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RF Balanced Device Characterization

Part 1 – January 14, 2003

Part 2 – January 23, 2003

Presented By:

Greg Amorese
David Ballo

RF Balanced Device Characterization

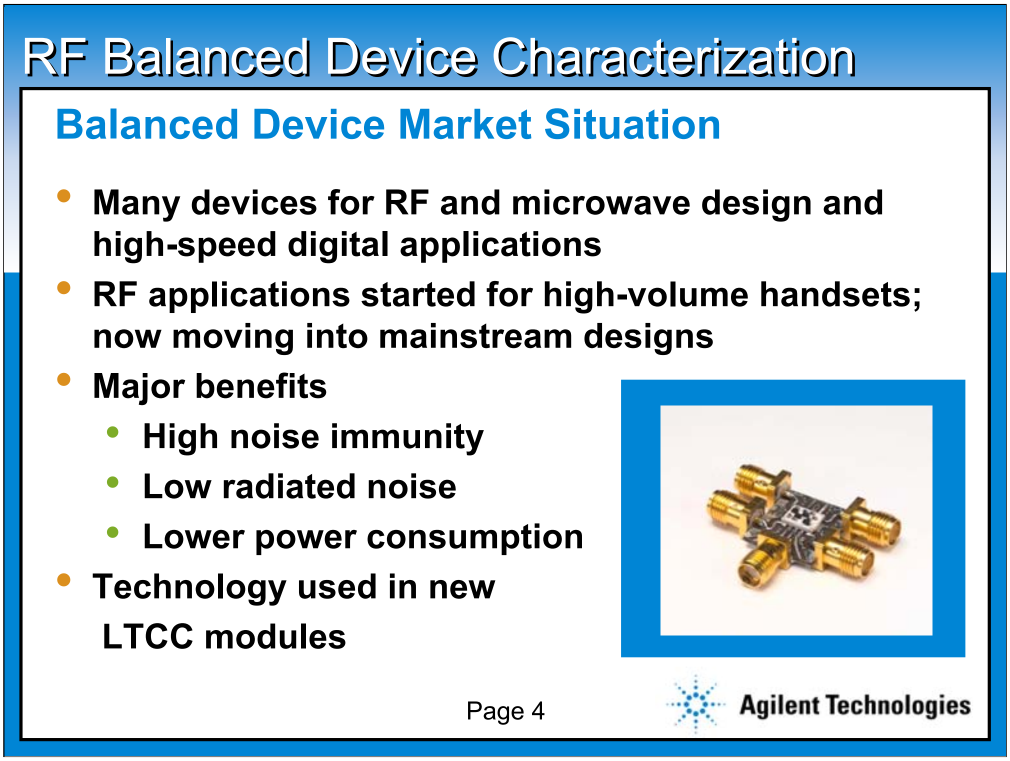
Part I Agenda (Today)

- *Balanced device overview*
- Measurement alternatives
- Mixed-mode S-parameters
- Balanced circuit design methodology
- Solution overview
- Measurement examples
- Conclusion

RF Balanced Device Characterization

Part II Agenda (January 23rd Broadcast Date)

- Detailed comparison of measurement alternatives
- Fixturing for balanced device measurements
- Calibration
- Introduction to using mixed-mode S-parameters for component and circuit design
- Conclusion



RF Balanced Device Characterization

Balanced Device Market Situation

- Many devices for RF and microwave design and high-speed digital applications
- RF applications started for high-volume handsets; now moving into mainstream designs
- Major benefits
  - High noise immunity
  - Low radiated noise
  - Lower power consumption
- Technology used in new LTCC modules

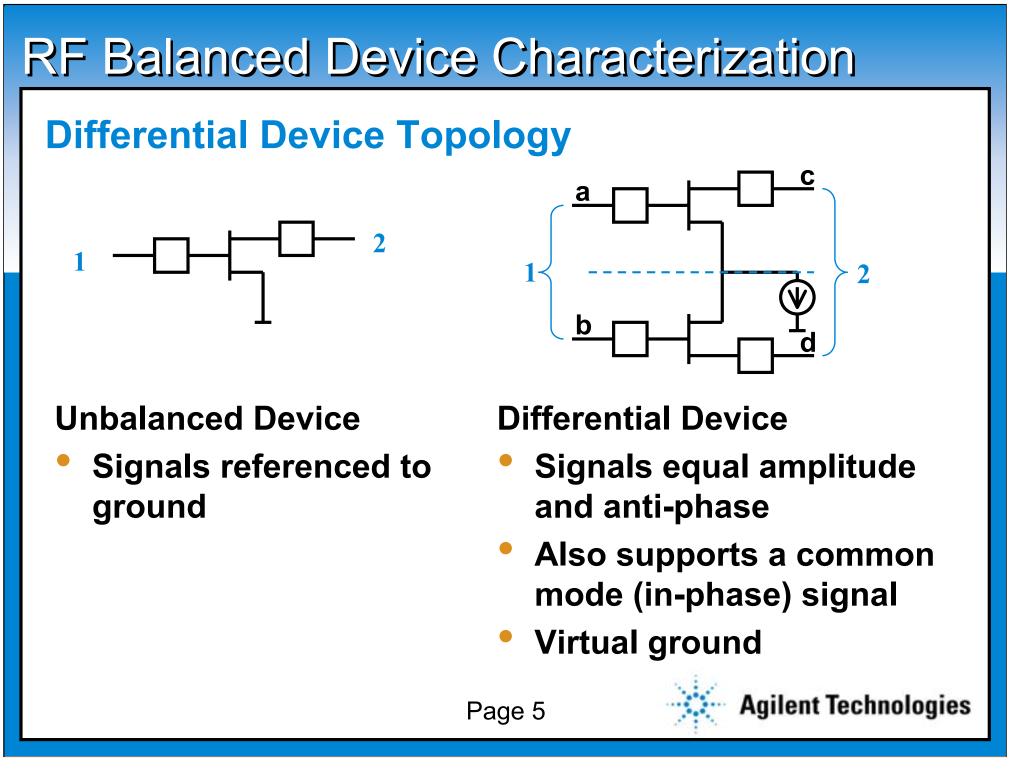
Balanced circuits have been used for many years because of their desirable performance characteristics. They have been mostly used in lower frequency analog circuitry and digital devices, and much less so in RF and microwave applications.

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.

Well-balanced circuits not only have reduced noise susceptibility, they also will have lower radiation of the signals those circuits are carrying (i.e. reduced EMI radiation).

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.



RF Balanced Device Characterization

Differential Device Topology

Unbalanced Device

- Signals referenced to ground

Differential Device

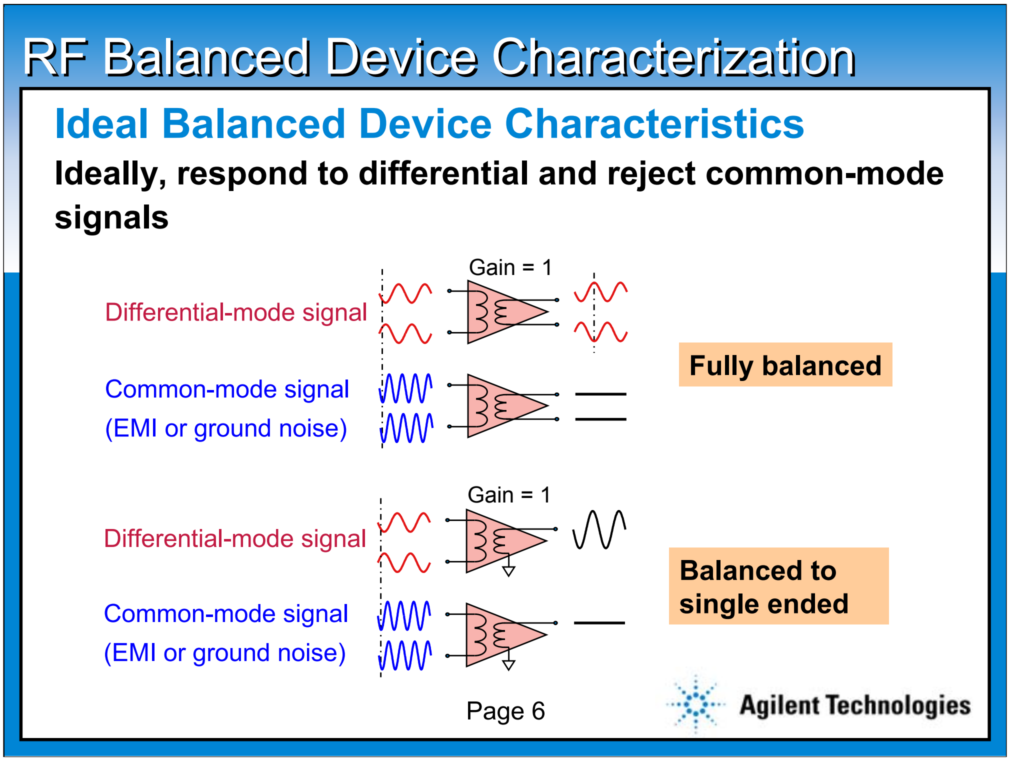
- Signals equal amplitude and anti-phase
- Also supports a common mode (in-phase) signal
- Virtual ground

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.



RF Balanced Device Characterization

Ideal Balanced Device Characteristics

Ideally, respond to differential and reject common-mode signals

Differential-mode signal

Common-mode signal
(EMI or ground noise)

Fully balanced

Differential-mode signal

Common-mode signal
(EMI or ground noise)

Balanced to single ended

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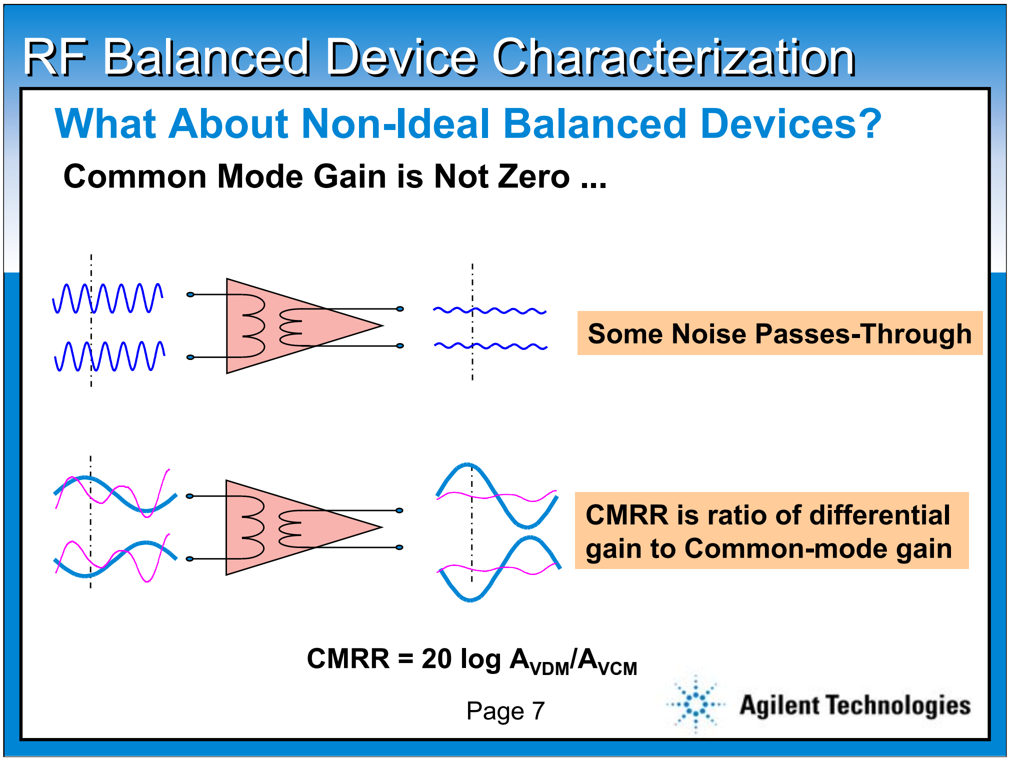
Differential signals are 180 deg. out of phase

Common mode signals are in phase

Differential input is desired mode of operation



RF Balanced Device Characterization

What About Non-Ideal Balanced Devices?

Common Mode Gain is Not Zero ...

Some Noise Passes-Through

CMRR is ratio of differential gain to Common-mode gain

CMRR = 20 log A_{VDM}/A_{VCM}

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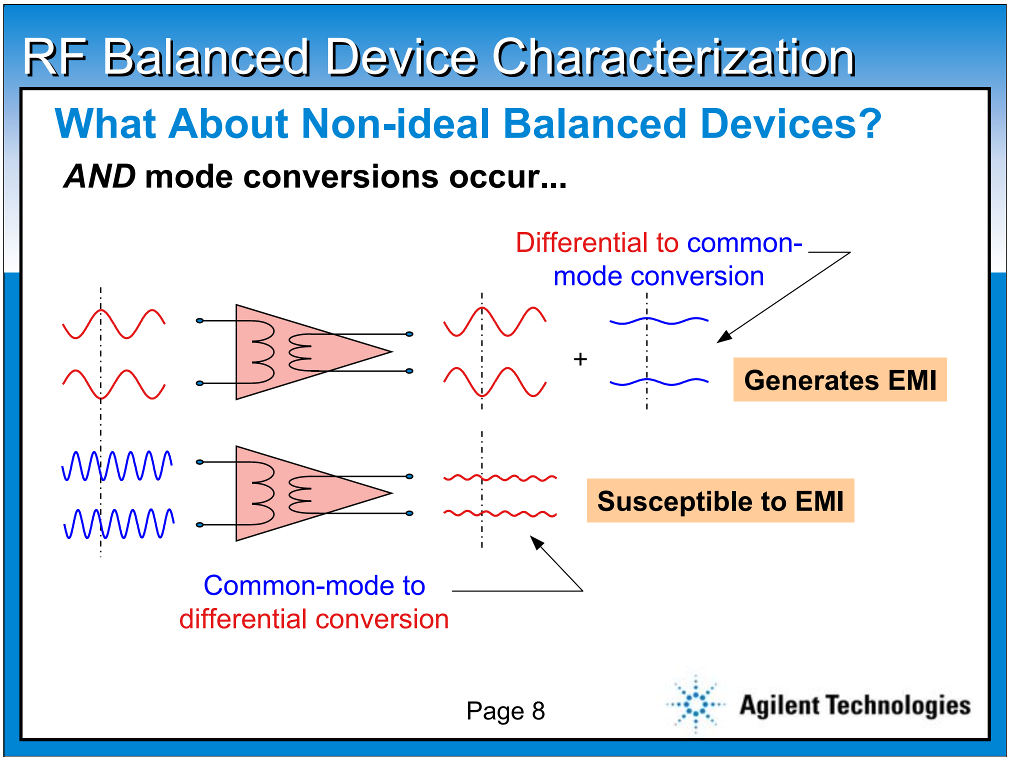
The previous slide showed the operation of an ideal balanced device. But designing high performance balanced components/devices and circuits is difficult and all devices will have some non-ideal behavior.

