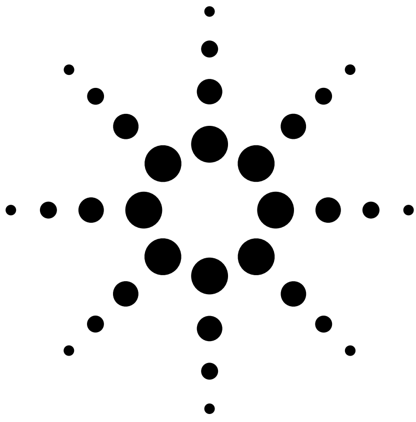
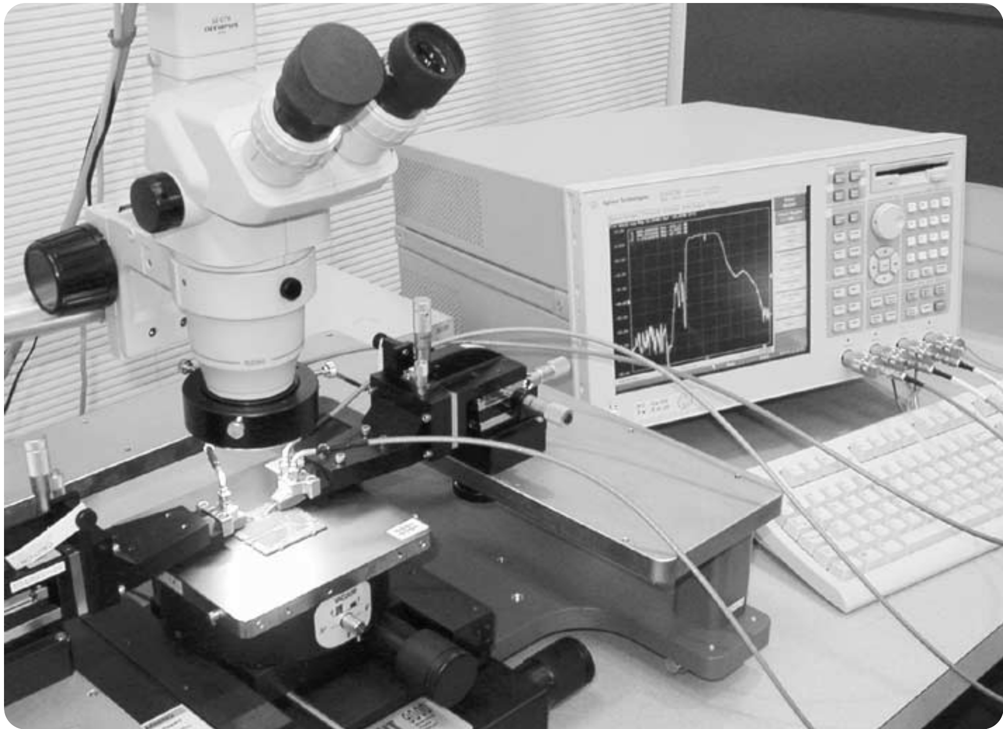
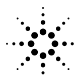


Agilent On-wafer Balanced Component Measurement using the ENA RF Network Analyzer with the Cascade Microtech Probing System

Product Note E5070/71-3



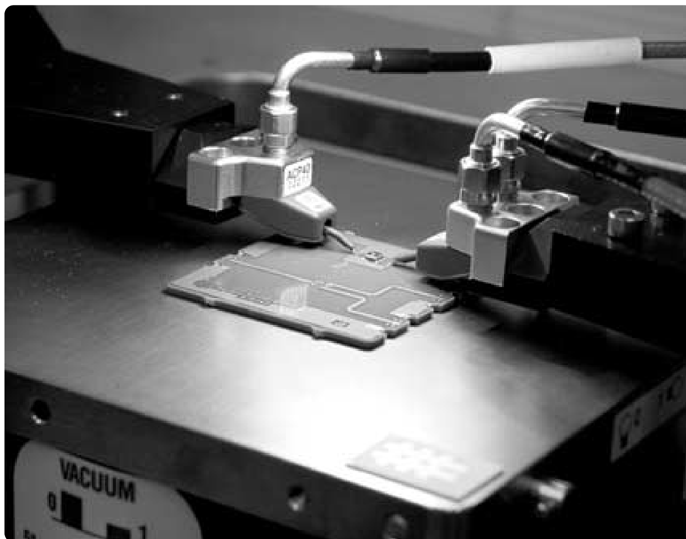


Agilent Technologies

Introduction

The use of differential circuit topologies is becoming increasingly more common in the development of a wide range of RF applications. The primary benefit of differential circuits is that they have good immunity from many sources of noise such as power supplies and adjacent circuitry. Differential circuits also have lower susceptibility to interference from electromagnetic coupling at the higher frequencies. Using differential topologies, these noise sources tend to couple in the common-mode and therefore cancel in differential mode. Due to these performance advantages, circuits using the differential and balanced components are being adopted for products such as cellular phones and high-speed digital equipment.

The ENAs RF network analyzer, together with the Cascade Microtech probing system, make it possible to obtain fast, accurate measurements for on-wafer multiport component. This complete on-wafer solution provides balanced conversion and delivers mixed-mode S-parameter measurements so that balanced components also can be accurately characterized.



1. System configuration

The system configuration of the multiport probe measurement system, using the ENA with the Cascade probe station and innovative dual-tip Air Coplanar probe (ACP), is shown in Figure 1.

This solution enables on-wafer balanced devices and circuits to be characterized to frequencies as high as 8.5 GHz. The ENA offers built-in balanced measurements, matching circuit simulation and port characteristics impedance conversion, all of which deliver balanced components evaluations.

Furthermore, easy probing to on-wafer balanced components can be realized by combining with a dual-tip ACP (Figure 3) provided by Cascade Microtech.

