEE Transactions on Microwave Theory & Techniques, Vol. MTT-43, July 1995.

True Mode Stimulus

When combined with the dual source option (option 031), DifferentialView™ software (option 043) provides True Mode Stimulus (TMS) capability that calibrates, controls and manipulates the phase and magnitude between the two internal sources. The option integrates drive changes with the user RF calibrations to ensure an accurate phase relationship is delivered to the DUT. The dual sources are phase synchronized and the phase registers programmed according to a calibration process. Hardware clocking and synchronization ensure repeatable phase programming and measurements on the measurement channels will enable real-time correction of the phase angles as needed[2]. Figure 5 below shows a simplified block diagram of the two options.

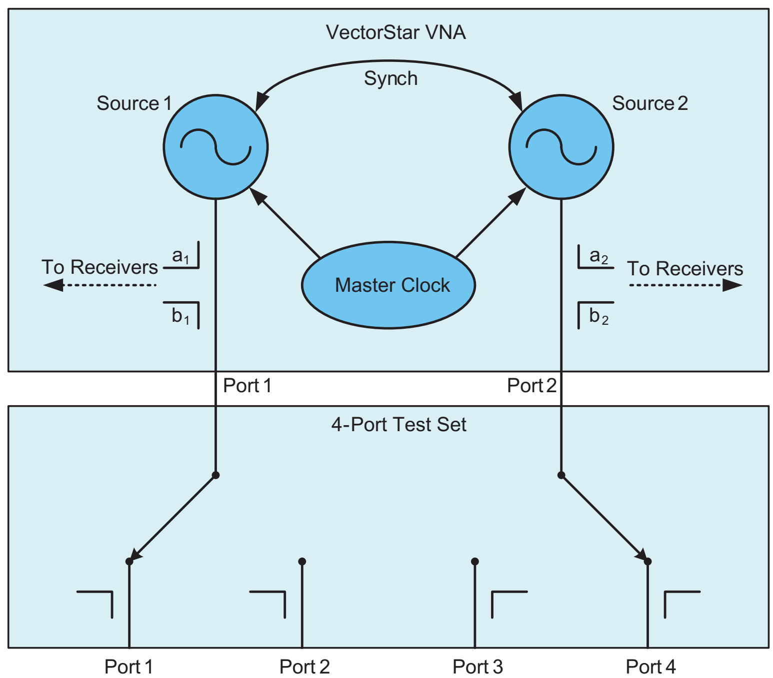


Figure 5. *Simplified Block Diagram of Dual Source (Option 031) and Phase Synchronization (Option 043*

[2] For a more detailed discussion of the Dual Source and DifferentialView™ Options, refer to Chapter 24, "Dual Source and DifferentialView™ (Options 031 and 043)", in the VectorStar Measurement Guide [Anritsu Document #10410-00318].

True mode stimulus measurement overview

The True Mode Stimulus capability of the VectorStar VNA calibrates, controls, and manipulates the phase and magnitude between the two internal sources to ensure that the stimulus signals to the differential Device Under Test (DUT) are calibrated and accurate for differential or common-mode operation. The DifferentialView sidebar menu and configuration window (shown in Figure) provide easy access to all key parameters so there is no need to activate numerous configuration panels to edit your setup. DifferentialView also provides continuous measurement display while actively editing key parameters. In contrast, products from other venders hide the measurement with multiple configuration panels during editing of parameters and do not display key parameter settings during the measurement.

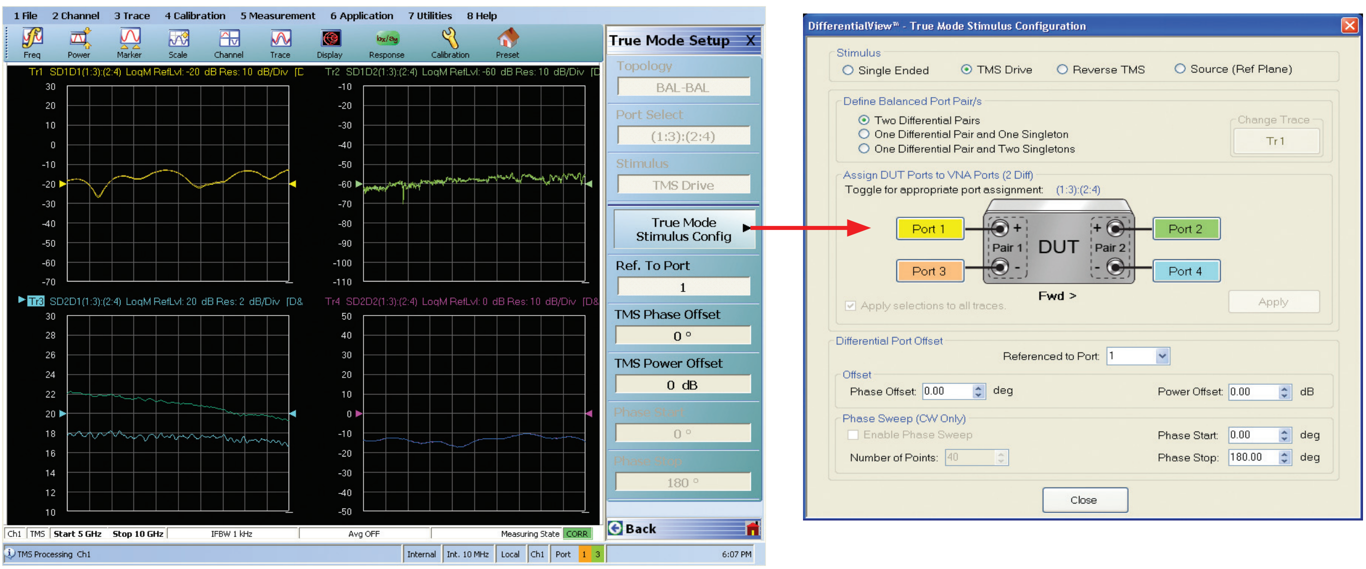


Figure 6. *DifferentialView allows the user to either edit TMS Parameters with the sidebar menu and watch the measurement display update in real time, or use the user friendly graphical TMS configuration window.*

Figure illustrates how TMS works during measurements of differential devices. The dual sources supply synchronized stimulus signals with calibrated phase and magnitude offsets, while DifferentialView continuously monitors the applied signals and corrects for any mismatch during the measurement to ensure the proper phase and amplitude relationships are seen at the differential input ports of the DUT.

