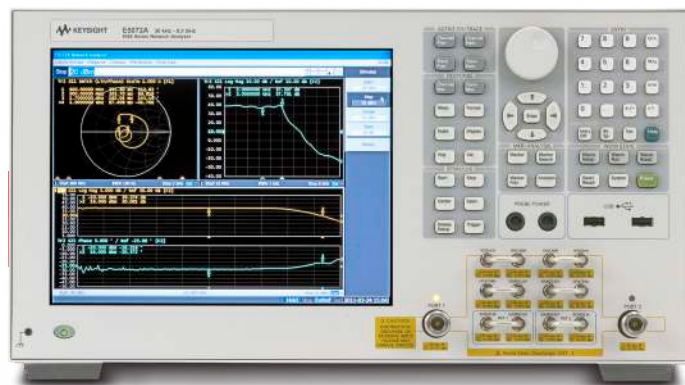


# Keysight Technologies

## Basics of RF Amplifier Measurements with the E5072A ENA Series Network Analyzer

### Application Note



### Introduction

The RF power amplifier is a key component used in a wide variety of industries such as wireless communication systems, medical equipments, and aerospace and defense areas. Characterizing the basic performance of the amplifiers is a critical stage in the R&D or manufacturing test environments. These amplifiers must meet strict performance specifications in order that the systems can comply with regulations.

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This application note illustrates how to setup fundamental amplifier measurements such as S-parameters, K-factor gain compression, harmonic distortion or pulsed measurements with a simple configuration using a vector network analyzer (VNA). Some advanced techniques using the Keysight Technologies, Inc. E5072A ENA Series Network Analyzer<sup>1</sup> will be covered in the note with step-by-step instructions of typical amplifier characterization.

1. See the E5072A technical overview, product number 5990-8004EN for more detail about the E5072A.

# Characterizing RF Amplifiers – Measurement Parameters

## S-parameters/stability factor

Traditionally, S-parameters (both reflection and transmission) measurements have been performed with VNAs. 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

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

Since K-factor requires all four S-parameters of devices under test (DUT), full 2-port calibration is necessary for most accurate measurements. Full 2-port calibration uses all four S-parameters, thus it is critical to make sure that all the S-parameters are accurate.

For measurements of high-gain amplifiers, external attenuation on the output port is often required to protect the VNA's receivers from damage, which degrades system dynamic range of reverse measurements such as S12 or S22. The E5072A has two built-in source attenuators on each port and the attenuation can be changed independently, allowing for uncoupled power level for port 1 and port 2. Uncoupling port power is useful for setting a very low source signal from port 1 and eliminating additional external attenuator on port 2 to improve dynamic range, which can also improve accuracy of reverse measurements and a K-factor calculated from all S-parameters. The block diagram of the E5072A in Figure 1 indicates the independent source attenuators for uncoupled power. Different power level can be set for each port by selecting different attenuation of the internal attenuator for the port.

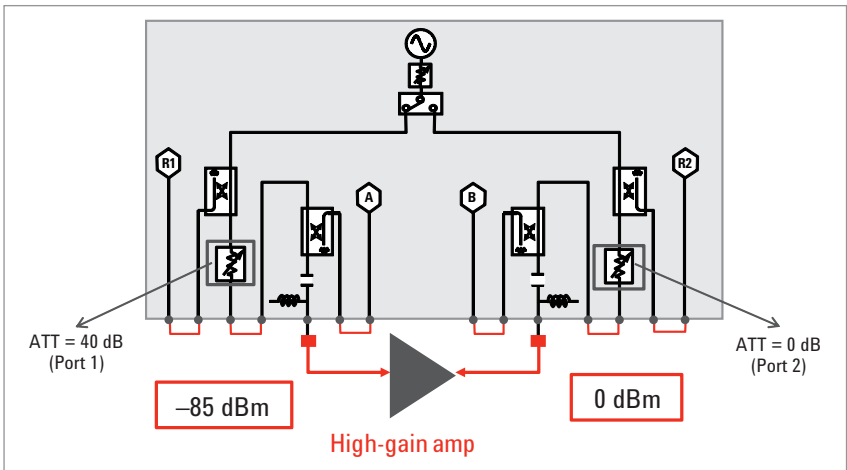


Figure 1. Internal source attenuators for uncoupled power.