One of the key issues is the degree of balance of the device and how our DUT may affect the whole circuits degree of balance. As the degree of balance becomes worse, the device will perform what is called "mode conversion". If a device converts some of its incoming differential signal to common mode on its output, then the system (whole circuit) will generate EMI radiation. If a device converts some of its incoming common mode signal (typically noise) to differential on its output, that reduces the systems noise immunity.



RF Balanced Device Characterization

What About Non-ideal Balanced Devices?

AND **mode conversions occur...**

Differential to common-mode conversion

Generates EMI

Susceptible to EMI

Common-mode to differential conversion

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The previous slide showed the operation of an ideal balanced device. But designing high performance balanced components/devices and circuits is difficult and all devices will have some non-ideal behavior.

One of the key issues is the degree of balance of the device and how our DUT may affect the whole circuits degree of balance. As the degree of balance becomes worse, the device will perform what is called “mode conversion”. If a device converts some of its incoming differential signal to common mode on its output, then the system (whole circuit) will generate EMI radiation. If a device converts some of its incoming common mode signal (typically noise) to differential on its output, that reduces the systems noise immunity.

RF Balanced Device Characterization

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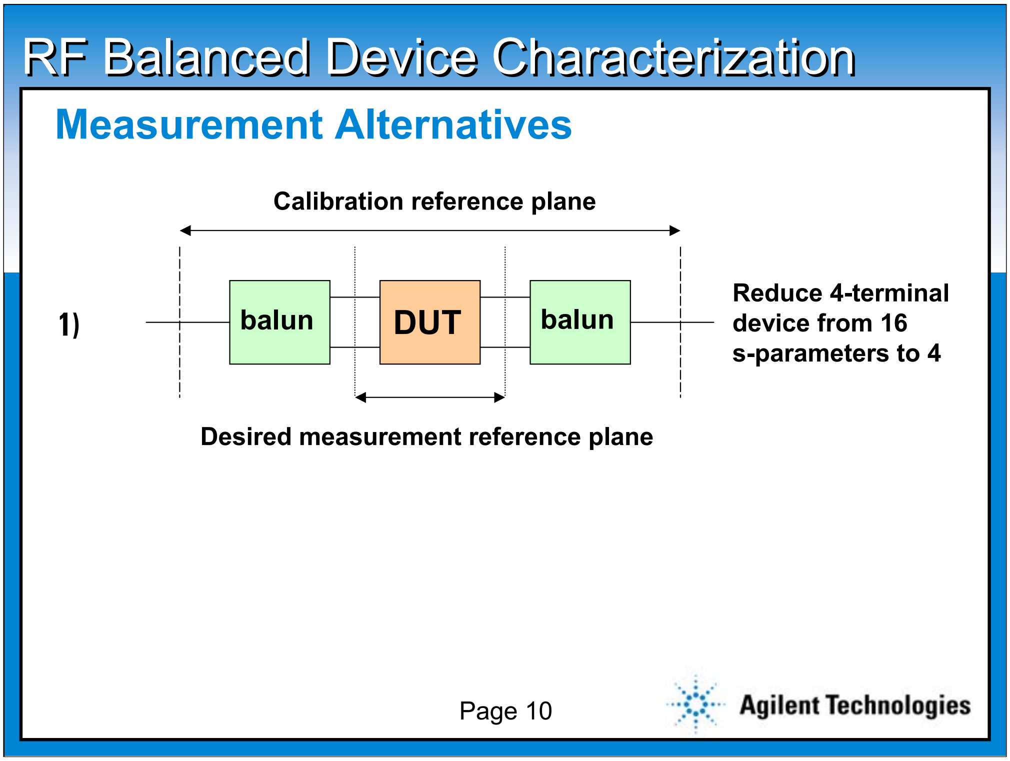
- Balanced device overview
- *Measurement alternatives*
- Mixed-mode S-parameters
- Balanced circuit design methodology
- Solution overview
- Measurement examples
- Conclusion



RF Balanced Device Characterization

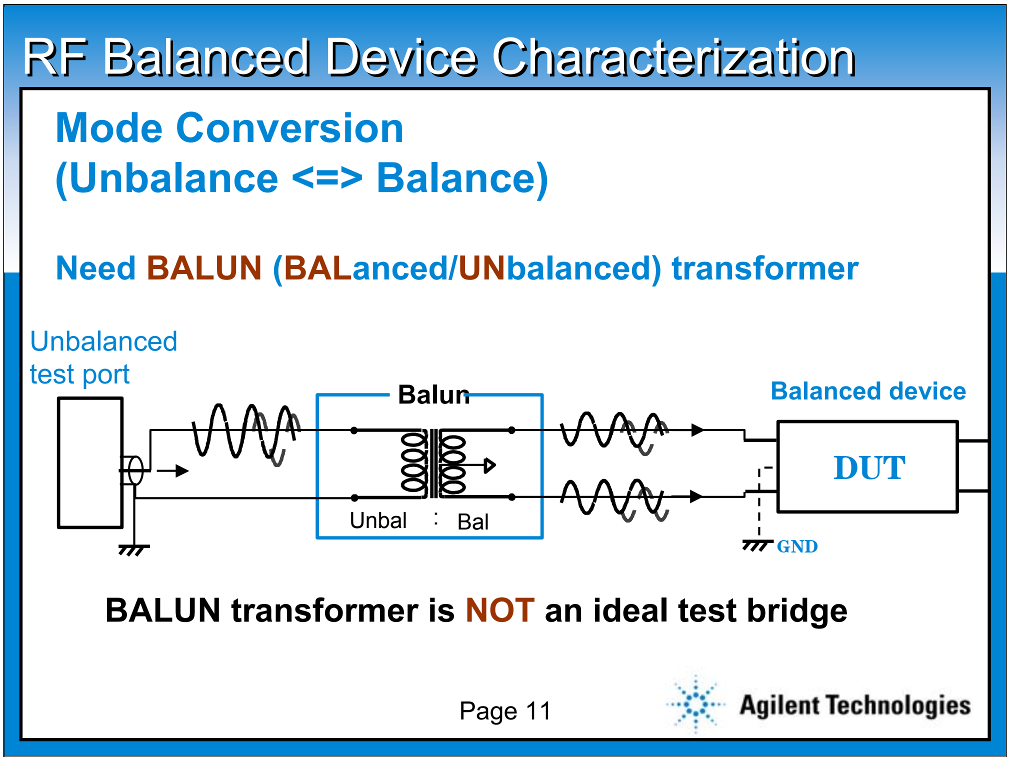
Measurement Alternatives

Calibration reference plane

Reduce 4-terminal device from 16 s-parameters to 4

Desired measurement reference plane

The first alternative (and historically most common) for measuring balanced devices 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.



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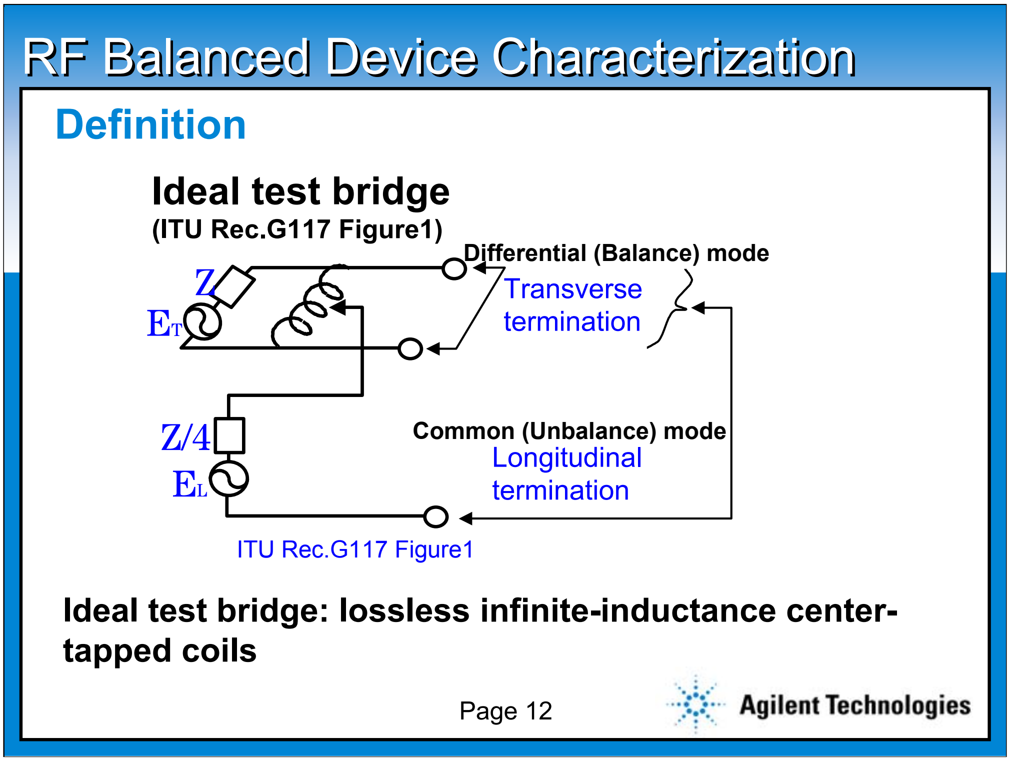
Mode Conversion
(Unbalance <=> Balance)

Need BALUN (BALanced/UNbalanced) transformer

BALUN transformer is NOT an ideal test bridge

It is important to note the difference between a balun and ideal test bridge. For example, you cannot look at the common mode performance of the device using a balun since no common mode signals are allowed through the balun due to it’s characteristics. A balun also looks like an infinite impedance to the device under test which will cause some measurement degradation because the device has a nominal impedance.



RF Balanced Device Characterization

Definition

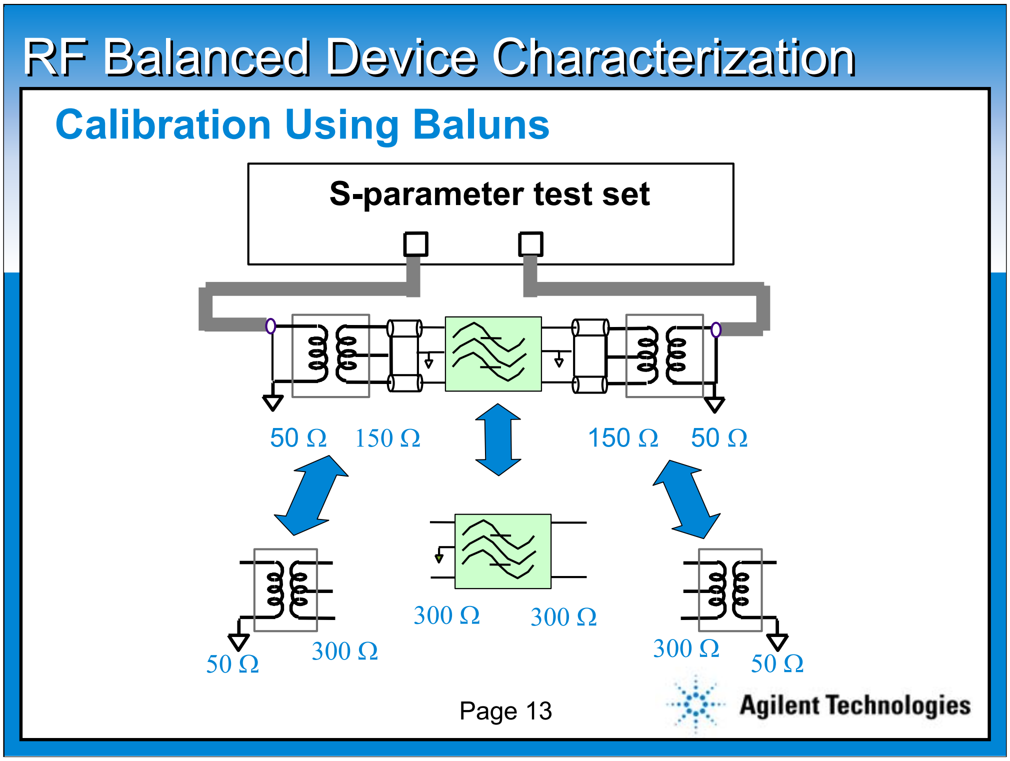
Ideal test bridge

(ITU Rec.G117 Figure1)

ITU Rec.G117 Figure1

Ideal test bridge: lossless infinite-inductance center-tapped coils

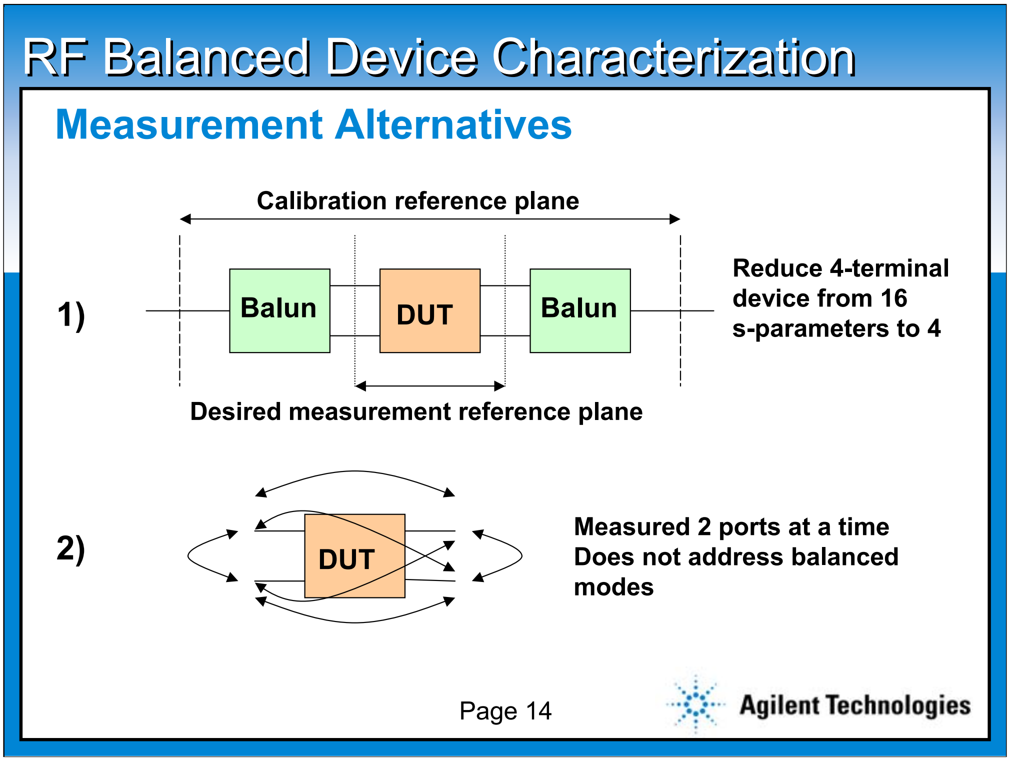
If we could specify the method of it would be using an ideal test bridge. The test bridge provides measurement capabilities for differential and common mode performance also known as mixed-mode parameters. In reality a physical structure such as this is very difficult to realize and even more difficult to perform a calibration on.