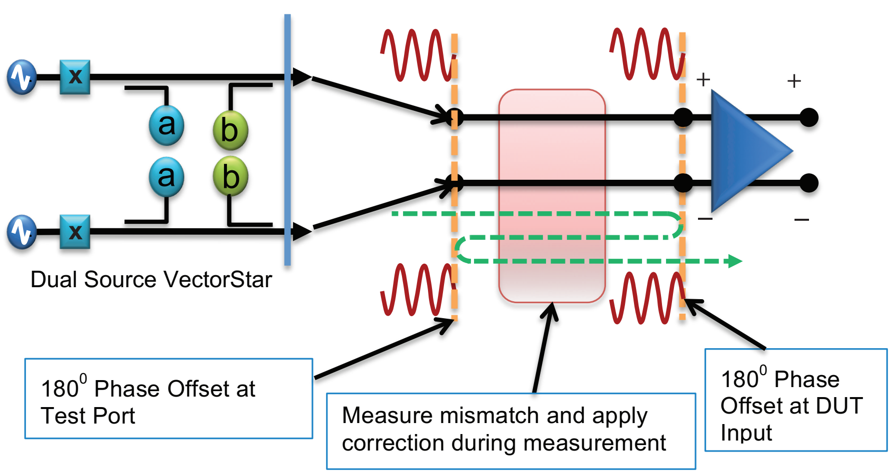


Figure 7. *TMS measurement of a differential device*

One consideration when using TMS for differential device measurements is that TMS correction requires measurement of DUT parameters in order to compensate for phase shifts due to source mismatch. Because of this requirement, a second set of measurement sweeps is necessary. Consequently, TMS mode is slower than standard super-positioning operation. Because of the added measurements and corrections resulting in slower measurements, it is common and recommended to use standard super-positioning (Single Ended) operation for passive and active devices operating in their linear region. Use TMS when operating devices in a compressed or non-linear state.

True Mode Stimulus Measurement Example

For this measurement example, the following functionality will be demonstrated:

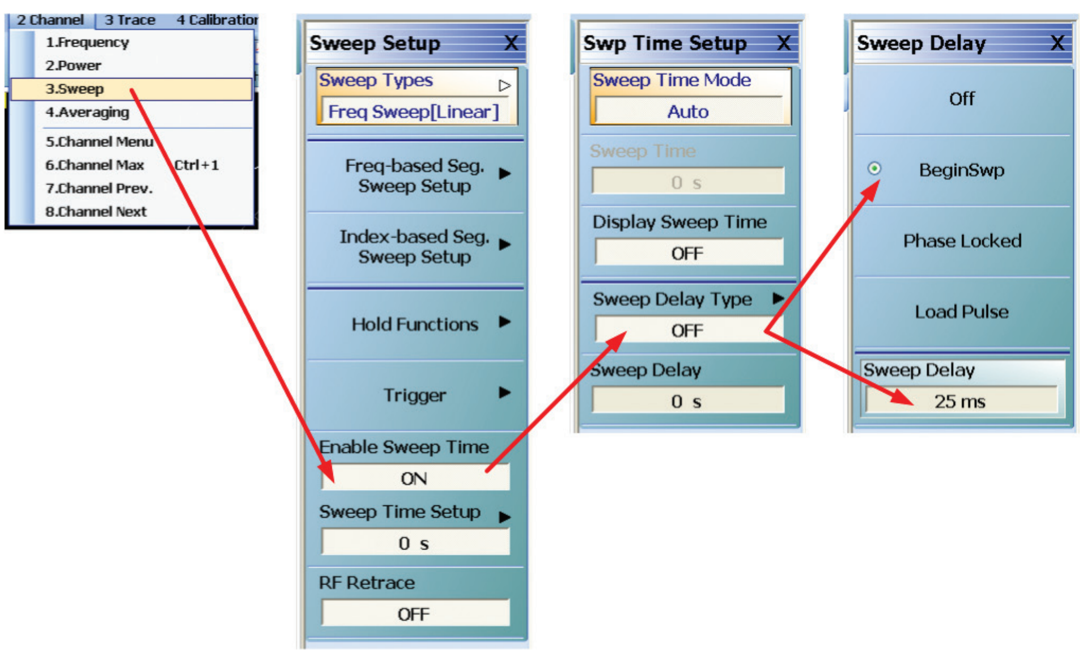
- True Mode Stimulus (TMS) measurements
- Phase sweep measurements of differential devices
- Verifying TMS correction performance

Minimum Equipment Requirements:

MS4642B VectorStar equipped with Dual Source options 031 and DifferentialView™ option 043
MN4694B 4-port test set
VectorStar calibration kit
SC8262 TMS Demo Kit (differential amplifier)

Measurement Procedure

1. Begin by performing a Preset of the VectorStar to ensure the system is in a known state.
2. Optional: When the 4-port test set is connected, the sweep may need a short delay at the beginning of the sweep. To configure the initial delay do the following:



2.1. From the menu bar, select Channel –> Sweep

2.2. In the Sweep Setup Menu

2.2.1. Enable Sweep Time – On

2.2.2. Select Sweep Time Setup

2.3. In the Swp Time Setup Menu

2.3.1. Sweep Time Mode – Manual

2.3.2. Select Sweep Delay Type

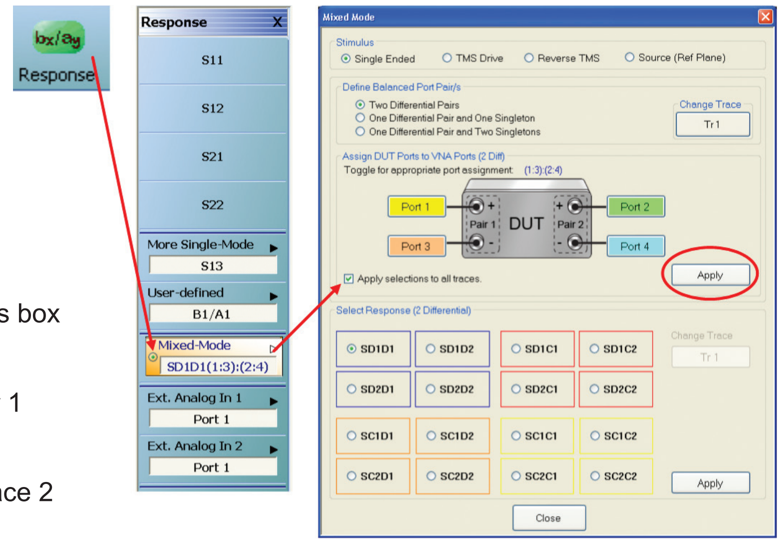
2.4. In the Sweep Delay Menu

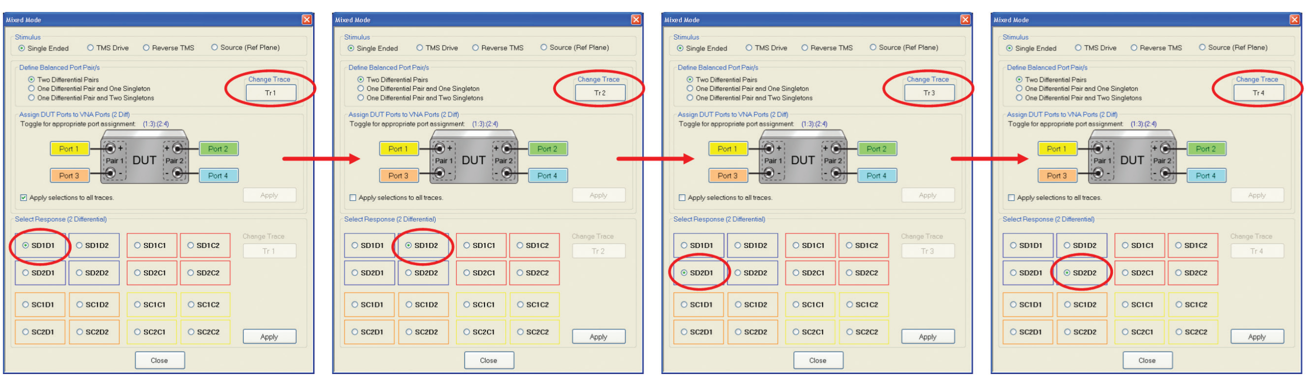
2.4.1. Set Sweep Delay Type to Beginning Sweep