The E5072A's equation editor allows users to enter defined equations or parameters such as K-factor or  $\mu$ -factor, and the result mathematically calculated from measured traces is displayed in real time. Equation can be based on any combination of existing traces or parameters or constants. (Figure 2)

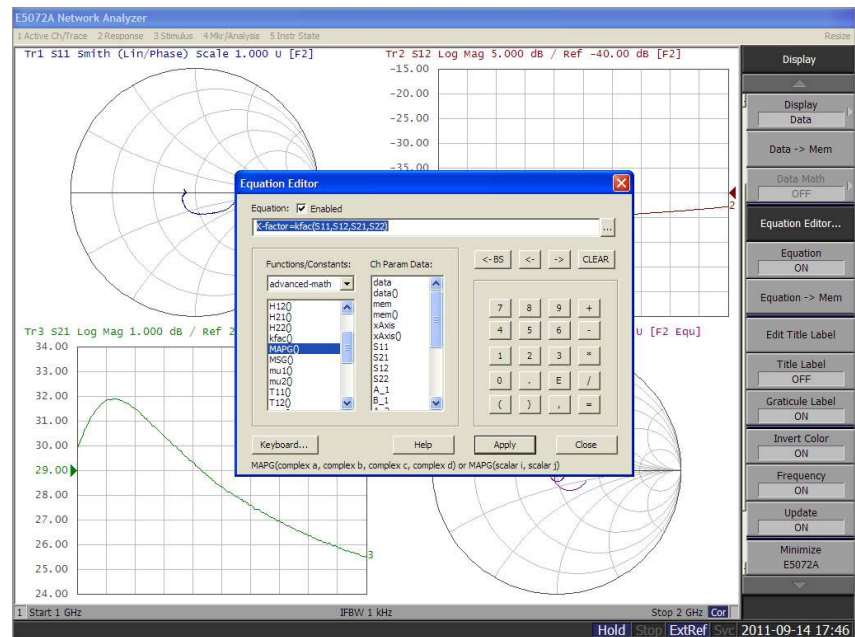


Figure 2. Calculation of K-factor using equation editor.

The following describes necessary steps to measure a K-factor with uncoupled power using the E5072A. [Front-panel keys] are shown in brackets, while the softkeys are displayed in bold. Values for parameters are inserted in parenthesis such as "(0 dBm)".

### Step 1 Setup of stimulus parameters

Stimulus parameters such as frequency, IF bandwidth (IFBW), number of points (NOP) should be entered before calibration and measurements. The power level from port 1 and port 2 is uncoupled and different output power level is set.

- [Sweep Setup] > Power > Port Pwr Couple (OFF)
- [Sweep Setup] > Power > Port Pwr & Att > Port 1 Pwr & ATT (e.g. -60 dBm)
- [Sweep Setup] > Power > Port Pwr & Att > Port 2 Pwr & ATT (e.g. 0 dBm)

## Step 2 Calibration

Full 2-port calibration is necessary for the measurements and performed under [Cal] key of the E5072A.

## Step 3 Setup of equation editor

Any traces can be selected to show K-factor with equation editor. Equation editor is turned on to display calculated K-factor on the selected trace.

### [Display] > Equation Editor

Select "advanced-math" under Functions/Constants and enter equation, "**K-factor = kfac(S11, S12, S21, S22)**" or "**K-factor = kfac(1,2)**" Check the equation checkbox to enable the equation. Linear magnetite is selected as a trace format for K-factor.

### [Format] > Lin Mag

Figure 3 shows the comparison of measurement results with coupled power and uncoupled power from port 1 and port 2. K-factor with lower trace noise can be calculated by using uncoupled power.