RF Balanced Device Characterization

Calibration Using Baluns

Another issue when using baluns is that we need many baluns (in theory 1 or 2 for each D UT impedance that we expect to measure). So we need many baluns. But we also have to calibrate our system and the affect of these non-ideal interfaces to our DUT's. Since no certified balanced standards exist (except at very low frequencies), we cannot directly do a calibration after the balun. The typical solution used is to do a traceable calibration at the standard connectors (e.g. SMA) and then perform a normalization by using a through (typically connecting the 2 baluns back-to-back. But a normalization has many limits on what errors can be corrected for. For example, the phase and amplitude imbalance of each of the baluns cannot be determined even though those can cause very major erros in the measurement of our DUT.



RF Balanced Device Characterization

Measurement Alternatives

1)

Reduce 4-terminal device from 16 s-parameters to 4

2)

Measured 2 ports at a time
Does not address balanced modes

The second approach 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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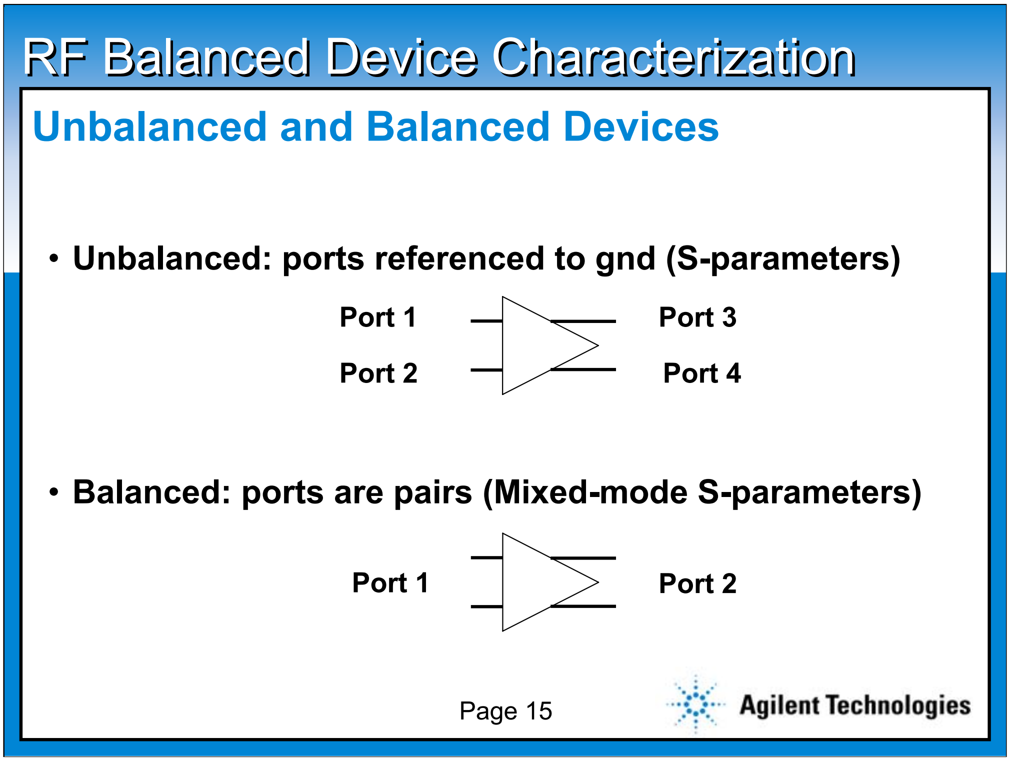

RF Balanced Device Characterization

Unbalanced and Balanced Devices

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

- Balanced: ports are pairs (Mixed-mode S-parameters)

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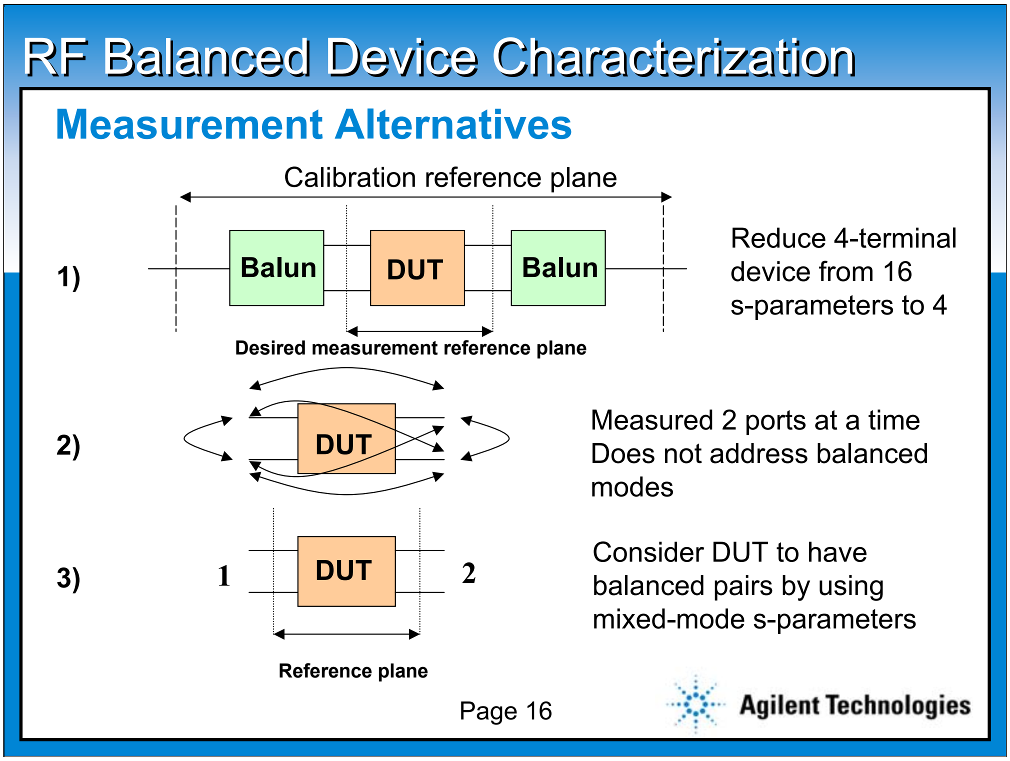

RF Balanced Device Characterization

Measurement Alternatives

1) Reduce 4-terminal device from 16 s-parameters to 4

2) Measured 2 ports at a time
Does not address balanced modes

3) Consider DUT to have balanced pairs by using mixed-mode s-parameters

The third method that is preferred for its accuracy, completeness, and ease of interpretation is to characterize the DUT using mixed-mode s-parameters such as measured on the Agilent Differential & Multiport Measurement Systems. In this example we treat the 4-terminal device as having only 2 ports but each of those ports are balanced ports (potentially carrying both common mode and differential mode signals). When we use this approach we can define the behavior of our device using "mixed-mode s-parameters".

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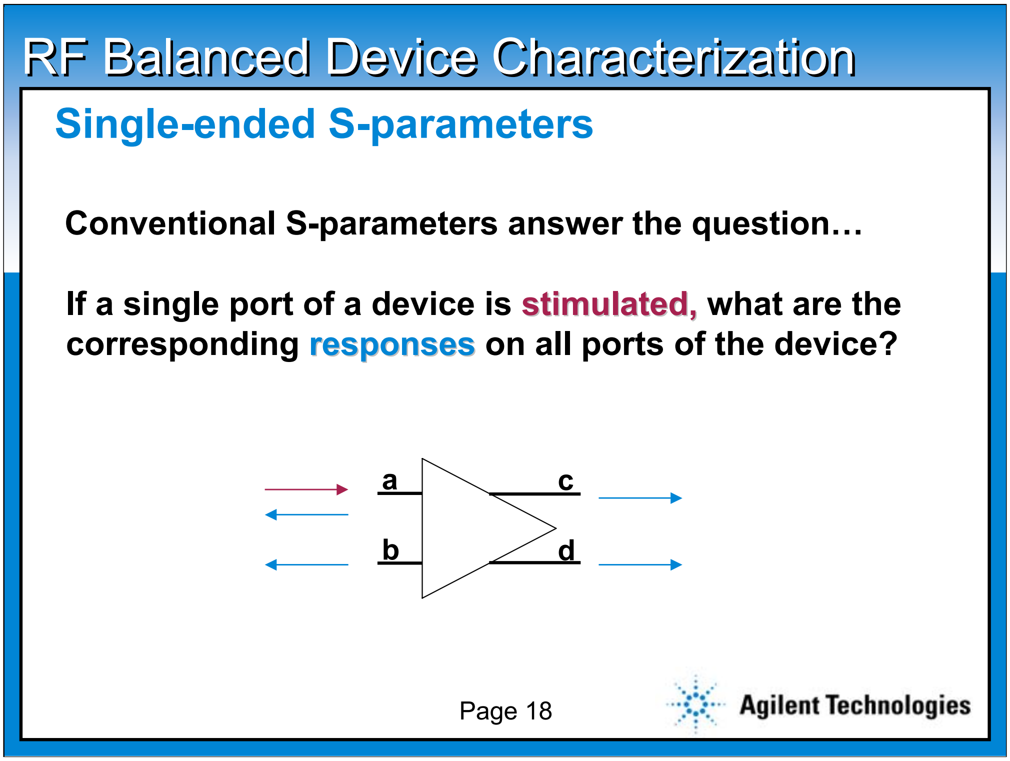


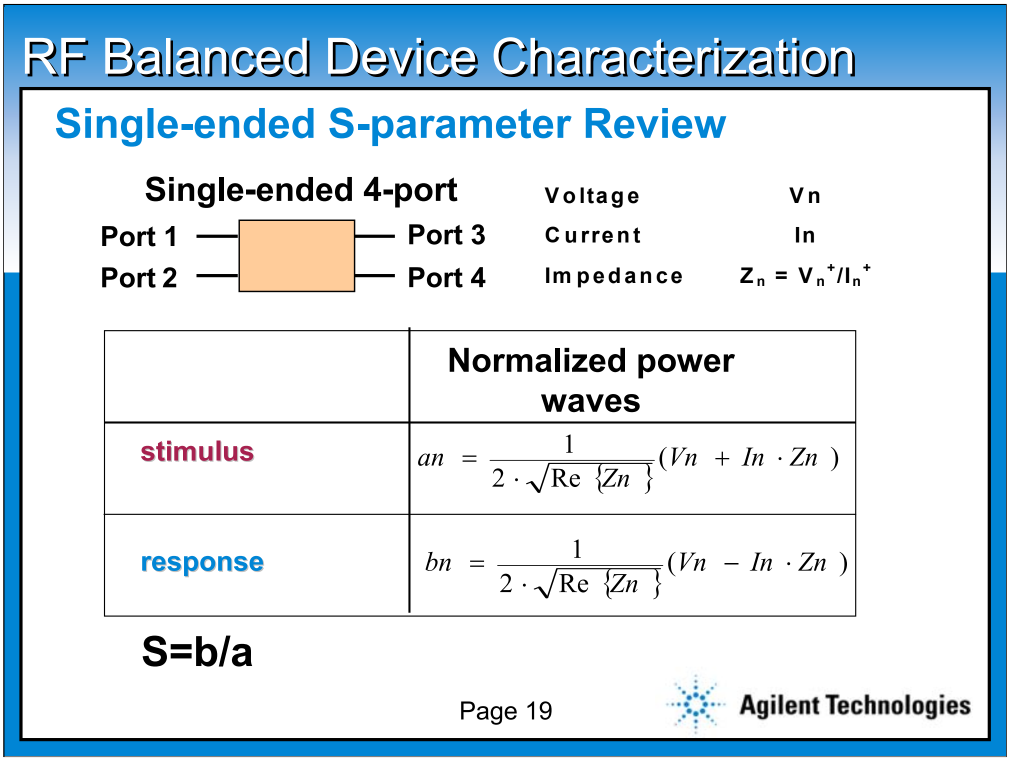
RF Balanced Device Characterization

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.



RF Balanced Device Characterization

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	$an = \frac{1}{2 \cdot \sqrt{\mathrm{Re}\,\{Zn\}}}(Vn + In \cdot Zn)$
response	$bn = \frac{1}{2 \cdot \sqrt{\mathrm{Re}\,\{Zn\}}}(Vn - In \cdot Zn)$

S=b/a

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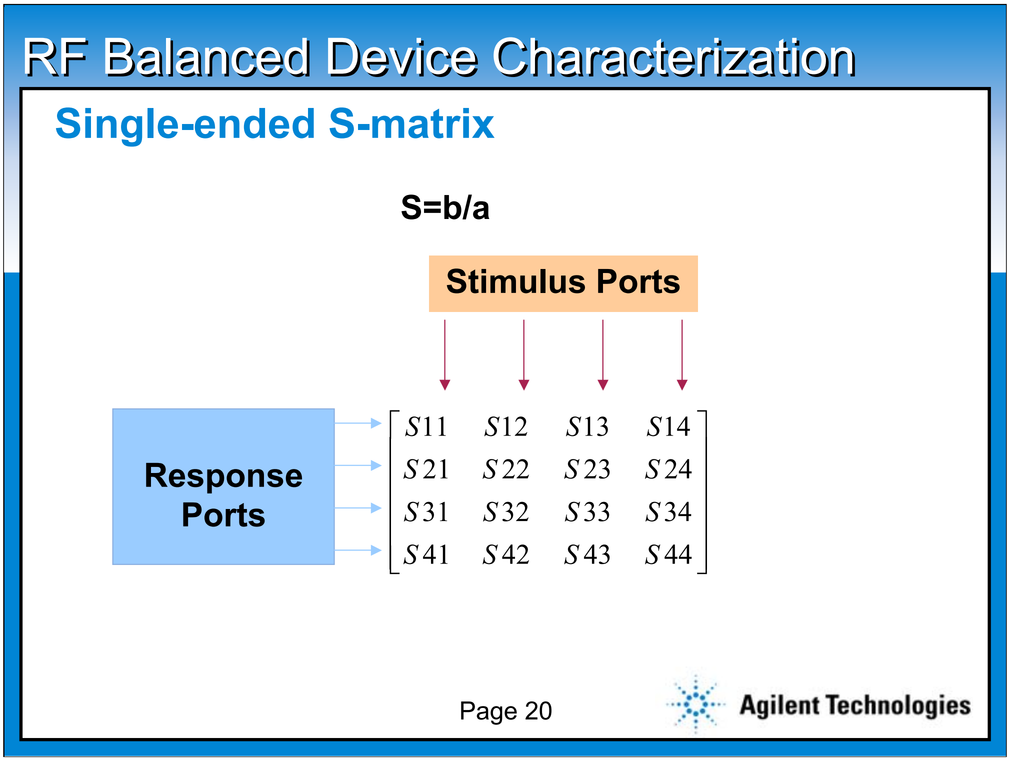
We have looked at the intuitive description of mixed-mode s-parameters. Now let's look at a more mathematical description.

