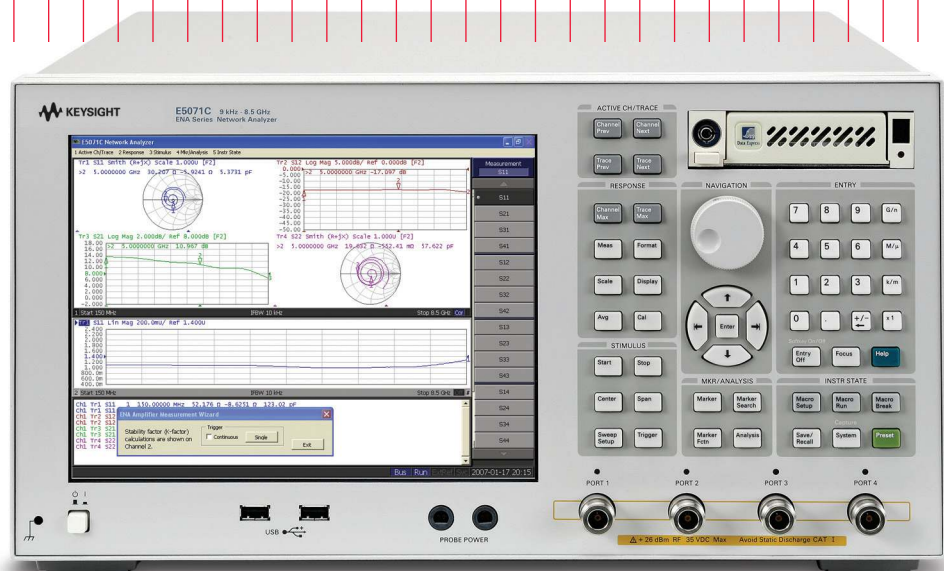


Keysight Technologies

Advanced Measurement Techniques for RF Amplifiers Using Unique Functions of the Keysight E5071C ENA

Application Note



Introduction

The RF amplifier is a key component used in a wide variety of industries such as wireless communication systems, medical equipment, and automotive devices. Characterizing the performance of these amplifiers is a critical stage in the design and verification process. These amplifiers must meet strict performance specifications in order that the systems can comply with regulations. In addition, the devices have their own criteria to meet from a business point of view, such as power efficiency, reliability, physical size and cost.

This application note will briefly review the basic measurement fundamentals of characterizing amplifiers with network analyzers. Also some unique testing techniques using the ENA E5071C network analyzer will be introduced and described in more detail.

Measurement of Amplifier Parameters

Traditionally, transmission and reflection measurements have been performed with network analyzers. As well as basic S-parameters of devices, designers and manufacturers have to carefully look into various parameters calculated from the S-parameters.

K-factor is one of the examples and a significant parameter especially for amplifier designers. This factor can be calculated from all the S-parameters of two-port devices (S11 to S22), and represents the stability of amplifiers. When K-factor is greater than 1 while delta is smaller than 1, the amplifier is unconditionally stable and no oscillation is expected for any load.

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|}$$

where

$$\Delta = S_{11}S_{22} - S_{12}S_{21}$$

The E5071C with the firmware revision A.08.00 or above features an equation editor that allows users to enter a defined equation and display the result mathematically calculated from measured traces. Once a valid equation is entered and enabled, the trace is replaced with the results of the equation in real-time. Figure 1 shows the measurement example of K-factor with the ENA.

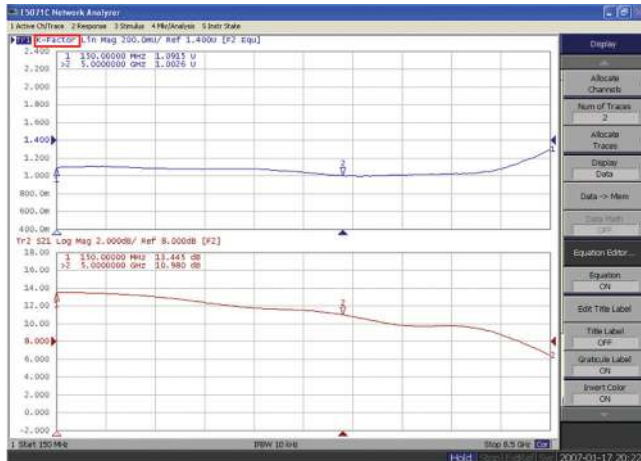


Figure 1. Measurement example of K-factor.