2.4.2. Set Sweep Delay to 25 ms (this should be modified until the distortion at the 2.5 GHz bandswitch point is minimal). Note: if the cal and measurement response parameters remain the same then this step is typically not needed.

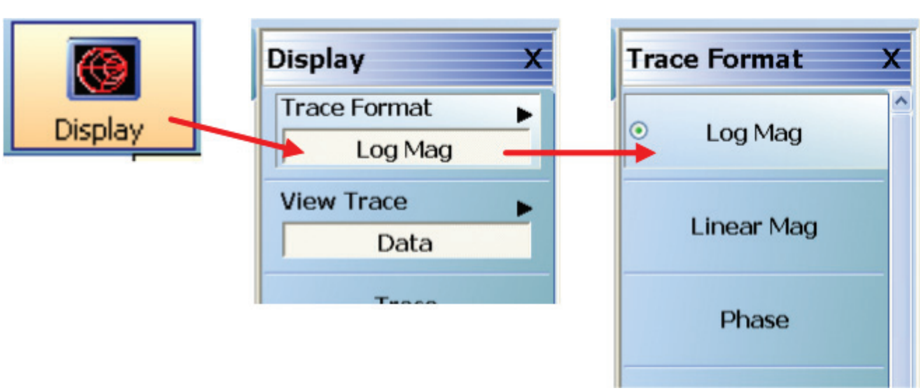
Now we will setup the VectorStar to Plot Mixed Mode Parameters.

3. On the Menu bar Select Response
4. From the Response Side Menu, select Mixed Mode
5. In the Mixed Mode Menu
    5.1. Stimulus: Select Single Ended
    5.2. Define Balanced Port Pair/s: Select Two Differential Pairs
    5.3. Assign DUT Ports to VNA Ports
        5.3.1. Pair 1 = Port 1 and Port 3
        5.3.2. Pair 2 = Port 2 and Port 4
        5.4. Check the Apply selections to all traces box
6. Select Apply
7. Verify the Change Trace box is selected for Tr 1
8. Select SD1D1 for trace 1 and select Apply
9. Click the Change Trace button and choose trace 2
10. Select SD1D2 for trace 2 and select Apply
11. Change to trace 3 and set for SD2D1 and select Apply
12. Change to trace 4 and set for SD2D2 and select Apply





13. It is best to leave the system in Single Ended mode for now as the calibration will be faster.
14. Close the Mixed Mode dialog box by selecting Close
15. Set the traces to the desired Trace Format. It is suggested to start off with all traces in Log Mag format.

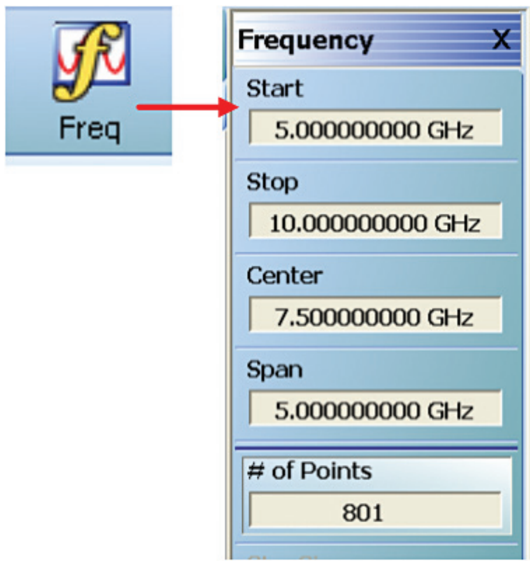


Set Measurement parameters and Calibrate for Differential/True Mode Stimulus Measurements

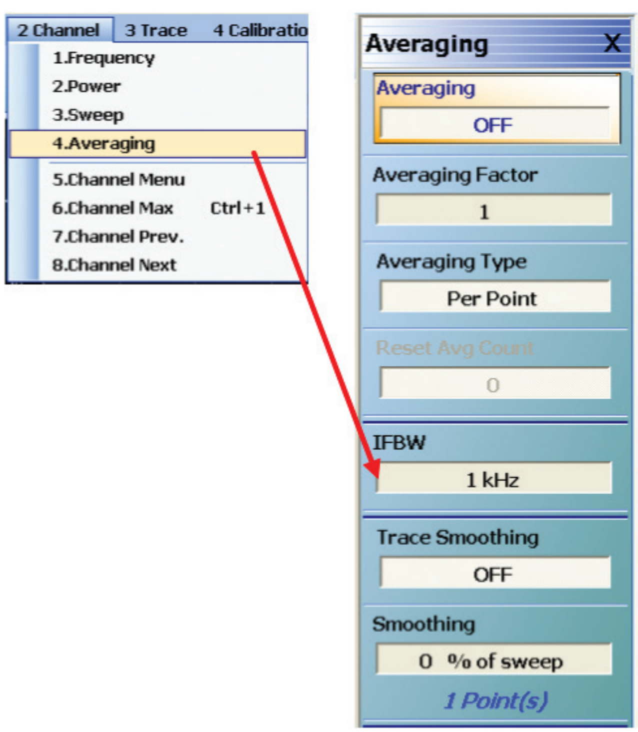
16. Begin by first setting the parameters:

16.1. Frequency. For this demonstration, we will set the Start Frequency at 5 GHz and the Stop Frequency at 10 GHz.

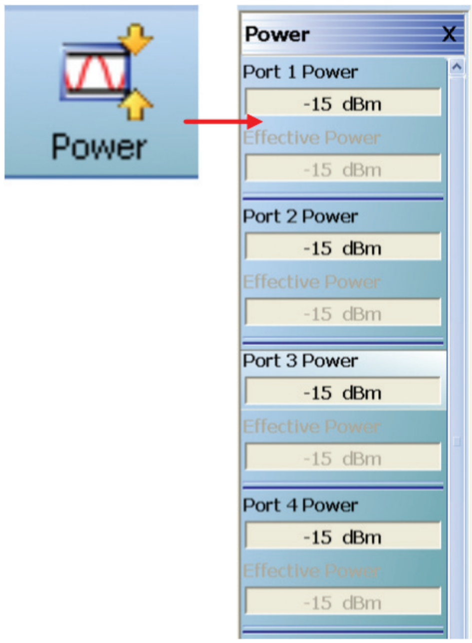
16.2. Points. Set the point count to 801. This will give enough resolution for times when zooming in is helpful.



