



Balanced Device Characterization



Agilent Technologies
Innovating the HP Way

This paper describes a method and a system for accurately and comprehensively characterizing the linear performance of balanced devices. It removes the last barriers to wide adoption of balanced devices in RF and microwave applications.

Outline

- **Characteristics of Differential Topologies**
- **Measurement Alternatives**
- **Unbalanced and Balanced Performance Parameters**
- **Balanced Devices Design Methodology**
- **System Implementation**
- **Measurement Example**
- **Conclusion**

This paper on balanced device characterization will cover the following topics:

First we will review the characteristics of balanced devices to understand why they are increasing in popularity for RF applications.

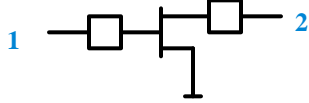
After that we will look at commonly used techniques for measuring these devices and their advantages and disadvantages.

Next we will consider a way of describing the behavior of balanced devices, and how this relates to a design methodology.

A system for characterizing balanced devices has been developed and will also be described.

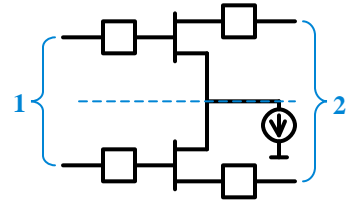
Finally, before concluding, an example of a measurement on a balanced SAW filter will be discussed.

Differential Device Topology



Unbalanced Device

- Signals referenced to ground



Differential Device

- Signals equal amplitude and anti-phase
- Also supports a common mode (in-phase) signal
- Virtual ground

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. Practically speaking, 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 (anti-phase) component, and a common-mode (in-phase) component.

A balanced circuit operating in common-mode has no performance advantages over a single-ended circuit. The advantages of this topology come from operating the device in differential mode.

When a device is driven differentially, a virtual ground is established along its axis of symmetry. At the virtual ground, the potential at the operating frequency does not change with time regardless of the signal amplitude.

Performance Attributes of Differential Circuits

- Noise Immunity from:
 - Power Supplies
 - Digital Hash
 - External EMI
- Minimize Radiation from Circuit
- Even-Order Harmonic Suppression
- RF Grounding Quality Less Critical

Balanced circuits have been used for many years because of their desirable performance characteristics. They have been mostly used in lower frequency analog circuitry and digital devices, and much less so in RF and microwave applications.

One benefit of differential circuits is that they have good immunity from many sources of noise such as that from power supplies, adjacent circuitry, and other external sources that are coupled either electrically or electromagnetically. These noise sources tend to couple in the common-mode, and therefore cancel in differential mode.

Cancellation also occurs at even-harmonic frequencies since signals that are anti-phase at the fundamental frequency are in-phase at the even harmonics.

The quality of the virtual ground in a differential circuit is independent of the physical ground path. Therefore, differential devices can tolerate poor RF grounds better than unbalanced devices.

Enablers

- Demand for Higher Performance, Lower Cost RF IC's
- Improved RF Device Performance
- Higher Yield RF IC's
- Improved RF Simulation Tools
- Increased IC Density

Since differential circuits have so many performance advantages, and have been used for years, why are they not more common in RF and microwave designs?

There have been several technological advancements in recent years that have enabled this to happen. Probably the most important is that there is a demand for higher performance, lower cost IC's in high volumes.

Along with the market demand has come improvements in technology. This includes higher performance, particularly higher gain, transistors, and higher yield RF IC's.

More accurate electrical models of circuit elements, packages, and interconnects combined with more powerful circuit simulation tools have allowed for more complex, higher density RF IC's.

Challenges

- Measurement Tools Are Mostly Unbalanced
- No Balanced VNA Calibration Standards
- No Balanced RF Connector Standards
- No Standard Reference Impedance (Z_0) for Balanced Devices

If differential circuits are so good, then why are they still not used in all RF applications?

The truth is that they are increasingly more common. The major stumbling blocks are that most test equipment is intended for single-ended devices. The related infrastructure is also unbalanced. This includes the things that are often taken for granted, such as calibration standards, transmission lines and connectors, and even an industry-standard reference impedance.

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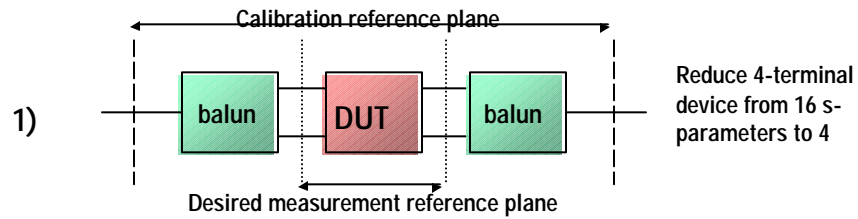
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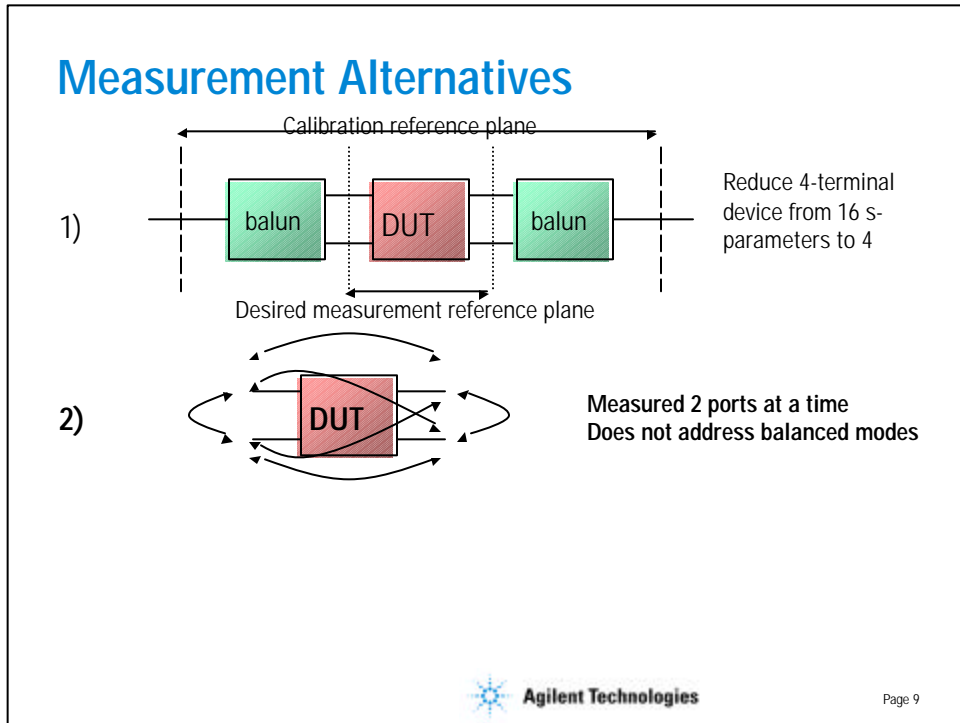
Measurement Alternatives