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.



RF Balanced Device Characterization

Single-ended S-matrix

S=b/a

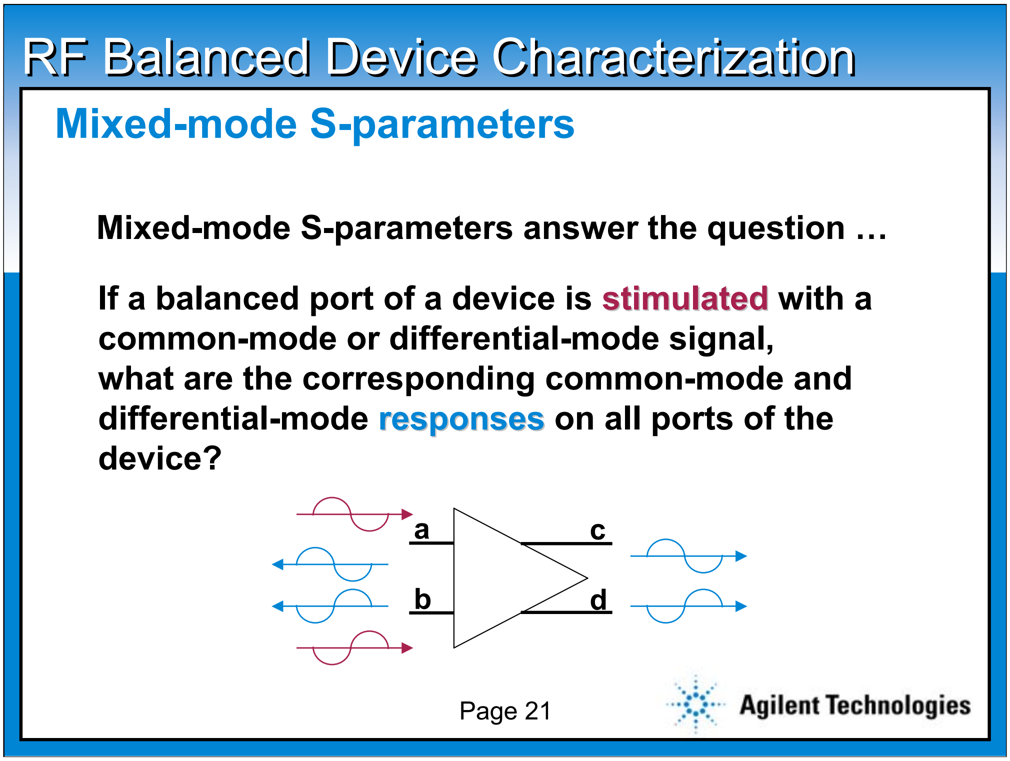
Stimulus Ports

Response Ports

$$\begin{bmatrix} S11 & S12 & S13 & S14 \\ S21 & S22 & S23 & S24 \\ S31 & S32 & S33 & S34 \\ S41 & S42 & S43 & S44 \end{bmatrix}$$

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.



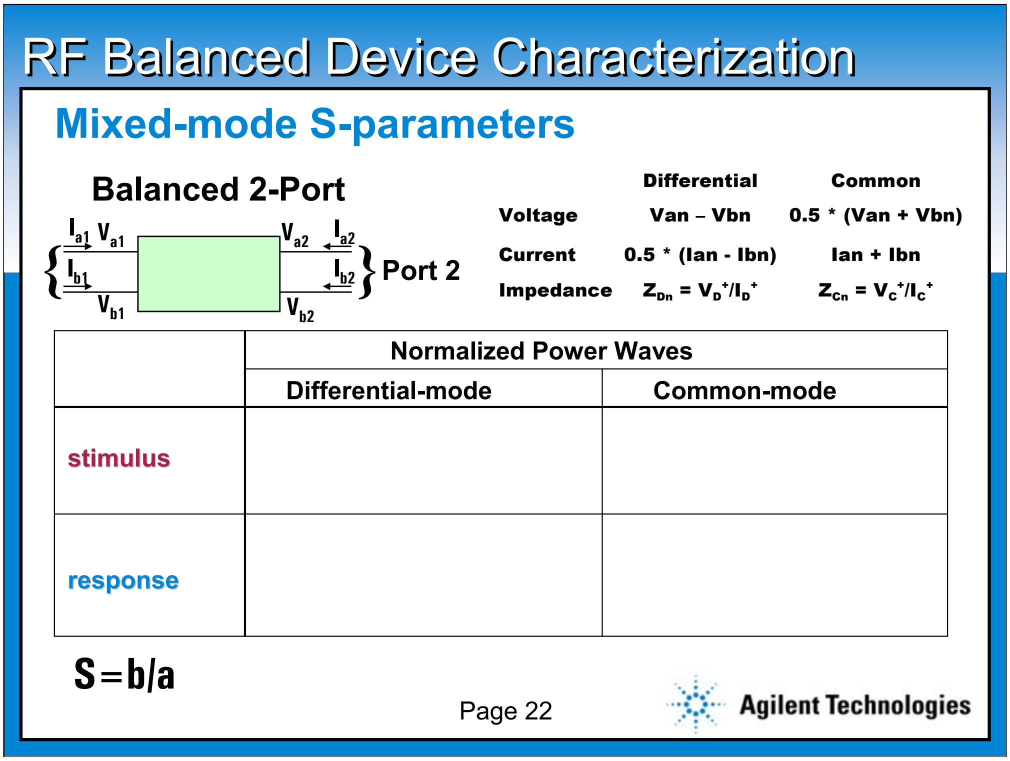
RF Balanced Device Characterization

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 to the single ended (traditional) s-parameters, 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?



RF Balanced Device Characterization

Mixed-mode S-parameters

Balanced 2-Port

	Differential	Common
Voltage	Van – Vbn	0.5 * (Van + Vbn)
Current	0.5 * (Ian - Ibn)	Ian + Ibn
Impedance	$Z_{Dn} = V_D^+/I_D^+$	$Z_{Cn} = V_C^+/I_C^+$

	Normalized Power Waves	
	Differential-mode	Common-mode
stimulus		
response		

$$S = b/a$$

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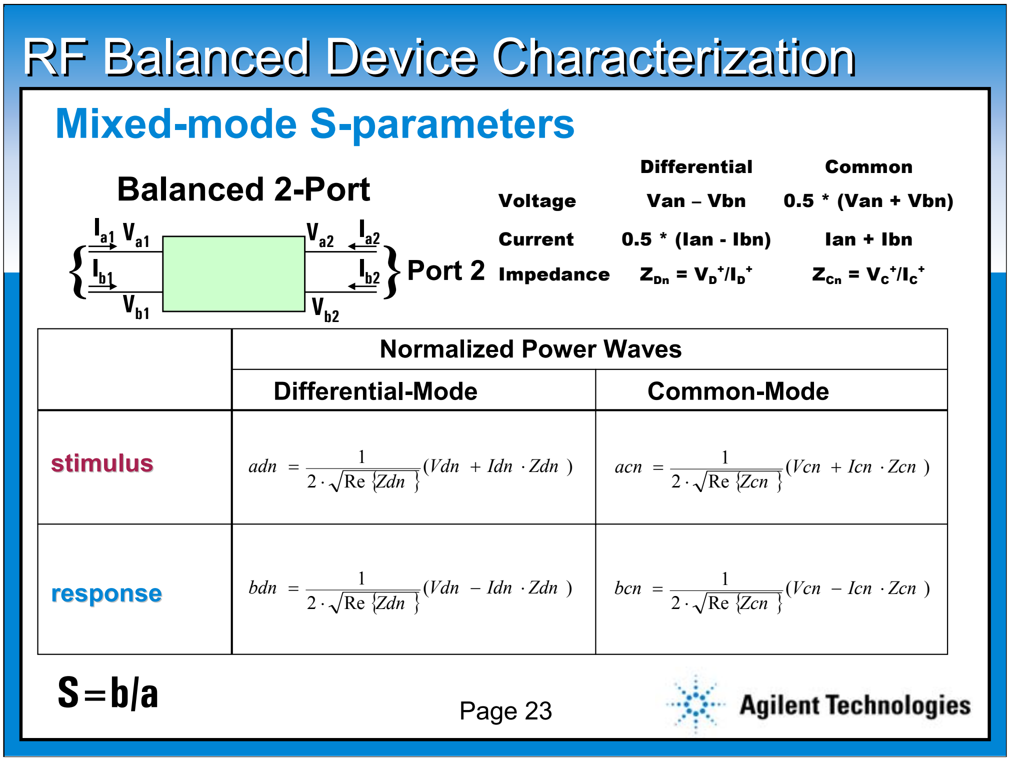
As with the single-ended case, we can also define normalized power waves on the ports of a balanced device. In this case they are mode-specific. The differential and common-mode voltages and currents defined earlier can be used for this, resulting in normalized power waves having the exact same form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



RF Balanced Device Characterization

Mixed-mode S-parameters

Balanced 2-Port

	Differential	Common
Voltage	**Van – Vbn**	**0.5 * (Van + Vbn)**
Current	**0.5 * (Ian - Ibn)**	**Ian + Ibn**
Impedance	$Z_{Dn} = V_D^+/I_D^+$	$Z_{Cn} = V_C^+/I_C^+$

	Normalized Power Waves	
	Differential-Mode	**Common-Mode**
stimulus	$adn = \frac{1}{2 \cdot \sqrt{\mathrm{Re}\{Zdn\}}}(Vdn + Idn \cdot Zdn)$	$acn = \frac{1}{2 \cdot \sqrt{\mathrm{Re}\{Zcn\}}}(Vcn + Icn \cdot Zcn)$
response	$bdn = \frac{1}{2 \cdot \sqrt{\mathrm{Re}\{Zdn\}}}(Vdn - Idn \cdot Zdn)$	$bcn = \frac{1}{2 \cdot \sqrt{\mathrm{Re}\{Zcn\}}}(Vcn - Icn \cdot Zcn)$

S=b/a

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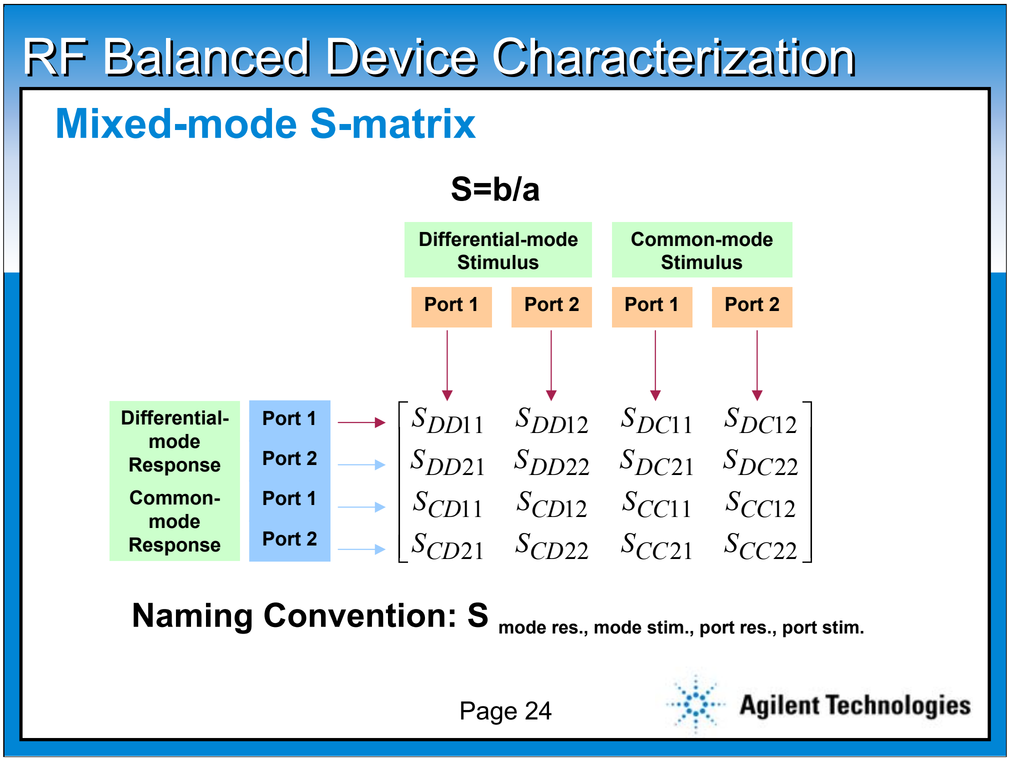


RF Balanced Device Characterization

Mixed-mode S-matrix

S=b/a

$$\begin{array}{llcccc}
 & & \text{Differential-mode Stimulus} & & \text{Common-mode Stimulus} & \\
 & & \text{Port 1} & \text{Port 2} & \text{Port 1} & \text{Port 2} \\
\text{Differential-mode Response} & \text{Port 1} & S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\
 & \text{Port 2} & S_{DD21} & S_{DD22} & S_{DC21} & S_{DC22} \\
\text{Common-mode Response} & \text{Port 1} & S_{CD11} & S_{CD12} & S_{CC11} & S_{CC12} \\
 & \text{Port 2} & S_{CD21} & S_{CD22} & S_{CC21} & S_{CC22}
\end{array}$$

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

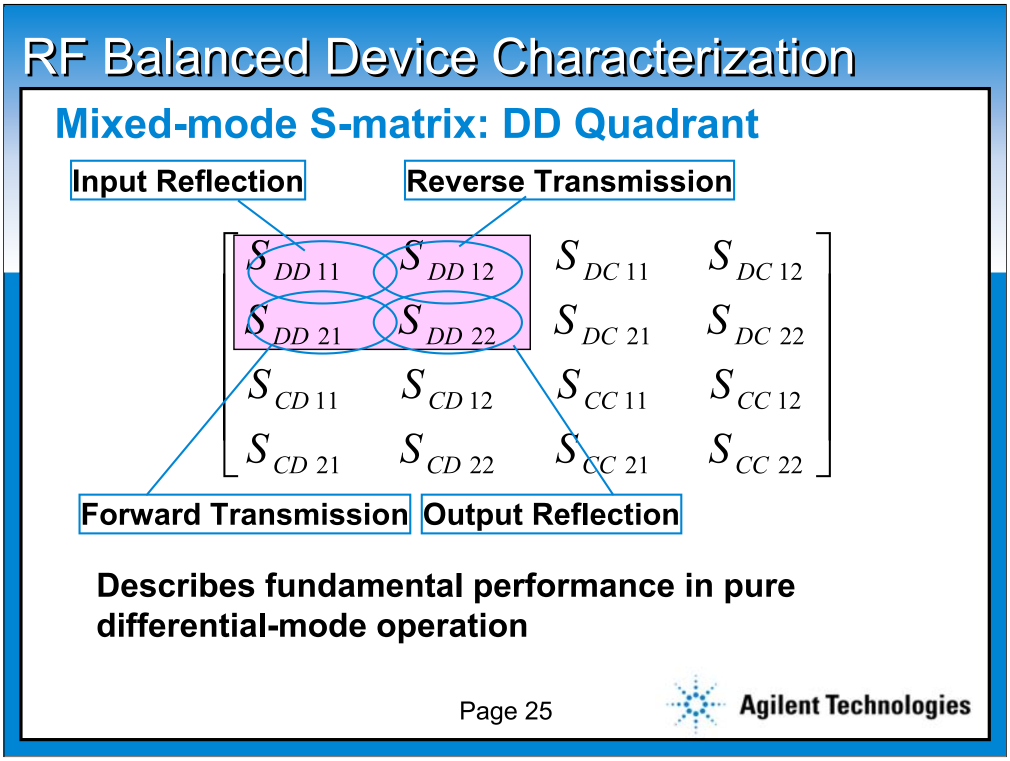
Again we can take a ratio of all of the possible combinations of response over stimulus for the differential and common-mode normalized power waves to calculate the mixed-mode s-parameters.

