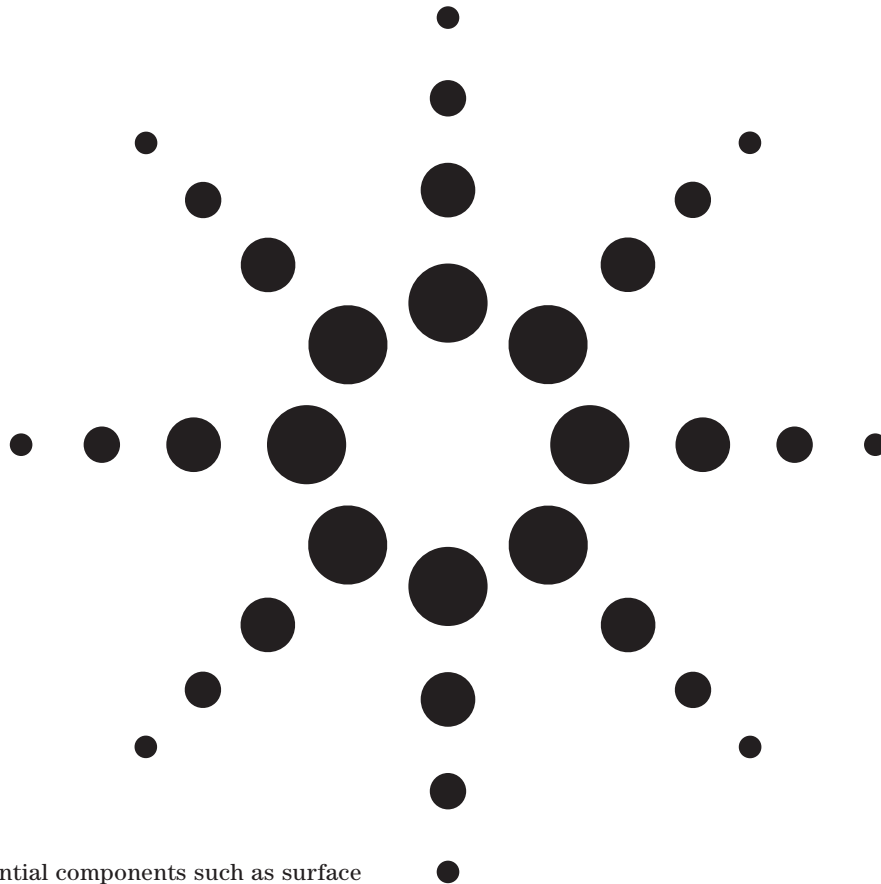


Multiport & Balanced Device Measurement Application Note Series

Concepts in Balanced Device Measurements

Application Note 1373-2



Introduction

The use of differential components such as surface acoustic wave (SAW) filters and differential amplifiers is becoming more common in the wireless industry because they have greater performance than their single-ended counterparts, such as the traditional single-ended three-terminal duplexer filters used in mobile handsets. Accurate measurement of these components is challenging as most vector network analyzers have single-ended RF ports that cannot directly measure differential parameters. However, there are several alternative methods of obtaining the differential parameters needed to characterize these devices. This article describes the challenges designers face in measuring the performance of differential components, and describes each of the most widely used techniques. While each technique produces a specific level of accuracy that depends on the characteristics of the device to be tested, the "calculated mix-mode" method provides the most accurate device characterization and has the fewest drawbacks.



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Differential devices

Two types of differential components, one with a single-ended output and the other with a differential output are shown in figure 1. The differential port of the devices consists of a pair of physical terminals. Differential components are unique in that signals are referenced not only to a common ground but to each other as well. The signals referenced to each other are called "differential mode" and the signals referenced to a common ground are called "common mode." Differential components can have both common mode and differential mode signals.

In most cases, the differential mode signals are out of phase because their phase relative to each other is 180 degrees, which creates a virtual ground along the axis of symmetry of the device. At the virtual ground, the potential at the operating frequency does not change with time, regardless of the signal amplitude. Common-mode signals are induced at the terminals of the device with the same phase and amplitude relationship.

While a differential component has no performance advantage over a single-ended component when used in common mode, it exhibits significant benefits when used in differential mode, because it will pass differential-mode signals and reject common-mode signals. For example, noise from a power supply will affect both terminals of the device equally with the same phase relationship. The device will characterize this noise as a common-mode signal on its terminals, and keep it from passing through. Since no device is ideal, some of the differential signal applied is converted into the common mode and some of the common-mode signal is converted into the differential mode as shown in figure 2. This is referred to as mode conversion, and is directly related to noise immunity of the device.

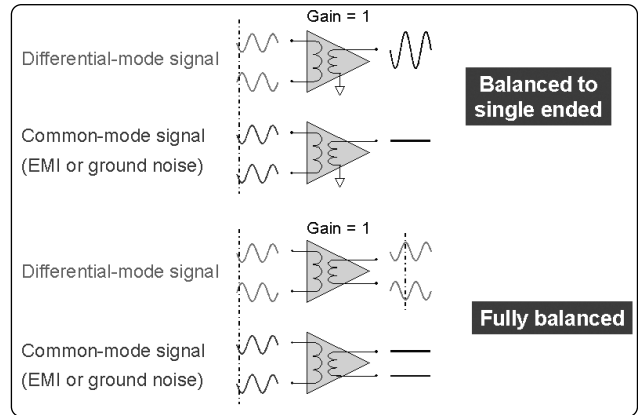


Figure 1: Two types of differential components, showing single-ended and differential outputs.