Typically there are two approaches that are used to measure balanced devices using a VNA. One is to convert each balanced port to a single-ended port using a balun, and measure that network on a single-ended VNA. One disadvantage to this approach is that it is inaccurate because the reference plane of the calibration is at the single-ended test port of the VNA, while the desired measurement reference plane is at the balanced port of the DUT. The balun in between is not ideal and will degrade the accuracy of the measurement. The other disadvantage is that this approach is not comprehensive since, at best, it can only portray the pure differential mode of operation, not the other three modes.

Another method is to measure the balanced device as a single-ended multiport device. This can be a very time consuming process since multiple two port measurements are needed to fully characterize the device. In addition, it can be misleading since the single-ended data may not give a representative indication of the performance of the device when it operates in one of its balanced modes.

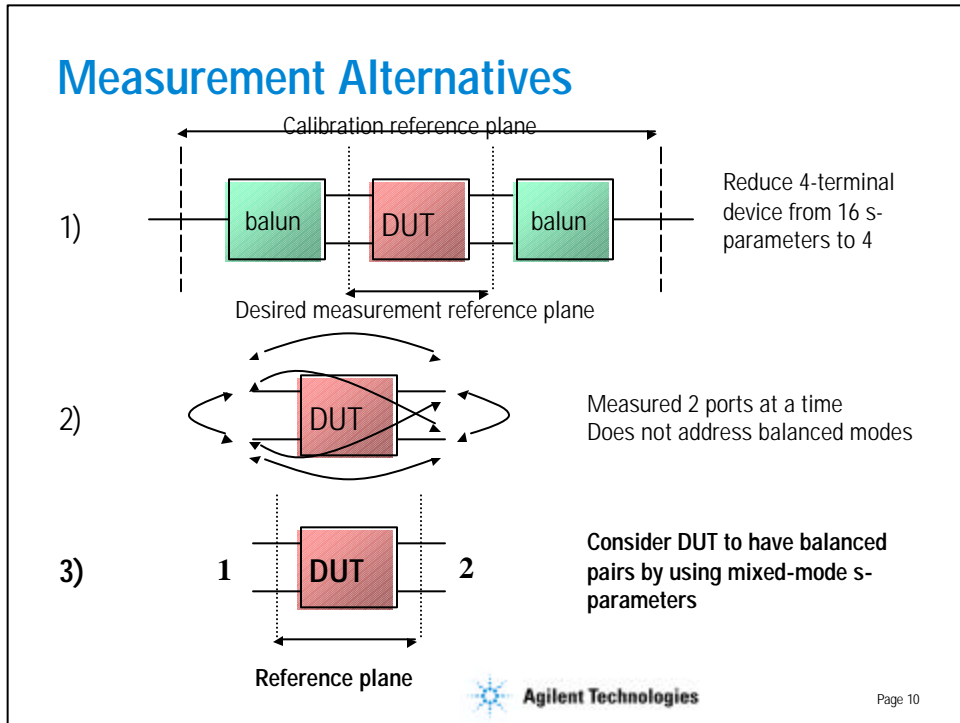
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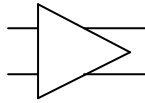
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How Many Ports Does this Device Have?



Example: Balanced Amplifier

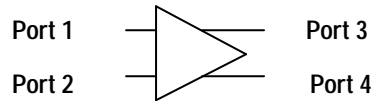
A multi-terminal device can be viewed in different ways, depending on how it is meant to be operated. For a device that is designed to be a single-ended four-port, its conventional four-port s-parameters can be measured and displayed.

In a balanced device, two terminals constitute a single port. Each balanced port will support both a common-mode and a differential-mode signal. This performance is described using mixed-mode s-parameters.

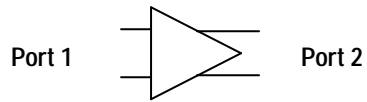
In the discussion that follows, we will go back and forth between single-ended and balanced device examples several times to compare and contrast the concepts.

Unbalanced and Balanced Devices

- **Unbalanced: ports referenced to gnd (S-parameters)**



- **Balanced: ports are pairs (Mixed-Mode S-parameters)**



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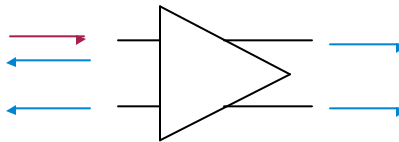
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Single-Ended S-Parameters

Conventional S-Parameters Answer the Question ...

If a single port of a device is **stimulated**,
what are the corresponding **responses** on all
ports of the device?



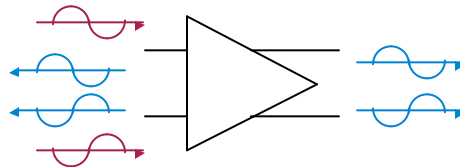
Let's compare what is meant by single-ended and mixed-mode s-parameters. Recall that with conventional single-ended s-parameters we are describing the performance of a device when it is stimulated on a single port, and the corresponding responses are observed on all of the ports.

Mixed-Mode S-Parameters

Mixed-Mode S-Parameters Answer the Question ...

If a balanced port of a device is **stimulated** with a common-mode or differential-mode signal,

what are the corresponding common-mode and differential-mode **responses** on all ports of the device?



The mixed-mode s-parameters concept is similar, except that instead of stimulating a single terminal of the DUT, with a balanced device we consider pairs of terminals to be stimulated in either a differential (anti-phase) or a common (in-phase) mode. With mixed-mode s-parameters we are asking, with a differential mode stimulus on a balanced port, what are the corresponding differential and common mode responses on all of the device ports? Likewise for a common mode stimulus, what are the differential and common mode responses?