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.



RF Balanced Device Characterization

Mixed-mode S-matrix: DD Quadrant

Input Reflection

Reverse Transmission

$$\begin{bmatrix} S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\ S_{DD21} & S_{DD22} & S_{DC21} & S_{DC22} \\ S_{CD11} & S_{CD12} & S_{CC11} & S_{CC12} \\ S_{CD21} & S_{CD22} & S_{CC21} & S_{CC22} \end{bmatrix}$$

Forward Transmission

Output Reflection

Describes fundamental performance in pure differential-mode operation

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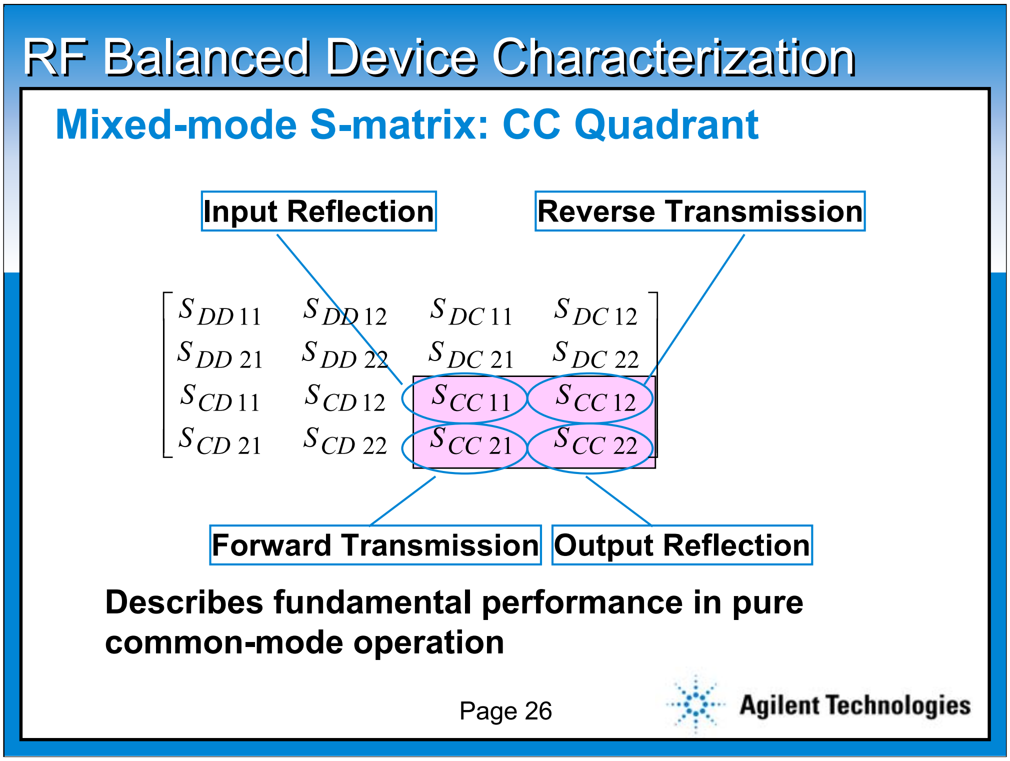
For a device with two balanced ports, the quadrant in the upper left corner of the mixed-mode s-matrix describes the performance with a differential stimulus and differential response. When the performance of the device is isolated to this specific mode, these four parameters describe the input and output 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.



RF Balanced Device Characterization

Mixed-mode S-matrix: CC Quadrant

Input Reflection

Reverse Transmission

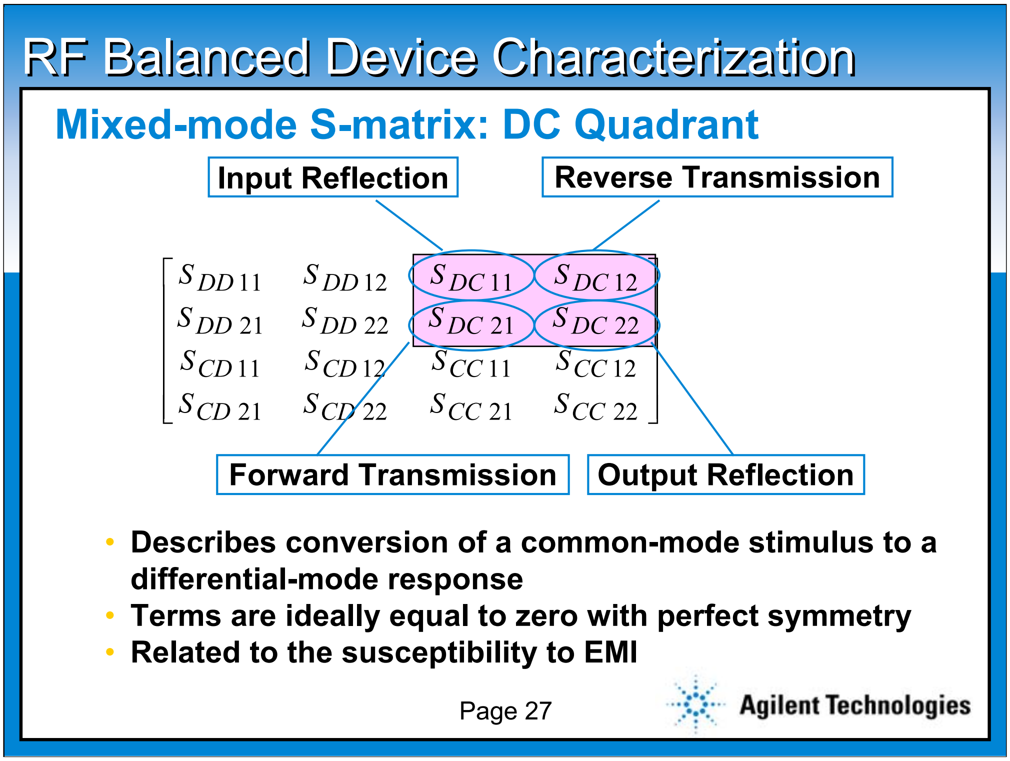
$$\begin{bmatrix} S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\ S_{DD21} & S_{DD22} & S_{DC21} & S_{DC22} \\ S_{CD11} & S_{CD12} & S_{CC11} & S_{CC12} \\ S_{CD21} & S_{CD22} & S_{CC21} & S_{CC22} \end{bmatrix}$$

Forward Transmission

Output Reflection

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.



RF Balanced Device Characterization

Mixed-mode S-matrix: DC Quadrant

Input Reflection

Reverse Transmission

$$\begin{bmatrix} S_{DD11} & S_{DD12} & \boxed{S_{DC11}} & \boxed{S_{DC12}} \\ S_{DD21} & S_{DD22} & \boxed{S_{DC21}} & \boxed{S_{DC22}} \\ S_{CD11} & S_{CD12} & S_{CC11} & S_{CC12} \\ S_{CD21} & S_{CD22} & S_{CC21} & S_{CC22} \end{bmatrix}$$

Forward Transmission

Output Reflection

- 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

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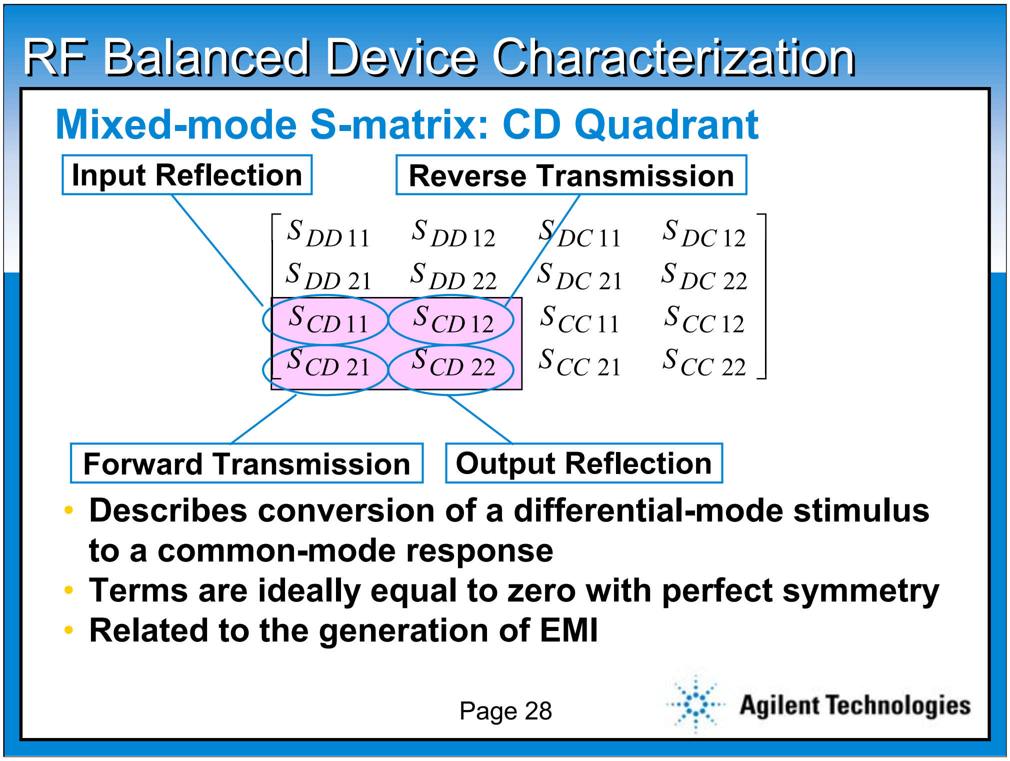
Finally, the parameters in the upper right corner describe the differential response of a device to a common-mode stimulus. Again, there are reflection parameters on each port, and transmission parameters in each direction.

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.

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.

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.



RF Balanced Device Characterization

Mixed-mode S-matrix: CD Quadrant

Input Reflection

Reverse Transmission

$$\begin{bmatrix} S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\ S_{DD21} & S_{DD22} & S_{DC21} & S_{DC22} \\ \boxed{S_{CD11}} & \boxed{S_{CD12}} & S_{CC11} & S_{CC12} \\ \boxed{S_{CD21}} & \boxed{S_{CD22}} & S_{CC21} & S_{CC22} \end{bmatrix}$$

Forward Transmission

Output Reflection

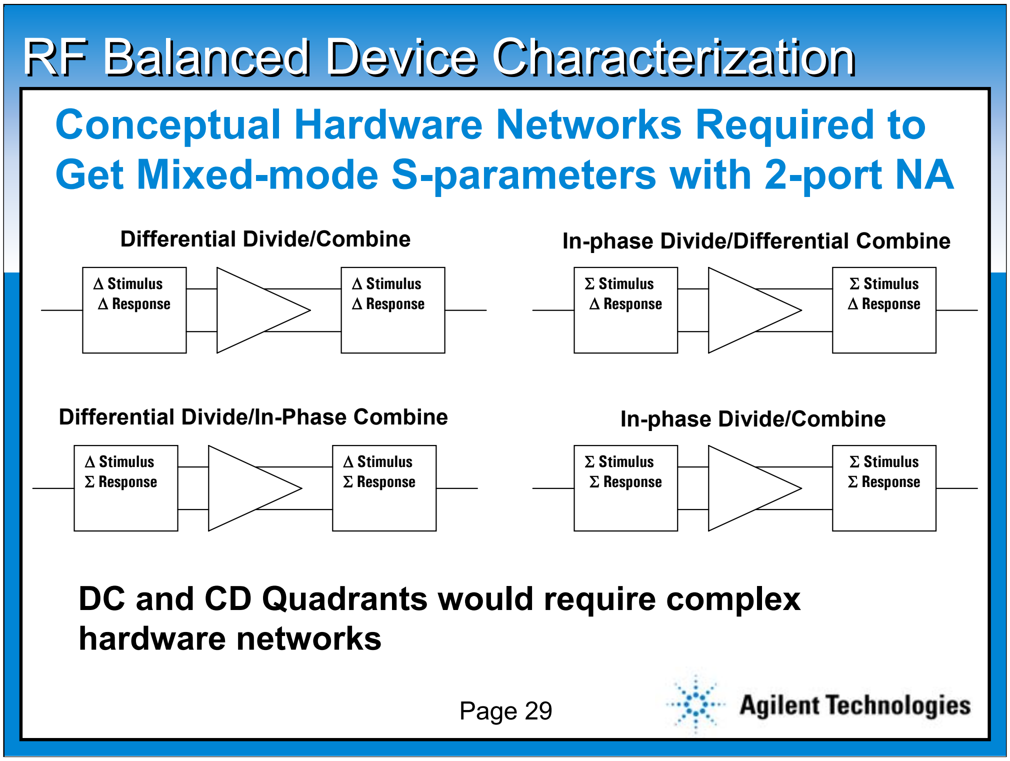
- Describes conversion of a differential-mode stimulus to a common-mode response
- Terms are ideally equal to zero with perfect symmetry
- Related to the generation of EMI

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.

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

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.



