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RF Balanced Device Characterization

January 15th, 2002

See the later presentations done Jan 14, 2003 and Jan 23, 2003
www.agilent.com/find/rfbalance

presented by:
Greg Amorese

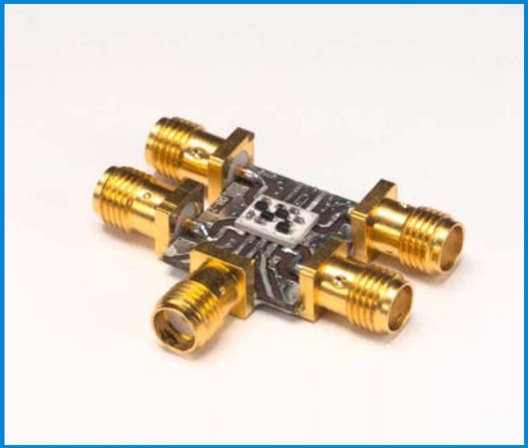
Agenda

- ***Balanced Device Overview***
- **Measurement Alternatives**
- **Mixed-Mode S-parameters**
- **Balanced Circuit Design Methodology**
- **Solution Overview**
- **Calibration**
- **Measurement Examples**
- **Conclusion**

RF Balanced Device Characterization

Balanced Device Market Situation

- Many devices for both RF design and high-speed digital applications
- Major benefits
  - High noise immunity
  - Low radiated noise
  - High density
  - Lower power consumption
- Technology used in new LTCC modules



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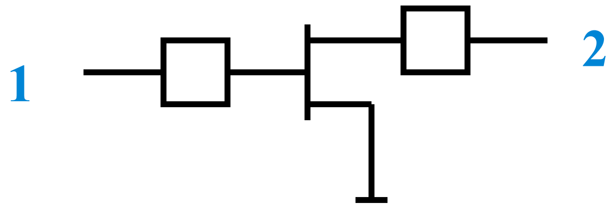
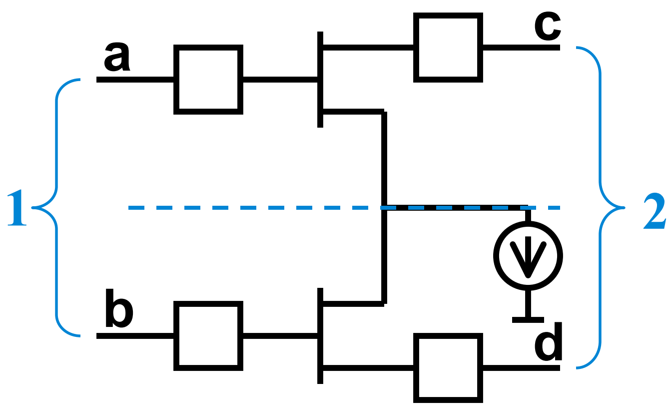
Device Evaluation Challenges

- Measurement tools are mostly unbalanced
- Traditional S-parameters provide limited insight into devices actual behavior
- No balanced VNA calibration standards
- No balanced RF connector standards
- No standard reference impedance (Z_0) for balanced devices