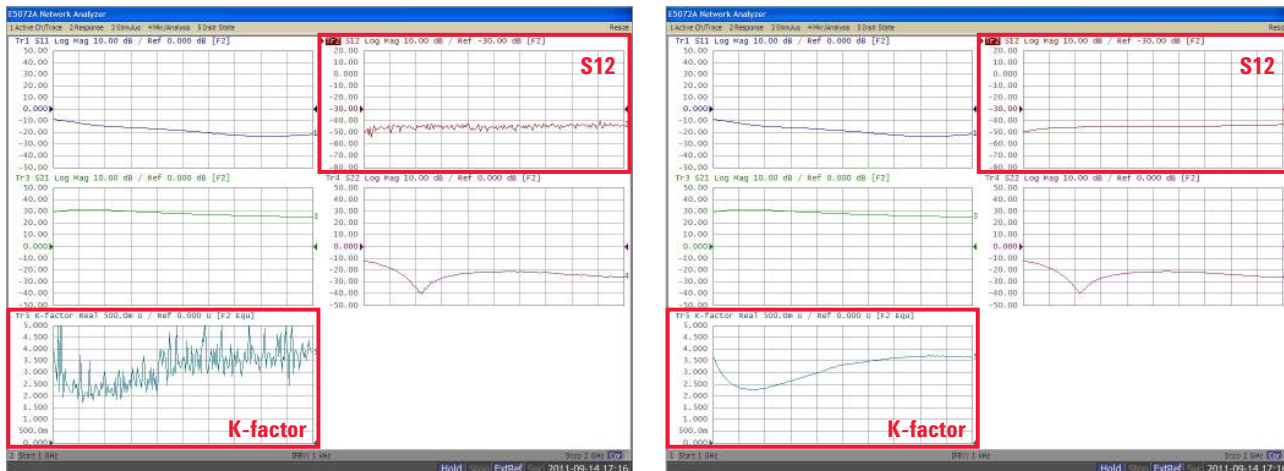


Figure 3. Comparison of K-factor results with coupled (left) and uncoupled (right) port power.

## Full 2-port correction for high-power amplifier

When designing amplifiers, it is always important to pay attention to stability in both small and large signal operation. Not only small signal stability but large signal stability should be monitored to secure stability of amplifiers under real operation. When testing high-power amplifiers, output power of the DUT can exceed input compression level or damage level of the internal receivers; large attenuation should be placed on the output port to protect receivers. The problem is the large attenuation degrades signal-to-noise (S/N) ratio or reverse measurements such as S12 or S22 with full 2-port correction. Especially for reflection measurements on DUT's the output port (S22 = B/R2), the source signal from the analyzer's port 2 will go through the attention, and reflected signal from the DUT must go through the attenuation again to reach the receiver B. This degrades measurement accuracy significantly. The measurement configuration is shown in Figure 4.

To solve this problem, the E5072A with a configurable test set provides access to the signal paths between the internal source, receivers, bridges, and the analyzer's test ports. The alternative configuration using the direct receiver access is illustrated in Figure 5. For forward measurements such as S21 (= B/R1), The DUT's output signal is measured at the receiver B via external coupler, and appropriate attenuation for protecting the receiver can be selected and inserted in the receiver path. Isolators with high isolation will attenuate the signal to the port 2 for protection of the analyzer from damage of high-power input. For reverse measurements such as S12 (= A/R2) or S22 (= B/R2), the S/N ratio can be improved by low-loss isolators inserted in the source path from the port 2 compared to the configuration with large attenuation in Figure 4. More accurate S12 or S22 measurements can be performed with the configuration.