RF Balanced Device Characterization

Conceptual Hardware Networks Required to Get Mixed-mode S-parameters with 2-port NA

Differential Divide/Combine

Δ Stimulus
Δ Response

Δ Stimulus
Δ Response

In-phase Divide/Differential Combine

Σ Stimulus
Δ Response

Σ Stimulus
Δ Response

Differential Divide/In-Phase Combine

Δ Stimulus
Σ Response

Δ Stimulus
Σ Response

In-phase Divide/Combine

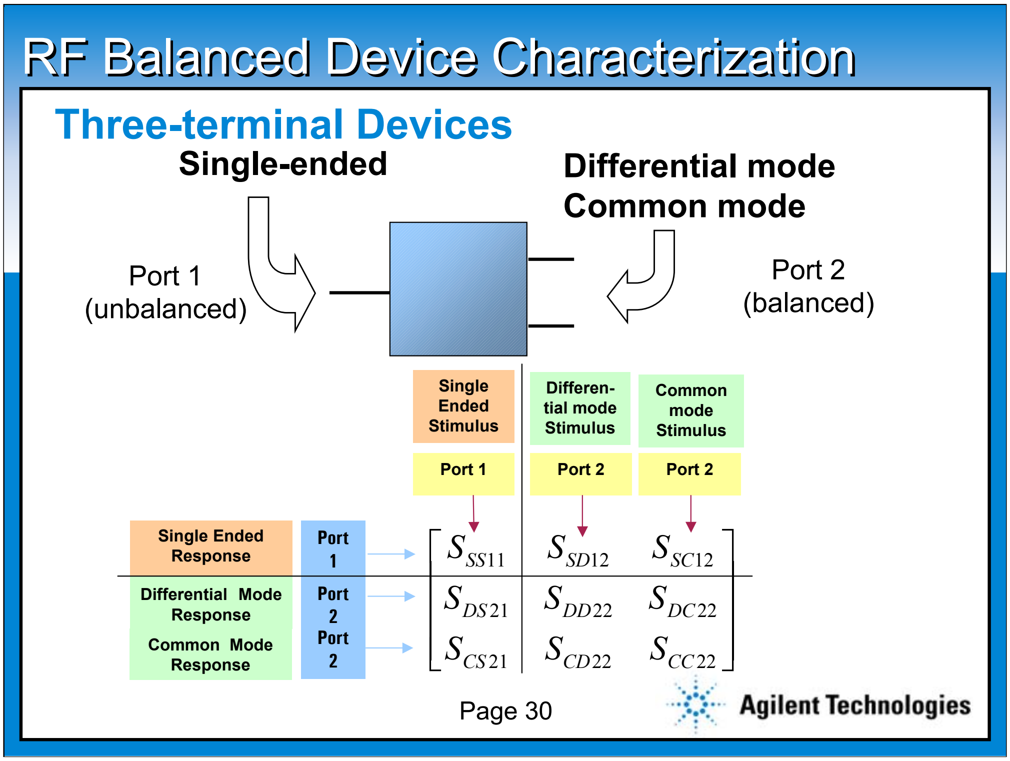
Σ Stimulus
Σ Response

Σ Stimulus
Σ Response

DC and CD Quadrants would require complex hardware networks

Agilent Technologies

In theory we could try to measure mixed-mode s-parameters by using a standard 2-port NA and special measuring circuits that would perform the signal conversion necessary based on the definitions of mixed-mode s-parameters. In practice making those special measuring circuits work well is almost impossible.



RF Balanced Device Characterization

Three-terminal Devices

Single-ended

Differential mode
Common mode

Port 1
(unbalanced)

Port 2
(balanced)

$$\begin{array}{c|c|c|c} & \text{Single Ended Stimulus, Port 1} & \text{Differential mode Stimulus, Port 2} & \text{Common mode Stimulus, Port 2} \\ \hline \text{Single Ended Response, Port 1} & S_{SS11} & S_{SD12} & S_{SC12} \\ \hline \text{Differential Mode Response, Port 2} & S_{DS21} & S_{DD22} & S_{DC22} \\ \text{Common Mode Response, Port 2} & S_{CS21} & S_{CD22} & S_{CC22} \end{array}$$

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.

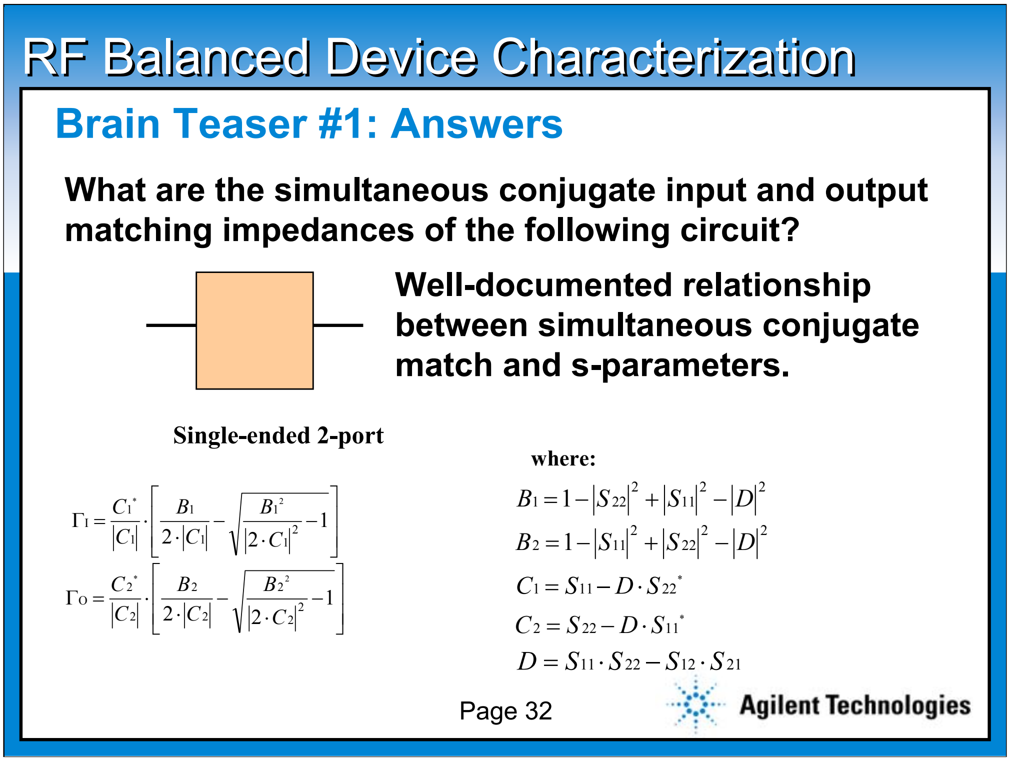
The s-matrix for such a device is again arranged with the stimulus conditions in the columns, and the response conditions in the rows. Notice that two columns and two rows describe each balanced port, and one column and one row describe each single-ended port.

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 revere directions.

RF Balanced Device Characterization

Agenda

- Balanced device overview
- Measurement alternatives
- Mixed-mode S-parameters
- *Balanced circuit design methodology*
- Solution overview
- Measurement examples
- Conclusion



RF Balanced Device Characterization

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

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

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

where:

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

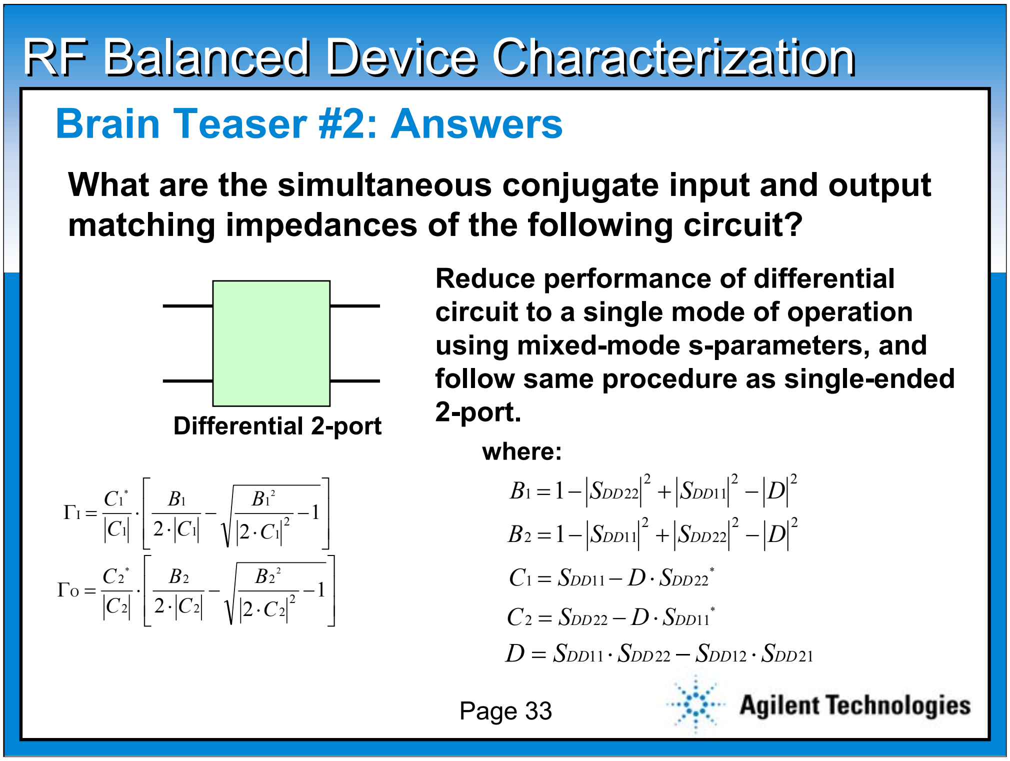
$$B_2 = 1 - |S_{11}|^2 + |S_{22}|^2 - |D|^2$$

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

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

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

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.



RF Balanced Device Characterization

Brain Teaser #2: Answers

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

Differential 2-port

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.

where:

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

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

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

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

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

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

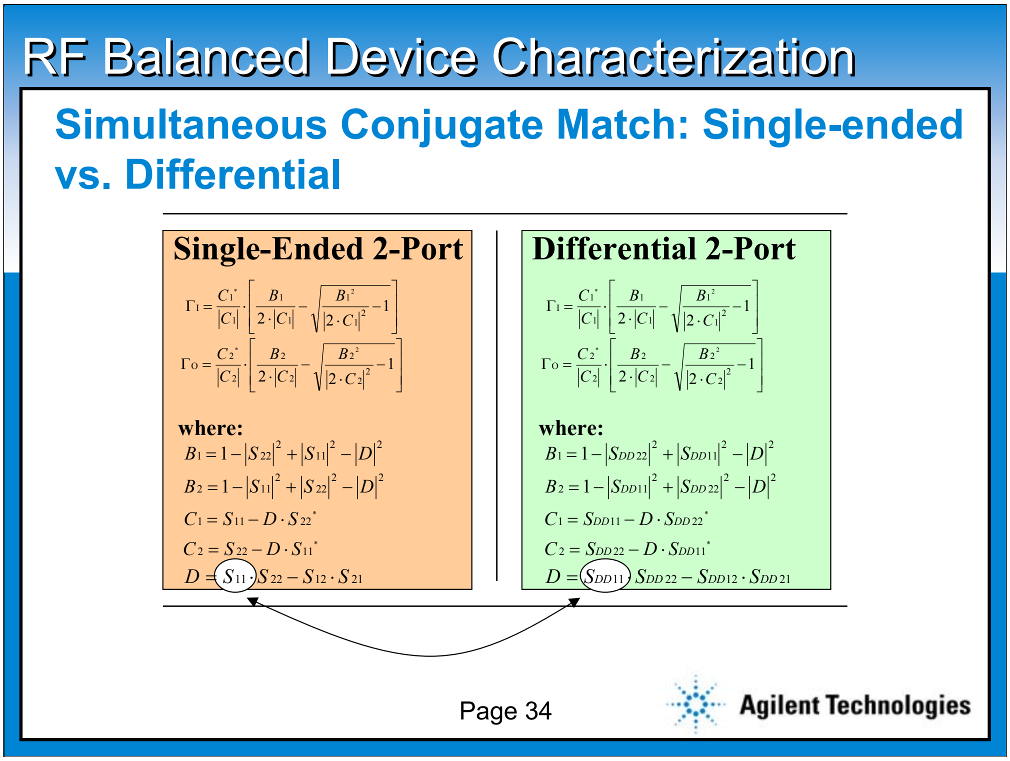
$$D = S_{DD11} \cdot S_{DD22} - S_{DD12} \cdot S_{DD21}$$

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.



RF Balanced Device Characterization

Simultaneous Conjugate Match: Single-ended vs. Differential

Single-Ended 2-Port

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

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

where:

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

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

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

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

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

Differential 2-Port

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

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

where:

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

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

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

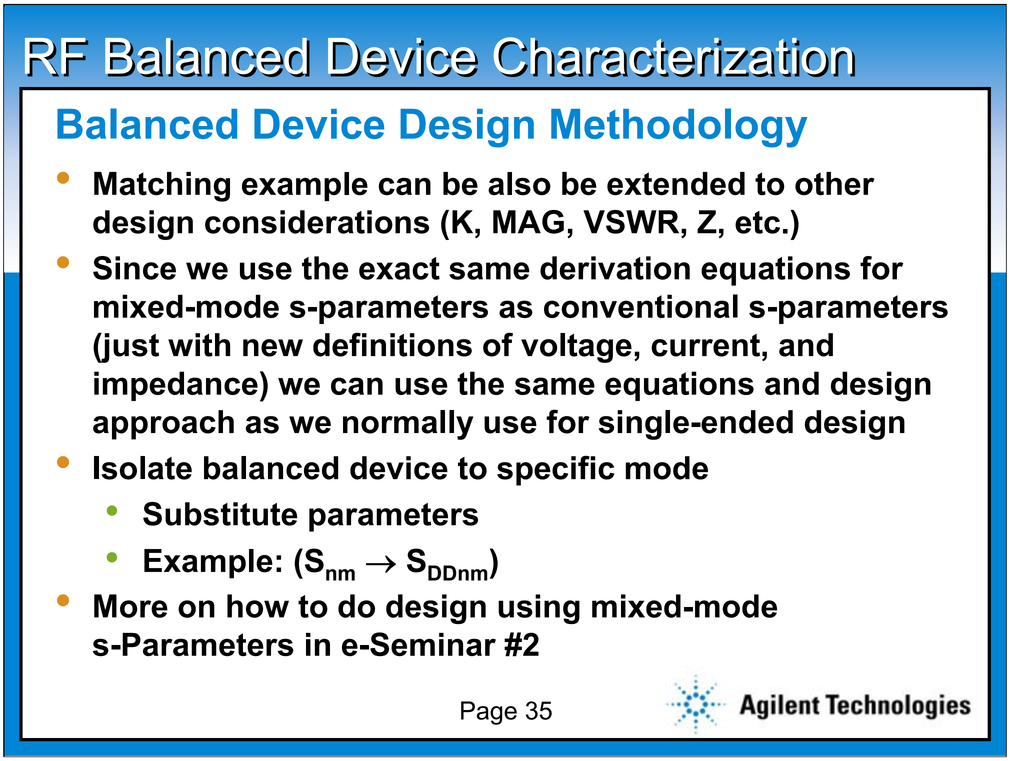
$C_2 = S_{DD22} - D \cdot S_{DD11}^*$

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

Agilent Technologies

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.