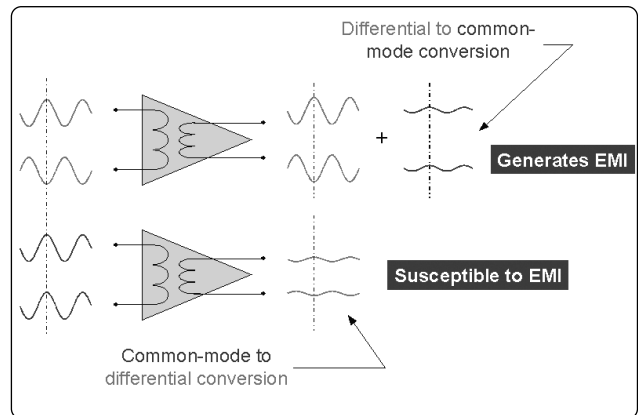


Figure 2: Mode conversion occurs when some of the differential signal is converted into the common mode and some of the common-mode signal is converted into the differential mode.

Measurement obstacles

While vector network analyzers are typically employed to measure an RF component, most are not designed for measuring differential parameters. Their RF ports are single-ended with common impedance values and cannot supply differential and common-mode signals to the device. Single-ended devices have impedances of 50 to 75 ohms, while differential components have no standard impedance values. To measure a four-terminal (two-port differential) component requires 16 S-parameters. These single-ended S-parameters are not sufficient to accurately characterize a differential component operating in differential mode. As a result, measuring differential components accurately using a single-ended analyzer cannot be accomplished without applying some type of hardware or software conversion to the single-ended data. Two common approaches use either a balun, or perform some type of mathematical transform.

The balun-based technique requires the balun to be placed between the differential port of the device and the single-ended port of the analyzer. The balun transforms the single-ended signal of the analyzer to a differential signal that is applied to the device. There are a number of problems with this approach. While the measurement plane should be at the terminals of the device, this is difficult to realize because there are no standard calibration standards for differential mode. As a result, a calibration must be performed at the single-ended input side of the balun. The analyzer is now measuring the performance of the differential component and balun as one device. The balun has finite return loss, insertion loss, amplitude balance, phase balance, and bandwidth, and becomes a major limiting factor in measuring the component. A balun also will not pass common-mode signals, so none of the mode conversion parameters of the device can be measured. Finally, the balun method will only provide information about the differential mode of the component.

Another method uses a mathematical transform to convert the single-ended data to differential parameters, and is called the mixed-mode S-parameter technique. It provides the common-mode and differential-mode parameters of the device, and is similar to single-ended measurement except that instead of stimulating a single terminal of the DUT, pairs of terminals are considered to be stimulated in either a differential (out-of-phase) or a common (in-phase) mode. A physical differential/common-mode stimulus to the device is not being provided. A single stimulus signal is actually supplied to each of the ports, and the response is measured. This single-ended data can then be transformed to mixed mode. The mixed-mode S-parameter technique essentially seeks to determine (with a differential-mode stimulus on a differential port) the corresponding differential and common mode responses on all of the device ports. For a common-mode stimulus, it attempts to determine the differential-mode and common-mode responses. A mixed-mode S-parameter matrix can be organized in a way similar to the single-ended S-parameter matrix, in which each column represents a different stimulus condition, and each row represents a different response condition (figure 3). Unlike the single-ended example, the mixed-mode S-parameter matrix not only considers the port but 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. Consequently, the first two subscripts in the matrix 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 S-parameter matrix fully describes the linear performance of a differential two-port network.

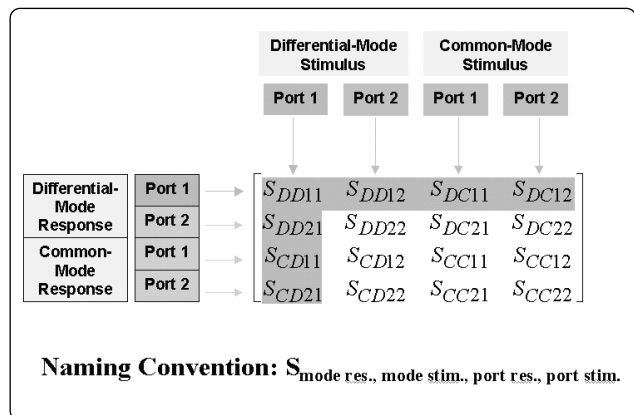


Figure 3: A mixed-mode S-parameter matrix can be organized in a similar way to the single-ended S-parameter matrix, in which each column represents a different stimulus condition, and each row represents a different response condition.

Differential measurement techniques

The techniques employed to measure a differential device in the following discussion are based on measurements made of a three-terminal SAW filter in an LTCC antenna switch module using an Agilent E8358A PNA Series vector network analyzer. The results are shown in figures 7 and 8.

The measured results are saved first into S-parameter files (s2p) using a two-port analyzer. For a three-terminal device this will require three two-port measurements resulting in three files for a total of 12 S-parameters. The next step is to import the files into ADS using the ADS instrument server as shown in figure 4. The data is read into Agilent's Advanced Design System (ADS) datasets with names that were specified during the ADS read process. A three-terminal device will have a total of nine S-parameters, which will require the cancellation of redundant terms in the 12 S-parameters. This cancellation procedure is performed by mapping the three datasets to one dataset as shown in figure 5. The resulting dataset is then used for the analysis. A three-port analyzer would directly provide the nine S-parameters, which could then be imported into ADS.