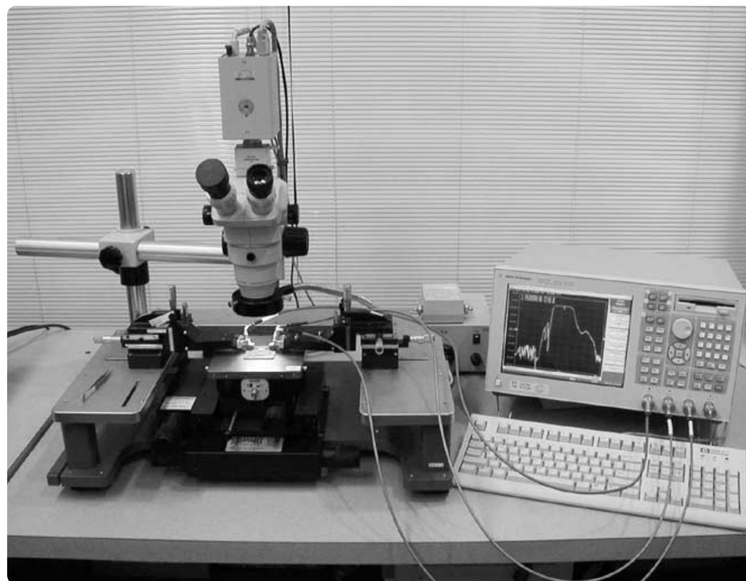


Figure 1. Multiport probing system configuration: Agilent ENA RF Network Analyzer and the Cascade Microtech Summit 9000 RF Probe Station

2. Dual-tip ACP and Impedance Standard Substrate (ISS)

ACP series covers a wide range of frequencies (DC-110 GHz), with probes available in single or multi-tip configurations. By maintaining a transmission line impedance all the way to the probe's tips and using a ground-signal-ground coplanar waveguide (CPW) launch, RF signals are delivered to the wafer with minimal attenuation and excellent impedance control. Wider probe pitch (center-to-center spacing of probe contacts) and the use of single-ground connections can be used at lower frequencies with reduced performance. Variable pitch configurations with flexible signal and/or ground contacts are not useful for network analyzer measurements since repeatable transition behavior is required for calibration.

The dual-tip ACP provides a precisely aligned second signal contact built into the Air Coplanar tip and connector block. This innovative tip technology provides outstanding compliance and tip visibility, which subsequently enables you to precisely contact the balanced port of the multiport device/differential circuit without considering the need for a complex contacting mechanism. This probe is available with GSGSG, GSGS, GSS, GSSG, SGS, SGSG, and SSG contact configurations. In on-wafer measurements, the known calibration standards are provided on an Impedance Standard Substrate, or ISS. Normal ISS structures include shorting bars, precisely trimmed loads, thru lines, and longer transmission lines. The range of ISSs, produced by Cascade Microtech, offering these high precision calibration standards is shown in Figure 2. The correct ISS to use depends on the probe tip configuration and pitch.

ENA Wafer Cal™ [1] is a software program created by Cascade Microtech that enables you to perform on-wafer mutliport calibration with simple operation (Figure 4). This software runs on the ENA and guides the user through the setup of the CalKit and calibration steps, thus reducing one of the greatest sources of error in calibration. Consequently, this program improves calibration accuracy and repeatability.

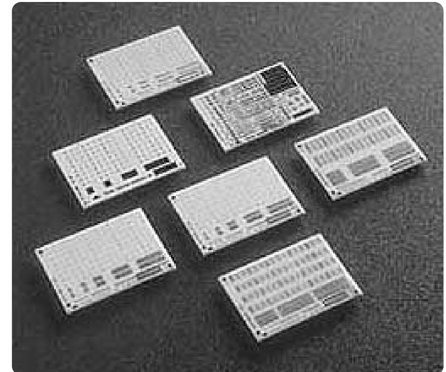


Figure 2. Impedance Standard Substrates (ISS)

Figure 3. Dual-tip ACP

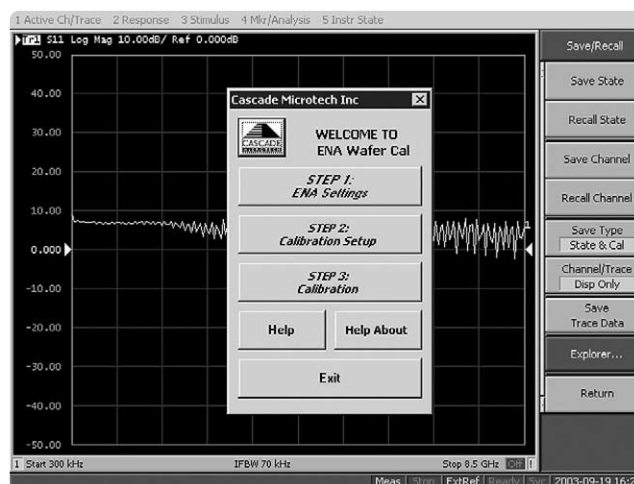


Figure 4. ENA Wafer Cal software

1. ENA Wafer Cal requires the "B" version of the ENA.

3. Full 4-port error correction using the dual-tip ACP

In order to perform an on-wafer full 4-port error correction, the dual-tip ACP and balanced ISS is the best choice.

For the full 4-port on-wafer calibration that was performed for this evaluation and documented in this paper, the following combination of products was used (Table 1).

Table 1. Products used for 4-port on-wafer measurements

Product	Model number	Remarks
ENA RF Network Analyzer	E5071B #414	300 kHz to 8.5 GHz 4 port test set
Cascade Microtech RF Probe Station	Summit 9000	
Dual-tip ACP	ACP40-D (GSGSG)	150 µm pitch
Impedance Standard Substrates (ISS)	005-016	General purpose
	126-102	150 µm pitch Balanced component evaluation

3-1. Calibration kit of the dual-tip ACP

The method used to calibrate the multiport system to the probe tip reference plane is the Short-Open-Load-Thru (SOLT) technique. For this technique, all the calibration standards must be perfectly known and this description is provided to the ENA as a correction of data known as a CalKit. Complying with coaxial calibration standards requires the use of unique devices that have a connector with only a single electrical characteristic. In on-wafer probing, the electrical behavior of the standards is dependent upon the probe and how it is placed. The shape and configuration of the standard will also be important. The SOLT standards are reasonably well modeled with simple lumped elements: open-circuit capacitance (C_{open}), short-circuit inductance (L_{short}), load inductance (L_{term}) and thru delay. Consequently, these terms known as calibration kit values are supplied with the probe not with the ISS.

The next section explains how to enter the calibration kit values with the ENA Wafer Cal software and a manual operation.

These values are found in a table in the lid of the probe box. Figure 5 illustrates where the values for C_{open}, L_{short} and L_{term} are located for a range of probe pitches. The thru delay for each thru path between the signal contacts of the probes can easily be calculated by dividing the physical distance between the signal contacts by the propagation velocity (130 µm/psec).