RF Balanced Device Characterization

Balanced Device Design Methodology

- Matching example can be also be extended to other design considerations (K, MAG, VSWR, Z, etc.)
- Since we use the exact same derivation equations for mixed-mode s-parameters as conventional s-parameters (just with new definitions of voltage, current, and impedance) we can use the same equations and design approach as we normally use for single-ended design
- Isolate balanced device to specific mode
  - Substitute parameters
  - Example: ($S_{nm} \rightarrow S_{DDnm}$)
- More on how to do design using mixed-mode s-Parameters in e-Seminar #2

Agilent Technologies

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.

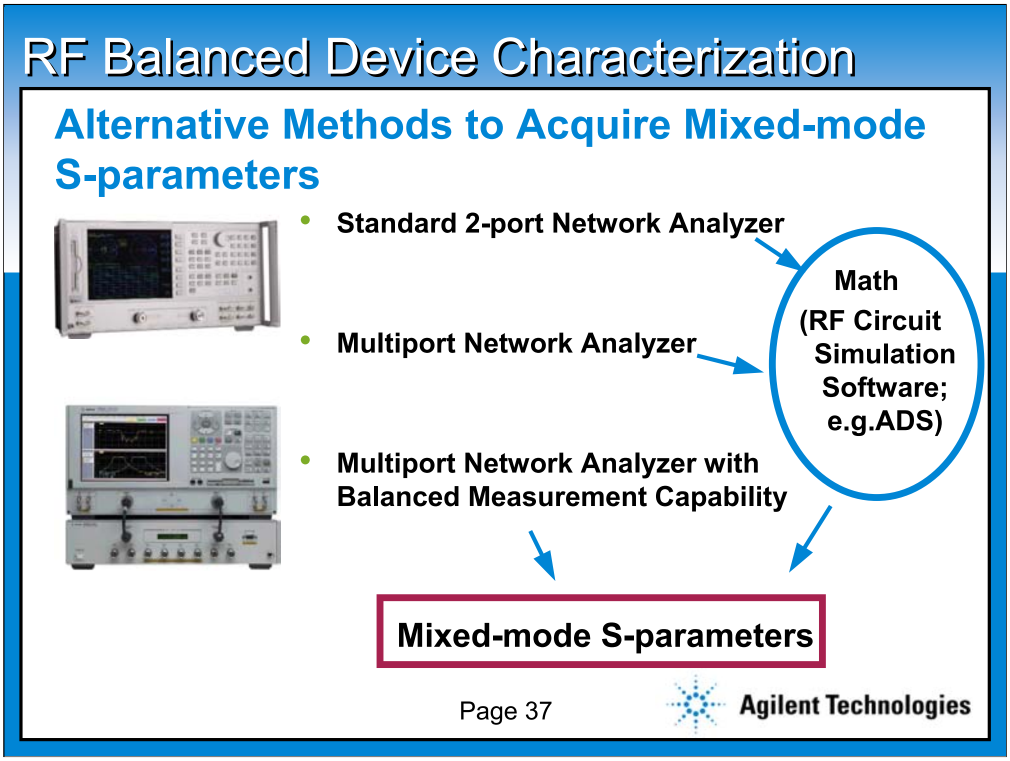
The reason, again, is that they have been mathematically derived in a similar manner as the single-ended parameters.

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.

RF Balanced Device Characterization

Agenda

- **Balanced device overview**
- **Measurement alternatives**
- **Mixed-mode S-parameters**
- **Balanced circuit design methodology**
- ***Solution overview***
- **Measurement examples**
- **Conclusion**



RF Balanced Device Characterization

Alternative Methods to Acquire Mixed-mode S-parameters

- Standard 2-port Network Analyzer
- Multiport Network Analyzer
- Multiport Network Analyzer with Balanced Measurement Capability

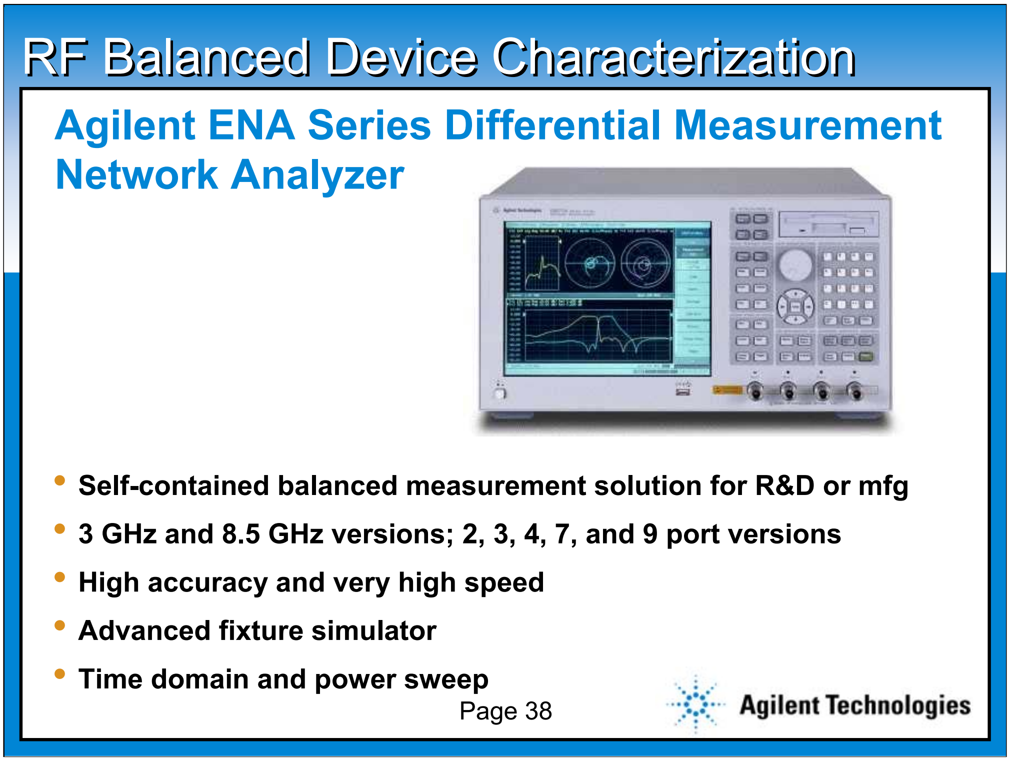
Math
(RF Circuit Simulation Software; e.g.ADS)

Mixed-mode S-parameters

Agilent Technologies

The primary measurement equipment recommended for LTCC device measurements is the Network Analyzer (NA). The NA's have an internal signal source and a tuned receiver. These 2 elements are coupled allowing extremely accurate, high dynamic range swept amplitude and phase measurements for devices that have high rejection ratios like the SAW devices contained in an LTCC. Whether the NA is a 2-port or multiport version, it has S-parameter test sets and sophisticated calibration capabilities to get very useful, accurate characteristics.

A "standard" NA has 2 ports for measuring both transmission and reflective responses. But these 2 ports only allow connection to 2 terminals of our DUT at a time. Since LTCC devices have more than 2 terminals (ports) then a version of a NA with more than 2 ports would be desireable. Such NA's exist and are termed Multiport NA's. If we have an LTCC with many ports but all ports are coaxial (unbalanced) then we can easily use a "normal" Multiport NA. If our LTCC device has balanced ports, then we could use a "normal" multiport NA along with some mathematical data manipulation, but it would be much more convenient to use a Multiport NA that already includes Balanced measurement capability.



RF Balanced Device Characterization

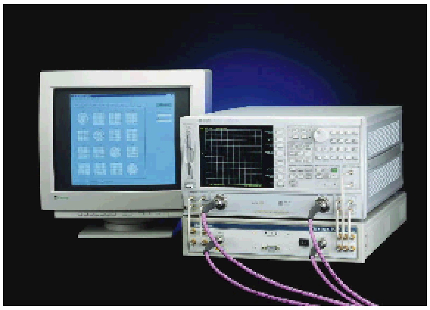
Agilent ENA Series Differential Measurement Network Analyzer

- Self-contained balanced measurement solution for R&D or mfg
- 3 GHz and 8.5 GHz versions; 2, 3, 4, 7, and 9 port versions
- High accuracy and very high speed
- Advanced fixture simulator
- Time domain and power sweep

Agilent Technologies

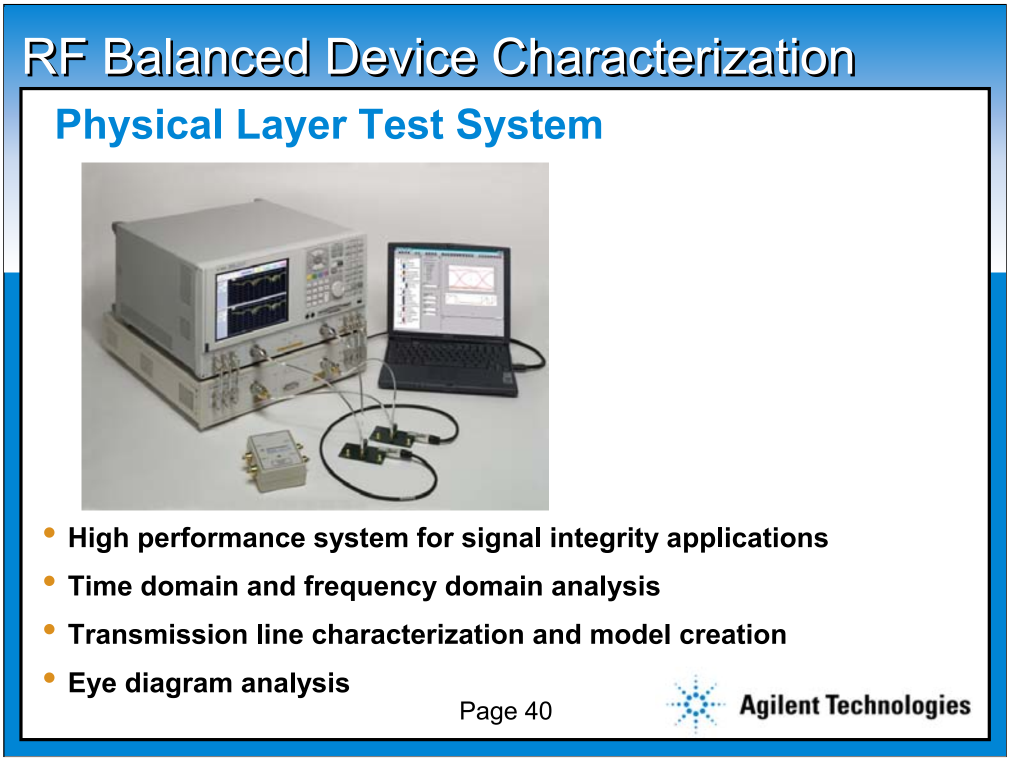
Agilent has also developed a new high speed series of multiport network analyzers. This is called the ENA series. This is an integrated multiport and balanced measurement solution (I.e. the instrument directly displays mixed-mode s-parameters). These network analyzers use a receiver per channel architecture resulting in very high speed high accuracy measurements.

Microwave Balanced Measurement Systems



- Versions up to 50 GHz
- Time domain option
- Agilent 8753, 8720, or PNA based solutions

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.



RF Balanced Device Characterization

Physical Layer Test System

- High performance system for signal integrity applications
- Time domain and frequency domain analysis
- Transmission line characterization and model creation
- Eye diagram analysis

Agilent Technologies

Agilent has also developed a high speed multiport test system for testing LTCC components. This test system is based on the PNA series network analyzer platform. The PNA platform offers many benefits for high speed testing including very fast sweep, excellent RF performance (such as dynamic range), and integrated automation capabilities. These capabilities along with an external test set and integrated multiport application provide the user a multiport test system for high speed multiport testing.

RF Balanced Device Characterization

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- **Balanced device overview**
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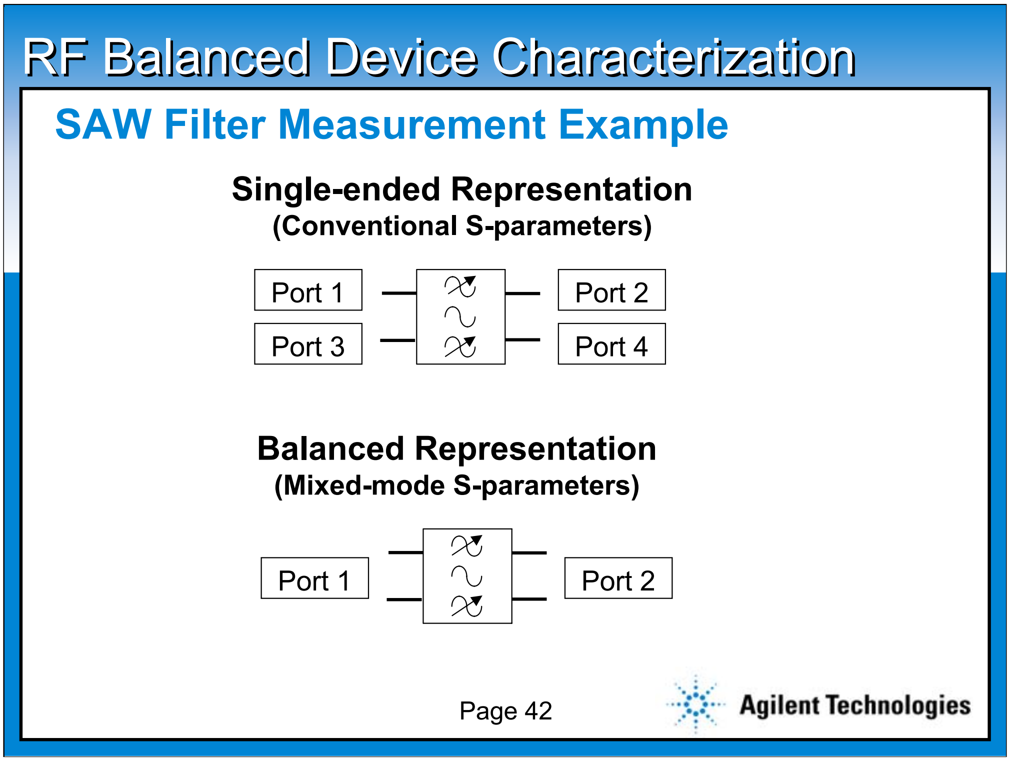