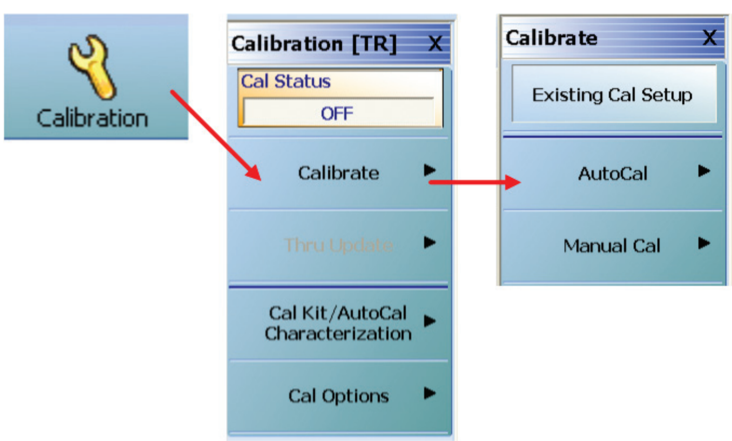
16.3. **IF Bandwidth and Averaging.** For the demo device 1 kHz IFBW is usually enough. If you anticipate needing to make some lower level measurements after the calibration you can try setting for 300 Hz.



16.4. Set Port Power - The demo device starts to compress around –25 dBm. Since the TMS mode is most useful when the DUT is heavily compressed you may want to perform your calibration around –15 dBm. Be sure to set all Ports to the same power level..



17. You can perform either a manual calibration or an AutoCal calibration. If an AutoCal is available it is recommended to use that for calibration.



18. If you choose to perform a manual calibration, remember to set up the test port connector type. Also note the thru path configuration in the Edit Cal Parameters dialog box. Designating the thru paths is important when the user needs to identify specific paths that are available.

Connect the DUT

19. Connect Ports 1:3 to the Differential Input and 2:4 to the Differential Output
20. Remember that we are still in single ended mode and operating the device in a compressed state. Optimize the display for best viewing. Your display should now look like Figure 6.

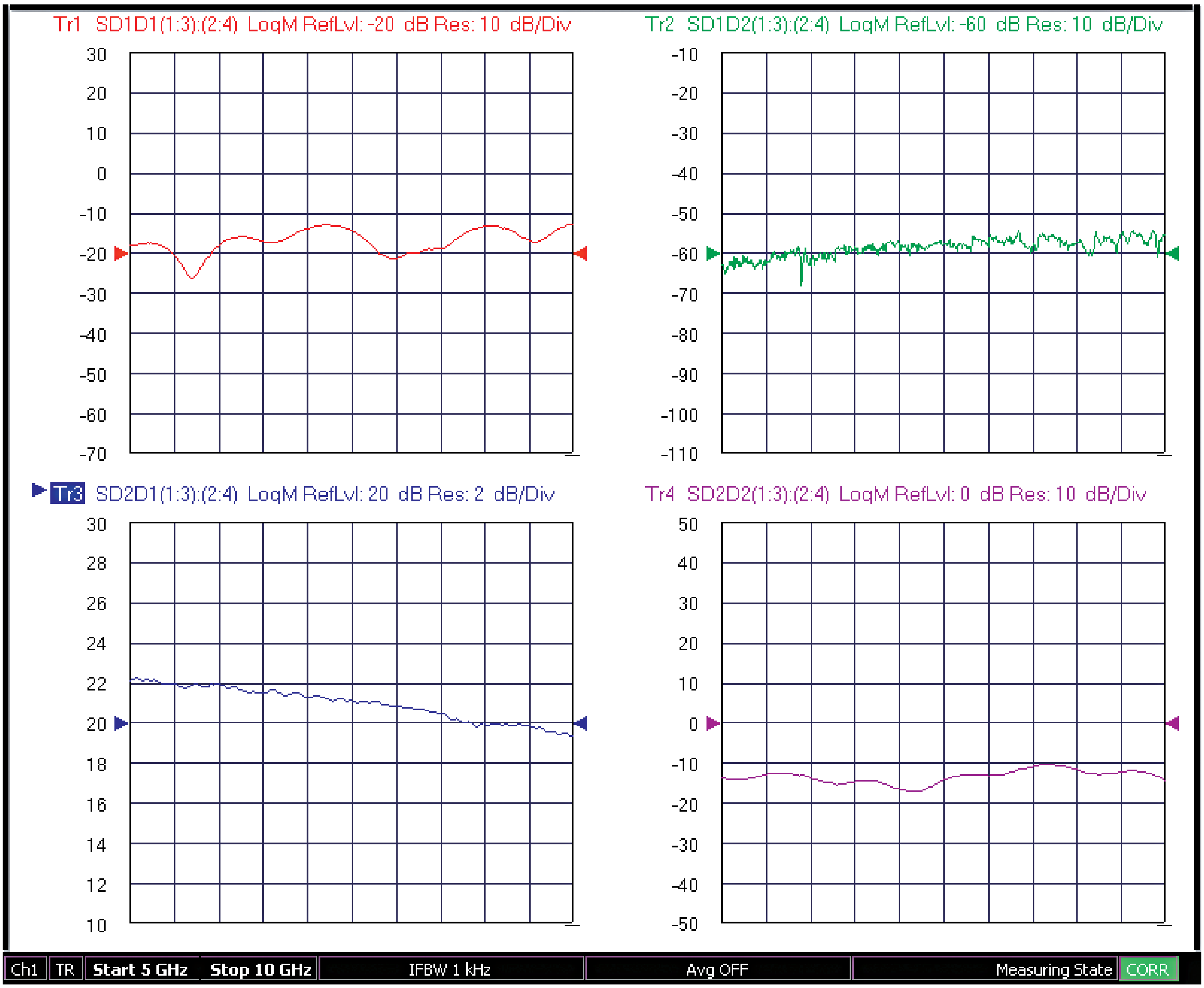
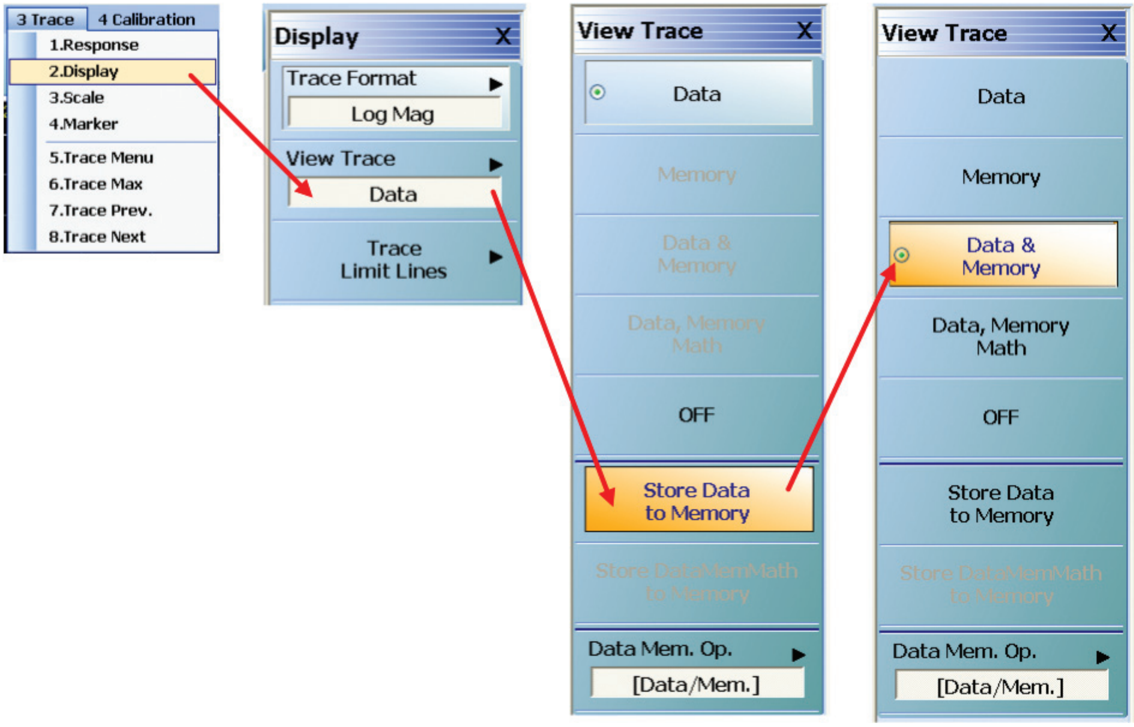