Pitch	C-Open fF	L-Short pH	L-Term pH
100	–11.0	33.5	36.5
125	–11.0	41.7	47.2
150	–11.0	49.8	57.8
200	–11.0	66.2	79.2
250	–11.0	82.5	100.5

Figure 5. Example of calibration kit values

It is very important to ensure an accurate calibration that the CalKit is entered correctly into the ENA. One of the most common error sources when performing an SOLT calibration is incorrect setup of the CalKit.

3-2. Defining the Calibration Kit using ENA Wafer Cal

The value of the ACP40-D calibration kit is entered into the ENA by using ENA Wafer Cal. ENA Wafer Cal provides a calibration setup dialog menu to make it easy for you to enter the calibration kit value (Figure 6).

1. Click the **[Open]** button to load a calibration setup file (Figure 7).
2. After clicking the **[Open]** button, you will be given a preview of the comments and descriptions contained in the calibration setup file that you have selected (Figure 8).
3. If the comments shown in the Standard Descriptions dialog match the desired calibration setup, then press **[Accept]** to load the file.
4. After entering calibration kit values in the calibration setup dialog, a file must be saved to ENA before continuing with the calibration process. Press **[Save As]** to save the current settings to a calibration setups file.
5. After the desired settings have been entered, you may store the calibration kit values in the ENA by pressing the **[CalKit to ENA]** button.
6. The calibration kit will be stored in the ENA's Cal Kit menu location 10 under the label "Wafer Cal". The on-wafer measurement should use this calibration kit.

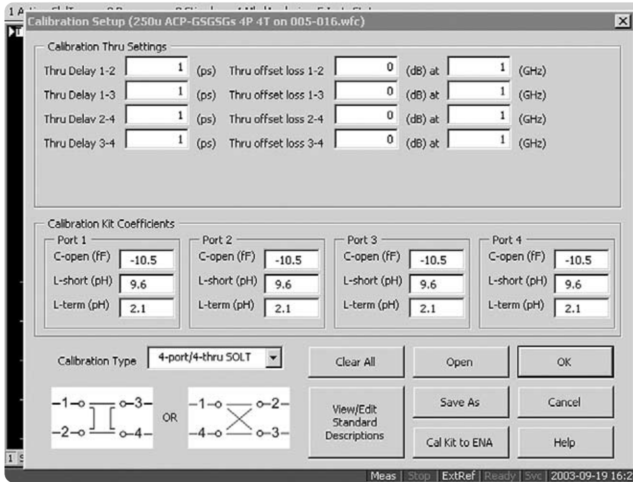


Figure 6. Calibration setup dialog menu

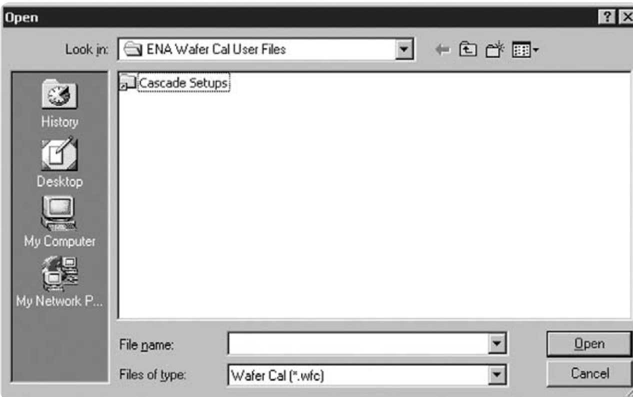


Figure 7. Loading a calibration setup file

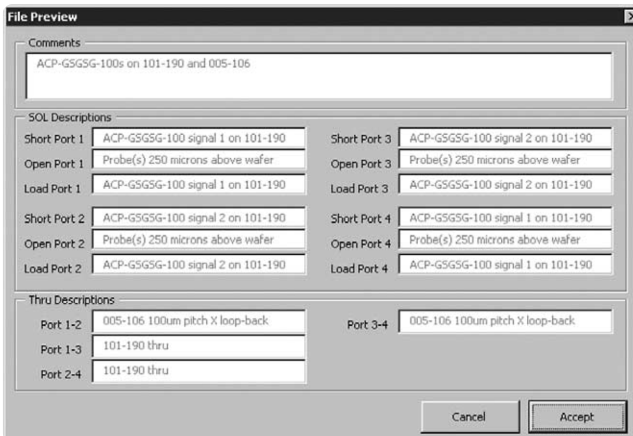


Figure 8. Preview menu of calibration setup file

3-3. Defining the Calibration Kit with manual operation

The procedure for correctly setting up the CalKit in the ENA to subsequently perform an on-wafer probe tip calibration using the dual-tip ACP and ISS is as follows.

1. Press the **[Cal]** key and choose **[User]** from the **[Cal Kit]** menu.
2. Press **[Define STDs]** in the **[Modify Cal Kit]** menu and then define each calibration kit.
3. First, define the open standard. Choose **[1.No Name]** and label the calibration kit in the **[Label]** menu. It is named temporarily as **[Open 1]**. Then choose **[Open]** in the **[STD Type]** menu. Enter the C-Open value that is indicated in the probe box (Figure 5) in **[C_0]**. Default values are used for all other values.
4. Define the short standard. Choose **[2.No Name]** and label the calibration kit in the **[Label]** menu. It is named temporarily as **[Short 1]**. Then choose **[Short]** at **[STD Type]** menu. Enter the L-Short value that is indicated in the probe box (Figure 5), in **[L_0]**. Default values are used for all other values.
5. Define the load standard. Choose **[3.No Name]** and label the calibration kit in the **[Label]** menu. It is named temporarily as **[Load 1]**. Then choose **[Load]** at **[STD Type]** menu. Enter the L-Term value that is indicated in the probe box (Figure 5) in **[Offset Delay]**. L-Term is given as an inductance value so that it needs to be exchanged into time (sec) parameter. For example, when L-Term is given as 2.0 pH, enter 500 Ω[2] in **[Offset Z0]** and 4.0 f sec (2.0 pH/500 Ω) also is entered in **[Offset Delay]**.