RF Balanced Device Characterization

Differential Device Topology





Unbalanced Device

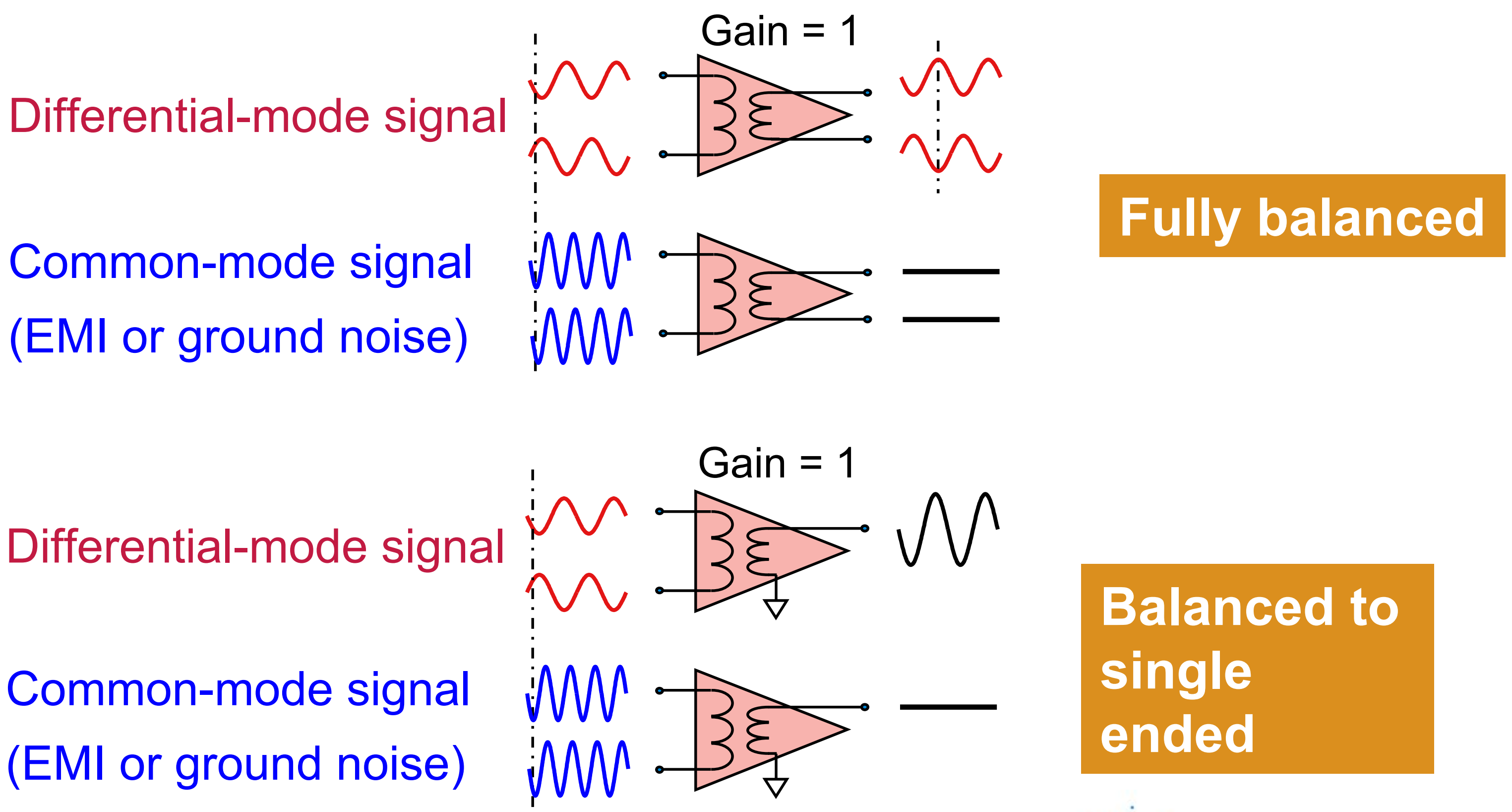
- Signals referenced to ground

Differential Device

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

Ideal Balanced Device Characteristics

Ideally, respond to differential and reject common-mode signals



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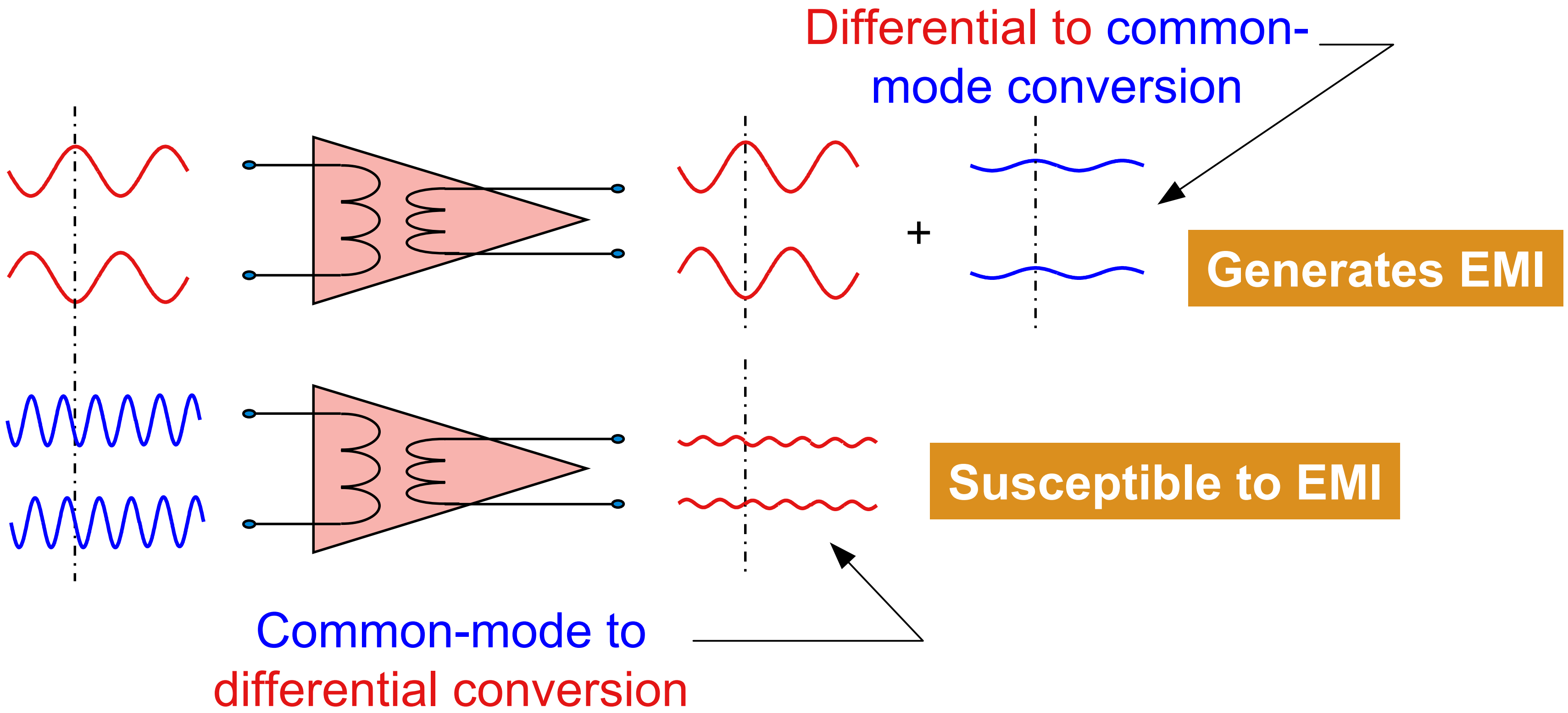
What About Non-Ideal Balanced Devices?

Mode conversions occur...



Agenda

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- *Measurement Alternatives*
- Mixed-Mode S-parameters
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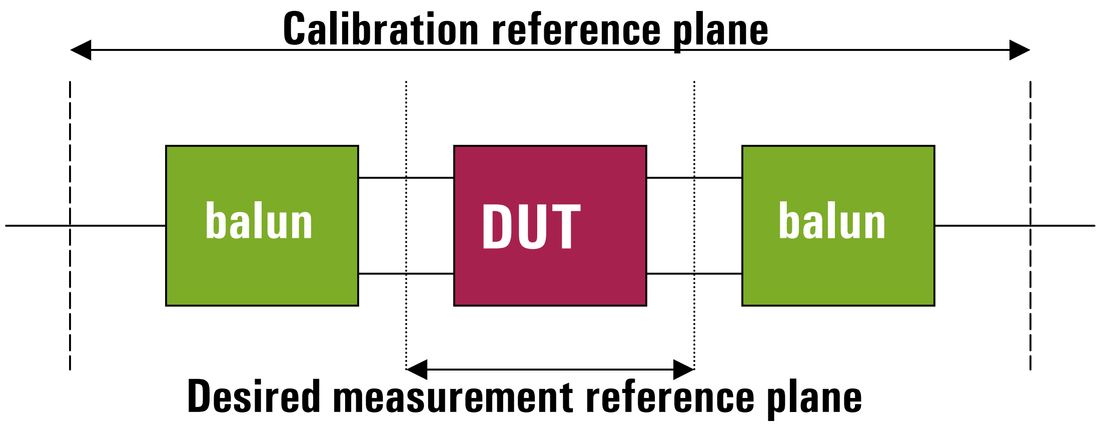
Measurement Alternatives

1)

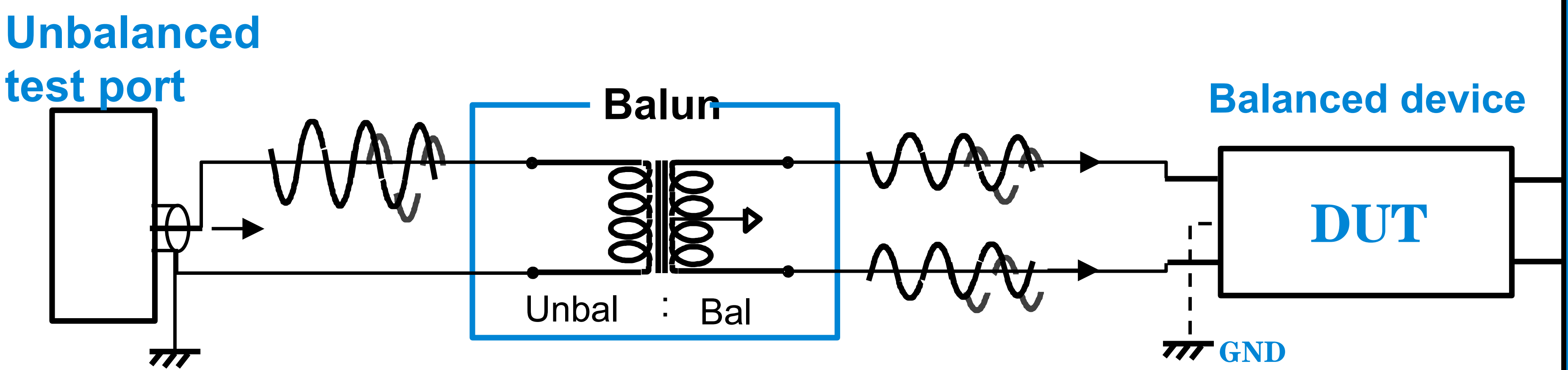


Reduce 4-terminal device from 16 s-parameters to 4

RF Balanced Device Characterization

Mode Conversion
(Unbalance < = > Balance)

Need BALUN (BALanced/UNbalanced) transformer

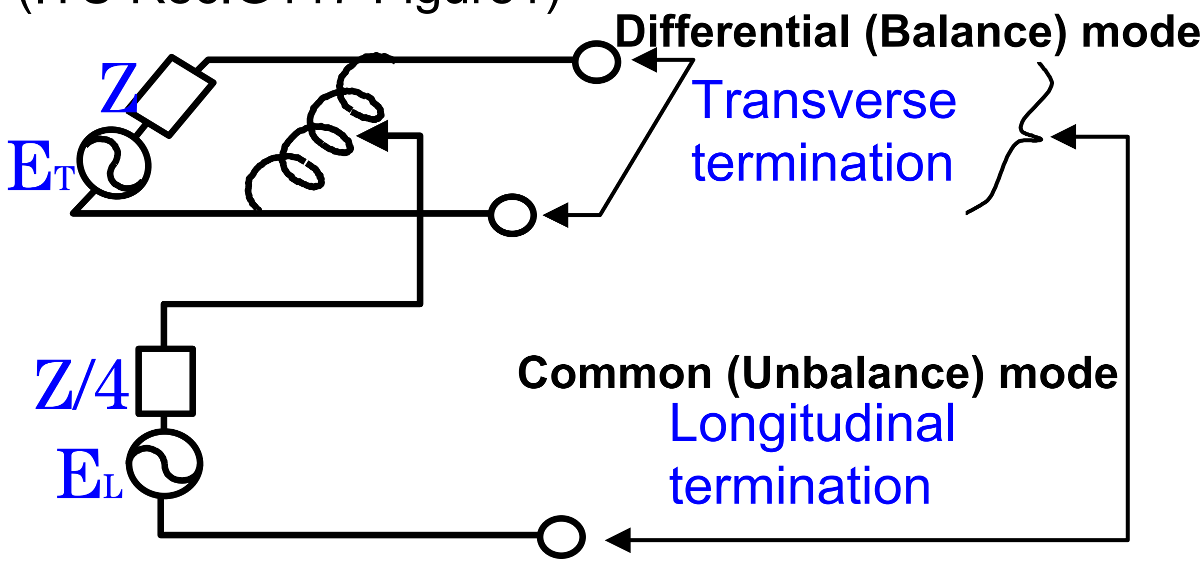


BALUN transformer is NOT an ideal test bridge

Definition

Ideal test bridge

(ITU Rec.G117 Figure1)