Figure 8. *Single-Ended Mixed Mode S-Parameters*

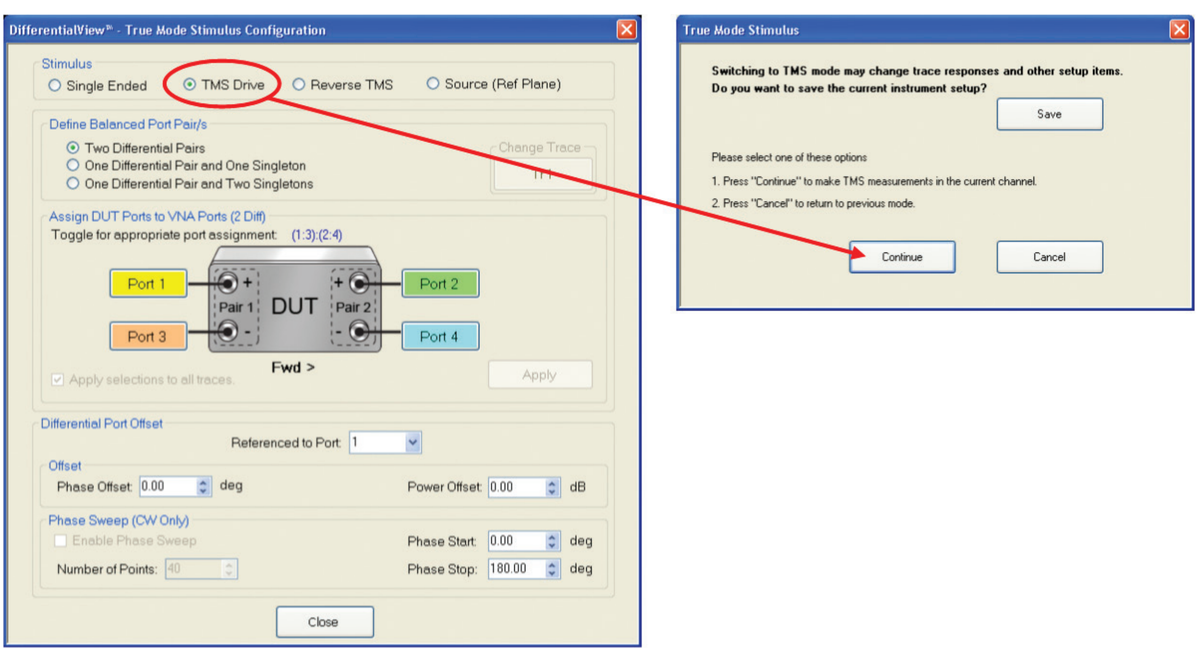
21. Select Each Trace and Save all 4 traces to memory and select Data and Memory view.



22. Go to the DifferentialView section of the instrument by selecting Application / True Mode Stimulus Setup.

23. Select True Mode Stimulus Config. Verify that the DUT is still configured properly (Input ports 1:3 and Output ports 2:4).

24. Activate the TMS mode by selecting the TMS Drive. Note that a pop up window is now displayed. If you haven't stored your calibration yet now is a good time. Click Continue to activate the TMS mode.



25. Note that the sweep change from an individual port to port sweep to a pairs sweep. Also note that it now takes 8 sweeps instead of 4 to complete the measurement update. This is because the TMS mode must first measure the S parameters of the device and the source match and load match of the VNA and then correct for the mismatch. The second set of sweeps then measures the S parameter performance of the device under the corrected (calibrated) condition.

Measuring a Differential Device in True Mode Stimulus Mode

26. Since you previously stored the single ended performance into memory and are already displaying Data & Memory, you now can see the difference in measuring a compressed differential device in single ended mode and True Mode Stimulus. Note that the major difference is usually in the SD2D1 display.

27. This is a display of differential S parameters with the input set for 180° offset. If the user wants to set the phase relationship for something other than 180° the offset can be adjusted by modifying either the magnitude or phase offset in the DifferentialView panel or on the main menu of the TMS application.

