UNDERSTANDING MIXED-MODE SCATTERING PARAMETERS

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OVERVIEW

HYPERLABS has positioned itself as the market leader in ultra-broadband baluns via the model HL9409 100GHz Balun, which is currently recognized as the industry standard. Baluns are three port devices used to convert unbalanced signaling to balanced signaling, or vice-versa. Standard single port scattering parameters (s-parameters) fail to convey the common mode or differential mode response of the balanced, or differential port. This application note explains how mixed-mode s-parameters can be deployed to provide this useful information.

INTRODUCTION

S-parameters are a frequency domain representation of the behavior of a network [1]. Similar to impedance and admittance matrices for an N-port network, s-parameters also provide a complete description of the network. Impedance and admittance matrices relate to the total voltages and currents at the ports while the scattering matrix relates to voltage waves incident and reflected from the ports [2]. They are comprised of complex numbers and are expressed in terms of both magnitude and phase. This is due to both the magnitude and phase of the input signal being changed by the network as a result of losses, reflections, and propagation time [1]. S-parameters can be measured directly from a vector network analyzer (VNA).

Quite often we refer to the magnitude only, because of how much gain or loss that occurs is typically of the most interest. However, the phase information is also extremely important and relates to the time delay incurred as the signal propagates from one port of the network to another port. The phase delay in the frequency domain (or propagation delay in the time domain), from the unbalanced port to the 0° and the 180° sides of the balanced port are extremely important in maintaining the integrity of the differential signaling.

Single-ended s-parameters are defined for a given set of frequencies and port impedance (typically 50 Ω), which can vary as a function of frequency for any real-world network. In the case where every port on the balun is single-ended and unbalanced, we get the schematic symbol as shown in *Figure 1a*.

There is an alternate case where Port 1 is unbalanced (50Ω), but we redefine the two single-ended ports (Port 2 and Port 3) to be a single differential 100Ω port, noted as Port 2 in *Figure 1b*. The s-parameter matrix developed from this depiction is referred to as mixed-mode s-parameters. Mixed-mode s-parameters provide the differential and common mode characteristics of the differential port in cases where the single-ended port or the differential port is being driven.

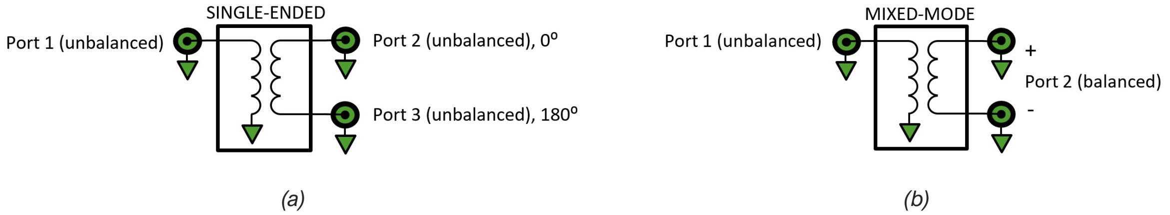


Figure 1: Schematic representation of a balun using (a) three single-ended ports and (b) one single-ended port and one differential port.

SINGLE-ENDED SCATTERING PARAMETERS

Single-ended s-parameters, shown in *Figure 3,* are the typical methodology for specifying the performance of an N-port network. In Figure *1a,* each port is driven independently, and the responses are measured on each of the three ports.

For baluns, key pieces of information can be gathered through this dataset.

- The phase from Port 1 to each of Ports 2 and 3 can be evaluated. This would be described as the *Phase Match* on the datasheet, which is extremely important when dealing with differential high speed signaling rates so that both the 0° and 180° signals are in alignment.

$$Phase\ Match\ (or\ Balance) = \angle[S_{31}](°) - \angle[S_{21}](°) \quad (1.1)$$

- The amplitude, or insertion loss, from Port 1 to each of Ports 2 and 3 can also be evaluated. This would be described as the *Amplitude Match (or Balance)* on the datasheet which is equally important when dealing with differential high speed signaling rates so both the 0° and 180° signal are at the same signaling level.

$$Amplitude\ Match\ (or\ Balance) = Mag[S_{31}](dB) - Mag[S_{21}](dB) \qquad (1.2)$$

- Another important specification obtained is the amount of signal that results on Port 3 when Port 2 is being driven. This would be referred to as the *Isolation* of the balun, or S_{32}.

$$Isolation = Mag[S_{32}](dB) \cong Mag[S_{23}](dB) \qquad (1.3)$$

Performance data for the HL9607 Isolation Balun are shown in *Figure 2* for each of the equations described above *(1.1 - 1.3).*