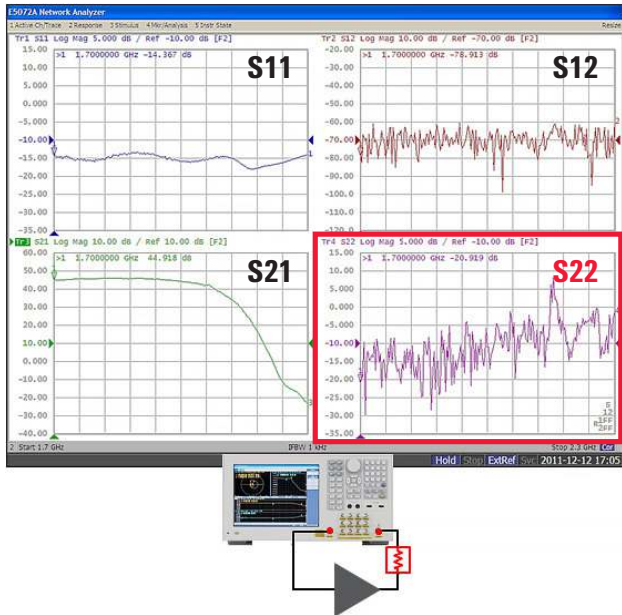


Figure 4. Measurement result of a high-power amplifier with a typical configuration with large attenuation.



Figure 5. Measurement result of a high-power amplifier with a configuration using direct receiver access.

The power level of measurement example using the both configurations is presented in Figure 6. The comparison is given for measurements of a high-power (+30 dBm) amplifier. When the typical configuration using large attenuation is selected (left), input power level of the receiver B for reverse measurements is attenuated down to  $-86$  dBm because of large attenuation in the DUT's output path. This very small power level results in degraded measurement accuracy for reverse measurements. Whereas input power level at the receive B can be optimized (e.g.  $-50$  dBm) by selecting appropriate components in the configuration using direct receiver access (right). Note that higher input power level can be applied to the DUT for reverse measurements, which improves the S/N ratio and measurement accuracy for S12 and S22.

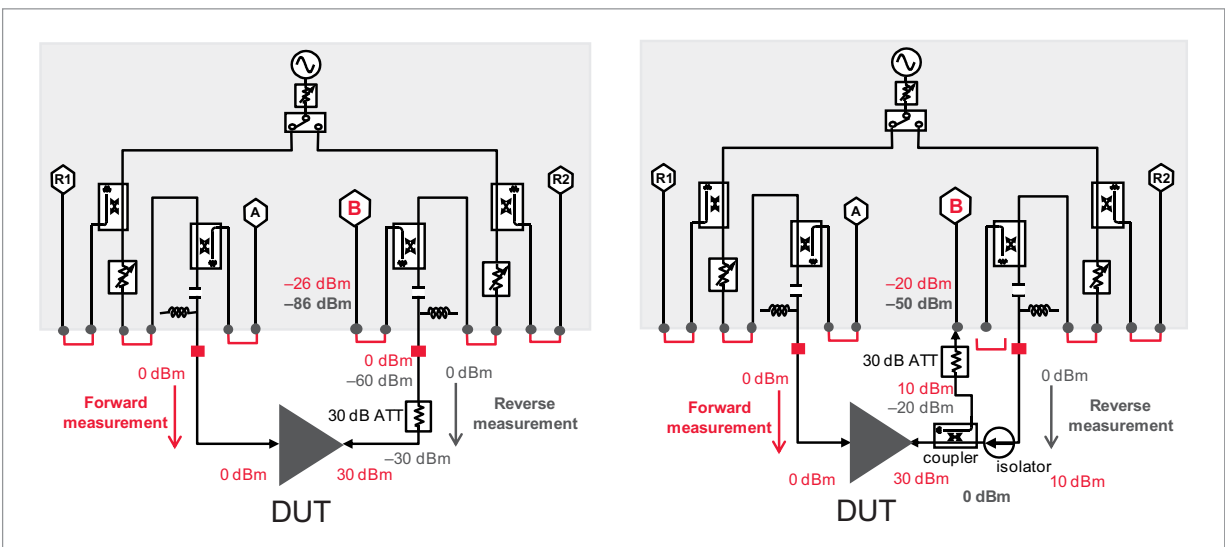


Figure 6. Comparison of power level using the configuration with large attenuation (left) and the configuration using direct receiver access (right).

### Gain with leveled output power

Some power amplifiers are tuned and characterized when they are in saturation. The output level across specified frequency range needs to be very flat at a desired constant value, with less than 0.1 dB deviation across the band. Since the amplifier's gain varies across the band, external power leveling of output power to account for the gain variation is necessary for device characterization.