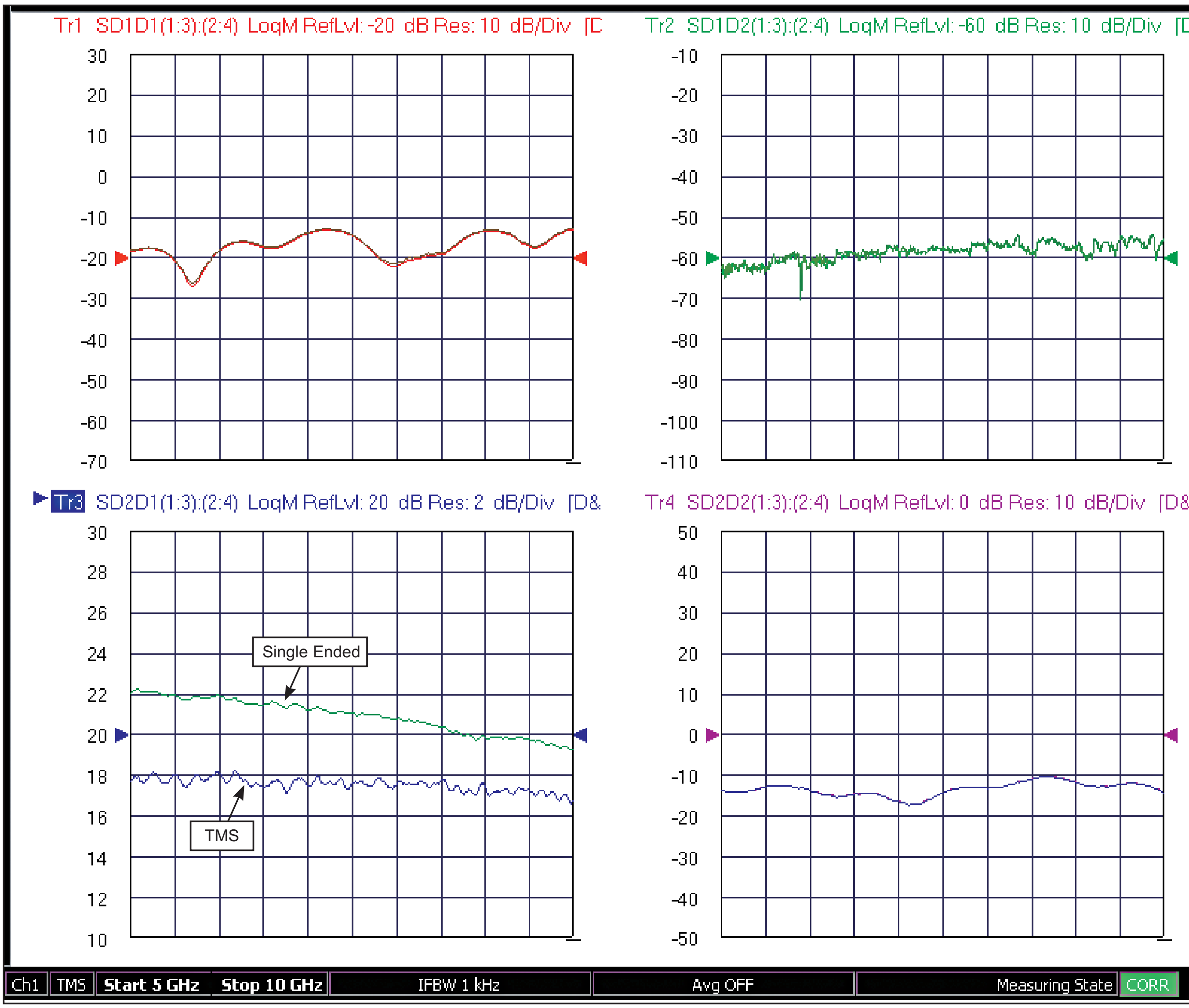


Figure 9. *Single-Ended Mixed Mode S-Parameters*

Performing a Phase Sweep at the Differential Input

28. Activate the SD2D1 trace and turn on a marker. Set the marker for the area where the difference is the greatest. Maximize the trace and go to the frequency menu to turn on CW for the frequency of the marker.

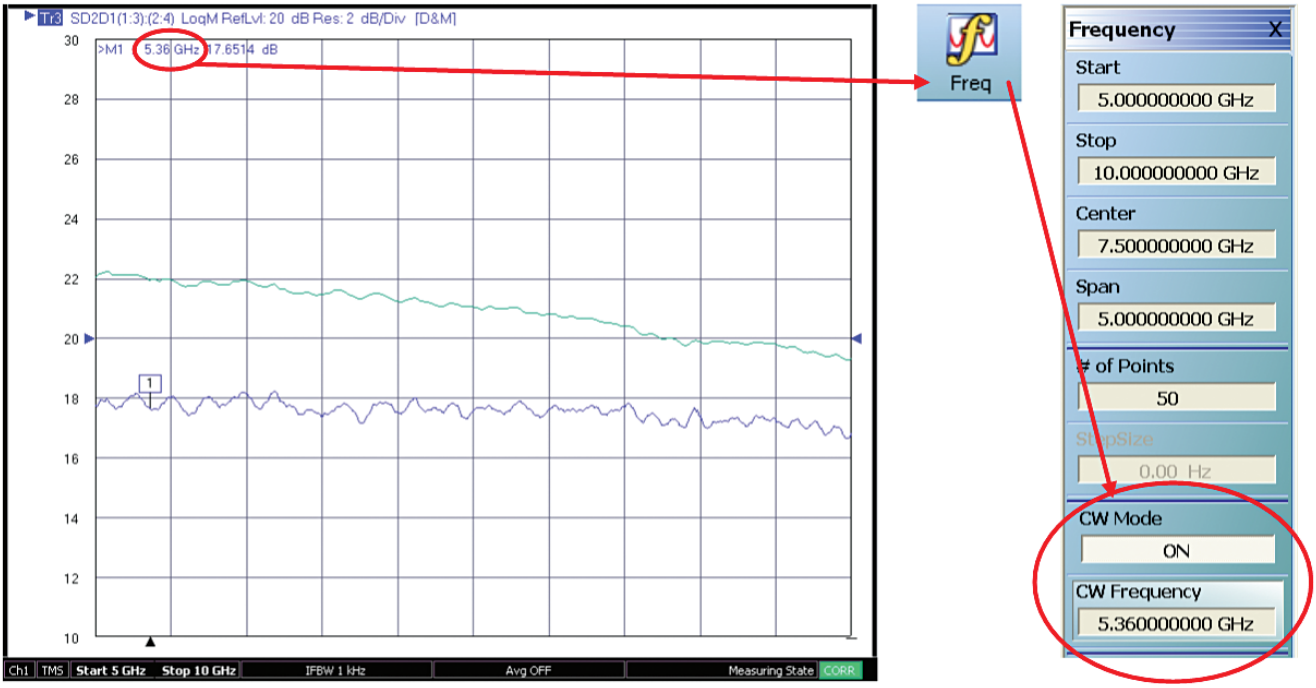
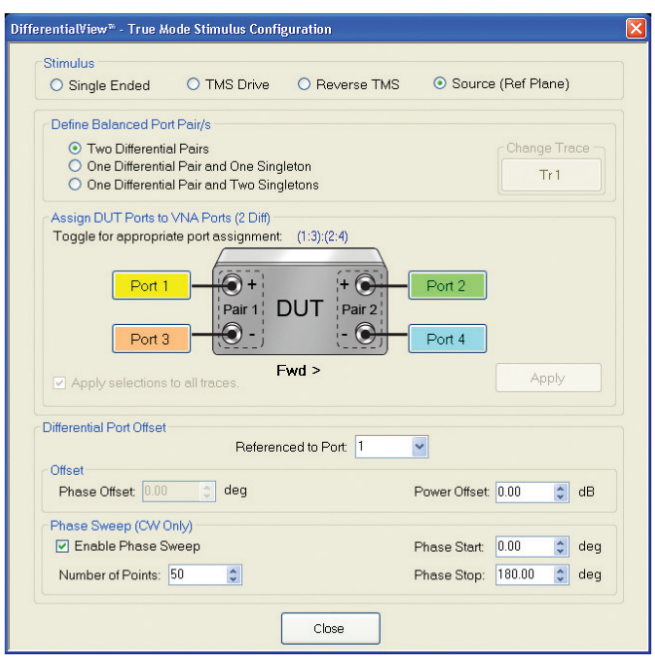


Figure 10. *SD2D1 Trace*

29. Now go back to the DifferentialView Panel and select Source (Ref Plane). Next select Enable Phase Sweep and enter about 50 points (this is now active because CW is now turned on). Set the phase sweep to a desired range (try around 0 to +180). Select Close.