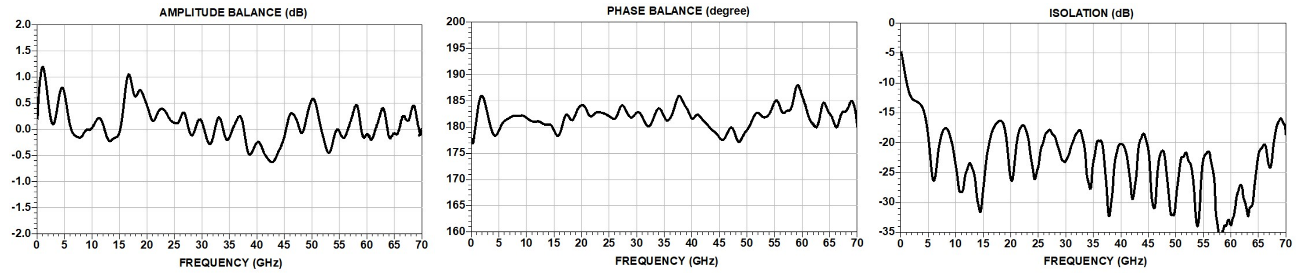


Figure 2: Example measurements of a Hyperlabs HL9607 Isolation Balun representing equations [1.1] – [1.3].

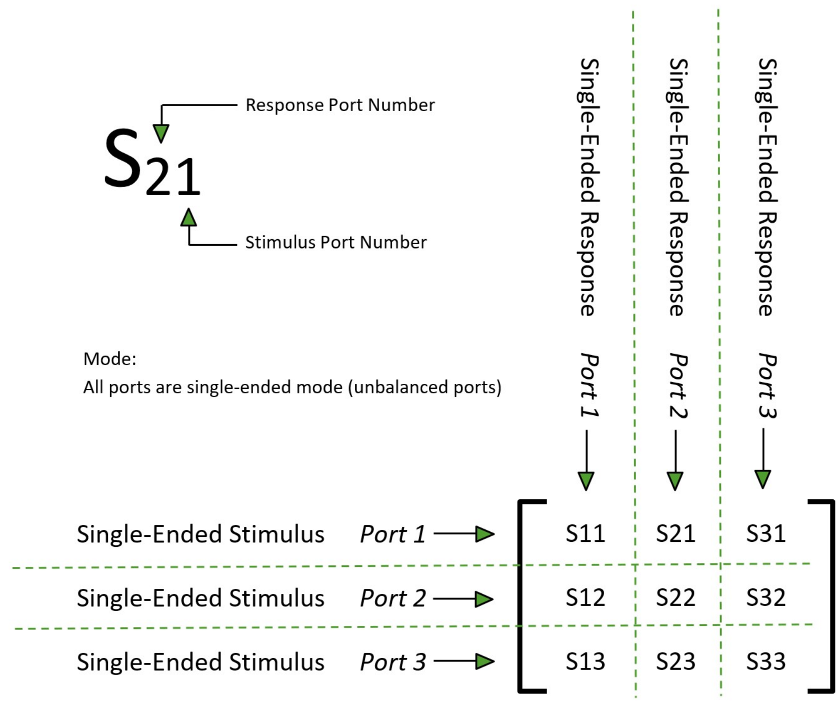


Figure 3: Graphical representation of a scattering matrix 3-port device using single-ended stimuli.

MIXED-MODE SCATTERING PARAMETERS

Mixed-Mode scattering parameter matrices (*Figure 4)* are a different representation of the single-ended matrix described in the Single-Ended Scattering Parameters section. If the single-ended matrix is representative of a linear system, the mixed mode matrix can be calculated directly from the single-ended matrix. Instead of three, single-ended ports, the two ports on the balanced side of the balun are combined to form a single 100 Ω differential port, as shown in *Figure 1b.*

From this representation, the calculated two-port, mixed-mode s-parameter matrix of the balun can be expressed through the single-ended mode of Port 1 and common (and differential) mode on Port 2, as shown in *Figure 5*