A simple extension of the mixed-mode concept can be applied to devices having a combination of differential and single-ended ports, as is the case with the three-terminal SAW filter. The four-terminal matrix can be converted to a three-terminal matrix by removing the port 1 differential mode stimulus and response as illustrated by the shaded row and column in figure 3, page 3. In this scenario, the differential and common modes on the differential ports and one mode on the single-ended port must be considered.

The S-parameter matrix (figure 6) for such a device is arranged with the stimulus conditions in the columns, and the response conditions in the rows. The mode on the single-ended port is referenced with an 'S' for single-ended instead of a 'C' for common mode because only one mode is available on this port. Two columns and two rows describe each differential 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 differential 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.

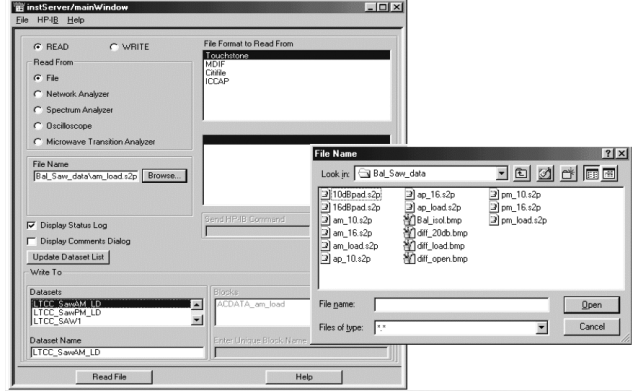


Figure 4: The ADS instrument server is used to import S-parameter files

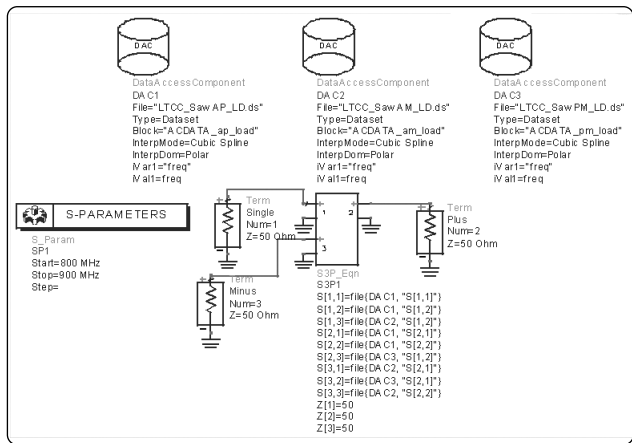


Figure 5: Cancel redundant terms by mapping three datasets to one

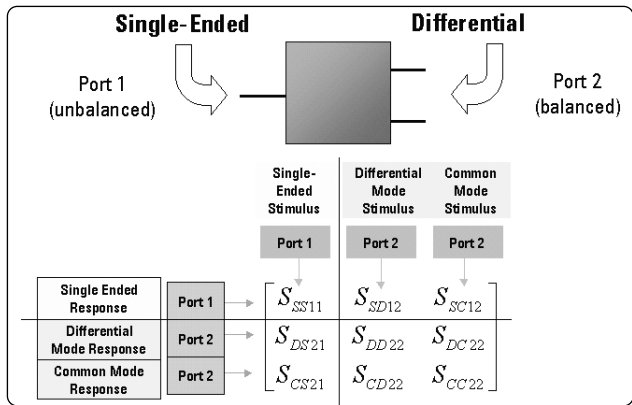


Figure 6: When the four-terminal matrix is converted to a three-terminal matrix, the differential and common modes on the differential ports and one mode on the single-ended port must be considered. The S-parameter matrix for this configuration is arranged with the stimulus conditions in the columns, and the response conditions in the rows.

Single-ended method

Measuring the differential device as a single-ended multiport device is the simplest method, but it is time-consuming because multiple two-port measurements are needed to fully characterize the device. In addition, it can produce misleading results because the single-ended data may not give a representative indication of the performance of the device when it operates in one of its differential modes. This occurs because the single-ended data does not provide accurate information of differential performance. For example, S_{21} is the insertion loss measurement from the antenna terminal (terminal 1) to the rx+ terminal (terminal 2). It is not the same as the insertion loss measurement from the antenna to the differential port. In figure 7, there is offset between the values of S_{31} and S_{21} , which represents the overall balance between the two terminals that make up the differential port. This offset may be caused by an asymmetrical device topology that will result in a decrease in differential mode performance. Ideally, S_{31} and S_{21} should have the same amplitude characteristics.

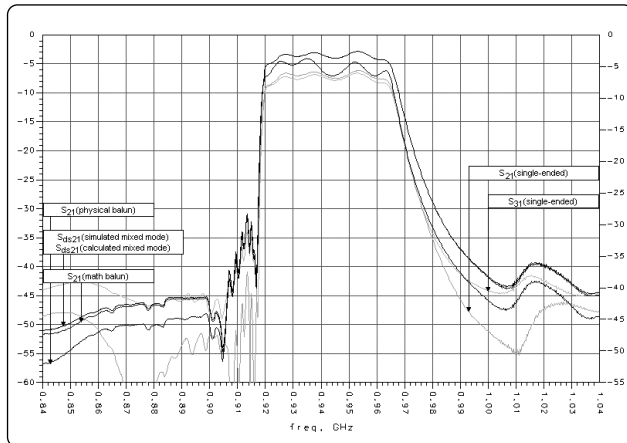


Figure 7: Offset between the values of S_{31} and S_{21} represents the overall balance between the two terminals that make up the differential port. This image also contains the comparison of the balun methods and mixed-mode methods.