30. With the display set for a SD2D1 Log Mag plot you should now see a plot similar to this:

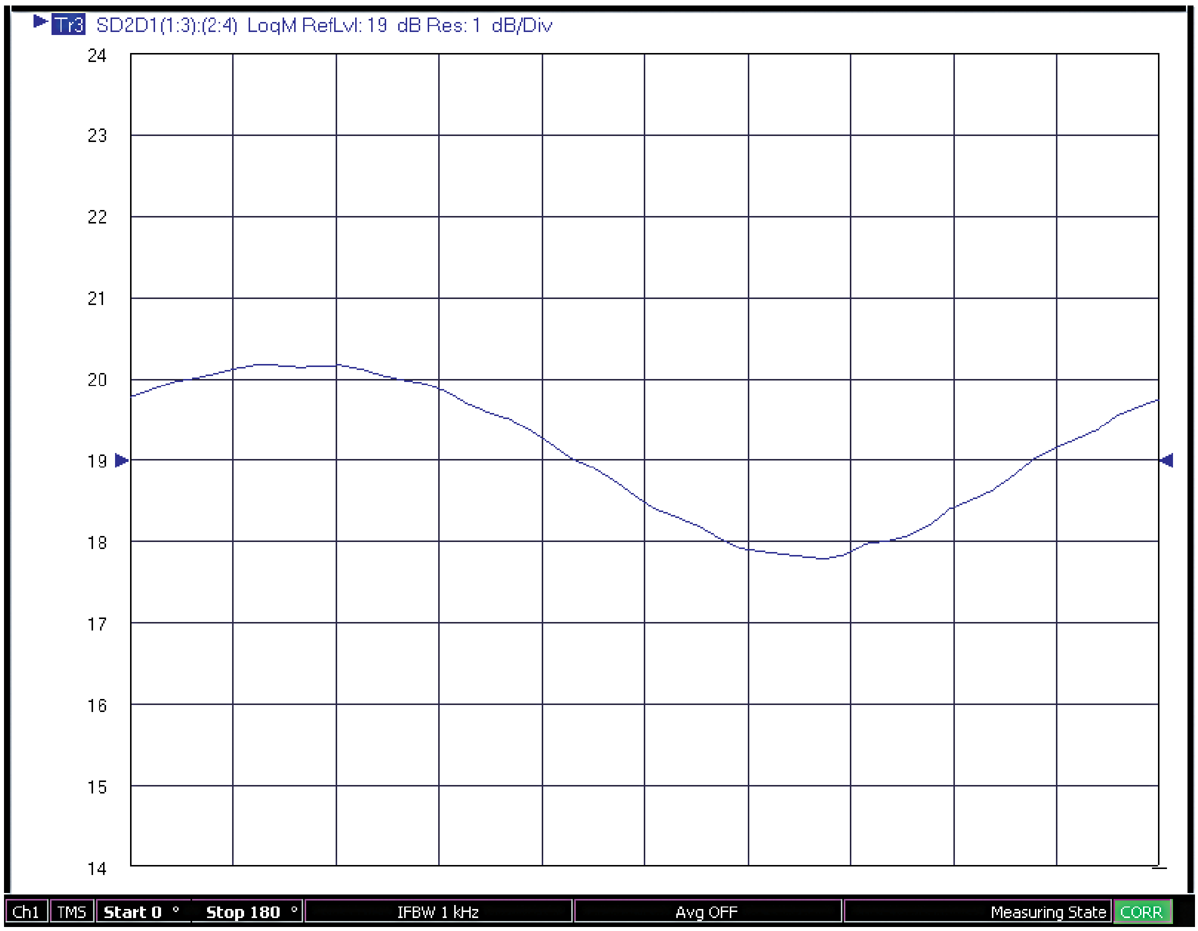
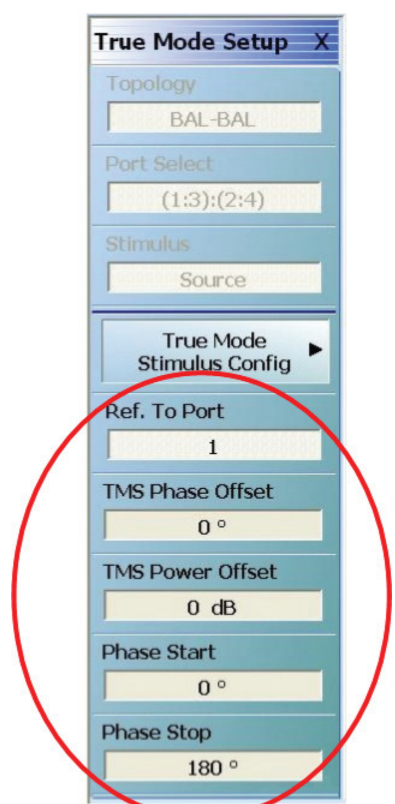


Figure 11. *SD2D1 Phase Sweep*



31. Notice that the start stop phase setting is displayed and editable in the menu bar. Try changing the start or stop setting to shift the display. Also try adjusting the TMS power offset to further compress the device and characteristics.

32. Note that this interaction is not available on competitive VNAs. For those units you must go through at least 4 different menu selections, the configuration panel will pop up and hide the measurement, you must then edit the parameters blindly, and then exit the configuration panel to see the results. With VectorStar DifferentialView you can monitor performance changes while modifying the parameters.

Verifying True Mode Differential Accuracy

As mentioned previously, True Mode Stimulus operation is needed when making measurements on devices that are highly compressed. Unlike a linear device, a compressed, nonlinear device is not predicable and consequently, the super-positioning technique is not accurate. Because the device is nonlinear the input will be highly sensitive to impedance mismatch. For proper TMS mode operation, the VNA must therefore compensate for mismatch interactions and apply proper corrections during the measurement. Consequently, the degree of proper correction to the applied signals will determine how accurate the stimulation signals are applied and how accurately the device is stimulated with an ideal phase offset. Since the device is nonlinear, small variations in magnitude or phase at the input may have large differences in the output performance of the device, so maintaining the correct fixed phase offset at the input of the DUT is important for accurate device characterization.