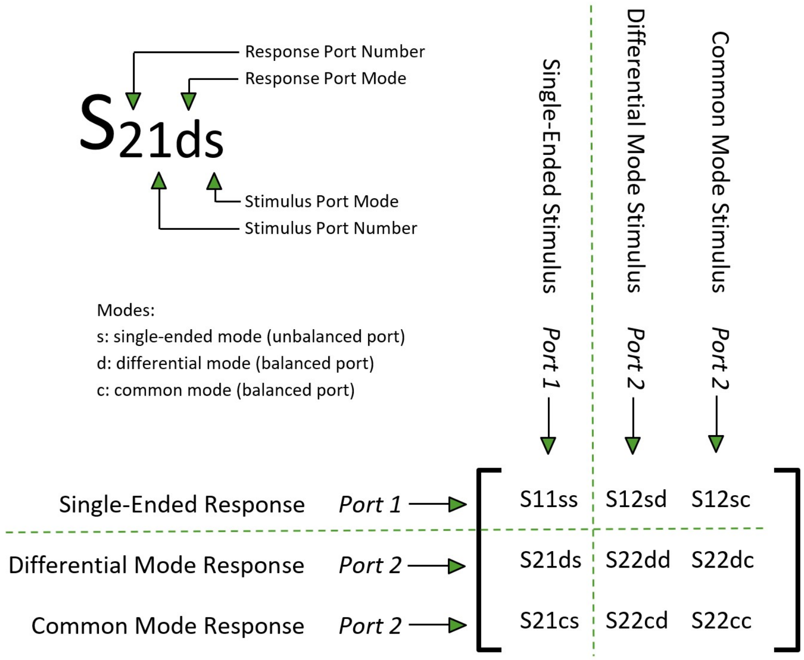
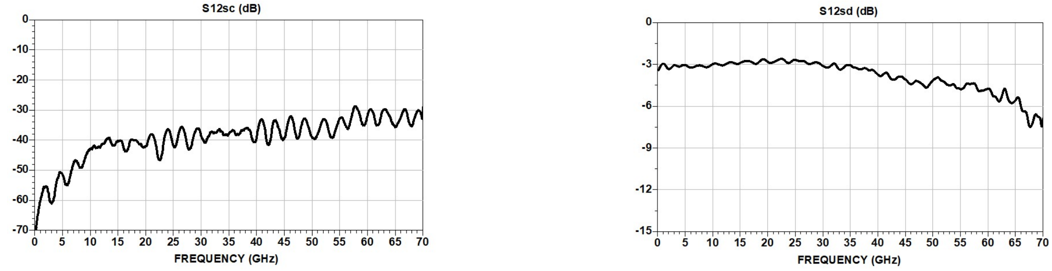


Figure 5: Graphical representation of a 2-port (single-ended mode to differential mode) mixed-mode scattering matrix. [3]

As an example of the usefulness of these parameters, S_{12sc} and S_{12sd} will be considered. These two mixed-mode s-parameters represent the output of the single-ended port (Port 1) when the differential port (Port 2) is being driven with a common mode signal, S_{12sc}, and a differential signal, S_{12sd}. HYPERLABS' baluns exhibit a significant amount of common mode rejection while converting the differential signal at industry leading bandwidths. *Figure 6* shows the small amount of signal transmitted to the single-ended port from a common mode stimulus (a) as well as the significant transmission of the differential drive to the single-ended port *(b) of an HL9607 balun.*



(a) *(b)*

Figure 6: mixed-mode drive to single-ended output, (a) common mode (b) differential mode.

Another term derived from mixed-mode s-parameters is common mode rejection ratio Common-Mode Rejection Ratio (CMRR). CMRR is a metric used to quantify the ability of the represented device to reject common-mode signals, i.e. those signals that appear simultaneously and in-phase on both ports of the differential input.

CMRR is defined as the ratio of powers of the differential gain to the common-mode gain found in equation *(1.4) [4]*.

$$CMRR(dB) = 20 * \log 10 \left\{ \frac{S_{21ds}}{S_{21cs}} \right\} \quad (1.4)$$

Figure 7 shows the CMRR of the HYPERLABS' HL9607 Isolation Balun.

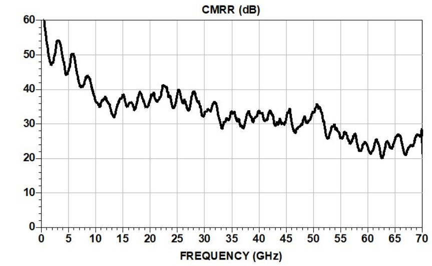


Figure 7: Graphical representation of the HL9607 CMRR calculated from the mixed-mode scattering matrix.

In conclusion, *Figure 5* defines each of the mixed-mode parameters for a device with three physical ports, while *Figure 8* presents the majority of the mixed-mode s-parameters for the HYPERLABS' HL9607 Isolation Balun.

S11ss: Single-ended return loss of the unbalanced port being driven single-ended.

S12sd: Differential mode input to single-ended output insertion loss.

S12sc: Common mode input to single-ended output insertion loss.

S21ds: Single-ended input to differential mode output insertion loss.

S22dd: Differential mode return loss of the balanced port when the port is driven with a differential mode input.

S22dc: Differential mode response of the balanced port when the port is driven with a common mode input.

S21cs: Single-ended input to common mode output insertion loss.

S22cd: Common mode response of the balanced port when the port is driven with a differential mode input.

S22cc: Common mode return loss of the balanced port when the port is driven with a common mode input.