Delta method

With the delta method, the single-ended transmission phase characteristics of the device are measured. The topology of most differential devices will constrain the electrical length of the two terminals comprising the differential port to give a 180-degree phase shift between them. This parameter is directly related to how well the device performs in differential mode. Figure 8 shows the phase difference between the two terminals (S_{31} and S_{21}) of the differential port measured single-ended as with the single-ended method. There should be 180 degrees of phase difference between the two terminals. The difference in phase shown in the figure is not exactly 180 degrees, which results from the asymmetries of the device. This method also does not yield insight into the full mixed-mode S-parameter matrix.

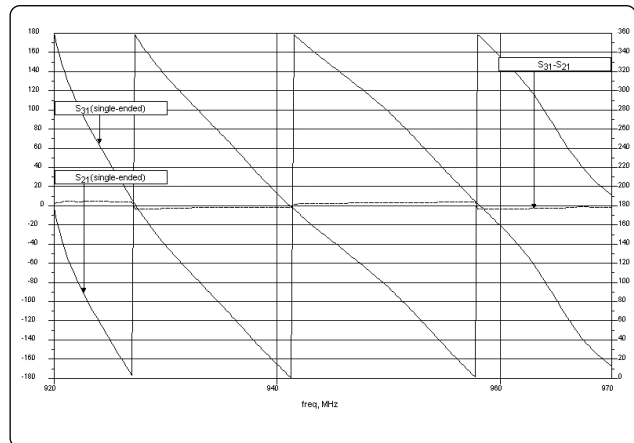


Figure 8: The phase difference between the two terminals (S_{31} and S_{21}) of the differential port measured single-ended as with the single-ended method.

Physical balun method

As was discussed earlier, a balun may be used to convert the single-ended port of the network analyzer to the differential port of the device, which transforms the impedance of the differential device to the impedance of the network analyzer. In this case, the differential port impedance is 100 ohms and the single-ended port impedance of the analyzer is 50 ohms. This method will provide some degree of accuracy about the differential characteristics of the device but does not provide information on common-mode performance. The accuracy of this method is also highly dependent on the calibration reference plane and the characteristics of the balun.

Mathematical "ideal balun" method

The single-ended data may also be imported into a circuit simulator such as Agilent's ADS. This data can then be transformed to differential data using a balun circuit component in the simulator (figure 9). As with the physical balun method, the common-mode performance of the device cannot be measured. The circuit component is an ideal balun, so the common-mode impedance is infinite (where the non-center tapped reflection coefficient equals +1). Any common-mode signals at the output of the device will reflect from the balun and possibly back to the output as an error signal, depending on the mixed-mode performance of the device. The same will be true when using a physical balun, but the reflection coefficient will differ depending on its characteristics. The mixed-mode performance of the device cannot be measured using a balun, so there is no way to determine what the error result may be. The same is true for the center-tapped balun (where the reflection coefficient equals -1).

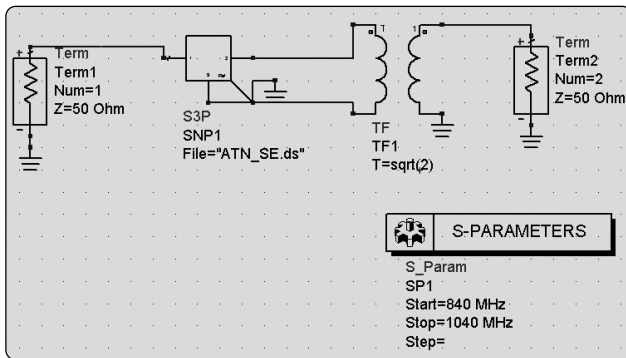


Figure 9: If the single-ended data is imported into Agilent's Advanced Design System (ADS) simulation tool, it can be transformed to differential data using a balun circuit component.

Simulated mixed-mode method

A circuit simulator can also be used to measure mixed-mode S-parameters of the differential device as illustrated in figure 10. A center-tapped balun is used to perform the differential-mode conversion and also provides the mechanism for the common-mode terms. The common-mode conversion occurs at the center tap of the balun where only common-mode signals will appear because of the characteristics of the balun. These common-mode signals are then terminated through a balun into a 25-ohm termination, which is the common-mode impedance of the SAW device. This configuration will allow all the mixed-mode characteristics of the device to be measured. It also provides the appropriate terminations for differential- and common-mode signals so that mode conversion terms do not cause errors like those produced by the balun method.