Power Added Efficiency (PAE) is another important parameter. This parameter represents the efficiency of the power consumed in amplifiers: the ratio of the power generated by an amplifier to the power supplied to the amplifier. The supplied power can be obtained by measuring the total bias current and the voltage of the DC power supply. The latest ENA, E5071C has input connectors for DC voltage measurements (2 AUX ports on the rear panel), enabling it to obtain the PAE of amplifiers in parallel with RF measurements.

In addition to the linear performance, non-linear parameters are also very important for full characterization of the amplifier's performance. One of the key non-linear parameters on amplifiers is 1 dB gain compression. Gain compression occurs when the input power of an amplifier is increased to a level that reduces the gain of the amplifier and causes a nonlinear increase in output power. The E5071C offers up to 65 dB power sweep range, which provides the easy and simple characterization of compression behavior of the amplifiers.

Excessive non-linear distortion in amplifier gain causes adjacent channel interference resulting in poor network data transmission rate in communication systems. Traditionally, harmonic distortion measurements have been performed with the combination of a signal generator and a spectrum analyzer. However, the ENA offers frequency-offset mode (FOM) functionality which enables the source and receiver to sweep at different frequencies for harmonics measurements. By combining the frequency-offset sweep and receiver calibration with a power meter, high speed and accurate absolute power measurements can be performed. This can replace the traditional method for measuring harmonic distortion using the combination of a signal generator and a spectrum analyzer. Figure 2 shows a measurement example of harmonic performance. The input port of a 900 MHz amplifier is connected to port 1 of the ENA, and the output is connected to port 2. The left picture is the result of the absolute power measurement for an amplifier. By using the FOM functionality, harmonic spurious response along with a fundamental spectrum can be observed with the receivers on the ENA. The right picture presents the frequency-dependency of each spectrum. The trace of the carrier frequency, 2nd harmonic, and 3rd harmonic are allocated on channel 1, 2 and 3 respectively, and the traces can be obtained with a sequential sweep on each channel. In addition to the absolute power level, frequency responses of fundamental and each harmonic signal can be obtained with the ENA.

The ENA offers a built-in macro function based on VBA (Visual Basic for Application) programs that enable the analyzer to set up and execute measurements automatically. Also within a VBA program, users can customize and define parameters by calculating from the result traces and display on the ENA screen just like the equation editor function. There are various sample programs available from Keysight Technologies, Inc. that users can make the most of for easy setup and testing devices. (Figure 3)

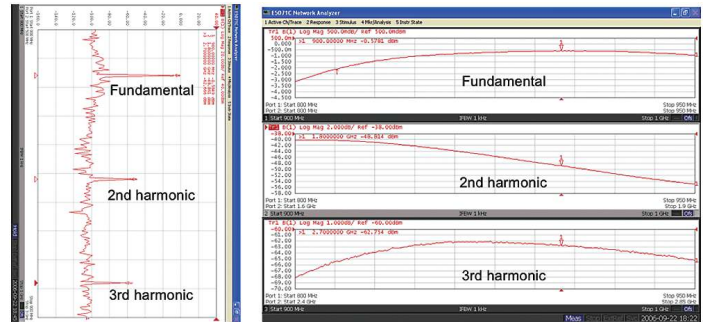


Figure 2 Measurement example of harmonic performance. (frequency-offset sweep on left; frequency response of each harmonic wave on right)