Conventionally this type of test has been made with a combination of a signal generator, a power meter and spectrum analyzer. The simple test configuration is shown in Figure 7. The DUT's output power is monitored by a power sensor via coupler, and the source power from signal generator is adjusted to achieve target power level of the DUT's output. Since this power leveling sequence requires that all the measurement instruments are controlled by a system controller and measurements have to be synchronized for each data point, total measurement process takes long time to complete. Also overall cost of test system with multiple instruments for calibration and repair becomes very expensive.

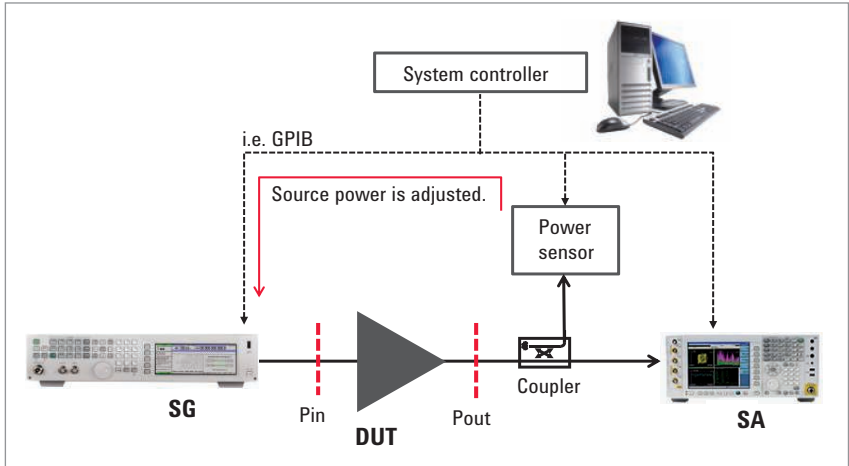


Figure 7. Conventional test configuration for power leveling.



The E5072A has capabilities of power calibration techniques for accurate measurements which offer the replacement to legacy test systems with multiple instruments. Especially its receiver leveling function using the receiver measurement offers fast leveling of input or output power of the DUT during measurements. The complexity of rack and stack test system can be reduced by using the useful features available with the E5072A.

### 1. Power calibration

If you need to characterize the amplifier at a specific input power, power calibration using a power meter/sensor connected to the E5072A should be performed prior to measurements. The output power level of the E5072A's test port is adjusted automatically to achieve the desired power level at the calibration plane (usually DUT's interface). Power calibration transfers the accuracy of the power sensor connected to the E5072A's source, and sets the power level at the DUT's input to a specified tolerance level with deviation of less than 0.1 dB or below.

### 2. Receiver calibration

Receiver calibration is necessary for absolute measurements in dBm using the E5072A's receivers. The calibration mathematically removes frequency response in the receiver path and adjusts the E5072A's readings to the same as the targeted power level calibrated by power calibration. With the receiver calibration, it is possible to achieve accurate absolute power measurements (in dBm) with the E5072A to monitor input or output power of the DUT.

### 3. Receiver leveling

The E5072A has receiver leveling function that uses the receiver measurements to adjust the source power level across a frequency or power sweep. Before each measurement sweep, a variable number of background sweeps are performed to repeatedly measure power at the receiver. Those power measurements are then used to adjust the E5072A's source power level for providing targeted leveled power at the DUT's interface. With this receiver leveling function, you can achieve great power level accuracy with faster throughput compared to conventional leveling methods using a power meter and power sensor.

These power calibration techniques with the E5072A enable test system designers to simplify complicated test systems that are conventionally used for amplifier measurements.

The following describes necessary steps to measure the amplifier's gain over frequency with leveled output power using the power calibration techniques of the E5072A. The test configuration is shown in Figure 8. An optional attenuator is required before port 2 to absorb the high power from the DUT for protection of internal receivers. Refer to appendix A "Power-Handling Consideration" for details on the E5072A's power-handling capability.