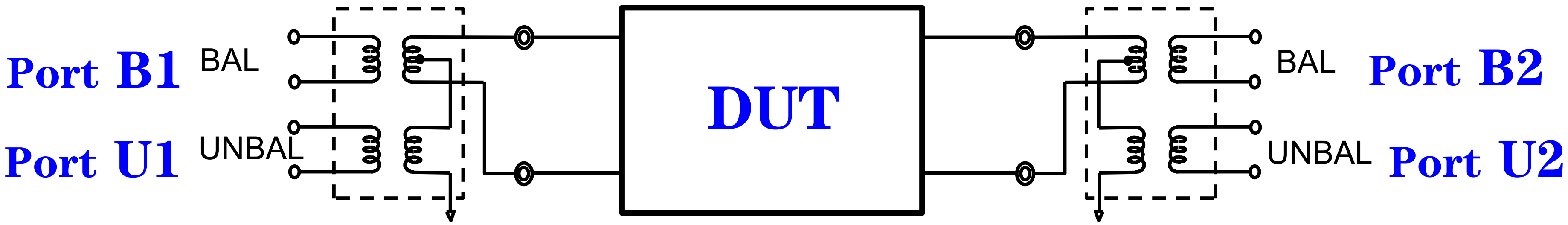


ITU Rec.G117 Figure1

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

RF Balanced Device Characterization

Balanced Device Test Parameters

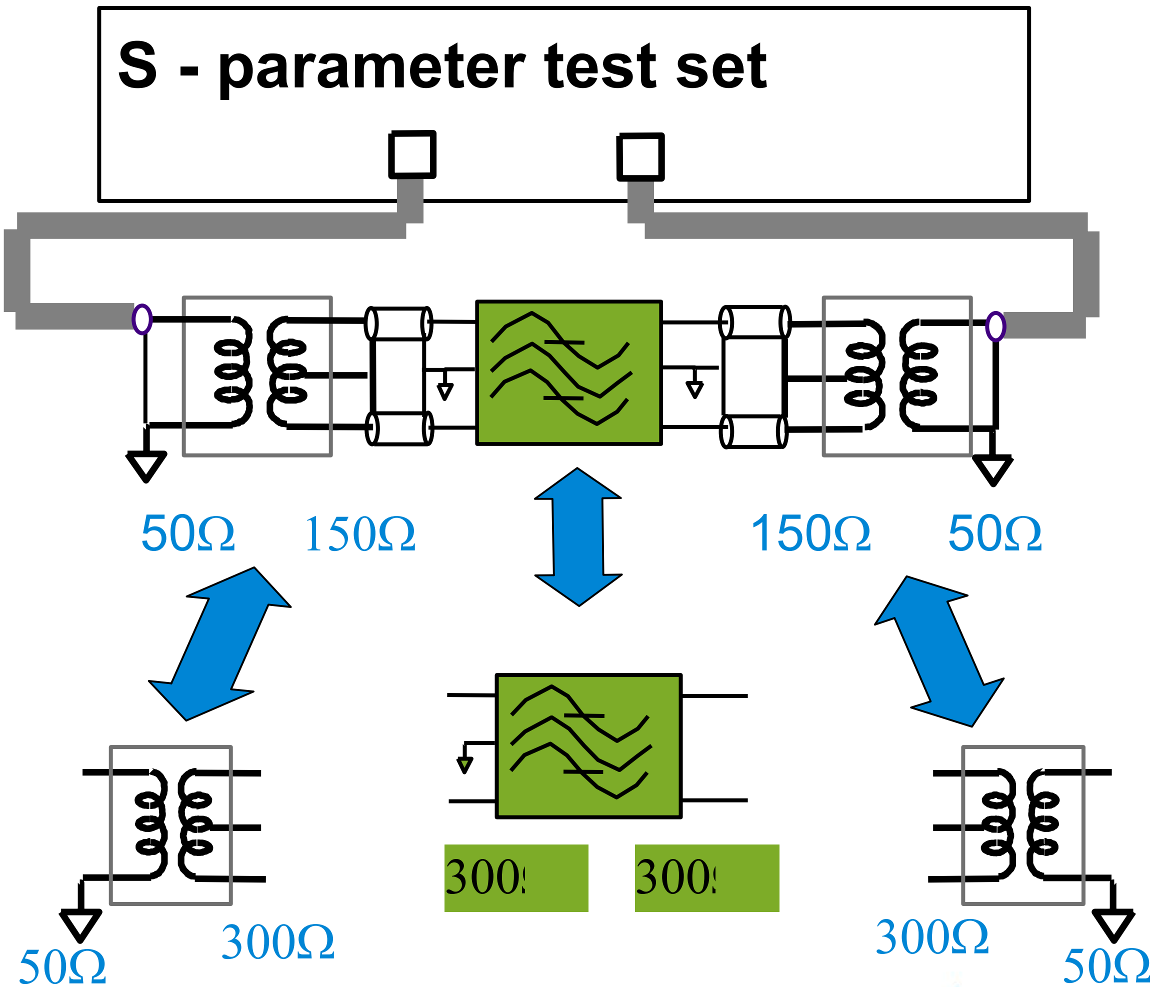


Characteristic Impedance (Zc) : [Balanced], [Unbalanced]
Input Impedance (Zin) : [Balanced], [Unbalanced]
Insertion Loss (Attenuation) : SB2B1 [Balanced], SU2U1 [Unbalanced]
Return Loss : SB1B1 [Balanced], SU1U1 [Unbalanced]

Conversion Loss , Rejection Ratio : (Balance to Unbalance Parameters)
TCTL (Transverse Conversion Transfer Loss) : SU2B1
LCTL (Longitudinal Conversion Transfer Loss) : SB2U1
LCL (Longitudinal Conversion Loss) : SB1U1
CMRR (Common Mode Rejection Ratio)

RF Balanced Device Characterization

Calibration using Baluns



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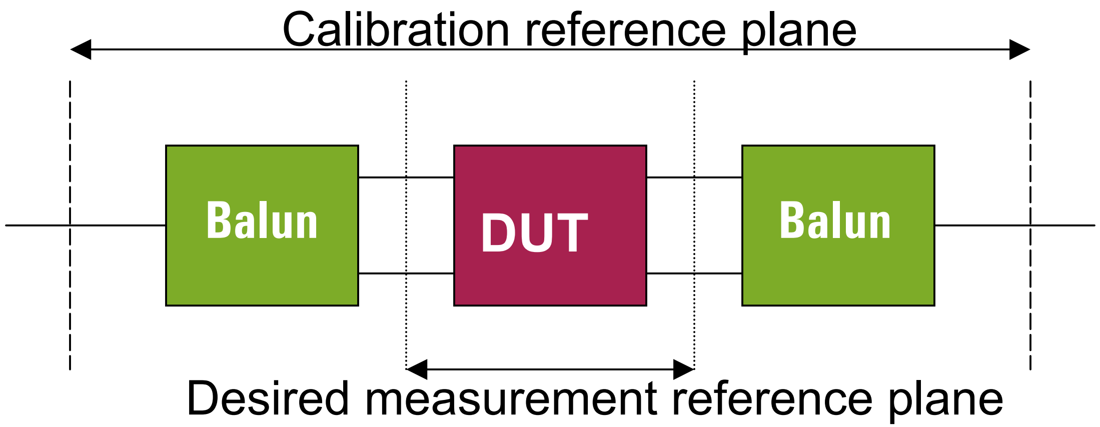
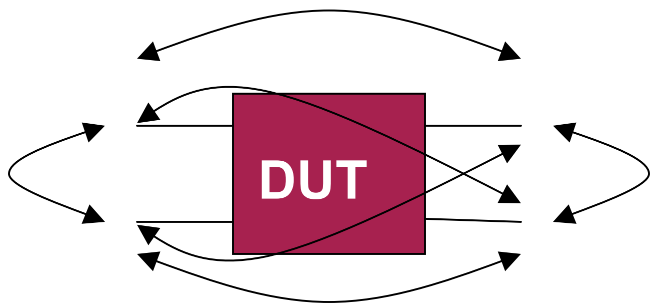
Measurement Alternatives

1)



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

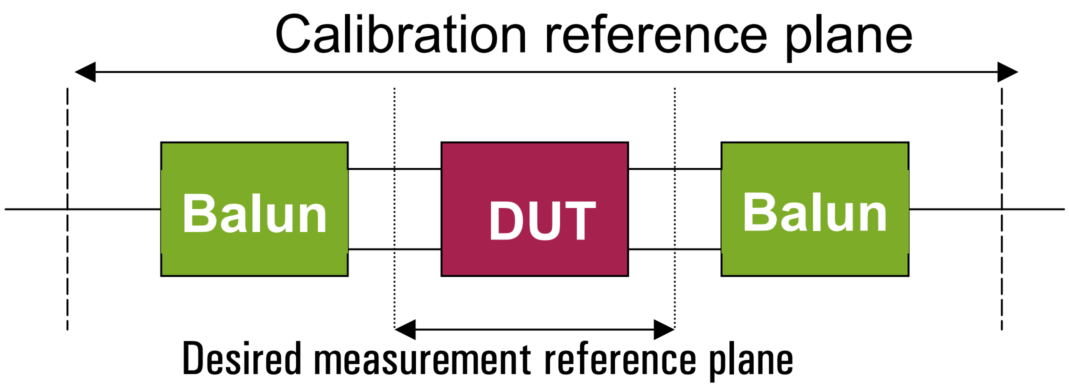
2)