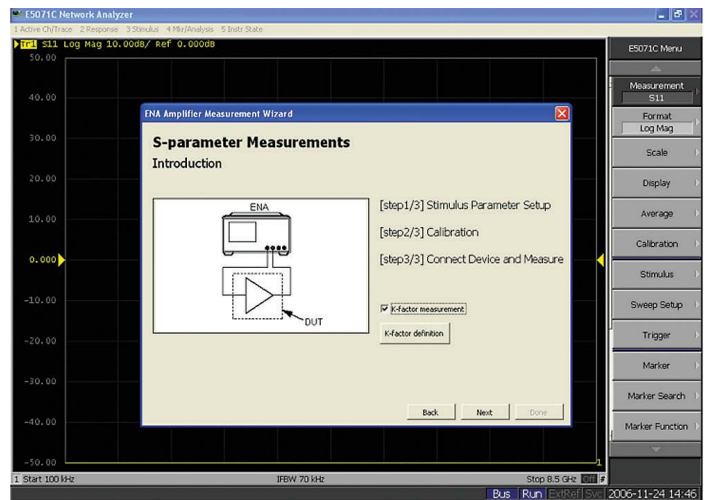


Figure 3. A sample VBA program for amplifier measurements. ("Amplifier Measurement Wizard")

Pulsed RF Measurement

Some power devices are not designed to operate continuously. For example, GSM power amplifiers used in cellular handsets are highly optimized for efficiency in burst operation and thus do not operate correctly with a continuous wave (CW) signal. Some power amplifiers would undergo thermal breakdown if tested with continuous RF signals at the desired amplitude level. Therefore, pulsed RF techniques must be employed for accurate S-parameter measurements, and current network analyzers have trigger functionality to make such measurements.

Figure 4 indicates the timing of pulsed measurements on GSM amplifiers. The GSM signal is produced as a 577 microsecond pulse with a period of 4.616 milliseconds. Sampling or data acquisition in network analyzers must take place during the RF pulse, and this is achieved by externally triggering the network analyzers to measure the appropriate points in time.

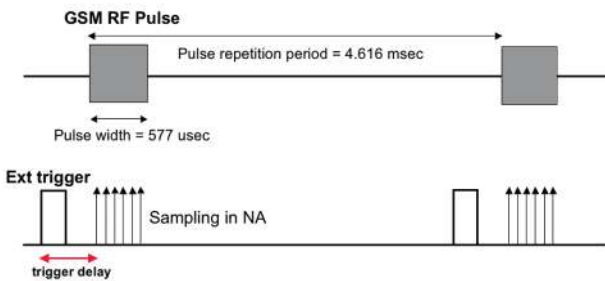


Figure 4 Timing of external trigger and GSM RF pulse

Figure 5 shows a typical test setup of making pulsed measurements for GSM amplifiers. The pulsed RF signal from a pulse generator is used as an external trigger for measurements in a network analyzer. This trigger signal must be synchronized with the RF pulse. The Keysight 81100 family is recommended for a pulse/pattern generator.

As used in mobile handsets for GSM systems, the output power level of the amplifiers can reach more than +30 dBm. Since the maximum input level of the E5071C is limited to its maximum output level (i.e. +10 dBm for up to 5 GHz), an appropriate amount of attenuation is necessary at the output of the devices. Note that the higher input level will result in compression at the receivers of the E5071C, which increases errors on measured traces, or even damage the internal hardware of the analyzer.

When using the Ecal module for high-power measurements with a high attenuation, there is one thing to take into consideration. The ENA has an auto-detect feature which allows for the arbitrary connection between the ECal and the ENA. For up to about 20 dB of loss between the ENA and the ECal, this feature works correctly. However, if more attenuation is inserted between the ENA and the ECal, it is necessary to turn off this auto-detect feature and manually configure the connection with the ECal ports.

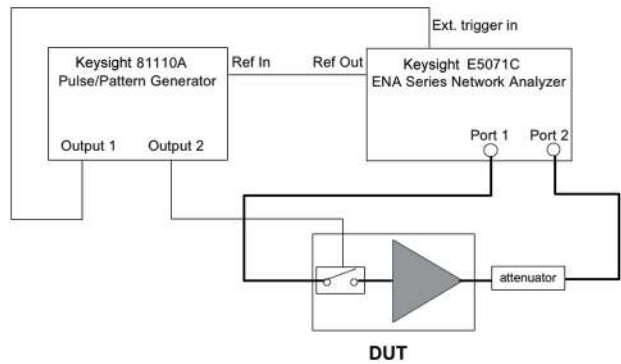


Figure 5 Typical test setup of pulsed measurement

It is important to remember that there is some latency or delay between the external pulse trigger and when the sampling actually starts in the network analyzer. This means the network analyzer must be triggered before the RF pulse is applied from a pulse generator. In order to achieve data acquisition at the desired points in time, the ENA supports the function of adjusting the timing between the external trigger input and the beginning of sampling. This trigger delay can be set up by a pulse generator as well with more accurate resolution.