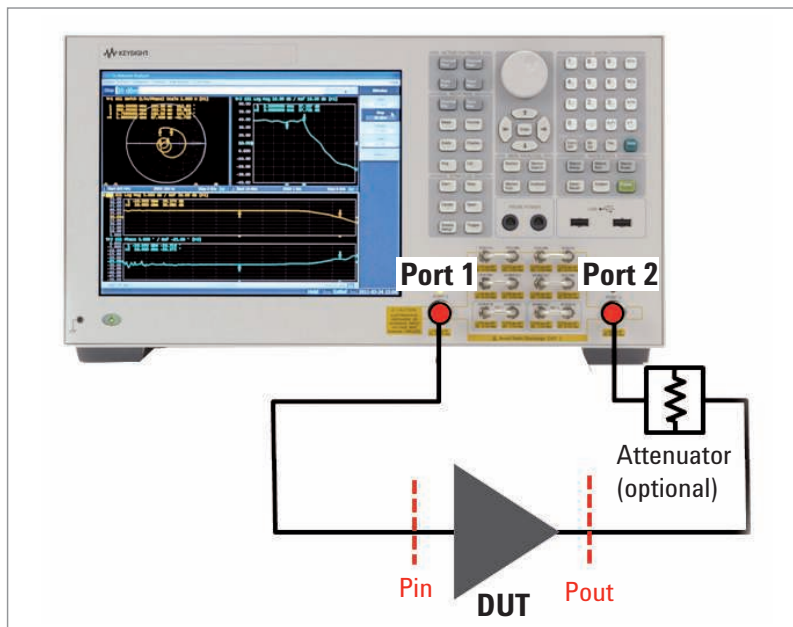


Figure 8. Configuration example of gain measurement.

The measurement process is described in the following steps:

- Step 1** Setup of stimulus parameters
- Step 2** Power calibration
- Step 3** Receiver calibration
- Step 4** Calibration
- Step 5** Receiver leveling

#### Step 1 Setup of stimulus parameters

Stimulus parameters such as frequency, IFBW, NOP should be entered before calibration and measurements. Measurement traces are allocated to measure the DUT's gain, input power or output power level over the frequency with the trace 1, 2 or 3 respectively. The DUT's input power is monitored by absolute measurement using the E5072A's internal receiver R1 of port 1, while the output power is monitored by measurements of the receiver B of port 2.

- [Display] > Num Trace (3)
- [Display] > Allocate Trace (x3)
- Activate trace 1 and [Meas] > S21, [Format] > Log Mag
- Activate trace 2 and [Meas] > S21, [Format] > Phase
- Activate trace 3 and [Meas] > Absolute > R1 (1)
- Activate trace 4 and [Meas] > Absolute > B (1)

## Step 2 Power calibration

Power calibration with a connected power sensor is performed to get accurate power level at the calibration plane (DUT's input). Keysight U2000 Series USB power sensor can be directly connected on the USB port of the E5072A, and the calibration procedure can be controlled by the E5072A firmware. (Figure 9)

- (1) Connect a power meter/sensor to the E5072A.
- (2) Configure setup of power sensor. (Below instructions are given for calibration with a USB power sensor.)  
**[System] > Misc Setup > Power Meter Setup > Select Type (USB)**  
**[System] > Misc Setup > Power Meter Setup > USB**
- (3) Set target power level  
The target power level for power calibration is set. The power level at the calibration plane is adjusted by power calibration.  
**[Sweep Setup] > Power (e.g. -10 dBm)**
- (4) Set tolerance and maximum iteration for power calibration  
Measurement sweep of power calibration is continued until the power level at the calibration plane is adjusted within the accuracy tolerance. Maximum iteration allows you to set the maximum number of sweeps for power calibration until the required accuracy is obtained.  
**[Cal] > Power Calibration > Tolerance (e.g. 0.05 dB)**  
**[Cal] > Power Calibration > Max Iteration (e.g. 10)**
- (5) Perform power calibration  
**[Cal] > Power Calibration > Take Cal Sweep**