Displaying the amount of error in the phase relationship between the two input signals is performed by setting up an a1/a3 plot and is a good way to demonstrate the accuracy of the TMS mode when using VectorStar. We have found in side-by-side comparisons that VectorStar is approximately 5 times more accurate than a leading competitor's product in maintaining the proper 180 degree phase relationship. The difference varies depending on how compressed the device is; less compression means less correction is needed. Also, lower frequencies are less challenging.

The next section will show how to set up the display and demonstrate differential phase offset accuracy.

1. Maximize one of the traces for a SD1D1 display
2. Verify the power is at a level where the device is nonlinear. For the demo DUT -15 dBm should be good enough.
3. Set the frequency range for a display where there is enough variation over frequency to see some ripple. 5 to 10 GHz should be enough.
4. Go to the Response menu and set the trace for an a1/a3 display. Be sure port 1 is the driving port.
5. Verify the system is in SE mode by going to the DifferentialView panel.
6. Set the display for a Phase display. Store data to memory and perform a Data/Memory Math. Expand on the trace by scaling down.
7. Notice that you may have anywhere from a few degrees to as much as 20 degrees of phase variations. This is because the phase relationships between the two signals are not locked (not in TMS mode).
8. Go to the DifferentialView configuration panel and set the system for a TMS mode operation by selecting the TMS Drive. Remember to re-store the Data trace into memory to refresh the Data/Memory Math display.

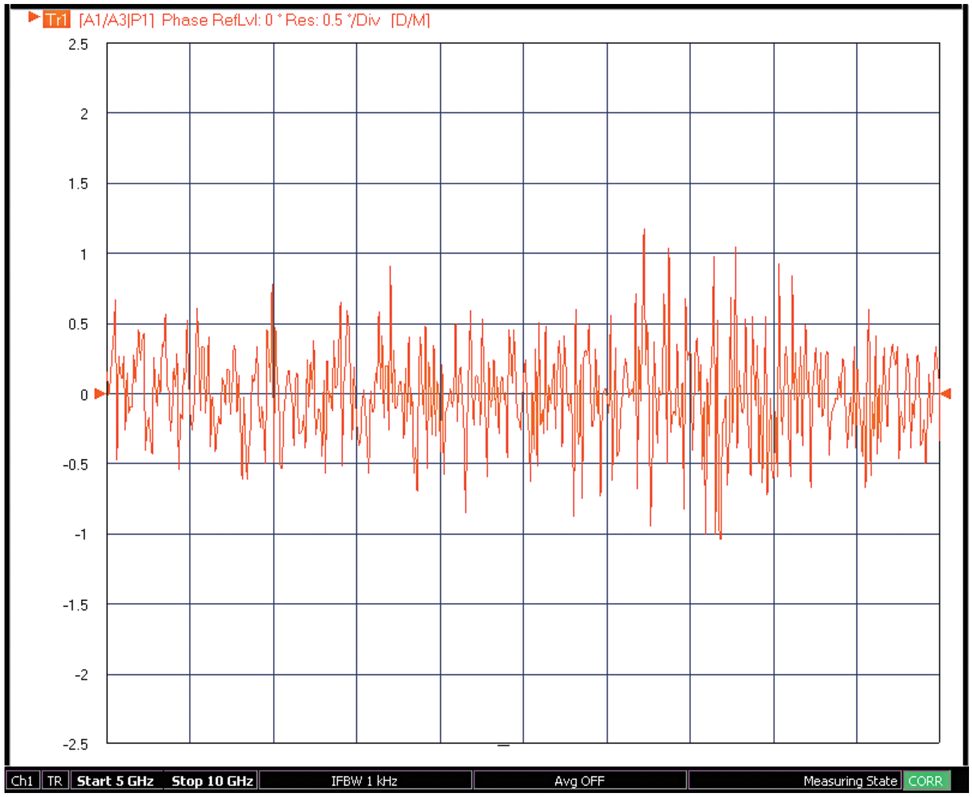


Figure 12. *Single Ended Phase Error*

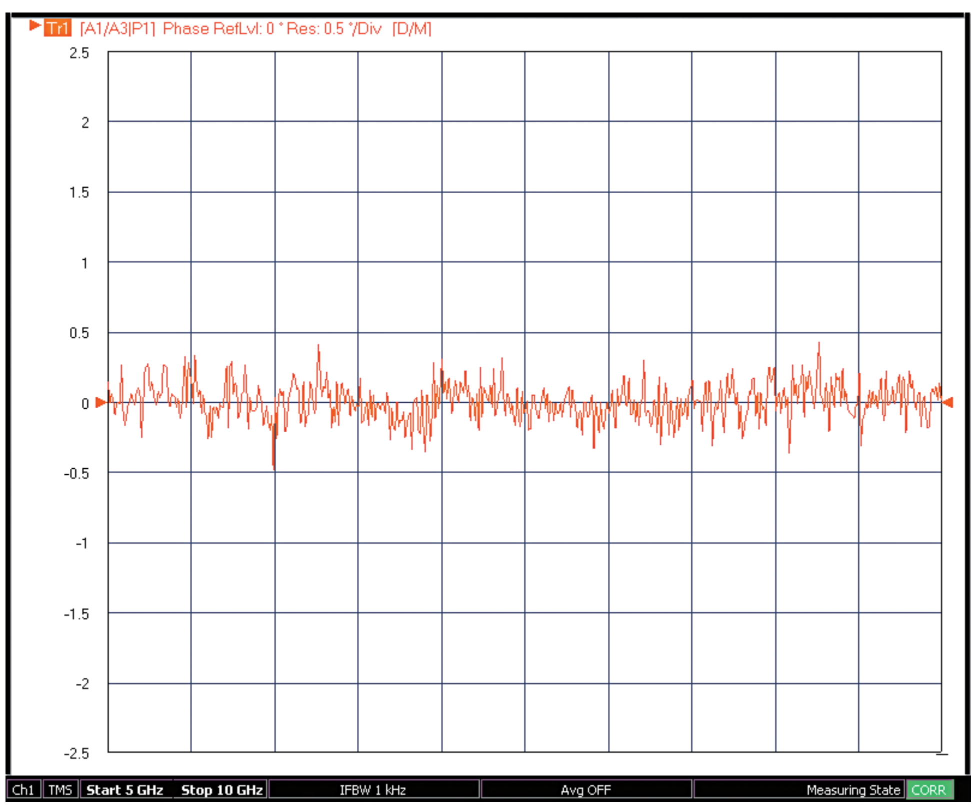


Figure 13. *TMS Phase Error*

Summary

For passive devices or active devices operating in their linear region, it is sufficient to use single ended measurement techniques. As the demonstration above has shown, when differential devices are measured in a compressed or non-linear state, single-ended measurement techniques introduce significant errors. The solution to this problem is to stimulate these devices using True Differential Stimulus signals and then measure them as they would normally be driven. The Anritsu VectorStar VNA with Dual Source option 031 and Differential View Option 043 allows the user to easily setup and makes these measurements. In addition, the Anritsu VectorStar is the only VNA on the market that allows the user to change TMS phase and amplitude parameters and see the measurement results in real time.

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