   As shown in the following equations, this calculation comes from the following equations, which look for characteristic impedance of the transmission line and the transmission delay.

$$Z_0 = \sqrt{\frac{L}{C}}\ [\Omega] \quad \text{or Offset_delay} = \sqrt{LC}\ [\text{sec}]$$

Then

$$\text{Offset_delay} = \frac{L}{Z_0}\ [\text{sec}]$$

6. Define the thru standard. As shown in Figure 10, two different thru standards are used for thru calibration, so the both standards should be defined individually. Choose **[4.No Name]** and label the calibration kit in the **[Label]** menu for the Thru 1. It is named temporarily as **[Thru 1]**. Then choose **[Delay/Thru]** at **[STD Type]** menu and then enter the thru value in **[Offset Delay]**. The value of the thru delay to be entered should be calculated as described in Section 3-1. Typically, this thru delay is 1 psec.
   Choose **[5.No Name]** and label the calibration kit in the **[Label]** menu for the Thru 2, which has a shape of a square bracket.
   It is named temporarily as **[Thru 2]**. Then choose **[Delay/Thru]** at **[STD Type]** menu and then enter the thru value in **[Offset Delay]**. The value of the thru delay to be entered should be calculated as described in Section 3-1. Typically, this thru delay is 2.7 psec when using the 150 µm pitch probe.
7. When the definition of the necessary standard is finished, press **[Label Kit]** and enter the new label for the calibration kit.
8. After each calibration standard is defined, each standard should then be registered in the **[Specify CLSs]** menu. Once each calibration standard is registered in the **[Specify CLSs]** menu, each calibration standard will be enabled when you perform the calibration. For example, register **[Open 1]**. Choose **[Open]** in the **[Specify CLSs]** menu then choose **[Open 1]** which was registered in the example above. Then, **[Open 1]** will be enabled. The rest of the standards also need to be registered in the **[Specify CLSs]** menu.

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2. To minimize the phase error, offset delay values should be set as small as possible. In this example, the large Offset Z0 (500 Ω) is used to obtain small offset delay.

3-4. Full 4-port error correction procedure

The ENA supports full 2-port, full 3-port, and full-4-port error correction. This section explains the procedure to perform an on-wafer full 4-port error correction using the dual-tip ACP and balanced ISS.

The fundamental calibration operation process is the same with both ENA Wafer Cal and a manual operation; however, ENA Wafer Cal provides a Calibration Wizard function that guides the user through the setup of the CalKit and calibration steps, thus greatly reducing operation errors (Figure 9).Although the ENA requires six thru measurements for thru calibration, ENA Wafer Cal supports 4-Thru calibration so that you can reduce two calibration steps shown in Figure14.

From here, this section explains the calibration procedure using the calibration kit, which is defined by a manual operation.

As shown in Figure 10, the open, short, load, and thru calibration standards are available on the balanced ISS. Full 4-port error correction can be performed with these standards.

1. Choose the full-4 port error correction
   Press the **[Cal]** key then choose **[4-Port Cal]** from the **[Calibrate]** menu. Choose **[Reflection]** from the **[4-Port Cal]** menu, then perform the error correction for reflection measurement. When you enter the **[Reflection]** menu, the Open/Short/Load calibration menu is displayed for each test port. Make sure the calibration standards that are defined above (Open 1, Short 1, and Load 1) are displayed on the menu. If each calibration standard is not displayed, it needs to be registered in the **[Specify CLSs]** menu. Once registered, perform the calibration in accordance with the **[Reflection]** menu.
2. Open calibration is performed for each test port by using the open on the ISS. Refer to Figure 11.
3. The short calibration is performed for each test port by using the short on the ISS. Refer to Figure 12.
4. The load calibration also is performed for each test port by using the precisely trimmed loads (50 Ω ±0.3%) on the ISS. Refer to Figure 13.

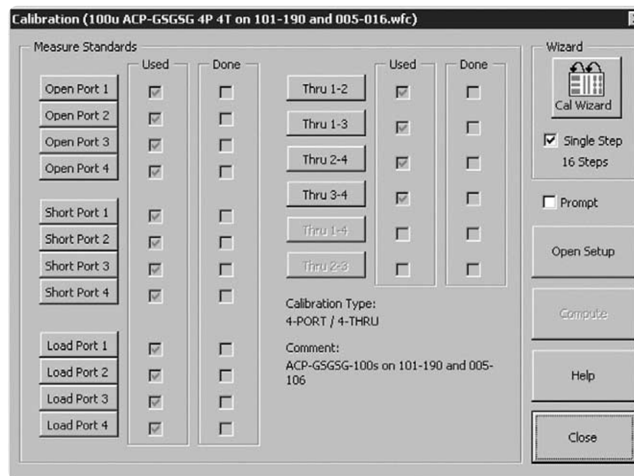

Figure 9. Calibration Wizard

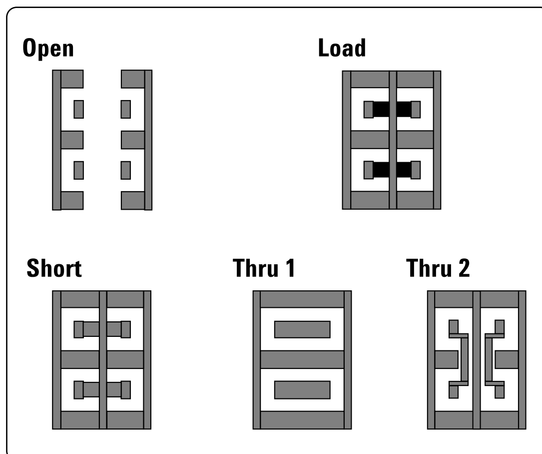

Figure 10. Calibration standards on balanced ISS

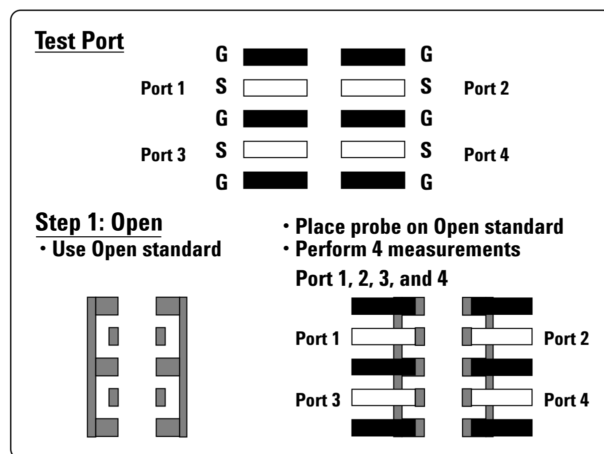

Figure 11. Open calibration

5. After the open, short, and load calibrations are performed, press the **[Return]** key at the bottom. Choose the **[Transmission]** menu, then perform the error correction for transmission measurement. When you enter the **[Transmission]** menu, the thru calibration menu is displayed for each test port. Make sure the calibration standard (Thru 1), which is defined above, is displayed on the menu. If the thru calibration standard is not displayed, it needs to be registered in the **[Specify CLSs]** menu.