Note that there is some inherent settling time on the ENA before the setup of parameters such as sweep frequency, IFBW, or power level. The typical delay time of the E5071C is about 13 microseconds for a zero-span measurement. In order to adjust the time between the trigger and the data acquisition, an appropriate value has to be entered on *[Trigger Delay]* to account for this settling time. To minimize the variation of this delay time for accurate timing setup, it is recommended that the low-latency external trigger mode be turned on with the *[Low Latency]* soft key.

In general, calibration should be done under pulsed conditions. The proper trigger delay value must be entered before performing calibration to make sure that data acquisition is being performed during the pulsed signals. In transmission measurements, enhanced response calibration improves accuracy compared to a response calibration. Although this calibration technique is not as accurate as a full 2-port calibration, it provides a fast measurement with a single frequency sweep.

The necessary steps for the pulsed RF measurement on the ENA are as follows:

(1) Configure measurement parameters (sweep frequency, IFBW, power level, etc.)

(2) Set up the trigger parameters by soft keys under *[Trigger]*:

[Trigger Source]: External Trigger

[Trigger Event]: On Point

[External Trig Input]: Positive or Negative Edge

[Trigger Delay]: (in microseconds)

[Low Latency]: On

(3) Perform calibration

To turn off the auto-detect function for the ECal module:

[Cal] > *[ECal]* > *[Orientation]*: Manual

[Cal] > *[ECal]* > *[Orientation]* > *[Port1]*: (ex.) A

[Cal] > *[ECal]* > *[Orientation]* > *[Port2]*: (ex.) B

Select calibration technique under *[Cal]*

(4) Perform measurement

The pulsed measurement example on a GSM amplifier is presented in Figure 6. While the internally triggered measurement shows the intermittent trace (in blue) indicating that the analyzer fails to capture the data, the externally-triggered synchronous measurement result (in red) shows the correct frequency response of the DUT.

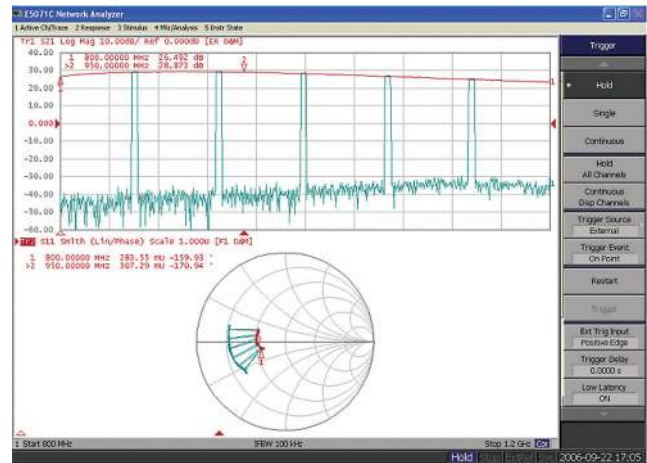


Figure 6 Pulsed measurement example

Characterizing Differential Amplifiers

Noise is always a limiting factor in communication systems. To improve Signal-to-Noise (S/N) ratio in systems, the use of differential components such as differential SAW filters and differential amplifiers is becoming more common because they have better performance in rejecting unwanted noise than single-ended components. The noise in a system is characterized as a common-mode signal and the differential components prohibit the noise from being transmitted through the devices. An accurate measurement of these components is a significant challenge since most network analyzers have single-ended RF ports.