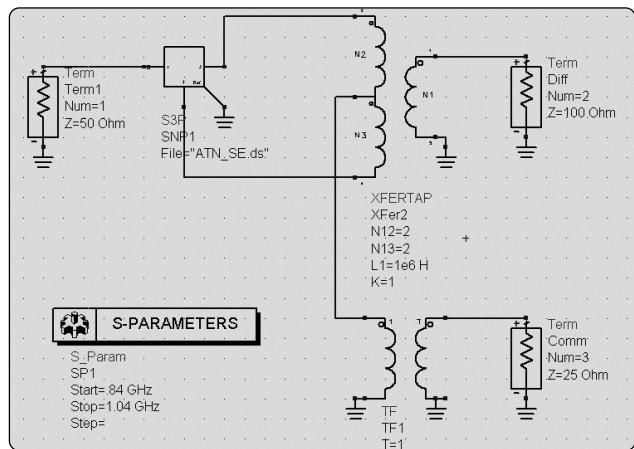


Figure 10: A circuit simulator can also be used to measure mixed-mode parameters of the differential device.

Calculated mixed-mode S-parameters method

Bockleemann and Eisenstad¹ have analyzed a method to convert the single-ended data to mixed-mode using mathematical algorithms. These algorithms show the relationship between nodal waves generated by a standard vector network analyzer and the associated common and differential waves that realize mixed-mode S-parameters. This method is highly beneficial because of the quick and simple method of conversion. It does not require a circuit simulator and therefore can be performed in real time using a compiled math function library. For example, the mixed-mode S-parameters of a differential device can be accurately measured in a manufacturing environment in which differential measurement speed and accuracy are of high concern.

Balun versus mixed-mode method

The results obtained from the mathematical balun and mixed-mode measurement methods can be quite different as shown in figure 11. The device under test used in the example exhibited mode conversion, and in conjunction with the balun, induced an error in the measurement. To continue this discussion, the differential insertion loss (S_{ds21}) of the three-terminal SAW filter is measured with a balun at the output to perform the differential-to-single-ended conversion to the network analyzer. The balun is again assumed to be ideal (lossless) in this analysis.

The network analyzer supplies a signal to the single-ended port of the device, and this signal is attenuated by the device's insertion loss and shows up at the output of the device as a differential signal. The signal is then converted back to single-ended using the balun so it can be measured using the network analyzer. This signal is the desired differential measurement result using the balun method. A portion of the incident signal that was applied to the input of the device is converted to common mode (S_{cs21}) at the output, which is called mode conversion. The common-mode signal encounters the common-mode match (S_{cc11}) of the balun, which has a common-mode reflection coefficient of +1. A grounded center-tapped balun would have a common-mode reflection coefficient of -1.

This characteristic causes the entire signal to be reflected back to the device, where it encounters the device's common-to-differential-mode match (S_{dc22}), and is converted to a differential signal that passes through the balun to the analyzer. The infinite loop created by S_{cc11} (balun) and S_{cc22} (DUT) terms accounts for second-and-higher-order terms. It can be consolidated using the power series expansion technique. The goal is to measure the pure differential performance of the device, so these signals show up as error in the measurement as demonstrated in figure 12. The total measured signal (including error) is calculated as in Equation 1.

$$\text{Error Signal} = S_{cs21} * S_{cc11_balun} * S_{dc22} + S_{cs21} * S_{cc11_balun} * S_{cc22} * S_{cc11_balun} * S_{dc22} + \dots$$

$$\text{Error Signal} = S_{cs21} * S_{dc22} * S_{cc11_balun} * (1 + (S_{cc22} + S_{cc11_balun})^1 + (S_{cc22} * S_{cc11_balun})^2 + (S_{cc22} * S_{cc11_balun})^3 + \dots)$$

$$\text{Using Power Series expansion: } (1 + (S_{cc22} + S_{cc11_balun})^1 + (S_{cc22} * S_{cc11_balun})^2 + (S_{cc22} * S_{cc11_balun})^3 + \dots) = \frac{1}{1 - S_{cc22} * S_{cc11_balun}}$$

$$\text{Error Signal} = \frac{S_{cs21} * S_{dc22} * S_{cc11_balun}}{1 - S_{cc22} * S_{cc11_balun}}$$

$$\text{Measured} = S_{ds21} + \frac{S_{cs21} * S_{dc22} * S_{cc11_balun}}{1 - S_{cc22} * S_{cc11_balun}}$$

Equation 1.

The designer's goal would ideally be to terminate the common-mode signal from the device so that it does not affect the other measurement modes. Using mixed-mode S-parameters, it is possible to get an accurate measurement of S_{ds21} insertion loss without the common-mode error.

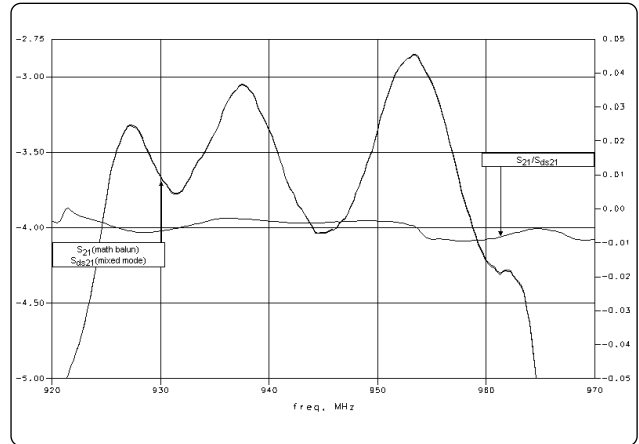


Figure 11: The error due to the mode conversion of the device can be calculated by comparing the mathematical balun results to the mixed-mode results.