   When the dual-tip ACP is used, the thru calibration between the probes, which are facing each other, is performed as shown in Figure 14. The thru calibration between each dual-tip probe also needs to be performed as shown in Figure 15.

6. When **[Transmission]** calibration is finished, press the **[Done]** key. Calibration coefficients will then be computed and the error correction applied. Make sure that a "Cor" mark is indicated in the status bar on the bottom right of the display of the ENA. When "Cor" is indicated, error correction is turned on.

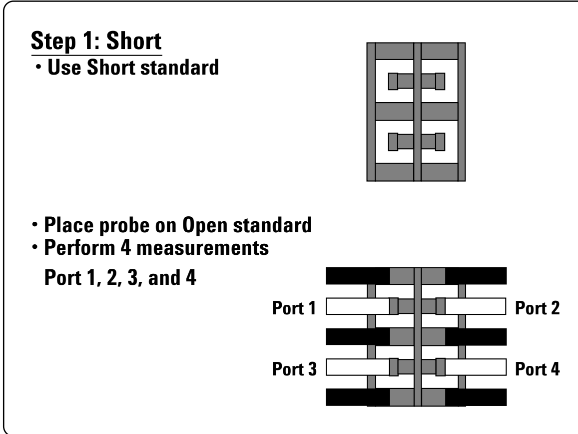

Figure 12. Short calibration

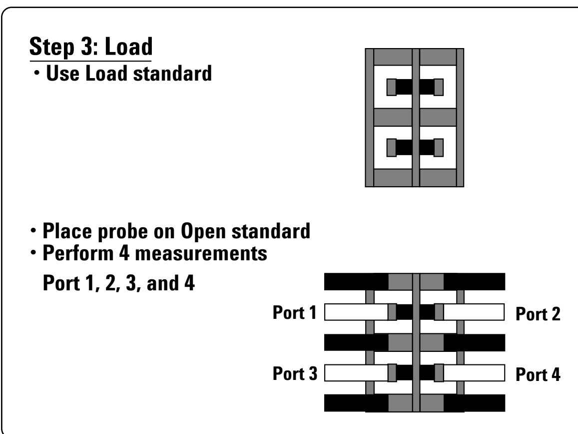

Figure 13. Load calibration

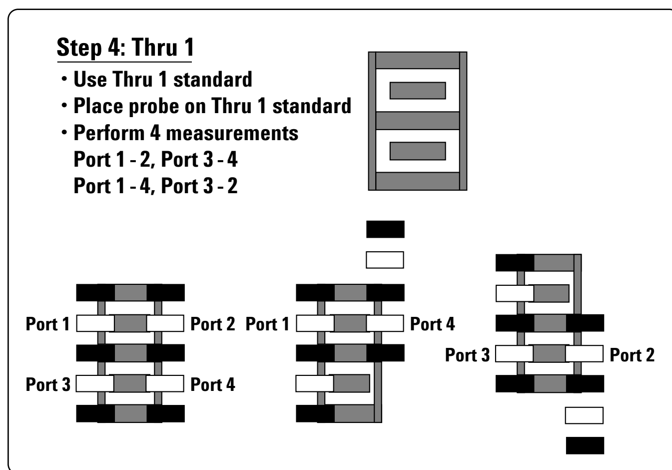

Figure 14. Thru calibration

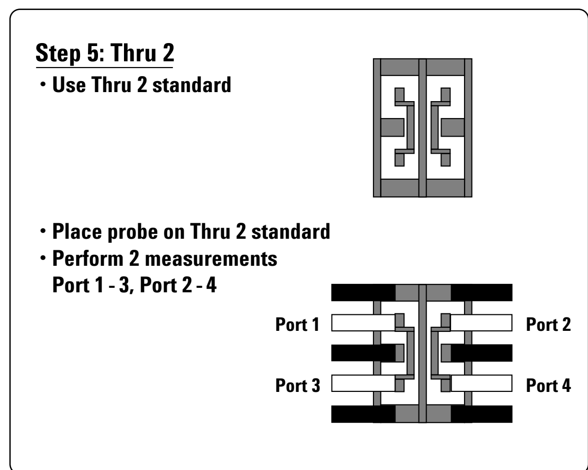

Figure 15. Thru calibration between the two signals on each dual-tip ACP probe

3-5 . The verification of full 4-port error correction

After every calibration, it is very important to verify the measurements to make sure that the calibration steps were successful. For one-port measurements, an open stub is good for verifying a high magnitude with a linear phase offset. This type of verification element can be found on the general purpose ISS and is synthesized by doing a one-port measurement of a transmission line as shown in Figure 16.

The verification procedure is as follows.

1. Contact the probe head of port 1 to one side of the open stub on the ISS. Then, display a measured trace of S_{11} in both the Smith chart and the log magnitude format. The open stub measurement is equal to the transmission line measurement, so if the open stub is ideal, the S_{11} trace forms concentric circles on the circumference of the Smith chart. However, residual inductance and capacitance, which exist on the stub, affect the measurement results, and the measurement trace looks like a spiral. When it seems to be non-symmetrical or it protrudes from the circumference of the Smith chart, the C_0, L_0, L_T values of the calibration kit need to be adjusted.
2. An alternative is to verify whether the trace of S_{11} in the log magnitude screen decreases with increasing frequency. Figure 17 shows the verification results of full 4-port error correction.

   As shown in this figure, the S_{11} trace on the Smith chart moves clockwise round the edge of the Smith chart with increasing frequency.