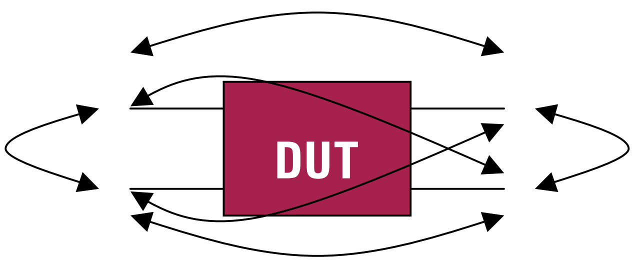
Measured 2 ports at a time
Does not address balanced modes

RF Balanced Device Characterization

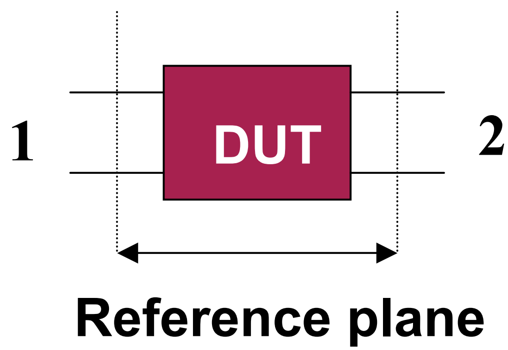
Measurement Alternatives

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

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- Measurement Alternatives
- *Mixed-Mode S-parameters*
- Balanced Circuit Design Methodology
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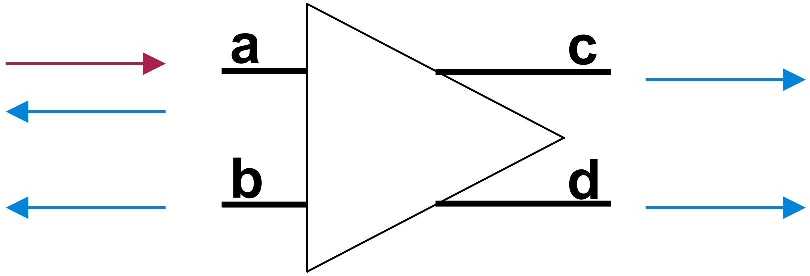
Single-Ended S-Parameters

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?**



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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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Single-Ended S-Matrix

S=b/a

Stimulus Ports

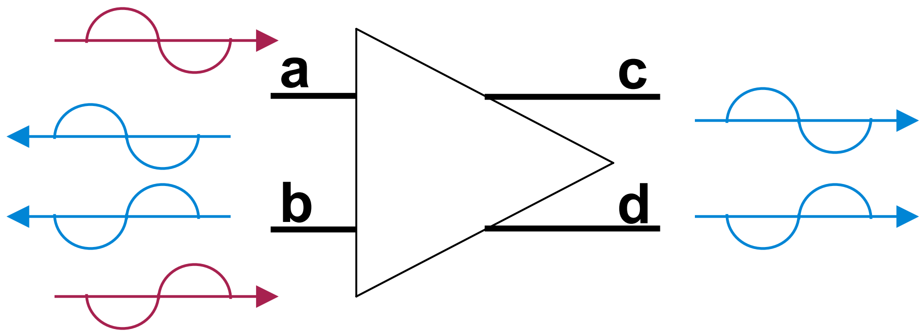
Response Ports

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

Mixed-Mode S-Parameters

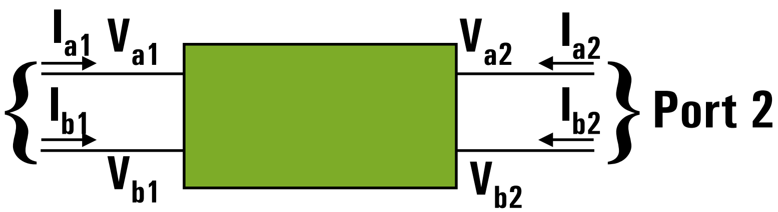
Mixed-mode S-parameters answer the question …

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?



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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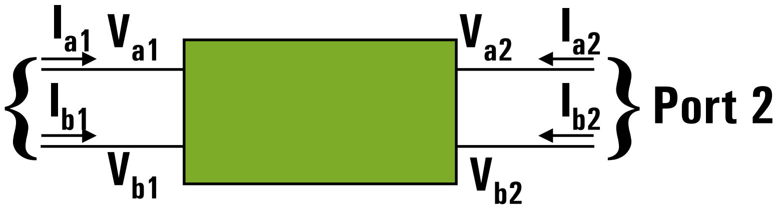
Mixed-Mode S-Parameters

Balanced 2-Port



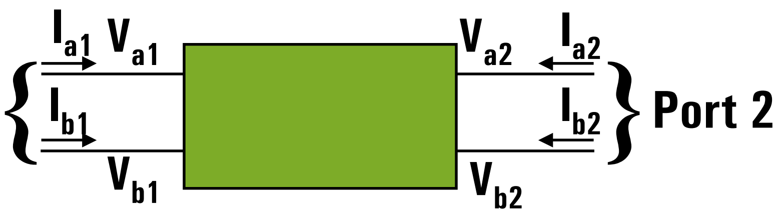
	Differential	Common
Voltage	Van – Vbn	0.5 * (Van + Vbn)
Current	0.5 * (Ian - Ibn)	Ian + Ibn
Impedance	$Z_{Dn} = V_D^+/I_D^+$	$Z_{Cn} = V_C^+/I_C^+$

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

$$S = b/a$$

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	$bdn = \frac{1}{2 \cdot \sqrt{\mathrm{Re}\{Zdn\}}}(Vdn - Idn \cdot Zdn)$	$bcn = \frac{1}{2 \cdot \sqrt{\mathrm{Re}\{Zcn\}}}(Vcn - Icn \cdot Zcn)$

$$S = b/a$$

RF Balanced Device Characterization

Mixed-Mode S-Matrix

S=b/a

		Differential-Mode Stimulus		Common-Mode Stimulus	
		Port 1	Port 2	Port 1	Port 2
Differential-Mode Response	Port 1	S_{DD11}	S_{DD12}	S_{DC11}	S_{DC12}
	Port 2	S_{DD21}	S_{DD22}	S_{DC21}	S_{DC22}
Common-Mode Response	Port 1	S_{CD11}	S_{CD12}	S_{CC11}	S_{CC12}
	Port 2	S_{CD21}	S_{CD22}	S_{CC21}	S_{CC22}

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

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

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

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

RF Balanced Device Characterization

Mixed-Mode S-Matrix: DC 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 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**

RF Balanced Device Characterization

Mixed-Mode S-Matrix: CD Quadrant

Input Reflection

Reverse Transmission

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

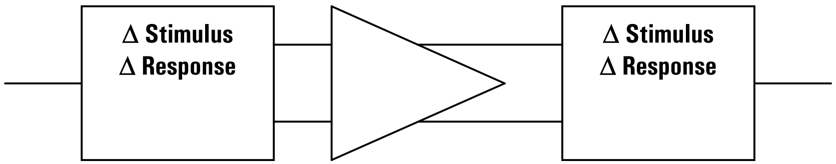
Forward Transmission

Output Reflection

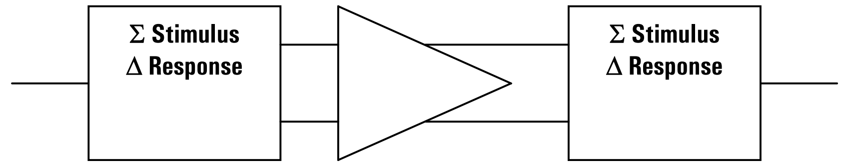
- **Describes conversion of a differential-mode stimulus to a common-mode response**
- **Terms are ideally equal to zero with perfect symmetry**
- **Related to the generation of EMI**

Conceptual Hardware Networks Required to Get Mixed-Mode S-Parameters with 2-port NA