There are several techniques to acquire the characteristics of these differential components. The most convenient way is to use a “mathematical” transform to convert the single-ended data obtained by the network analyzer to differential parameters. The ENA has a Fixture Simulator function that calculates the effect of this conversion. Although this technique provides accurate results of differential characteristics in most cases, it is true that some designers of differential amplifiers are curious about the differential behavior when a physical differential-/common-mode stimulus is being applied to the device. The 4-port ENA offers a simple way to characterize components with true differential signals through the use of a hybrid balun. A hybrid junction is a component that converts single-ended signals from a network analyzer to differential-mode signals (out-of-phase) and common-mode signals (in-phase). This enables evaluations of both differential- and common-mode characteristics on balanced components.

Figure 7 is the test procedure of characterizing a differential amplifier with a 4-port ENA.

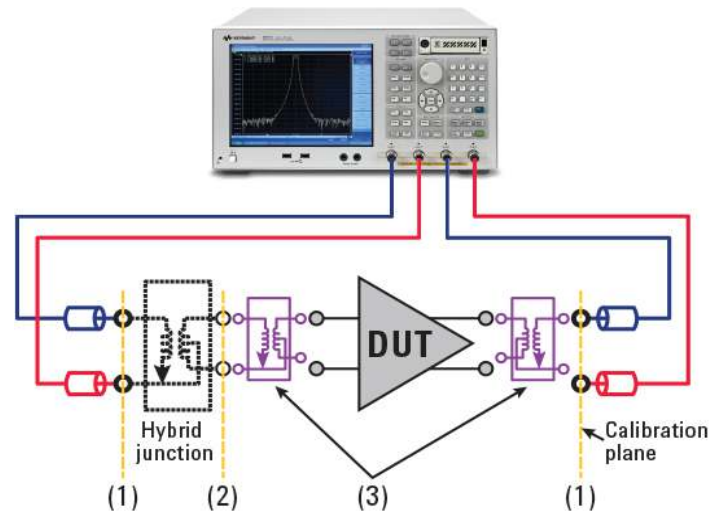


Figure 7. Test procedure of true differential measurement with 4-port ENA
 (1) Full 4-port Calibration.
 (2) Mathematical removal of a hybrid balun.
 (3) Restoration of single-to-balanced conversion effect.

The characterization of true differential operation can be achieved by the following procedure:

(1) Full 4-port calibration

Full 4-port calibration at the test cables has to be undertaken before the measurements are made. The calibration planes are located at the input of the hybrid junction and the output of the DUT.

(2) Mathematical removal of a hybrid junction

By using the 4-port de-embedding function of the Fixture Simulator, the characteristics of the hybrid junctions are removed from the S-parameters of the total network. Fixture Simulator functions can be found under the [Analysis] soft key.

```
[Fixture Simulator]>[De-embedding S4P]: ON
>[Topology]>[Select Topology]: A
>[Type (nwk1)]: De-Embed
```

The calibration plane is now moved to the input and output of the DUT. Characterization of the 4-port hybrid junction is required prior to this operation and the function is implemented in the firmware of the ENA network analyzer.

```
[Save/Recall] > [Save SnP] > [S4P]
```

(3) Restoration of single-to-balanced conversion effect

By de-embedding the hybrid junction, not only the S-parameters of the component but also the effect of the balun’s operation to physically convert single-ended signals to differential-/common-mode signals are removed from the S-parameters of the total network. In addition, only the single-ended S-parameters are displayed on the screen of a network analyzer. To acquire the differential-mode and common-mode (mixed-mode) S-parameters, it is necessary to perform a mathematical conversion with the Fixture Simulator. The mixed-mode S-parameters, including differential-mode gain (Sdd21) or common-mode gain (Scc21) will be displayed on the screen.

Figure 8 shows the measured results of a balanced amplifier by two techniques – (1) mathematical mode conversion with the Fixture Simulator, and (2) physical mode conversion using a hybrid junction described above.

Note that both methods provide identical results for differential-mode behaviors (i.e., Sdd11 or Sdd21) even in the non-linear region, while different results of common-mode characteristics can be seen. The correlation between the two measurements depends on the circuit topology of the amplifier under test. In most cases, the mathematical mode conversion technique is also useful for characterization of balanced amplifiers.