Single-Ended S-Parameter Review

Single-Ended 4-Port



Voltage V_n
 Current I_n
 Impedance $Z_n = V_n / I_n$

	Normalized Power Waves
stimulus	$a_n = \frac{1}{2 \cdot \sqrt{\text{Re}\{Z_n\}}} (V_n + I_n \cdot Z_n)$
response	$b_n = \frac{1}{2 \cdot \sqrt{\text{Re}\{Z_n\}}} (V_n - I_n \cdot Z_n)$

$$S = b/a$$



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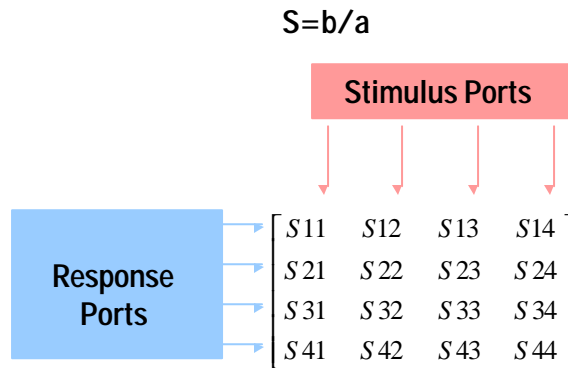
We have looked at the intuitive description of mixed-mode s-parameters. Now let's look at a more mathematical description.

For a single-ended device, RF voltages and currents relative to a common ground can be defined at each terminal of the device. From these we can also define an impedance from the positive-going waves.

From the voltage, current, and impedance definitions, normalized power waves can be defined in stimulus and response. Stimulus power waves are defined as propagating into the DUT, and response power waves propagate away from the DUT.

The s-parameters are ratios of a response to a stimulus normalized power wave.

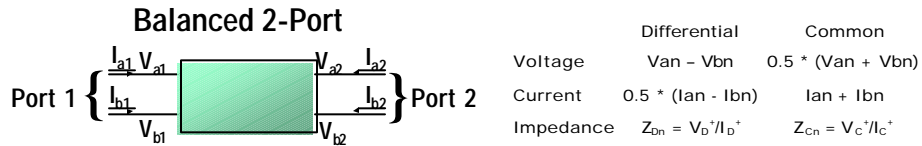
Single-Ended S-Matrix



An s-parameter is defined as the ratio of two normalized power waves: the response divided by the stimulus. A full s-matrix describes every possible combination of a response divided by a stimulus.

The matrix is arranged in such a way that each column represents a particular stimulus condition, and each row represents a particular response condition.

Mixed-Mode S-Parameter Basics

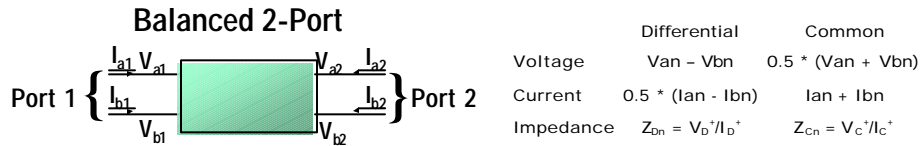


For a balanced device, we are not necessarily interested in voltages and currents referenced to ground. Instead, we can define differential and common mode voltages and currents on each balanced port. Likewise, we can also define differential-mode and common-mode impedances.

As with the single-ended case, we can also define normalized power waves on the ports of a balanced device. In this case they are mode-specific. The differential and common-mode voltages and currents defined earlier can be used for this, resulting in normalized power waves having the exact same form as the single-ended case. Only the definitions of “voltage” and “current” are changed.

Mathematically, the differences between conventional single-ended s-parameters and mixed--mode s-parameters are few. Both are defined as ratios of normalized power waves.

Mixed-Mode S-Parameter Basics



	Normalized Power Waves	
	Differential-Mode	Common-Mode
stimulus	$a_{dn} = \frac{1}{2 \cdot \sqrt{\text{Re}\{Z_{Dn}\}}} (V_{dn} + I_{dn} \cdot Z_{Dn})$	$a_{cn} = \frac{1}{2 \cdot \sqrt{\text{Re}\{Z_{Cn}\}}} (V_{cn} + I_{cn} \cdot Z_{Cn})$
response	$b_{dn} = \frac{1}{2 \cdot \sqrt{\text{Re}\{Z_{Dn}\}}} (V_{dn} - I_{dn} \cdot Z_{Dn})$	$b_{cn} = \frac{1}{2 \cdot \sqrt{\text{Re}\{Z_{Cn}\}}} (V_{cn} - I_{cn} \cdot Z_{Cn})$

$$S = b/a$$

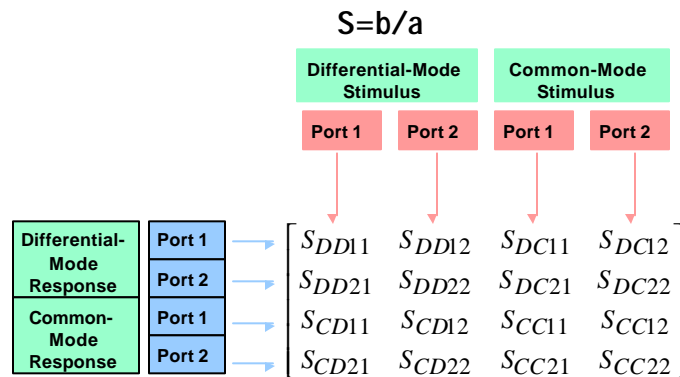


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Mixed-Mode S-Matrix



Naming Convention: $S_{\text{mode res., mode stim., port res., port stim.}}$



Again we can take a ratio of all of the possible combinations of response over stimulus for the differential and common-mode normalized power waves to calculate the mixed-mode s-parameters.

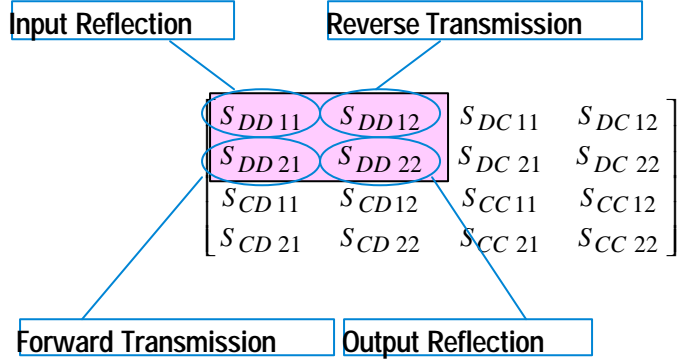
A mixed-mode s-matrix can be organized in a similar way to the single-ended s-matrix, where each column represents a different stimulus condition, and each row represents a different response condition.