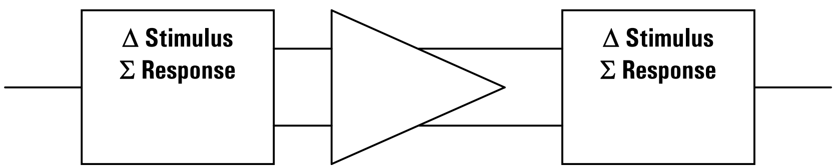
Differential Divide/Combine



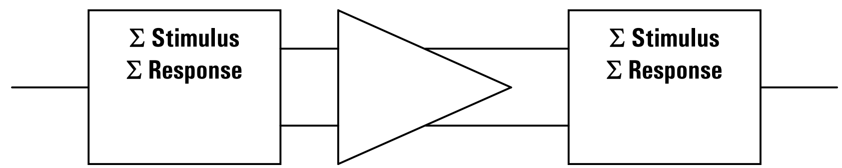
In-Phase Divide/Differential Combine



Differential Divide/In-Phase Combine



In-Phase Divide/Combine



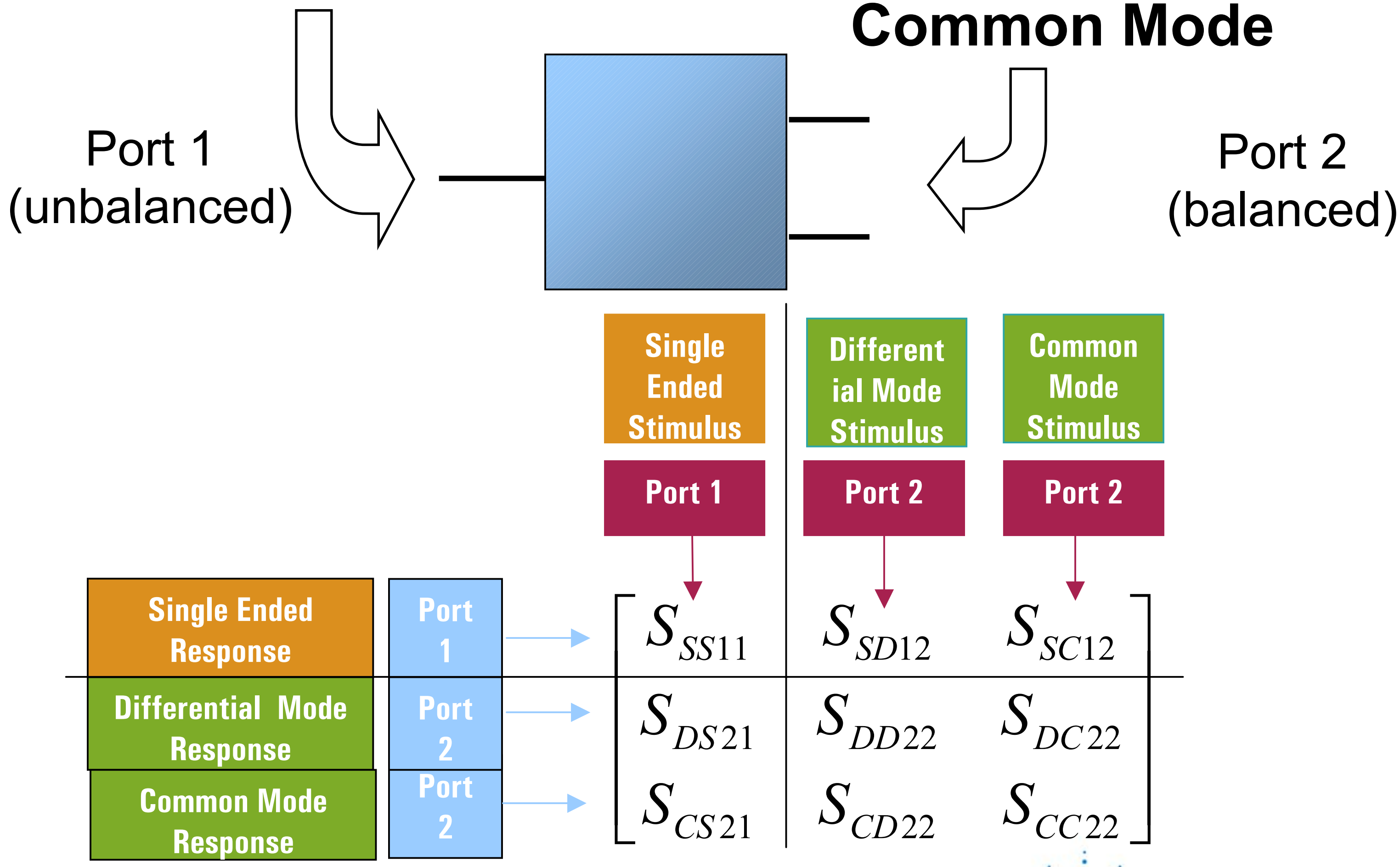
DC and CD Quadrants would require complex hardware networks

RF Balanced Device Characterization

Three-Terminal Devices

Single-Ended

Differential Mode
Common Mode



$$\begin{bmatrix} S_{SS11} & S_{SD12} & S_{SC12} \\ S_{DS21} & S_{DD22} & S_{DC22} \\ S_{CS21} & S_{CD22} & S_{CC22} \end{bmatrix}$$

RF Balanced Device Characterization

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- Balanced Device Overview
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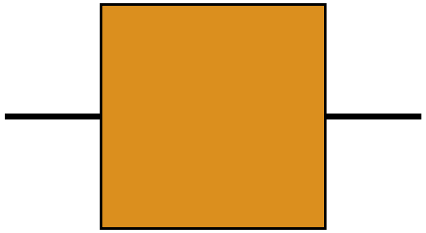
Brain Teaser #1

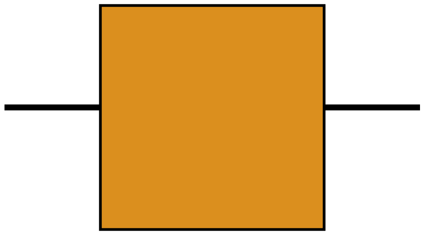
What are the simultaneous conjugate input and output matching impedances of the following circuit?



Single-ended 2-port

Brain Teaser #1: Answers

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



Single-ended 2-port

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

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

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

where:

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

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

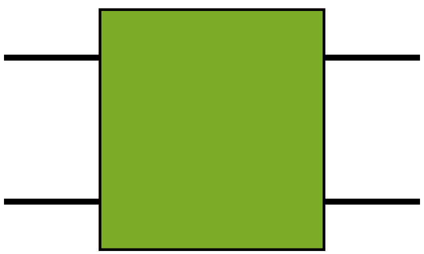
$$C_1 = S_{11} - D \cdot S_{22}^*$$

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

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

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.

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

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

where:

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

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

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

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

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

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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:

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

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

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

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

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

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: ($S_{nm} \rightarrow S_{DDnm}$)

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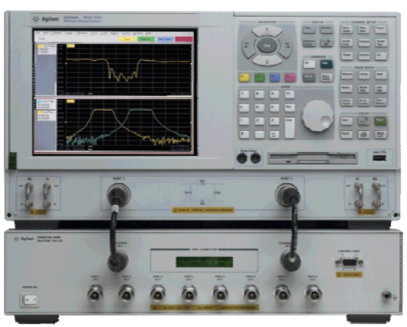
Alternative Methods to Acquire Mixed-Mode S-Parameters

- Standard 2-Port Network Analyzer
- MultiPort Network Analyzer



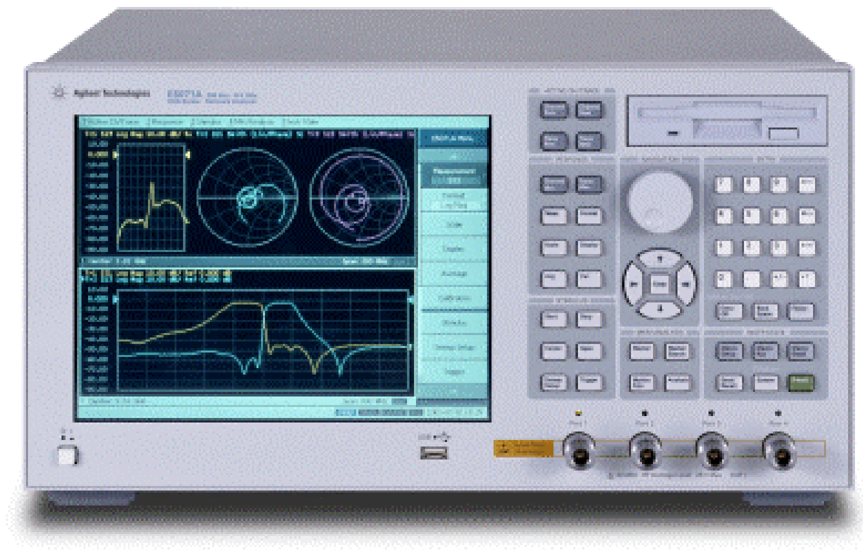
- MultiPort Network Analyzer with Balanced Measurement Capability