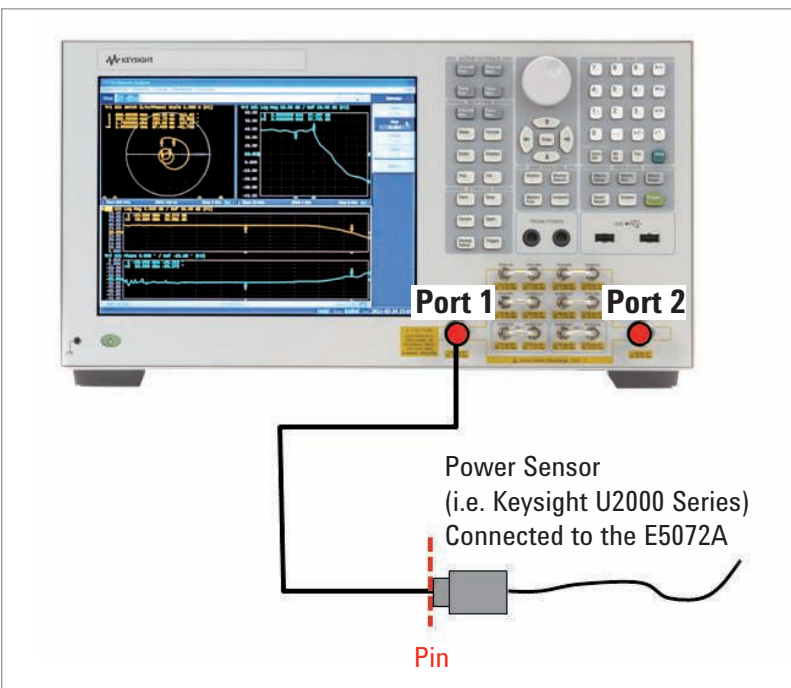


Figure 9. Power calibration using the power sensor.

### Step 3 Receiver calibration

Receiver calibration is performed prior to receiver leveling. Receiver calibration mathematically removes frequency response in the receiver path such as loss of a cable or attenuator, and displays the absolute value in dBm at the calibration plane for absolute measurements with the E5072A. After performing calibration by connecting a thru between port 1 with calibrated source power and port 2 of the receiver indicated in Figure 10, the power level in dBm at the calibration plane is displayed.

If the “B (1)” (the absolute value at receiver B when port 1 is selected for the source) is selected as a measurement trace, the DUT’s output power in dBm can be monitored with the measurement sweep of the E5072A. Also receiver calibration for the receiver R1 is performed to display the DUT’s input power with the trace “R1 (1)”.

- (1) Select source and receiver port to be calibrated.  
**[Cal] > Receiver Calibration > Select Receiver > R1 & B**  
**[Cal] > Receiver Calibration > Source Port (1)**  
**[Cal] > Receiver Calibration > Power Offset (0 dB)**
- (2) Perform receiver calibration  
**[Cal] > Receiver Calibration > Calibrate**