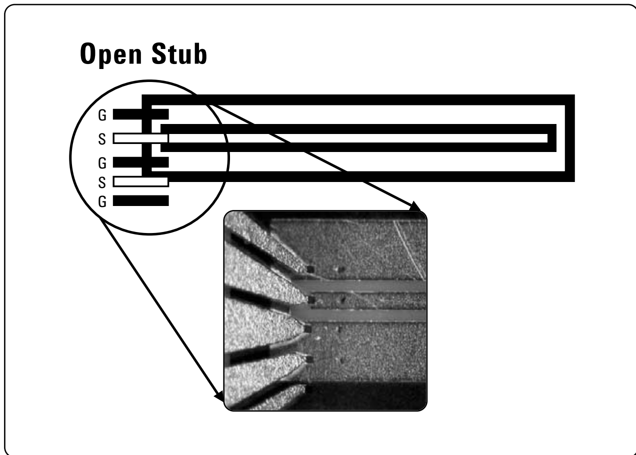

Figure 16. Verification of calibration performance using the open stub on the ISS

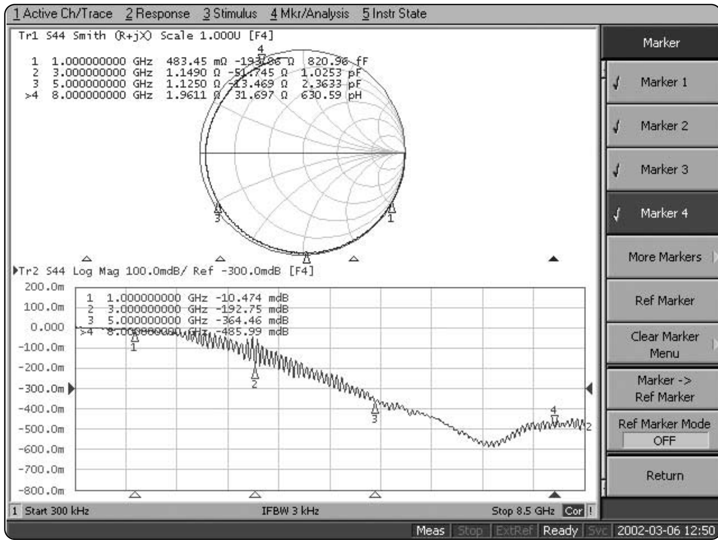

Figure 17. Verify the calibration of each test port

3. After verifying the calibration by repeating this one port measurement on each test port, a full 4-port verification measurement can be performed by using elements on the ISS. As shown in Figure 18, using a special thru pattern on the ISS, port 1 and port 2, and port 3 and port 4 are connected.

   The measurement performance with full 4-port error correction can be verified under this condition by checking the S-parameters from S_{11} to S_{44}. Reference data is shown in Table 2 and Figure 19. This measurement is performed from 6 GHz to 8.5 GHz frequency range.

   Note that this verification can be performed only on probes with 150µm pitch or less due to the limitation of available thru pitch on the ISS (005-016).

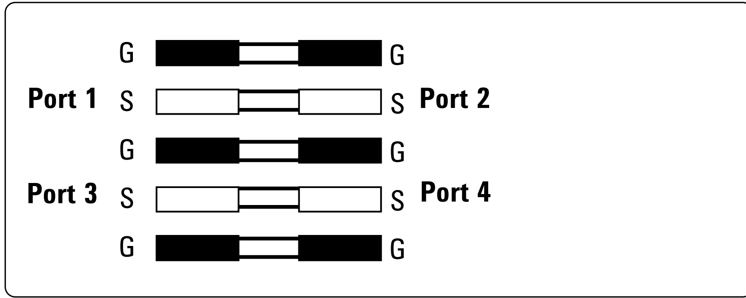

Figure 18. Verification of the full 4-port error correction

Table 2. Measured S-parameters with full 4-port error correction

Frequency range: 6.0 GHz – 8.5 GHz
Number of points: 801 points
IFBW: 3 kHz
Output power level: 0 dBm

Measurement item	S-parameters	Reference value
Insertion loss	S_{12}, S_{21}, S_{34}, S_{43}	0 ±0.1 dB
Return loss	S_{11}, S_{22}, S_{33}, S_{44}	–30 dB or less
Isolation (port 1 to 4, port 2 to 3)	S_{14}, S_{23}, S_{32}, S_{41}	–40 dB or less
Isolation (port 1 to 3, port 2 to 4)	S_{13}, S_{24}, S_{31}, S_{42}	–35 dB or less

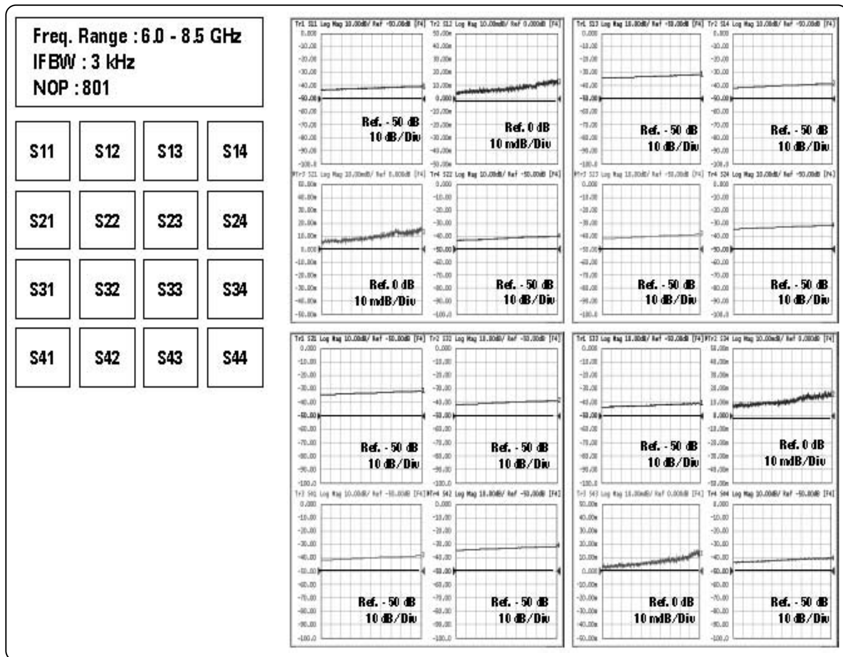

Figure 19. Measured S parameters (reference data)

4. The measurement performance of a balanced device

Previous sections have explained procedure for performing and verifying an on-wafer full 4-port error correction. However, the balanced device measurement performance cannot be verified if it is evaluated under the unbalanced condition, since it is different from the actual working condition. Verifications by the mixed-mode S-parameters are necessary to evaluate true balanced device measurement performance.

4-1. What are the mixed-mode S-parameters

Before describing the measurement performance of balanced devices, mixed-mode S-parameters will be explained briefly.

Conventional single-ended S-parameters are commonly used to express the performance of microwave and RF devices. These parameters describe the behavior of the device when it is stimulated on a single port. This works well for characterizing single-ended devices, but it can be misleading, or at best difficult to interpret, for devices with balanced ports. Expanding the definition of S-parameters for balanced device measurements, a set of mixed-mode S-parameters can be defined as shown in Figure 20. To easily interpret the mixed-mode data, the 4 x 4 matrix illustrated below can be subdivided into four quadrants with the following behaviors.