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

Mixed-Mode S-Parameters

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; Up to 4 ports
- High Accuracy and Very High Speed

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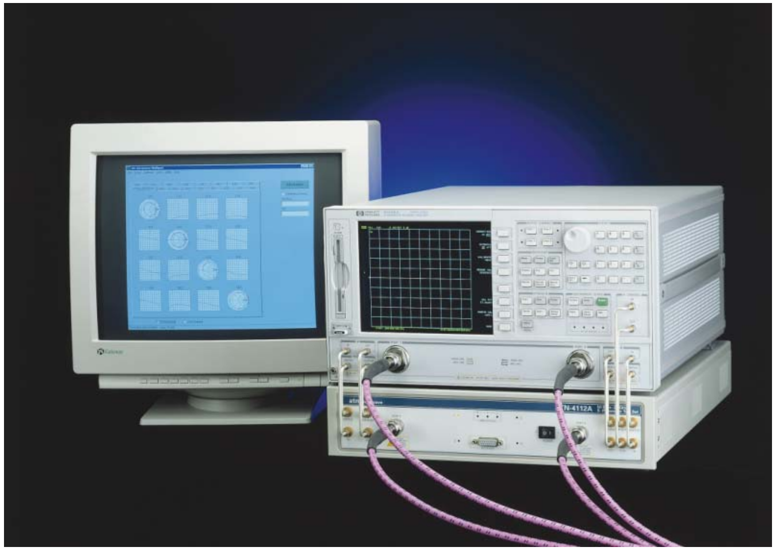
4-Port Balanced Measurement System



- **Excellent R&D Solution**
- **Versions up to 20 GHz**
- **Time Domain option**
- **Agilent 8753, 8720, or PNA based solutions**

RF Balanced Device Characterization

High Speed Multiport Device Test System

- **Excellent for High Port Count (e.g. LTCC) Devices**
- **Semi-custom Agilent PNA based Solutions**
- **Meets Both R&D or High-Speed Manufacturing Needs**

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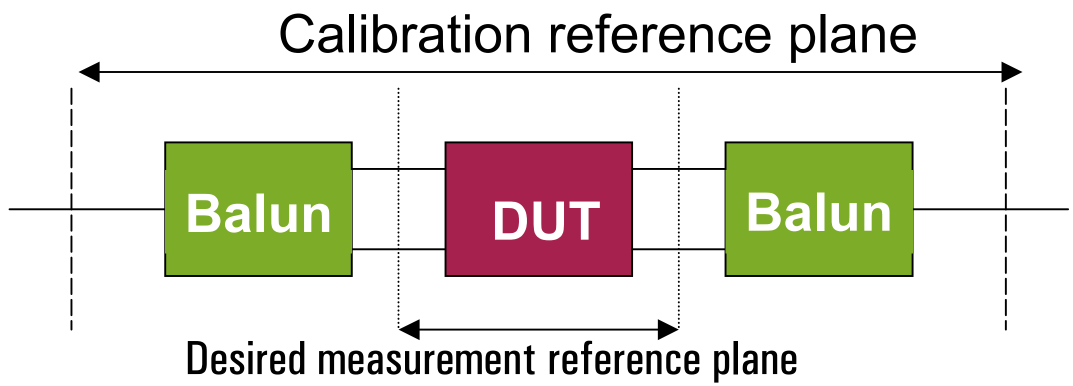
RF Balanced Device Characterization

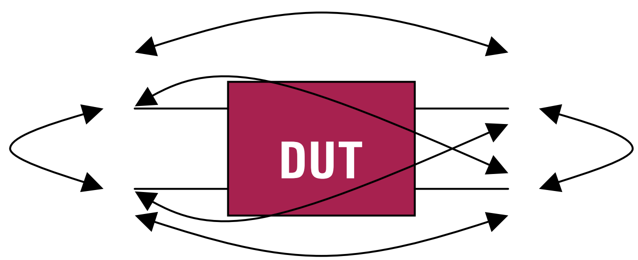
Calibration For Each Measurement Alternative

1)



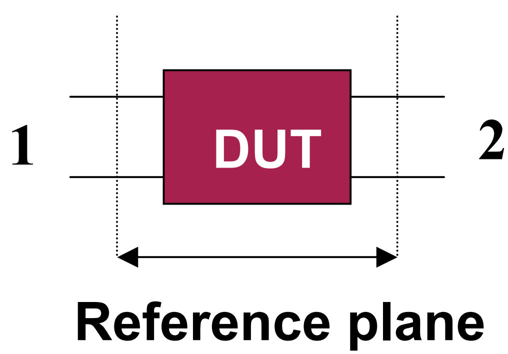
Ideally calibrate after baluns but no balanced standards exist

2)



Measure 2 ports at a time; use standard 2-port Network Analyzer Calibration process

3)

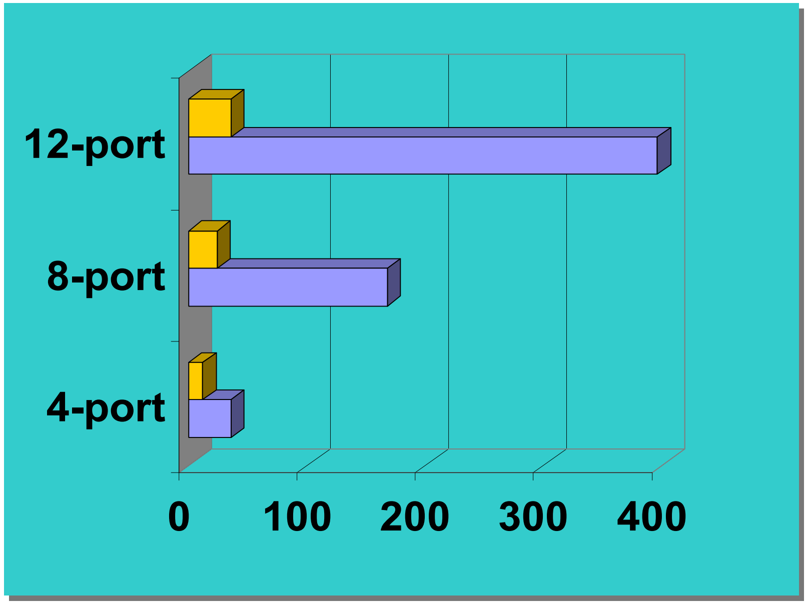


Measure multiple ports at a time; ideally use sophisticated multiport Calibration process

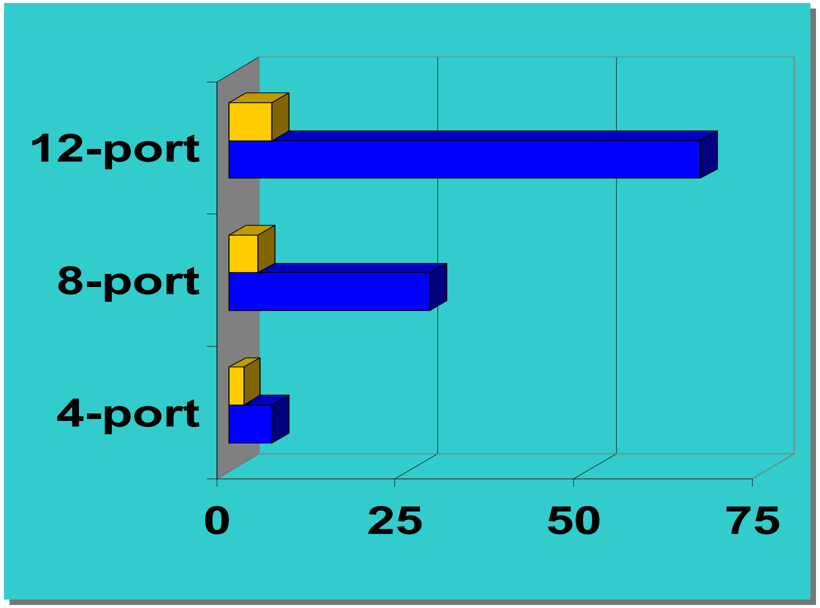
RF Balanced Device Characterization

Sophisticated Multiport Cal Eliminates Redundant Connections of Cal Standards

Reflection Connections



Through Connections



- **Sophisticated Multiport Cal**
- **Traditional 2-port VNA Cal**

RF Balanced Device Characterization

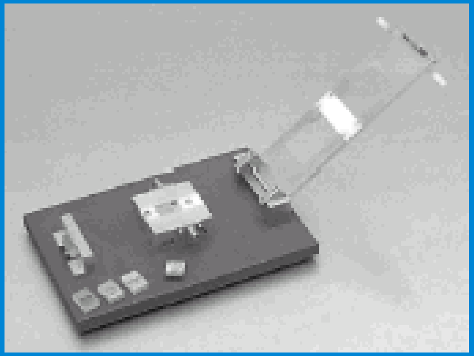
E-CAL (Electronic Calibration)