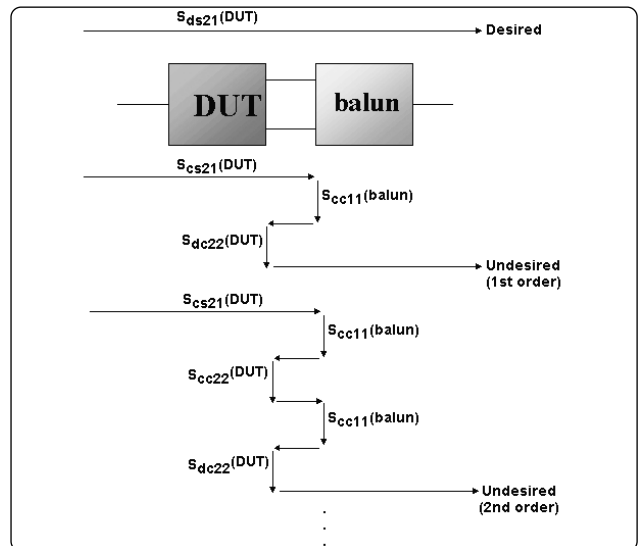


Figure 12: When measuring the differential performance of the device errors become apparent.

Physical, ideal, and non-ideal baluns

Even an ideal balun will cause some measurement error. The effects of using a simulated non-ideal balun measurement can be compared to a measurement that employs a physical balun. In this example, the component values for the balun were chosen from a manufacturer's data sheet. The simulation setup for the non-ideal balun is shown in figure 13. A calibration was performed at the terminals of the analyzer because there are no standard calibration standards for the differential mode. In figure 14, the difference in measurement results of the S_{ds21} term of the DUT for the three different balun measurements are apparent. The non-ideal and physical balun greatly degrade the measurement results.

There are two primary causes for these differences. First, the balun now contains non-ideal mixed-mode S-parameters such as insertion loss and input match. Since the ideal balun cannot be physically realized, it is necessary to consider actual physical balun parameters to illustrate the effects they will have on the differential measurement. The calibration plane is at the terminals of the balun and not at the terminals of the DUT, which means that the analyzer is measuring the three-terminal SAW filter and balun as one device, so the measurement results will be an aggregate of the two devices. These results illustrate the importance of the calibration reference plane and the need for mixed-mode S-parameters.

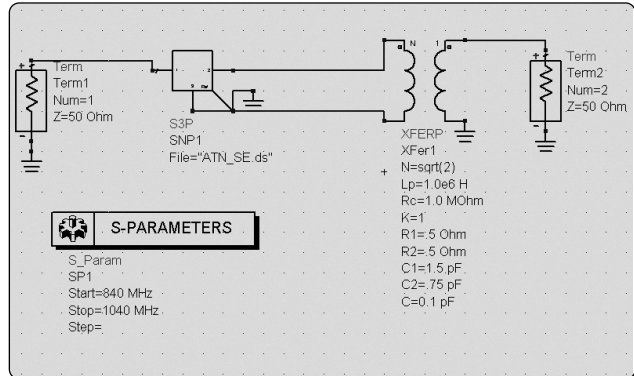


Figure 13: The simulation setup for the non-ideal balun.

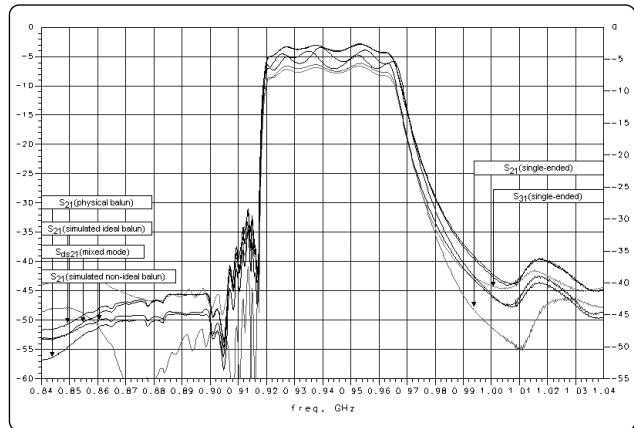


Figure 14: The three different balun-based techniques produce significant differences in measurement results of the S_{ds21} term of the DUT.

Fixturing and asymmetric device effects

While it would be desirable to perform the calibration at the device terminals, in some instances this is very difficult because in-fixture standards must be designed and characterized with an associated calibration kit definition for the network analyzer.

In our example the three-terminal SAW filter is in a fixture, and a calibration has been performed at the fixture's input terminals and not at the input plane of the device. The transmission line from the input terminals of the fixture to the input terminals of the device should have the same electrical characteristics, especially on the differential port of the SAW filter. Assume for this discussion that one of the transmission lines to the device on the differential side is longer than the other two transmission lines. This effect can be analyzed by using a simulator as shown in figure 15 in which the simulator's transmission line element represents the difference in actual electrical transmission line length of the fixture. This difference in length will affect some of the mixed-mode parameters of the device. For example, figure 16 shows the resulting common-mode-to-differential-mode match term (S_{dc22}) of the device that causes errors in the measurement when using a balun. The fixture offset has degraded the S_{dc22} term, which can further increase measurement error when using a balun. This result can also be realized for a differential device that is asymmetric because asymmetries in the device will affect the mode-conversion terms. Port extensions and de-embedding are useful features that can be used to remove fixturing effects (such as the asymmetric fixturing effect above) from a measurement if a calibration cannot be made at the terminals of the device. Port extensions are a feature available in some network analyzers that mathematically extend the measurement plane beyond the calibration plane to the terminals of the device. A port extension takes into account not only the electrical length of the fixture but also its loss.