Unlike the single-ended example, though, in the mixed-mode s-matrix we are not only considering the port, we are also considering the mode of the signal at each port.

The naming convention for the mixed-mode s-parameters must include mode information as well as port information. Therefore, the first two subscripts describe the mode of the response and stimulus, respectively, and the next two subscripts describe the ports of the response and stimulus.

The mixed-mode matrix fully describes the linear performance of a balanced two-port network. To understand the information contained in the mixed-mode s-matrix, it is helpful to examine each of its four modes of operation independently by dividing this matrix into four quadrants.

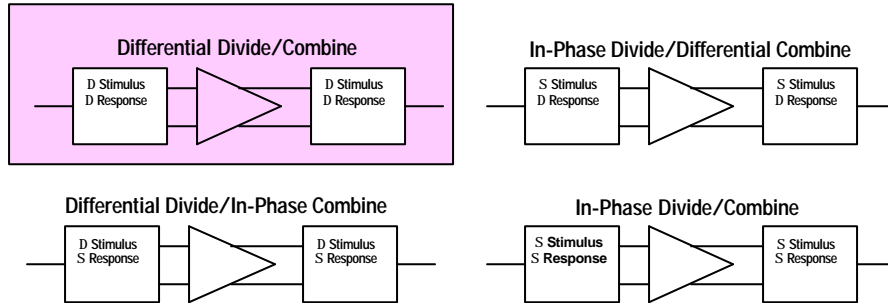
Mixed-Mode S-Matrix: DD Quadrant



Describes Fundamental Performance in Pure Differential-Mode Operation

For a device with two balanced ports, the quadrant in the upper left corner of the mixed-mode s-matrix describes the performance with a differential stimulus and differential response. When the performance of the device is isolated to this specific mode, these four parameters describe the input and output reflections, and the forward and reverse transmissions much in the same way a 2-port s-matrix describes the performance of a single-ended device.

Conceptual View of DD Quadrant

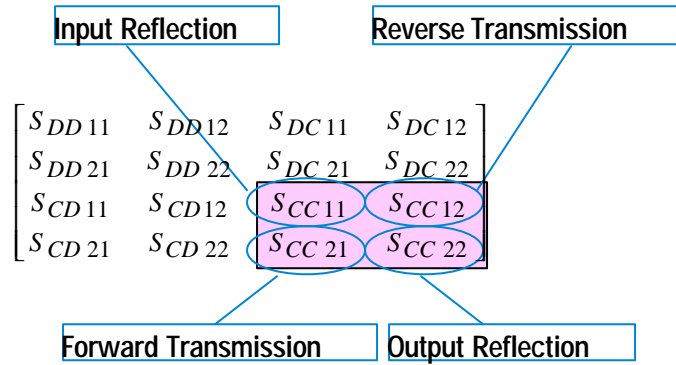


Hybrid Network:

- Divides Signals Differentially
- Combines Signals Differentially
- Is Ideal

The balanced ports can be converted to single-ended ports. An ideal hybrid will do this, but the performance will be isolated to the differential mode. The s-parameters of the resulting 2-port single-ended network are the s-parameters in the DD quadrant of the mixed-mode s-matrix.

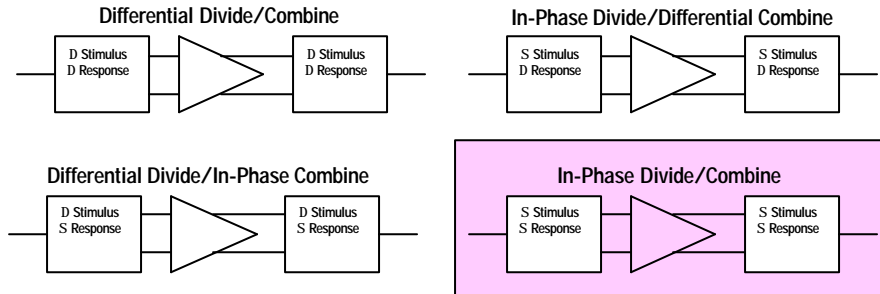
Mixed-Mode S-Matrix: CC Quadrant



Describes Fundamental Performance in
Pure Common-Mode Operation

For a device with two balanced ports, the quadrant in the lower right corner of the mixed-mode s-matrix describes the performance with a common-mode stimulus and a common-mode response. When the performance of the device is isolated to this specific mode, these four parameters describe the input and output reflections, and the forward and reverse transmissions.

Conceptual View of CC Quadrant

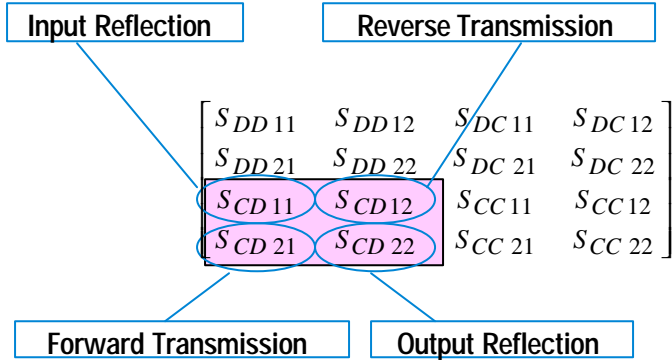


Hybrid Network:

- Divides Signals In-Phase
- Combines Signals In-Phase
- Is an Ideal Power Divider & Combiner

The balanced ports can also be converted to single-ended ports with an ideal power divider/combiner. In this case, the performance will be isolated to the common mode. The s-parameters of the resulting 2-port single-ended network are the s-parameters in the CC quadrant of the mixed-mode s-matrix.

Mixed-Mode S-Matrix: CD Quadrant



- Describes Conversion of a Differential-Mode Stimulus to a Common-Mode Response
- Terms Are Ideally Equal to Zero with Perfect Symmetry
- Related to the Generation of EMI

The parameters in the lower left corner describe the common-mode response of a device to a differential stimulus. As with the other modes, there are reflection parameters on each port, and transmission parameters in each direction.