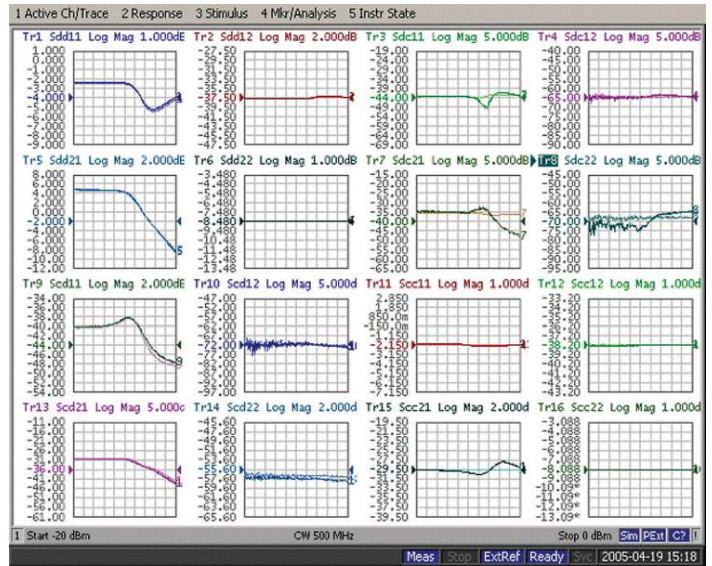


Figure 8 Comparison between mathematical mode conversion method (in thick color) and physical conversion with a hybrid junction (in thin color)

High-Power Measurements with External Test Set Mode

Some RF power devices require a drive level that is higher than a network analyzer can provide, so an external booster amplifier connected to the source port is required in order to drive the DUT in such cases. (Figure 9)

The problem with this configuration is the mismatch caused between the booster amplifier and the DUT. Since the reference signal is measured before the booster amplifier, the error due to the mismatch or the drift of the booster amplifier cannot be eliminated. Also the reflection measurements cannot be performed because of the high reverse isolation on the booster amplifier.

In order to solve these problems, the 4-port ENA offers an external test set mode that enables a flexible configuration when combined with external directional couplers and a booster amplifier. This test set mode allows the ENA's 4-ports to be arranged as a source port (S channel), reference port (R channel), and test ports for reflection and transmission responses (A & B channels). The configuration is presented in Figure 10. Note that since the source port is fixed on port 1 of the ENA with external test set mode, full 2-port calibration is unavailable and S_{22} or S_{12} cannot be obtained. Enhanced response cal is recommended to get the most accurate results with this mode.

By using external couplers, the incident signal can be measured in the reference channel of the ENA after the booster amplifier rather than before, which cancels the mismatch or drift of the booster amplifier and improves measurement uncertainty.

With this configuration, source power calibration with a power sensor and a power meter is highly recommended to remove the effect of the stimulus variation and insertion loss of external couplers. Uneveled source power from the ENA or power fluctuation at the booster amplifier can distort compression measurements of the DUT.

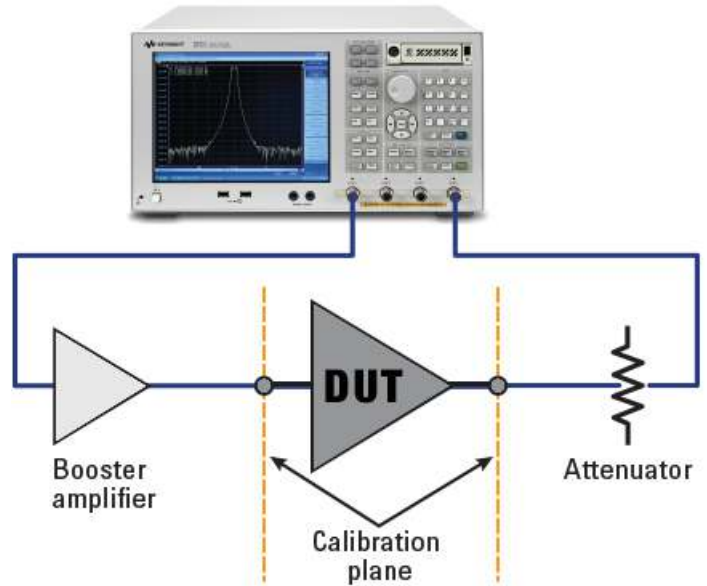


Figure 9. Test setup of high-power measurements using an external booster amplifier