- Automated "system" for performing calibrations
- 2- and 4-port configurations
- Single connection
- Calibrates all paths/permutations
- Resulting calibration is traceable

RF Balanced Device Characterization

Fixture Calibration

- **Methods for removing fixture effects from measurement:**
  - **Port extensions**
  - **Delay**
  - **TRL calibration**
  - **In-fixture SOLT calibration**
  - **De-embedding**
  - **Soft fixturing**



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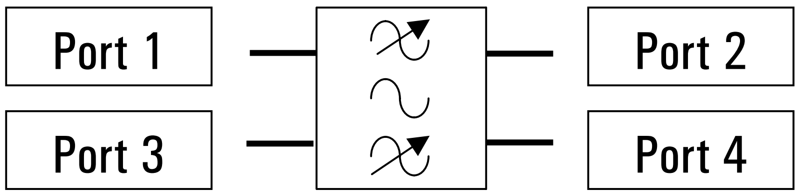
Agenda

- Balanced Device Overview
- Measurement Alternatives
- Mixed-Mode S-parameters
- Balanced Circuit Design Methodology
- Solution Overview
- Calibration
- *Measurement Examples*
- Conclusion

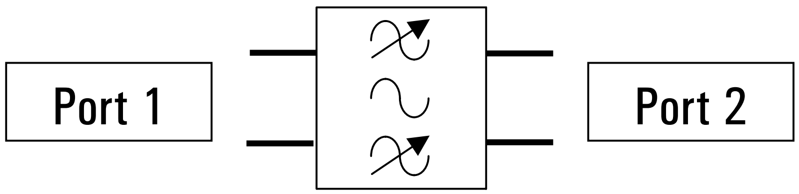
RF Balanced Device Characterization

SAW Filter Measurement Example

Single-Ended Representation
(Conventional S-Parameters)

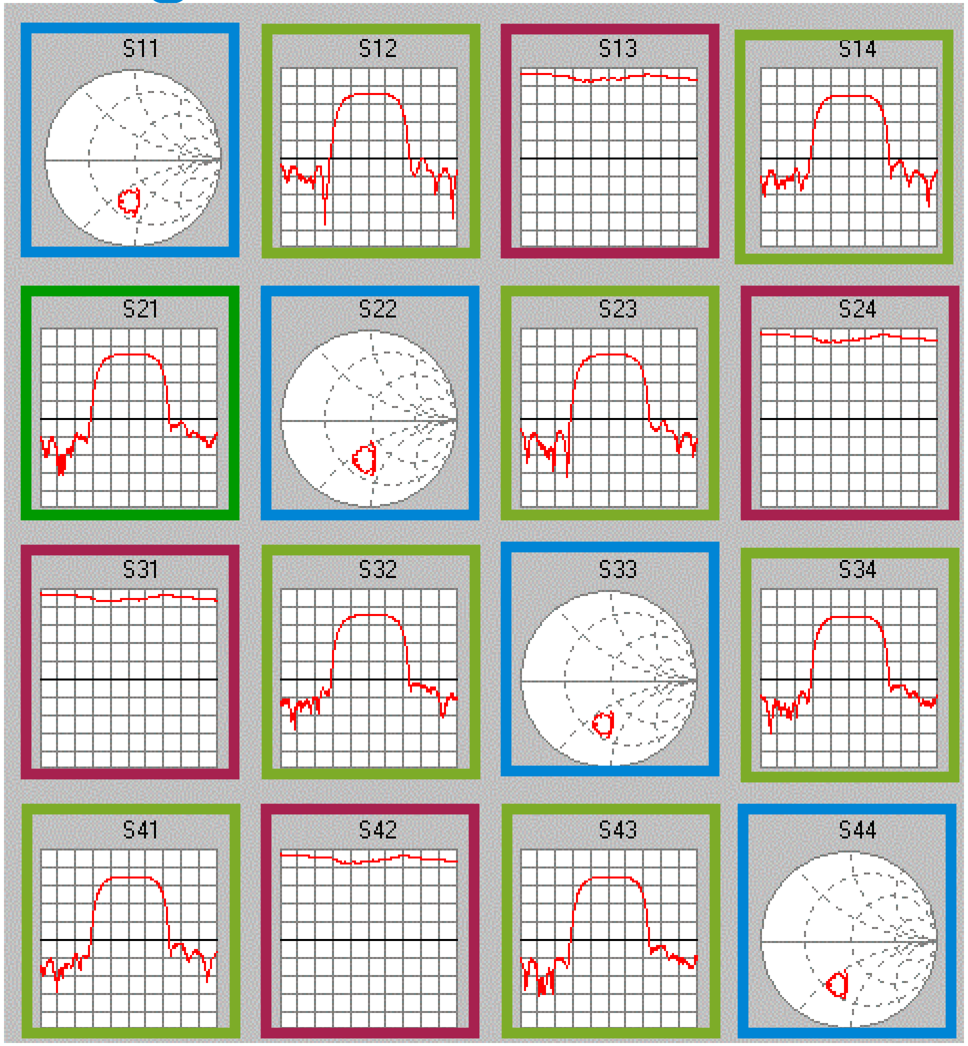


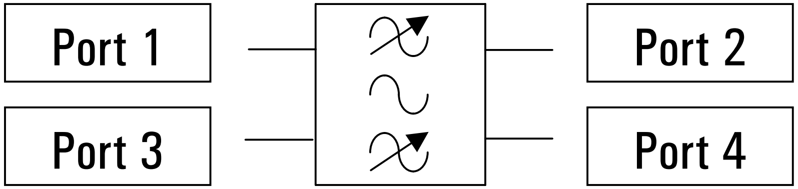
Balanced Representation
(Mixed-Mode S-Parameters)



RF Balanced Device Characterization

Single-Ended SAW Filter Performance



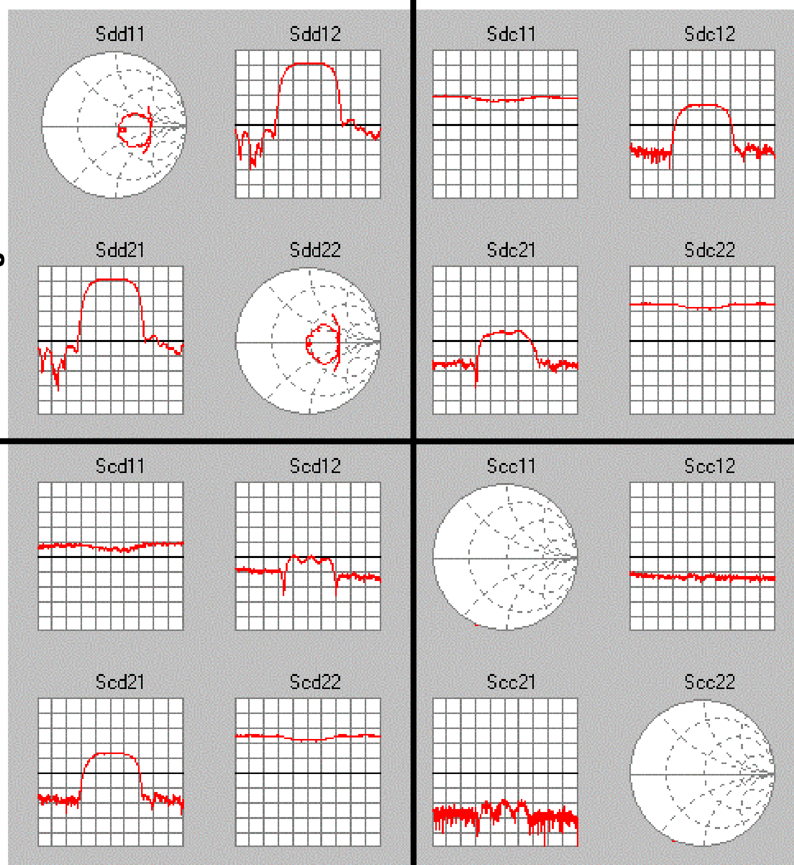


- **Reference Z = 350Ω (all ports)**
- **Capacitive component to port matches**
- **Insertion loss (14.5dB)**
- **Input-input coupling**
- **Output-output coupling**