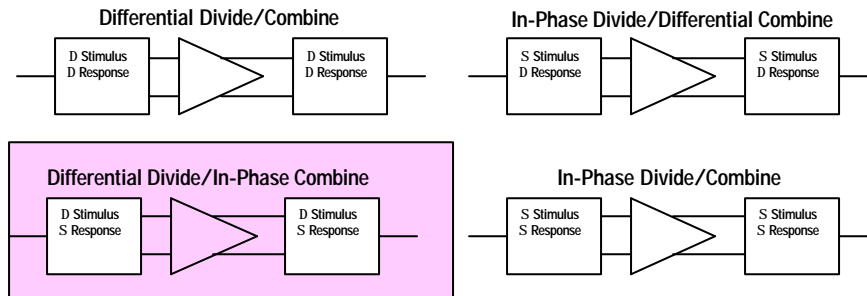
In an ideal balanced device that is perfectly symmetrical, there will be no conversion from differential mode to common mode. In that case, all of these terms will be equal to zero. As the device becomes asymmetrical, these terms become larger. Therefore, the mode conversion terms provide a measure of device symmetry.

Why is mode conversion important?

All of the performance benefits of differential circuits assume that the device is symmetrical. The benefits become diminished as the device becomes more asymmetrical.

Differential to common mode conversion is even related to the generation of EMI in a balanced device. The differential mode stimulus becomes converted to common mode, and appears on a ground return. From there it can be radiated as if from an antenna.

Conceptual View of CD Quadrant

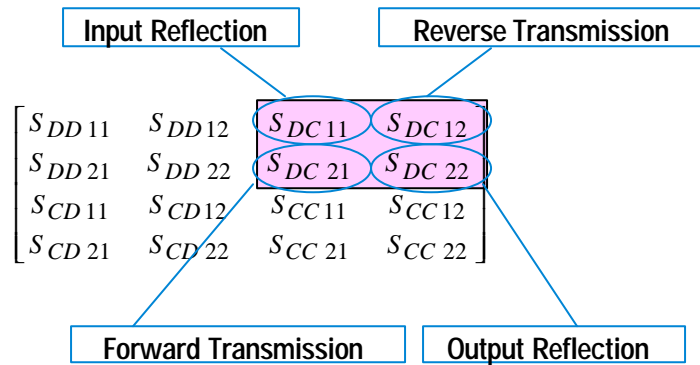


Network:

- Divides Signals Differentially
- Combines Signals In-Phase
- Is Non-Reciprocal

Once again we can convert the balanced port to a single-ended port to understand this mode more conceptually. In this case our network will have to divide the signal differentially as it propagates towards to DUT, and combine signals in-phase as they propagate away from the DUT. Therefore, our network will need to be non-reciprocal in addition to having perfect return loss, insertion loss, balance, and isolation.

Mixed-Mode S-Matrix: DC Quadrant



- Describes Conversion of a Common-Mode Stimulus to a Differential-Mode Response
- Terms Are Ideally Equal to Zero with Perfect Symmetry
- Related to the Susceptibility to EMI

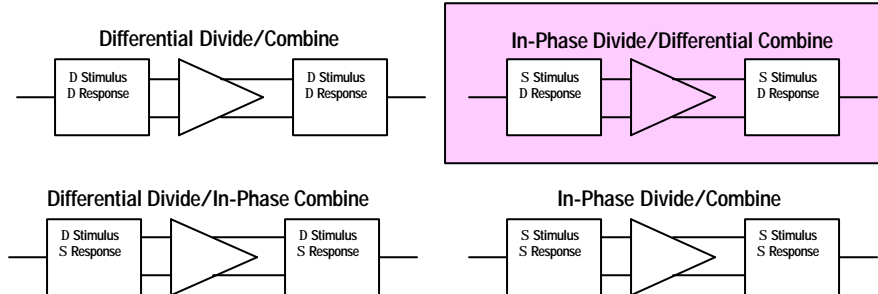
Finally, the parameters in the upper right corner describe the differential response of a device to a common-mode stimulus. Again, there are reflection parameters on each port, and transmission parameters in each direction.

In an ideal balanced device that is perfectly symmetrical, there will be no conversion from common mode to differential mode. In that case, all of these terms will be equal to zero. As the device becomes asymmetrical, these terms become larger. Therefore, the mode conversion terms provide a measure of device symmetry.

The same benefits of symmetry apply to this mode as discussed in the CD quadrant.

Where differential to common mode conversion is related to the generation of EMI in a balanced device, the common to differential terms are related to the susceptibility of a device to EMI. Common-mode noise, for example, can become converted to differential mode and degrade the signal-to-noise ratio of the system.

Conceptual View of DC Quadrant



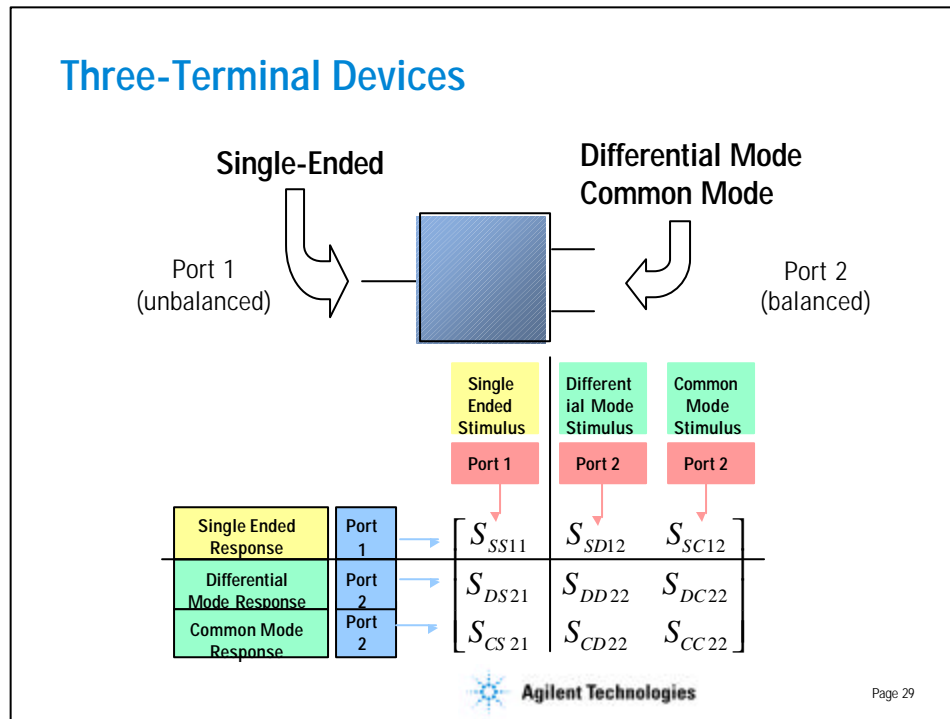
Network:

- Divides Signals In-Phase
- Combines Signals Differentially
- Is Non-Reciprocal

The balanced port can be converted to a single-ended port in this case with a network that divides the signal in-phase as it propagates towards to DUT, and combine signals differentially as they propagate away from the DUT. Once again, our network will need to be non-reciprocal in addition to being ideal.