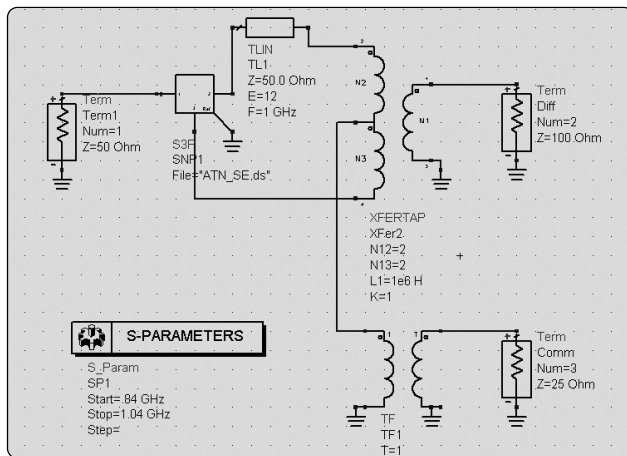


Figure 15: The effect of having one of the transmission lines to the device on the differential side longer than the other two transmission lines can be analyzed by using a simulator in which the simulator's transmission line element represents the difference in actual electrical transmission line length of the fixture.

De-embedding and embedding can also be used to remove the effects of a fixture from the measurement, which moves the measurement plane to the device terminals. A typical fixture will consist of a PC board (PCB), coaxial RF connectors to connect to the analyzer, and some type of non-coaxial connector to the DUT such as a Ball-Grid-Array (BGA). The S-parameter files of the fixture are required to de-embed it from the measurement results. Most analyzers, such as the Agilent ENA series, provide the de-embedding functionality but require the S-parameter files of the fixture to perform the operation.

A computer aided design application is often used to design the PC board. One de-embedding method is to use the computer design results in conjunction with ADS to model the fixture. The PCB usually consists of transmission lines of a specific impedance without the coaxial RF connectors. The PCB is fabricated for physical use and coaxial connectors added to allow connection of the PCB and DUT to the analyzer. A good design process will show correlation between the manufactured PCB and the computer design. The design results of the PCB can be exported into equivalent 's2p' files, which contain the S-parameter characteristics of the PCB without the coaxial RF connectors. Using ADS, the PCB S-parameter files can be imported and the fixture modeled as shown in figure 17. The inductance term is used to model the transition from the coaxial connector to the PCB transmission line. The fixture is then simulated and the required 's2p' files are generated and used to de-embed the fixture from the measurement. In all cases, the calibrated measurement plane should be at the terminals of the device.

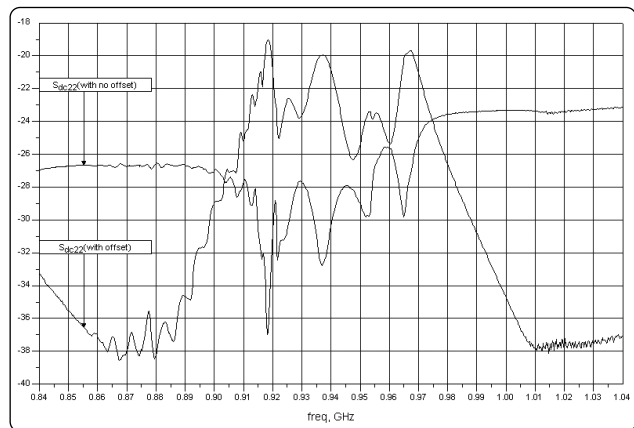


Figure 16: The common-mode-to-differential-mode match term (S_{dc22}) of the device causes errors in the measurement when using a balun.

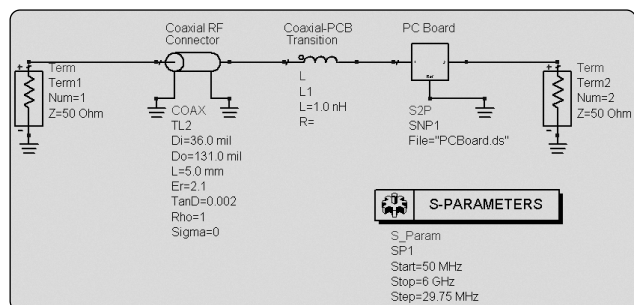


Figure 17: A PC board S-parameter files can be imported and the fixture modeled using ADS.

Multiport error-correction

It is very important to consider calibration and error-correction techniques when measuring multiport components. Most network analyzers are two-terminal instruments that enable accurate two-port calibrations using methods such as SOLT or TRL. The analyzer's correction terms and their effects are extremely important in understanding the measurement results. For example, the analyzer's load-match term becomes an important factor when measuring a component. After performing a two-port SOLT or TRL calibration, most analyzers will show a corrected load match of approximately 45 dB. This term is important when trying to get an accurate measurement in the passband of a device where the insertion loss is low. If measuring in the stopband, the load match term is not dominant in the measurement because the isolation of the device greatly attenuates any reflected error signal from the analyzer terminal with the load match. This effect is very important when measuring a multiport device.