RF Balanced Device Characterization

SAW Filter Measurement Example

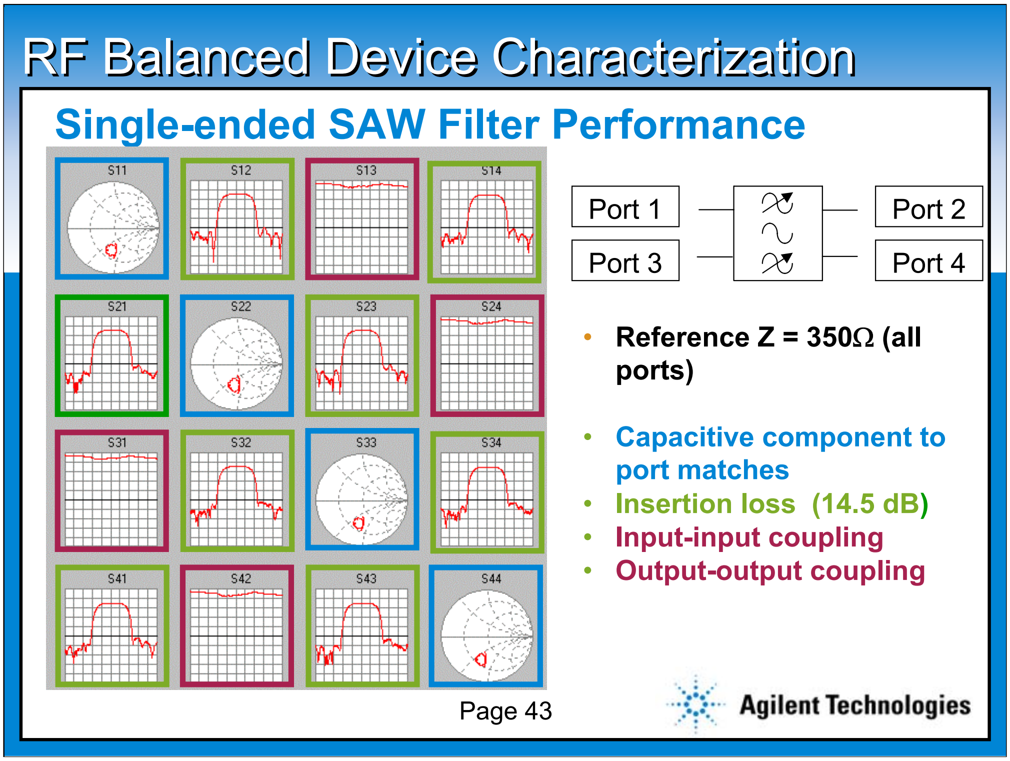
Single-ended Representation
(Conventional S-parameters)

Port 1
Port 3
Port 2
Port 4

Balanced Representation
(Mixed-mode S-parameters)

Port 1
Port 2

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.



RF Balanced Device Characterization

Single-ended SAW Filter Performance

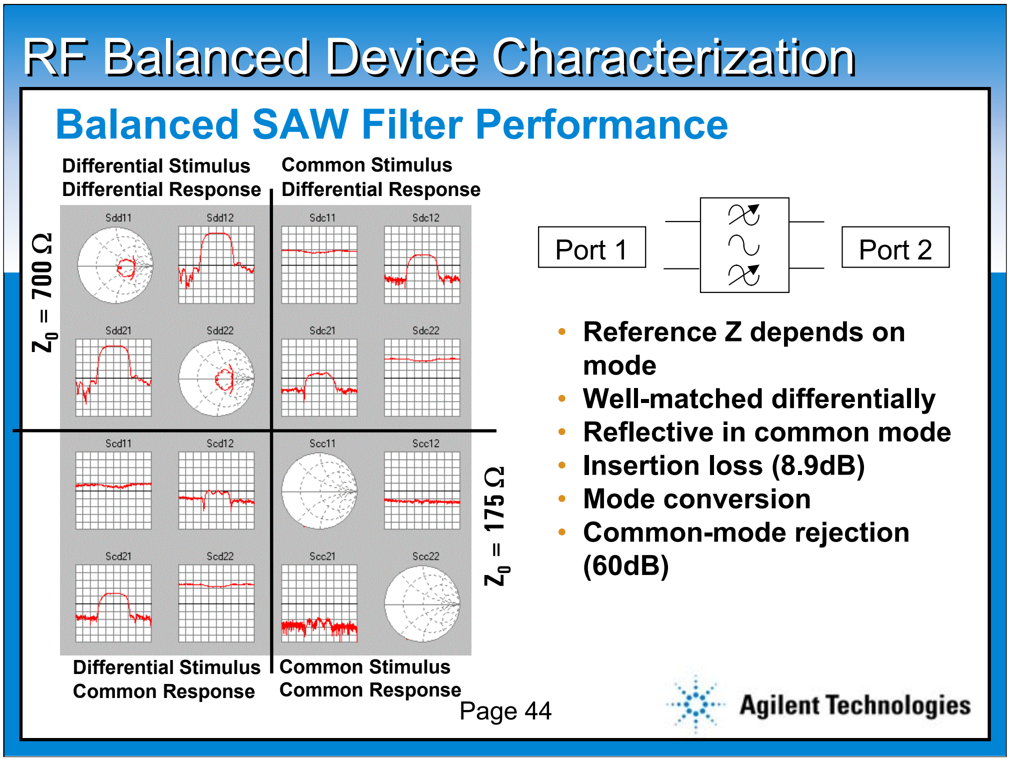
- Reference Z = 350Ω (all ports)
- Capacitive component to port matches
- Insertion loss (14.5 dB)
- Input-input coupling
- Output-output coupling

Agilent Technologies

The single-ended 4-port data is shown here. The device was designed to have differential port impedance 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.



RF Balanced Device Characterization

Balanced SAW Filter Performance

- Reference Z depends on mode
- Well-matched differentially
- Reflective in common mode
- Insertion loss (8.9dB)
- Mode conversion
- Common-mode rejection (60dB)

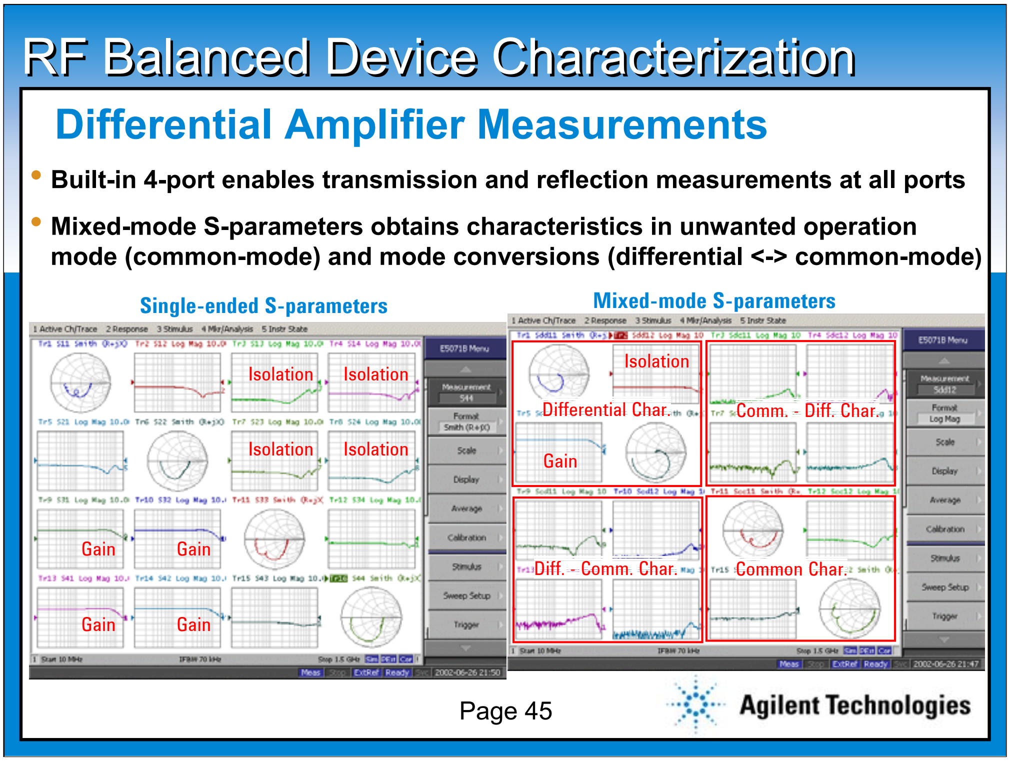
Agilent Technologies

This slide show 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.



RF Balanced Device Characterization

Differential Amplifier Measurements

- Built-in 4-port enables transmission and reflection measurements at all ports
- Mixed-mode S-parameters obtains characteristics in unwanted operation mode (common-mode) and mode conversions (differential <-> common-mode)

Single-ended S-parameters

Mixed-mode S-parameters

Here is a simple example to illustrate the importance of using mixed-mode s-parameters rather than single-ended s-parameters to characterize balanced devices.

Consider a simple differential amplifier. First we can examine the input matches on each of the four terminals and see that the device is matched on all four ports. We can also see that the gain from port 1 to port 3, and from port 2 to port 4 are each about 8dB.

When the device is driven differentially, we can see that the device is also matched on both its input and output ports, and that the differential-mode gain is also 8dB.

Finally we can see that the common-mode performance looks exactly like the differential-mode performance, with matched ports and a gain of 8dB. This device, therefore, has no common-mode rejection.

The similarity between the single-ended, differential-mode, anc common-mode performance of this device is a special case that results from the two halves of the device being perfectly isolated from each other by the ideal ground.

RF Balanced Device Characterization

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- **Balanced device overview**
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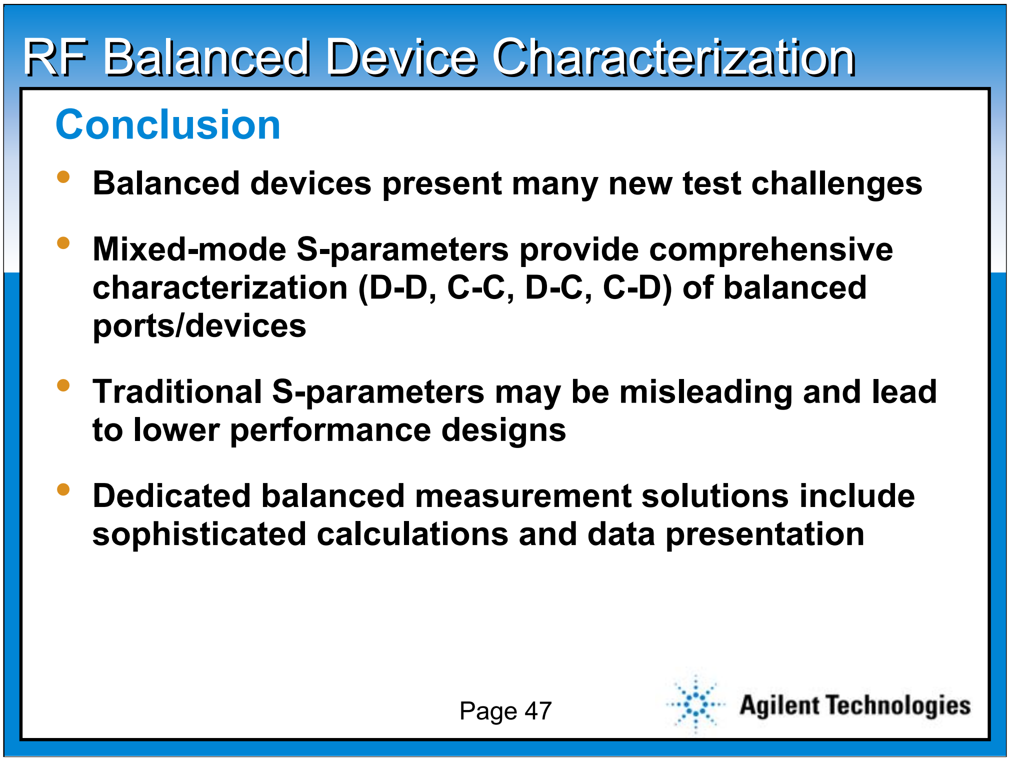


RF Balanced Device Characterization

Conclusion

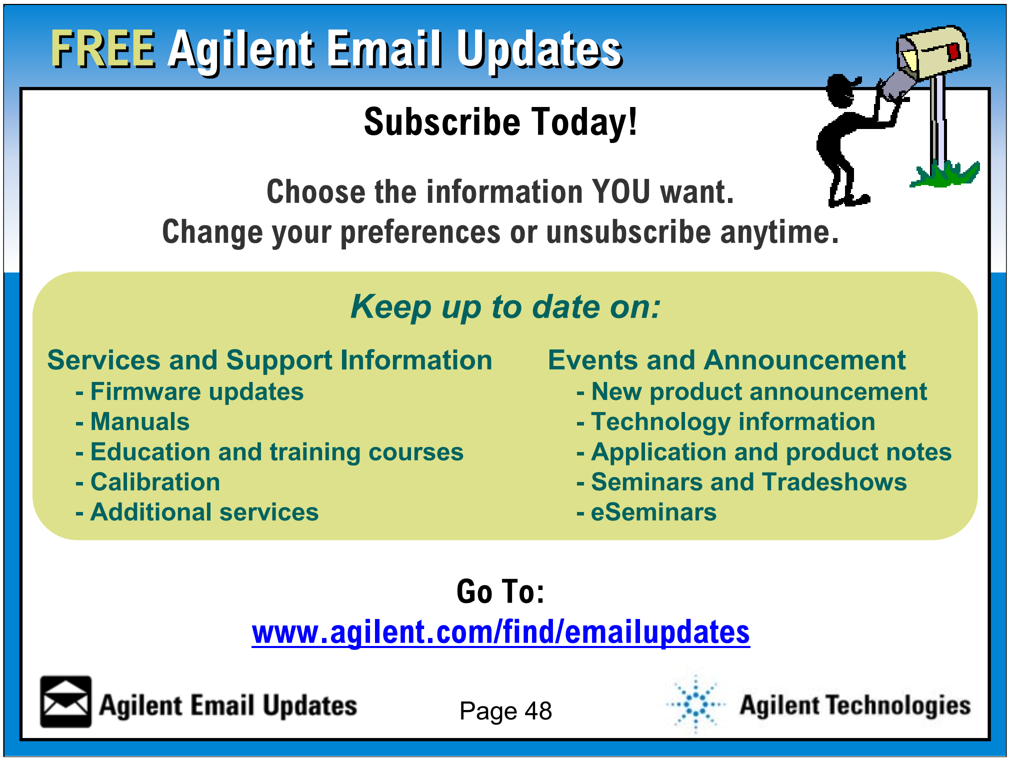
- **Balanced devices present many new test challenges**
- **Mixed-mode S-parameters provide comprehensive characterization (D-D, C-C, D-C, C-D) of balanced ports/devices**
- **Traditional S-parameters may be misleading and lead to lower performance designs**
- **Dedicated balanced measurement solutions include sophisticated calculations and data presentation**

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 to 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.



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