For propagation in a given direction, a device will not necessarily convert a differential signal to common mode with the same efficiency that it converts a common-mode signal to differential mode. For example, a device can be susceptible to EMI without generating EMI. Therefore, it is important to consider both the CD and the DC quadrants.

Three-Terminal Devices



The balanced device that was examined until now has had two balanced ports. A simple extension of the mixed-mode concept can be applied to devices having a combination of balanced and single-ended ports. In this scenario, we need to consider differential and common modes on the balanced ports, and one mode on the single-ended port.

The s-matrix for such a device is again arranged with the stimulus conditions in the columns, and the response conditions in the rows. Notice that two columns and two rows describe each balanced port, and one column and one row describe each single-ended port.

In this case the four parameters in the lower right corner describe the four types of reflection that are possible on a balanced port, the single parameter in the upper left describes the reflection on the single-ended port, and the other four parameters describe the differential and common mode transmission characteristics in the forward and reverse directions.

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Brain Teaser #1

What are the simultaneous conjugate input and output matching impedances of the following circuit?



Single-ended 2-port

Let's take a short break from our discussion of mixed-mode s-parameters to think about some concepts that are commonly used in the design of single-ended networks using s-parameters.

Consider a single-ended two port device, and assume that the s-parameters of the device are known. How would you determine the proper matching impedance that needs to be presented on the input and output terminals of the device to match the device on both ports simultaneously?

Brain Teaser #1: Answers

What are the simultaneous conjugate input and output matching impedances of the following circuit?



Well-documented relationship between simultaneous conjugate match and s-parameters.

Single-ended 2-port

$$\Gamma_1 = \frac{C_1^*}{|C_1|} \left[\frac{B_1}{2 \cdot |C_1|} - \sqrt{\frac{B_1^2}{2 \cdot |C_1|^2} - 1} \right]$$
$$\Gamma_0 = \frac{C_2^*}{|C_2|} \left[\frac{B_2}{2 \cdot |C_2|} - \sqrt{\frac{B_2^2}{2 \cdot |C_2|^2} - 1} \right]$$

where:

$$B_1 = 1 - |S_{22}|^2 + |S_{11}|^2 - |D|^2$$

$$B_2 = 1 - |S_{11}|^2 + |S_{22}|^2 - |D|^2$$

$$C_1 = S_{11} - D \cdot S_{22}^*$$

$$C_2 = S_{22} - D \cdot S_{11}^*$$

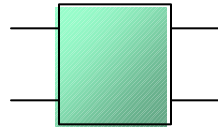
$$D = S_{11} \cdot S_{22} - S_{12} \cdot S_{21}$$



Although you may not have the answer on the tip of your tongue, there is a well-documented relationship between the s-parameters of a single-ended two-port and the simultaneous conjugate match. This relationship can be found in many reference books and articles.

Brain Teaser #2

What are the simultaneous conjugate input and output matching impedances of the following circuit?



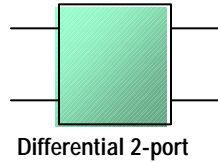
Differential 2-port

Let's return to our balanced device again.

If we are trying to design a differential-mode 2-port device, how can we determine the impedance that should be presented to the input and output of the device to simultaneously match its ports?

Brain Teaser #2: Answers

What are the simultaneous conjugate input and output matching impedances of the following circuit?



Reduce performance of differential circuit to a single mode of operation using mixed-mode s-parameters, and follow same procedure as single-ended 2-port.

$$\Gamma_1 = \frac{C_1^*}{|C_1|} \left[\frac{B_1}{2 \cdot |C_1|} - \sqrt{\frac{B_1^2}{2 \cdot |C_1|^2} - 1} \right]$$

$$\Gamma_0 = \frac{C_2^*}{|C_2|} \left[\frac{B_2}{2 \cdot |C_2|} - \sqrt{\frac{B_2^2}{2 \cdot |C_2|^2} - 1} \right]$$

where:

$$B_1 = 1 - |S_{DD22}|^2 + |S_{DD11}|^2 - |D|^2$$

$$B_2 = 1 - |S_{DD11}|^2 + |S_{DD22}|^2 - |D|^2$$

$$C_1 = S_{DD11} - D \cdot S_{DD22}^*$$

$$C_2 = S_{DD22} - D \cdot S_{DD11}^*$$

$$D = S_{DD11} \cdot S_{DD22} - S_{DD12} \cdot S_{DD21}$$



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This a place where many designers get stumped today because they look at this device as a four-port and know that the concept of simultaneous conjugate match does not exist for a device with more than two ports.

Earlier we showed how the mixed-mode s-parameters are defined mathematically, and how similar they are to single-ended s-parameters. A very powerful property of the mixed-mode s-parameters is that if a balanced device is isolated to a specific mode, the resulting two port parameters can be used exactly the way single-ended two-port s-parameters are used.

Even though our device has four *terminals*, it has only two *ports*, and we have defined it to be operating in a differential mode.

Therefore, if we isolate its operation to a differential mode, we know its performance from the upper-left quadrant of the mixed-mode s-matrix. This 2-by-2 sub-matrix can, therefore, be used the same way a 2-by-2 s-matrix is used for single-ended devices. The formulas are exactly the same, we simply substitute parameters.