Balanced SAW Filter Performance

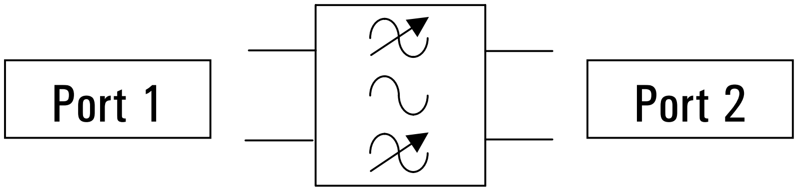
Differential Stimulus Differential Response | **Common Stimulus Differential Response**

$Z_0 = 700\ \Omega$



$Z_0 = 175\ \Omega$

Differential Stimulus Common Response | **Common Stimulus Common Response**



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

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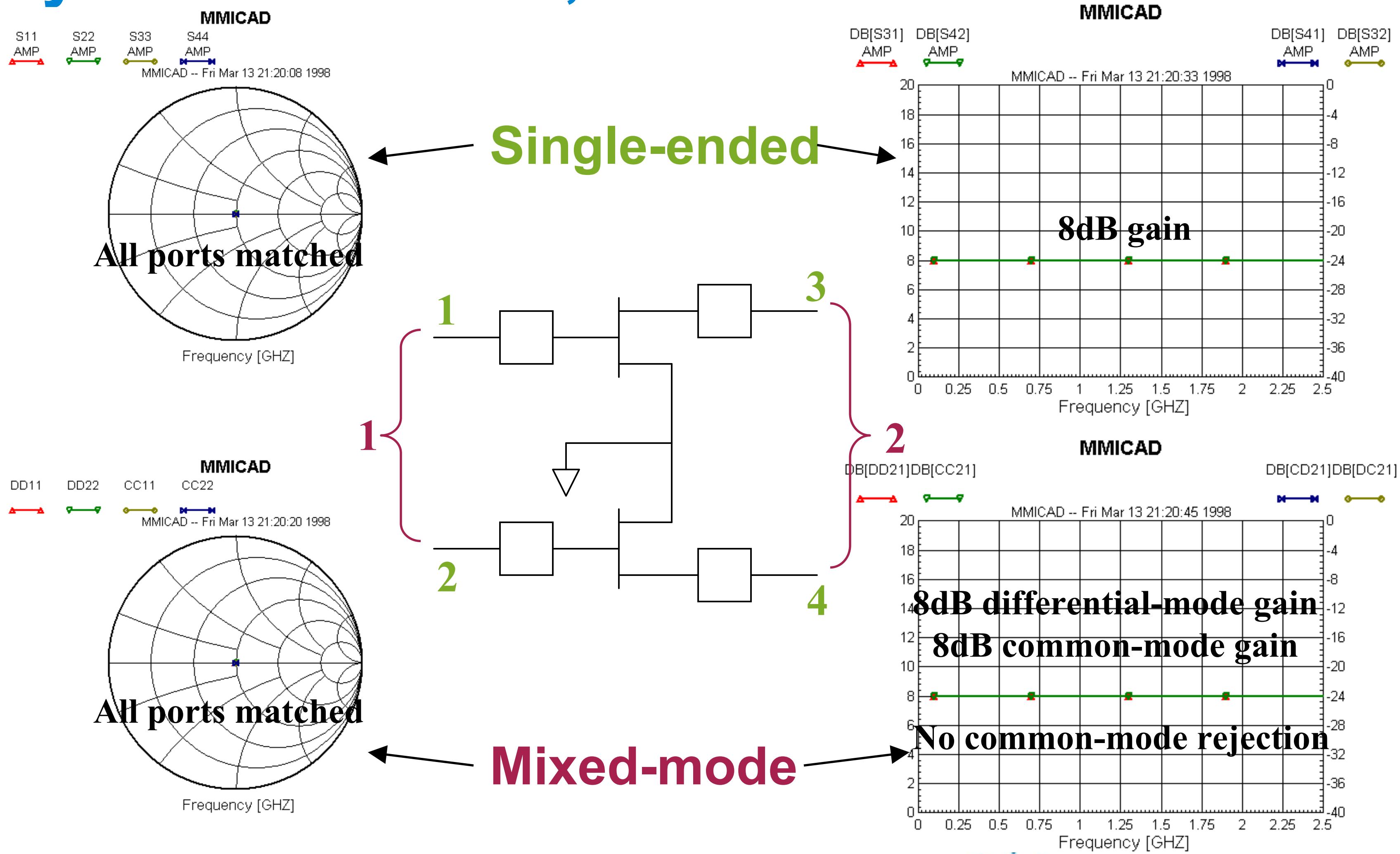
Symmetric Circuit, Zero Ground Z



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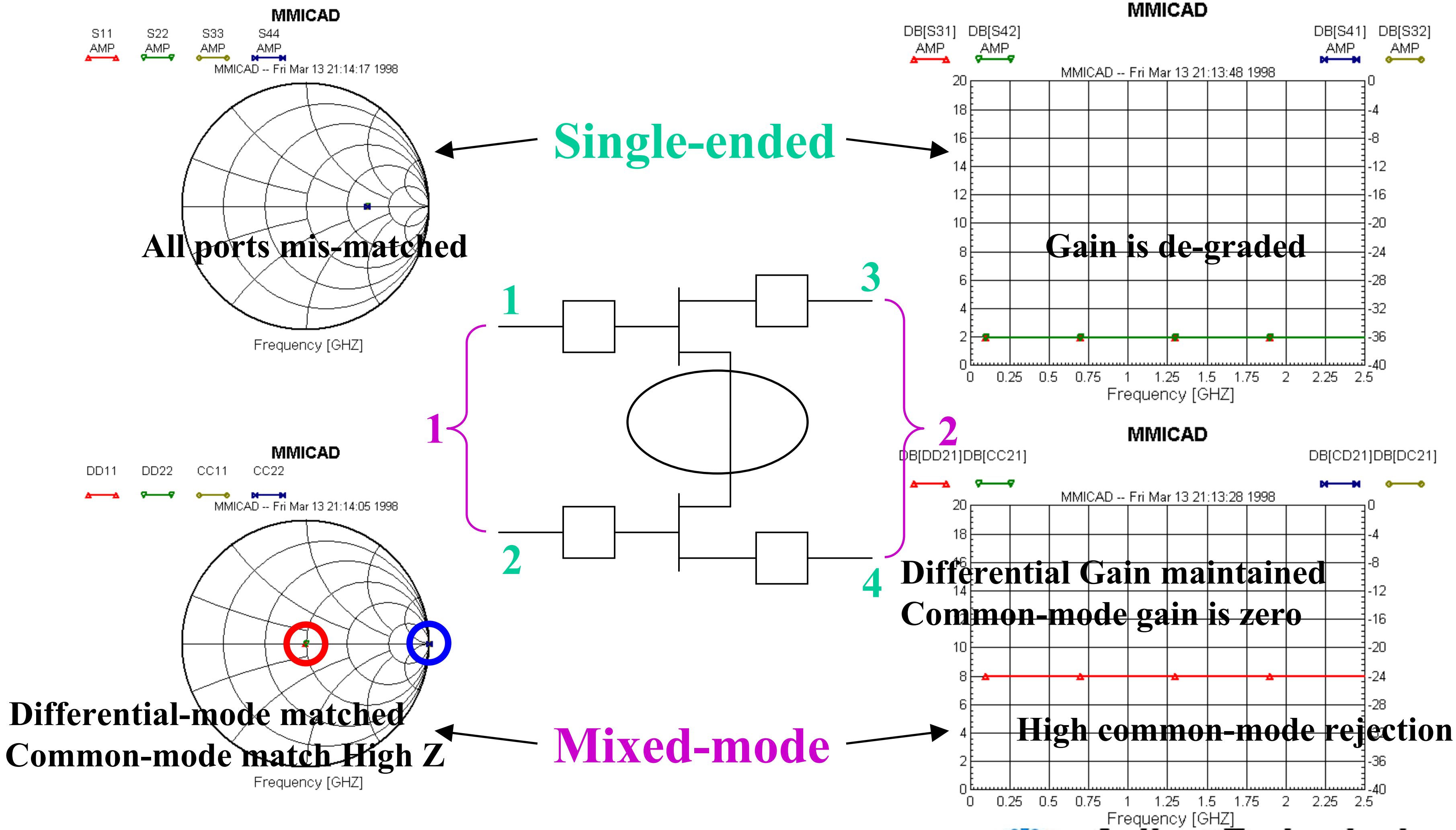
RF Balanced Device Characterization

Symmetric Circuit, Infinite Ground Z



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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 calibration

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