[1] "Back to Basics: S-parameters." Accessed: May 06, 2025. [Online]. Available: https://blog.teledynelecroy.com/2014/05/back-to-basics-s-parameters.html
[2] D. M. Pozar, Microwave Engineering, 4th edition. Hoboken, NJ: Wiley, 2011.3 – Keysight Technologies. Evaluating Balanced Devices.
[3] "Evaluating Balanced Devices (balance-unbalance conversion function)." Accessed: May 06, 2025. [Online]. Available: https://helpfiles.keysight.com/csg/e5071c/measurement/fixture_simulator/evaluating_balanced_devices_balance_unbalance_conversion.htm
[4] "Microwaves101 | Mixed-Mode S-Parameters." Accessed: May 06, 2025. [Online]. Available: https://www.microwaves101.com/encyclopedias/mixed-mode-S-parameters

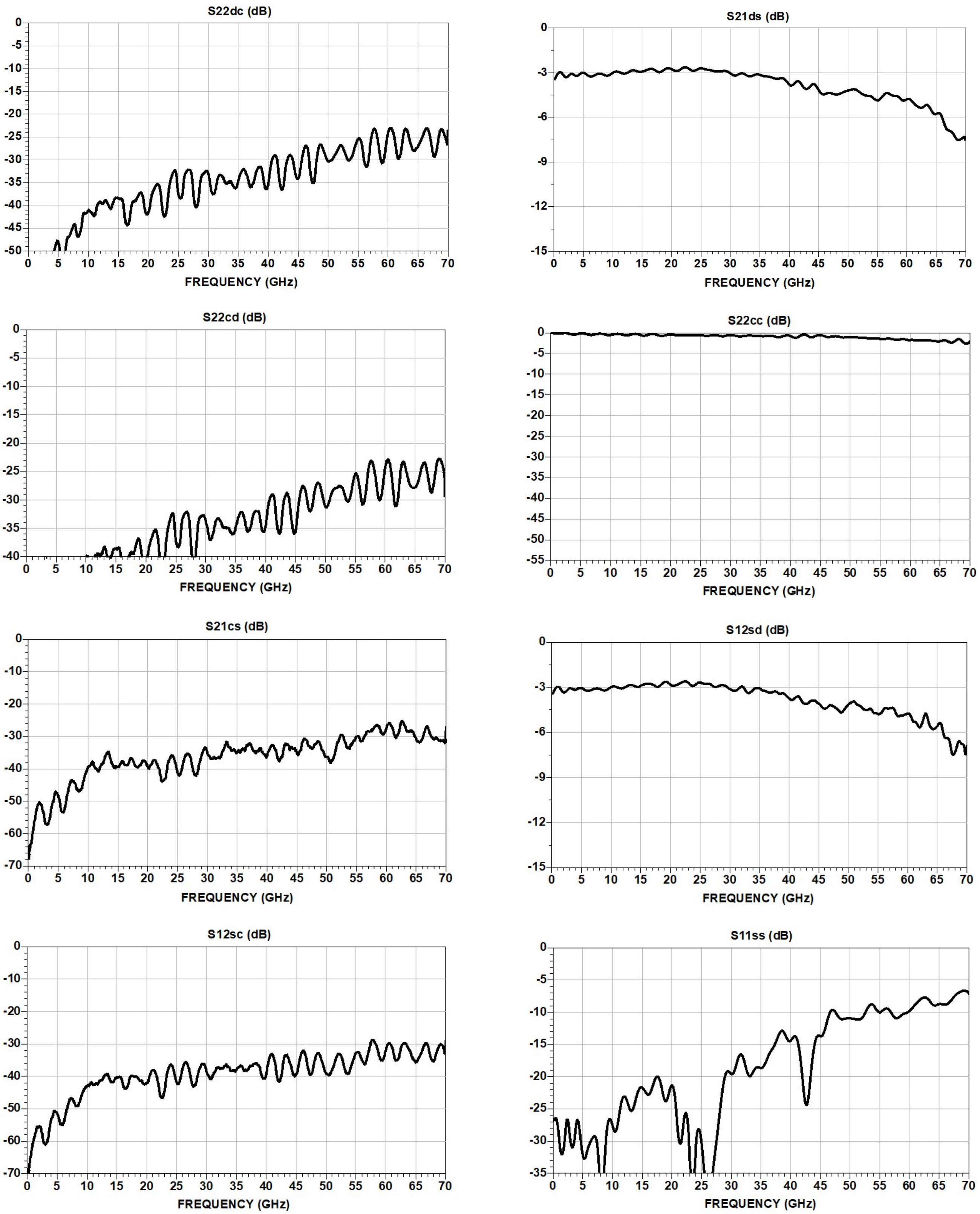


Figure 8: Mixed-Mode s-parameters for the HL9607 Isolation Balun.