Simultaneous Conjugate Match: Single-Ended vs. Differential

Single-Ended 2-Port

$$\Gamma_1 = \frac{C_1}{|C|} \left[\frac{B_1}{2|C|} - \sqrt{\frac{B_1^2}{2 \cdot |C|^2} - 1} \right]$$

$$\Gamma_0 = \frac{C_2}{|C|} \left[\frac{B_2}{2|C|} - \sqrt{\frac{B_2^2}{2 \cdot |C|^2} - 1} \right]$$

where:

$$B_1 = 1 - |S_{23}|^2 + |S_{11}|^2 - |D|^2$$

$$B_2 = 1 - |S_{11}|^2 + |S_{23}|^2 - |D|^2$$

$$C_1 = S_{11} - D \cdot S_{22}^*$$

$$C_2 = S_{22} - D \cdot S_{11}^*$$

$$D = S_{11} \cdot S_{22} - S_{12} \cdot S_{21}$$

Differential 2-Port

$$\Gamma_1 = \frac{C_1}{|C|} \left[\frac{B_1}{2|C|} - \sqrt{\frac{B_1^2}{2 \cdot |C|^2} - 1} \right]$$

$$\Gamma_0 = \frac{C_2}{|C|} \left[\frac{B_2}{2|C|} - \sqrt{\frac{B_2^2}{2 \cdot |C|^2} - 1} \right]$$

where:

$$B_1 = 1 - |S_{DD23}|^2 + |S_{DD11}|^2 - |D|^2$$

$$B_2 = 1 - |S_{DD11}|^2 + |S_{DD22}|^2 - |D|^2$$

$$C_1 = S_{DD11} - D \cdot S_{DD22}^*$$

$$C_2 = S_{DD22} - D \cdot S_{DD11}^*$$

$$D = S_{DD11} \cdot S_{DD22} - S_{DD12} \cdot S_{DD21}$$

Comparing these calculations one more time shows the similarities. They are identical except for a parameter substitution.

Using this technique, designing a differential device becomes as straightforward as designing a single-ended device.

Balanced Device Design Methodology

- Matching Example can be Also be Extended to Other Design Considerations (K, MAG, VSWR, Z, etc.)
- Reason is Parallel Approach to Parameter Derivation
- For Balanced Device, Use Identical Approach as Single-Ended Design
- Isolate Balanced Device to Specific Mode
 - Substitute Parameters
 - Example: ($S_{nm} \text{ @ } S_{Dnm}$)

The same formulas that relate single-ended two-port s-parameters to other performance parameters, such as stability factor, maximum available gain, VSWR, port impedance, and others, can also be applied to differential devices.

The reason, again, is that they have been mathematically derived in a similar manner as the single-ended parameters.

The implications are very significant. This allows the same design procedures that are used in the design of single-ended devices to be applied to the design of balanced devices. The key is to isolate the device to a specific mode of operation.

Outline

- Characteristics of Differential Topologies
- Measurement Alternatives
- Unbalanced and Balanced Performance Parameters
- Balanced Devices Design Methodology
- System Implementation
- Measurement Example
- Conclusion

This paper on balanced device characterization will cover the following topics:

First we will review the characteristics of balanced devices to understand why they are increasing in popularity for RF applications.

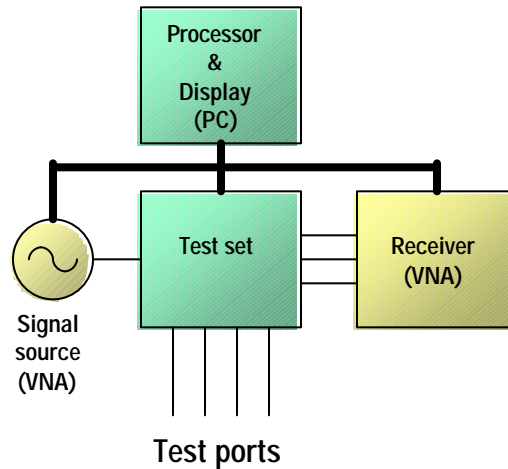
After that we will look at commonly used techniques for measuring these devices and their advantages and disadvantages.

Next we will consider a way of describing the behavior of balanced devices, and how this relates to a design methodology.

A system for characterizing balanced devices has been developed and will also be described.

Finally, before concluding, an example of a measurement on a balanced SAW filter will be discussed.

Hardware Architecture



The system that measures balanced devices and display mixed-mode s-parameters uses a hardware combination that includes a VNA and a balanced test set. An RF system is available using the 8753 or E835x PNA, as is a microwave system using the 8720.

The systems augment the Agilent VNA's by expanding the number of test ports from 2 to 4. The hardware configuration is not a switch matrix, but rather forms a true multiport test set that multiplexes into the source and receiver of the VNA.

The test set hardware increases the number of test ports to four, and the Windows-based software performs a true multiport vector error correction. This combination allows the accuracy of the two-port VNA to be extended to four-port unbalanced and two-port balanced device measurements.

It is important to note that a switch matrix approach is unsuitable for the balanced DUT application because the performance degradation resulting from using a switch matrix is not acceptable.

In this configuration, the VNA provides the source and receiver. The test set hardware provides the interface to the DUT, and the features that are normally part of the analyzer firmware, such as calibration routines, error correction, measurement routines, and user interface features, are built into the Windows-based software.

Configuration

RF Systems	Microwave Systems
VNA 8753C 8753D (opt. 011) 8753E (opt. 011) 8753ES (opt. 011 or 014) E835x PNA (opt. 015)	VNA 8720ES (opt. H32/H42)
Computer Pentium PC or better Windows 95, 98, or NT 1024 x 768 resolution or better 32MB RAM or more IEEE-488 Cards National Instruments (any) HP 82340, HP 82341	



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The VNA in the RF system requires either the delete test set option (011) or the configurable test set option (014 or 015).

In the microwave system, the 8720 VNA is augmented with two additional test ports on the test set hardware that complement the two built-in test ports. The option that provides the correct hardware hooks is H32 for a 3-channel system, or H42 for a 4-channel system.

In both cases the application software runs on a PC with the Windows 95, 98, or NT operating system. Both the test set and the VNA are completely controlled by the Windows-based software over the GPIB.

Complete System



- Complete Measurement with One-Time DUT Connection
- True 4-Port Test Set Hardware
- True 4-port vector error correction
- Accuracy of 2-port Measurement



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These photos show 6GHz and 20GHz systems that work with the 8753 and 8720 VNA's, respectively. This is a true 4-port measurement system with true 4-port error correction. Designing the systems in this way is essential for obtaining accurate mixed-mode s-parameter data.