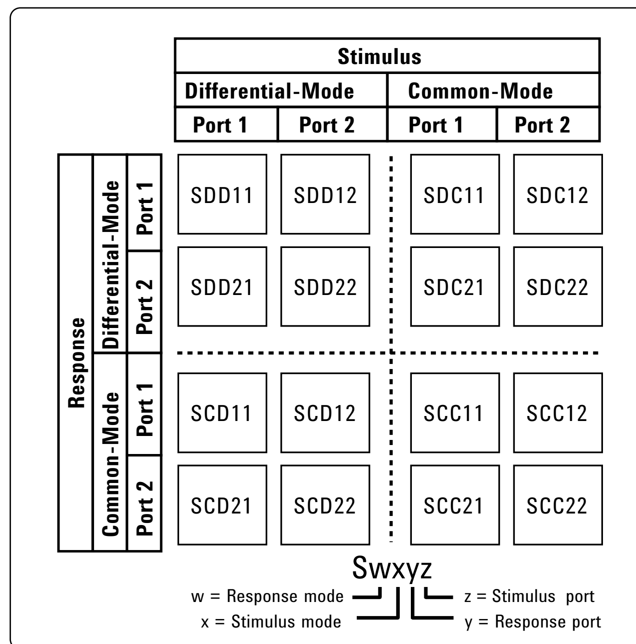

Figure 20. Mixed-mode S-parameters

1. The DD quadrant (differential-mode terms: S_{DD})

The DD quadrant, in the upper-left corner of Figure 20, describes the behavior of a device with a differential-mode stimulus and differential-mode response. In this mode, the 2 x 2 DD matrix gives the differential-mode input and output reflection coefficients, and forward and reverse transmission characteristics. These four parameters describe the fundamental character of a balanced device.

2. The CC quadrant (Common-mode terms: S_{CC})

The CC quadrant, in the lower-right corner of Figure 20, describes the behavior of a device with a common-mode stimulus and common-mode response. In this mode, the 2 x 2 CC matrix gives the common-mode input and output reflection coefficients, and the forward and reverse transmission characteristics. While these four parameters may not be of primary interest, in comparing the differential gain of the DD quadrant to the common-mode gain of the CC quadrant, the common-mode rejection ratio (CMRR) can be determined.

3. The CD quadrant (Mode conversion terms: S_{CD})

The CD quadrant, in the lower-left corner of Figure 20, describes the behavior of a device with a differential-mode stimulus and common-mode response. In this mode, the 2 x 2 CD matrix gives the differential-mode input and common-mode output reflection coefficients, and the forward and reverse transmission characteristics. In an ideal balanced device, all of these terms are equal to zero. The more mode conversion from differential-mode to common-mode that exists, the more likely there will be radiation from the system.

4. The DC quadrant (Mode conversion terms: S_{DC})

The DC quadrant, in the upper-right corner of Figure 20, describes the behavior of a device with a common-mode stimulus and differential-mode response. In this mode, the 2 x 2 DC matrix gives the common-mode input and differential-mode output reflection coefficients, and the forward and reverse transmission characteristics. In an ideal balanced device, these terms are all equal to zero. The more mode conversion from common-mode to differential-mode that exists, the more susceptible the system will be to common-mode noise.

For more details about mixed-mode S-parameters, refer to the application note 1373-2B *"Characterizing Differential Devices and Circuits Using Agilent's Balanced Component Measurement Solutions."*

4-2. Verification of mixed-mode S-parameters

The mixed-mode S-parameters measurement performance can be verified in the same manner as the 4-port error correction shown in Figure 21. Port 1 and port 2, and port 3 and port 4 are connected by using the thru pattern on the ISS.

Reference data is shown in Table 3 and Figure 22. This measurement is performed from 6.0 GHz to 8.5 GHz frequency range.

Using the dual-tip ACP to obtain the S-parameters measurement performance, isolation between the probe tips gets a little worse compared to the measurement using a coaxial cable. However, the values of mode conversion (SCD, SDC) parameters are less than –50 dB, which is better measurement performance even if it is compared to the measurement performance using the coaxial cable. Hence, it is very important to understand that the measurement performance of mixed-mode S-parameters cannot be verified by only checking the single-ended S-parameters.

Note that this verification can be performed only on probes with 150µm pitch or less due to the limitation of available thru pitch on the ISS (005-016).

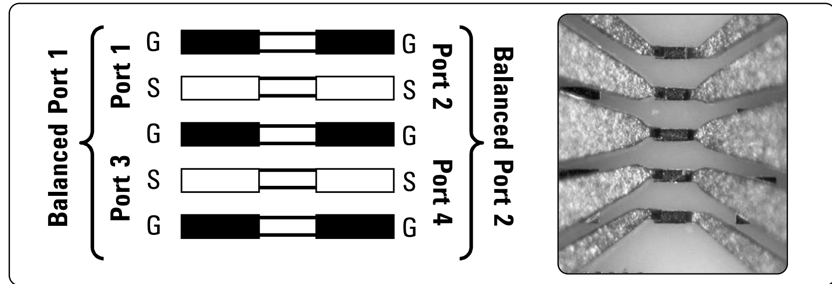

Figure 21. Verify the mixed-mode S-parameters

Table 3. Measured S-parameters with full 4-port error correction

Frequency range: 6.0 GHz – 8.5 GHz
Number of point: 801 points
IFBW: 3 kHz
Output power level: 0 dBm

Parameters	Mixed-mode S-parameters	Reference value
Differential-mode (DD)		
Reflection	S_{DD11}, S_{DD22}	–35 dB or less
Transmission	S_{DD12}, S_{DD21}	0 ±0.1 dB
Common-mode (CC)		
Reflection	S_{CC11}, S_{CC22}	–30 dB or less
Transmission	S_{CC12}, S_{CC21}	0 ±0.1 dB
Mode-conversion (CD)		
Reflection	S_{CD11}, S_{CD22}	–50 dB or less
Transmission	S_{CD12}, S_{CD21}	–50 dB or less
Mode-conversion (DC)		
Reflection	S_{DC11}, S_{DC22}	–50 dB or less
Transmission	S_{DC12}, S_{DC21}	–50 dB or less