An external multiport test set is typically connected to a two-port analyzer to measure a multiport component. Multiport test sets typically have an uncorrected load match of around 15 to 20 dB on the RF terminals. If a two-port calibration is used to measure a three-terminal device using the multiport test set, the uncorrected load match of the test set will be seen at the third terminal of the device, which may cause errors in the measurement (depending on the isolation of the device). This effect is shown in figure 18 when measuring the three-terminal SAW filter using two-port error correction and terminating the third terminal with a physical load that has 16 dB of return loss. The amount of error introduced into the measurement depends not only on the systematic error correction of the analyzer but on the device characteristics as well. If the device has high isolation between the corrected terminal and uncorrected terminal, the effects caused by the 16 dB load match will be less significant. This SAW filter has relatively low passband insertion loss between the single-ended input and the two output terminals that make up the differential port, so proper port termination is important to achieve accurate measurements. In addition, the third terminal must either be connected to a high quality (>40 dB return loss) load, or have three-port error correction applied. A three-port calibration on this device would be ideal for reducing all possible systematic errors. Network analyzers such as Agilent's ENA Series can measure a multi-terminal device with multiport correction applied to all terminals.

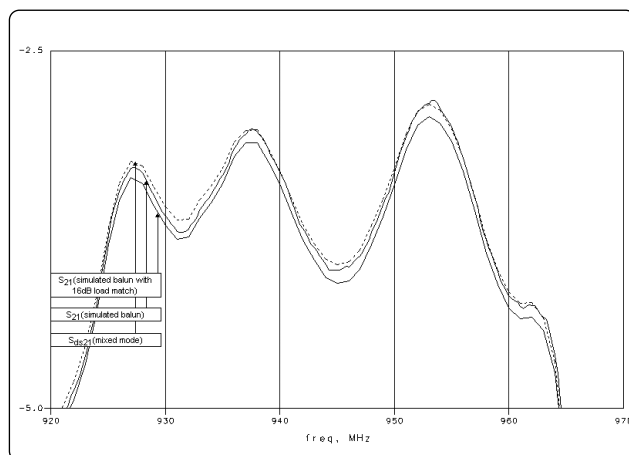


Figure 18: If a two-port calibration is used to measure a three-terminal device using the multiport test set, the uncorrected load match of the test set will be seen at the third terminal of the device, which may cause errors in the measurement (depending on the isolation of the device).

Conclusion

The simulated and calculated mixed-mode measurements have the same result, which would be expected because both methods provide all the differential characteristics of the device. However, the calculated mixed-mode method does not require a circuit simulator to perform the conversion. Figure 11 shows a comparison of the mathematical balun method versus mixed-mode S-parameters. The error caused by mode conversion of the device is clearly seen in this measurement comparison, and is the reason why the balun method result is not accurate.

Measuring a differential device can also be challenging because all the characteristics of the device must be measured without effects caused by fixturing. These effects can be removed from the measurement either by performing an in-fixture calibration, by using port extensions to lengthen the calibration reference plane, or by using de-embedding techniques to remove the fixture from the measurement, which effectively moves the measurement plane to the device terminals. While there are several techniques that can be used to measure the performance of a differential device, most have significant drawbacks.

Single-ended S-parameters do not provide accurate information on the differential performance, and balun techniques degrade measurement performance because of their inherent characteristics and calibration limitations. However, a multiport network analyzer with mixed-mode S-parameters and proper calibration techniques can produce fast, accurate characterization of differential devices in all of their modes of operation.

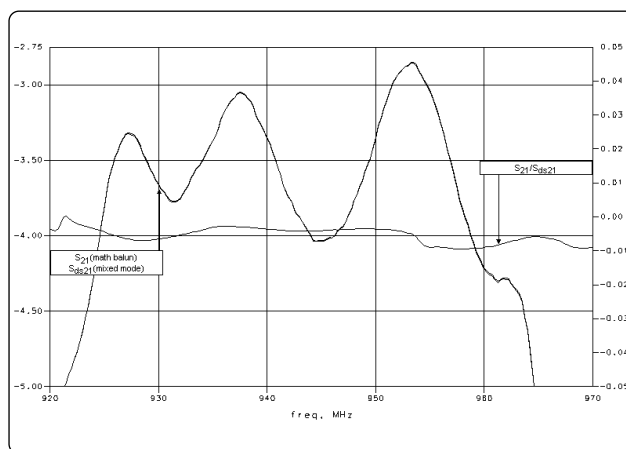


Figure 11: The error due to the mode conversion of the device can be calculated by comparing the mathematical balun results to the mixed-mode results.

Related literature

An Introduction to Multiport and Balanced Device Measurements, Application Note 1373-1, literature number 5988-5634

Applying Error Correction to Network Analyzer Measurements, Application Note 1287-3, literature number 5965-7709E

S-parameter Techniques for Faster, More Accurate Network Design, Application Note 95-1, literature number 5952-1130 (see also the interactive Application Note 95-1 at www.agilent.com)

Agilent ENA Series 2, 3, and 4 Port RF Network Analyzers, Brochure, literature number 5988-3765EN

Agilent Introduction to the Fixture Simulator Function of the ENA Series RF Network Analyzers: Network De-embedding/Embedding and Balanced Measurements, Product Note, literature number 5968-4923EN

Agilent PNA Series RF and Microwave Network Analyzers, Brochure, literature number 5968-8472E

High Performance Testing of Wireless Handset Front-end Modules, White Paper, 5988-4398E

Agilent Measurement Solutions for Balanced Components, Product Overview, literature number 5988-2186EN

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Key web resources

For more information on Agilent's balanced solutions please visit:
www.agilent.com/find/balanced

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