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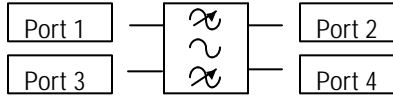
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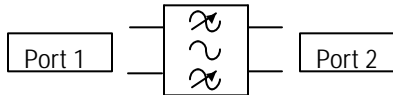
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SAW Filter Measurement Example

Single-Ended Representation (Conventional S-Parameters)

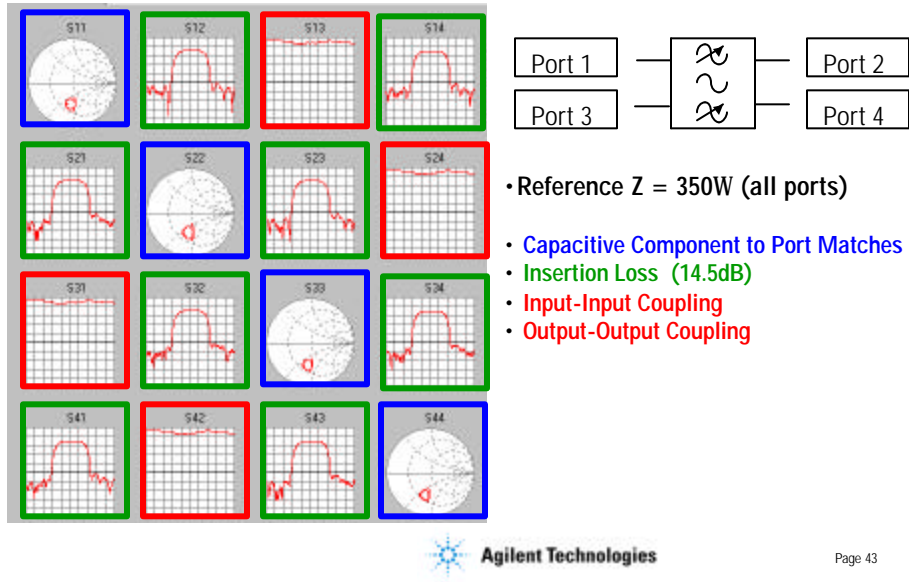


Balanced Representation (Mixed-Mode S-Parameters)



To illustrate the approach to balanced device characterization, measured data on a balanced SAW filter now will be discussed. We will look at both the single-ended data and the mixed-mode data to illustrate the importance of analyzing balanced devices in the intended mode of operation.

Single-Ended SAW Filter Performance

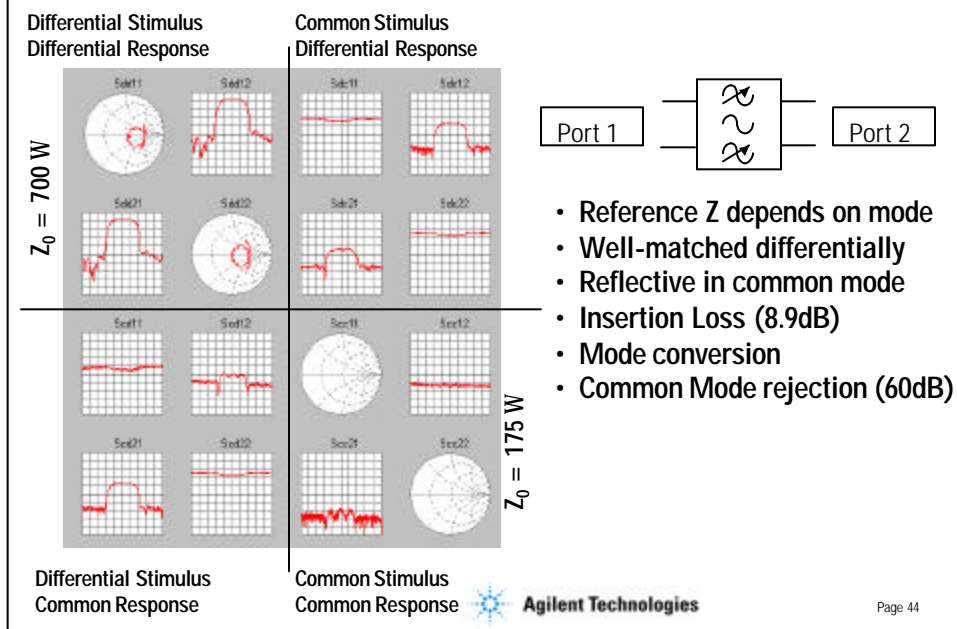


The single-ended 4-port data is shown here. The device was designed to have differential port impedances of 700 ohms. Therefore, the single-ended has been normalized to 350 ohms on each port. The single-ended port matches are shown along the diagonal. They all look similar, and exhibit a clear capacitive component to the impedance.

The parameters below the diagonal show the 6 transmission paths through the device. Among these are 4 that pass through the filter element, and 2 that describe the isolation between the balanced input and output pairs.

The six terms above the diagonal are the same 6 transmission paths in the opposite direction. Since this is a passive, reciprocal device, each parameter above the diagonal is equal to a parameter below the diagonal.

Balanced SAW Filter Performance



This slide shows the mixed-mode s-parameter data. The four quadrants describe the performance in each of its modes of operation.

The DD quadrant in the upper left corner shows the performance in a pure differential mode. This data is normalized to a reference impedance of 700 ohms differential. The input and output reflections now show a well-matched device. A differential device does not see the capacitance that a single-ended source sees. It is tempting to assume that the differential impedance is twice the single-ended impedance. In general this is not true as this example clearly shows. The transmission responses now give a much better indication of the performance of the device in its intended operating mode.

The CC quadrant is normalized to a reference impedance of 175 ohms common. In this mode the ports are very reflective, and very little of the signal is transmitted through the device (-70dB). A CMRR of 60dB can be calculated by dividing the differential-mode gain to the common-mode gain.

The CD and DC quadrants show the mode-conversion. These parameters are at least -25dB in-band. Whether this is acceptable depends on the system in which the device is used.

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Conclusions

- **Better accuracy than measurements made with a Balun**
- **Uses existing Calibration standards**
- **Comprehensive characterization (D-D, C-C, D-C, C-D)**
- **Describes behavior in intended operating mode**
 - not misleading like Single-Ended data
- **Insight into system performance considerations**

In conclusion, balanced devices are being increasingly used because of the many performance benefits they offer. The representation described here shows how the performance of balanced devices can be represented.

This technique provides much better accuracy than other commonly used alternate techniques, and does not require a new infrastructure of balanced calibration standards or balanced interconnect components.

The mixed-mode s-parameters comprehensively describe the performance of a DUT as a balanced device, and are not misleading like examining the single-ended s-parameters of a balanced device can be.

Measuring each operating mode of a balanced device provides very good insight into the impact that that device will have on the performance of the system.