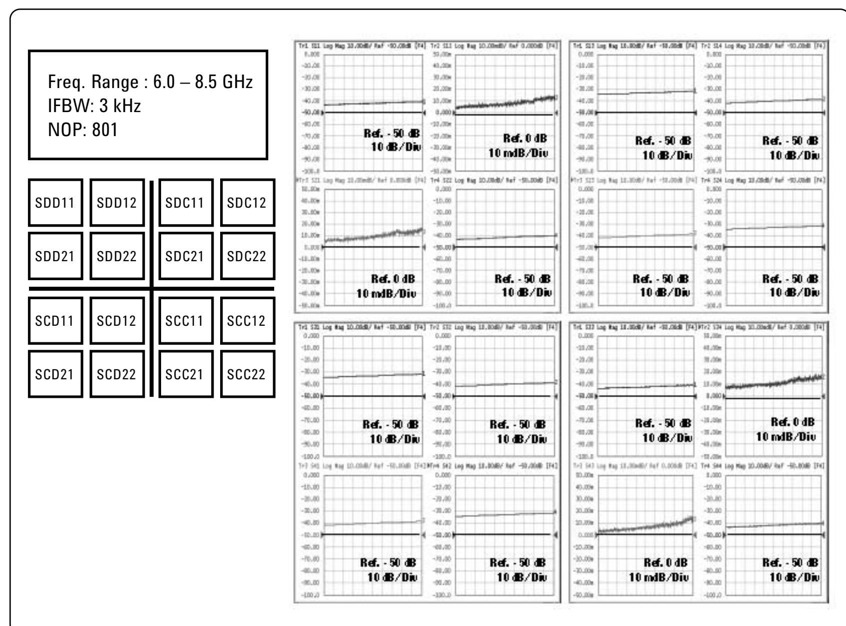

Figure 22. Measured mixed-mode S-parameters (reference data)

5. On-wafer balanced component evaluation

In this section, one example of balanced component evaluation using the ENA with dual-tip ACP is discussed.

5.1. Balanced surface acoustic wave (SAW) filter evaluation

As shown in Figure 23, the same balanced SAW filters on the test board are characterized using two different methods and the results are compared to each other. One method uses a SAW device embedded inside a probe launch. This enables the SAW device to be simply characterized using Cascade Microtech RF probes and removes the need for the de-embedding steps necessary when performing the measurements coaxially.

As shown in Figure 24, the balanced SAW filter (center frequency: 942.5 MHz) is a three-port device that has a single-ended input port and a balanced output port, making the combination of the single-tip ACP (GSG) and the dual-tip ACP (GSGSG) well suited for this evaluation.

Figure 25 shows the balanced SAW filter evaluation result, which compares the probe measurement data to the coaxial test fixture measurement data. In the case of coaxial test fixture measurement data, port extension is used for rotating the calibration plane close to the device.

From this measurement result, we can see that the on-wafer measurement performance using the probes achieves almost the same characteristics as the coaxial test fixture measurement. It can also be seen from Figure 25, that high dynamic range is obtained at the rejection band of the balanced SAW filter even if it is compared to the measurement result using the coaxial cable.

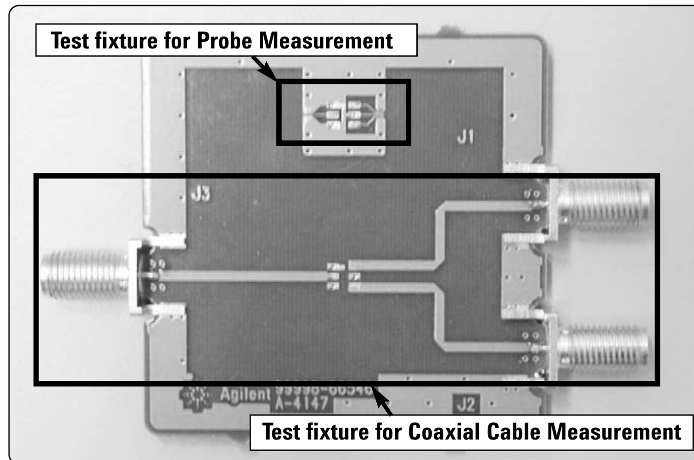

Figure 23. Test board for SAW filter evaluation

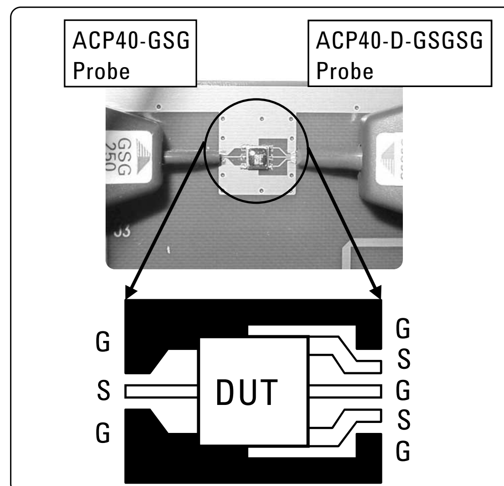

Figure 24. Balanced SAW filter measurement

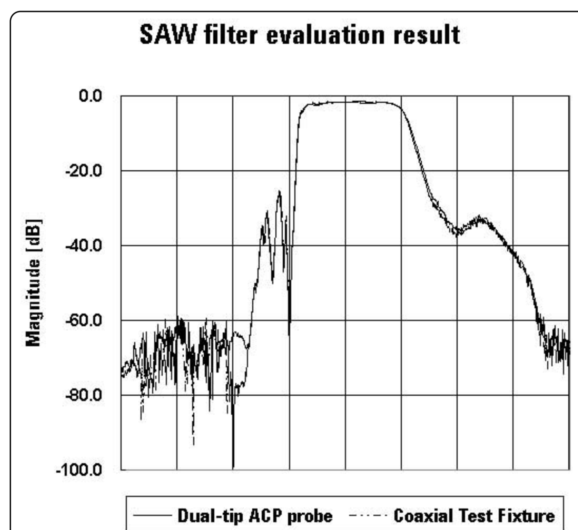

Figure 25. Balanced SAW filter evaluation result

Summary

In this product note, we discussed the calibration procedure and measurement performance of on-wafer balanced component evaluation by using the ENA and Cascade Microtech probing system. Usually, the network analyzers used in RF applications typically employ only two single-ended test ports. This makes characterizing high-frequency balanced devices a challenge. The Agilent ENA network analyzer with the Cascade Microtech dual-tip ACP and high precision calibration standards, provides both an accurate and convenient method for characterization of on-wafer balanced devices. By understanding how to perform and verify the on-wafer calibration, you will be able to achieve accurate on-wafer balanced device measurements and have absolute confidence in your results.

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