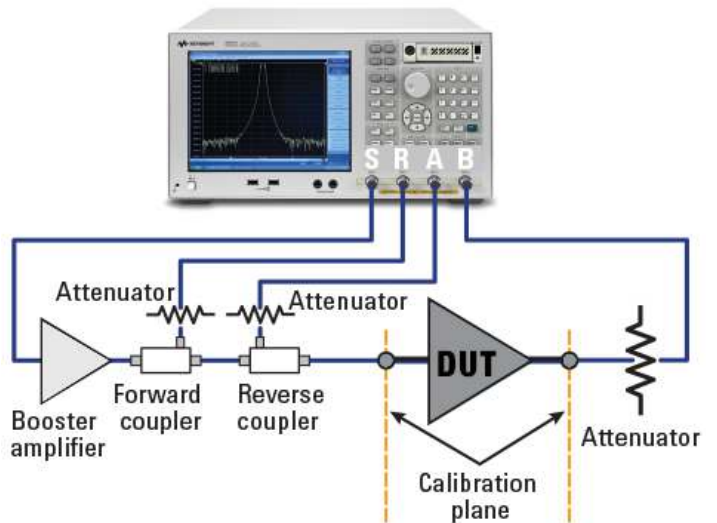


Figure 10. Test setup of high-power measurements with external test set mode in 4-port ENA

The configuration for source power calibration is illustrated in Figure 12. The ENA, connected to the power meter via USB/GPIB interface (i.e., Keysight 82357B), adjusts its source power level to apply the desired power level to the DUT input.

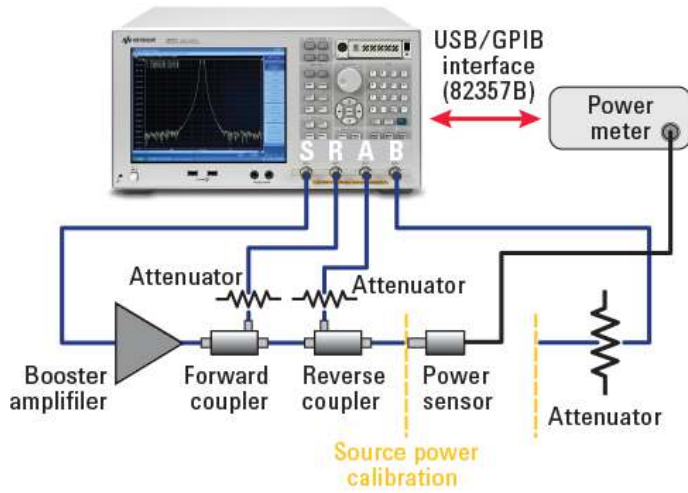


Figure 11. Source power calibration with power meter & sensor

The ENA supports the capability of compensating insertion loss or gain on the source path during source power calibration. By putting a negative value on a loss compensation table, users can adjust the desired power level even beyond the maximum output power level of the ENA.



Figure 12. Example of the loss compensation table for power calibration

The measurement procedure with external test set mode is as follows:

- (1) **Connect the external couplers and the DUT. (Figure 10)**
- (2) **Set up the external test set mode.**
[System] > [Service Menu] > [External Test Set]: Mode 1
- (3) **Select measurement parameters.**
[Meas]: S11 or S21
- (4) **Connect the power meter and sensor and perform source power calibration (Figure 11)**
[Cal] > [Power Cal] > [Loss Compen] (To edit the compensation table)
[Cal] > [Power Cal] > [Take Cal Sweep]
- (5) **Perform calibration under the [Cal] soft key.**

Summary

This application note reviewed the advanced measurement techniques on RF amplifiers with network analyzers and some measurement examples using the E5071C ENA network analyzer were introduced. RF amplifiers are used in a wide variety of industries and must meet strict performance specifications in order to fulfill their functions. The 4-port ENA is a suitable solution for full characterization of the performance on these amplifiers.

References

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