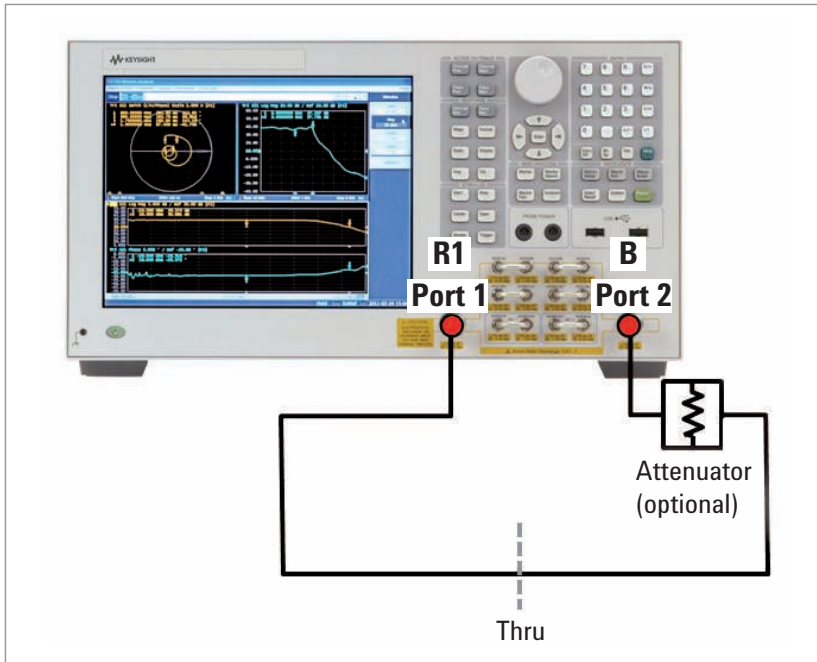


Figure 10. Receiver calibration.

## Step 4 Calibration

Perform response thru calibration with a thru standard. If the accurate reflection (S11) measurement is required as well, perform enhanced response cal by connection calibration standards such as open, short and load. (Figure 11)

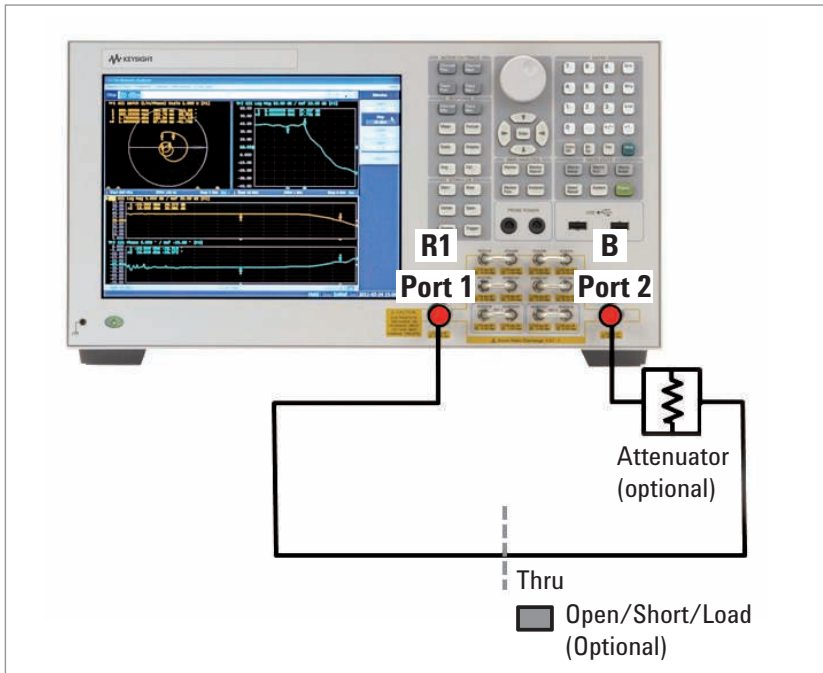


Figure 11. Calibration with calibration standards.

## Step 5 Receiver leveling

Receiver leveling is enabled to obtain the target power level at the calibration plane. Leveling sweeps are performed at each stimulus data point and the deviation from the target power level is applied to the source power level until the desired target power level is achieved. If the receiver B is selected as a receiver for receiver leveling, the DUT's output power level is adjusted within the specified tolerance value or the leveling sweeps continue until the specific number has been reached.

- (1) Select a receiver to be used for receiver leveling.  
**[Sweep Setup] > Power > Receiver Leveling > Port 1 > Receiver > B**
- (2) Set tolerance and maximum iteration  
**[Sweep Setup] > Power > Receiver Leveling > Port 1 > Tolerance (e.g. 0.1 dB)**  
**[Sweep Setup] > Power > Receiver Leveling > Port 1 > Max Iteration (e.g. 10)**
- (3) Turn on receiver leveling for port 1.  
**[Sweep Setup] > Power > Receiver Leveling > Port 1 > Leveling > ON**

Figure 12 shows the gain over frequency of an RF amplifier with leveled power targeted at  $-10$  dBm. The DUT's input power (Pin) and output power (Pout) are monitored simultaneously with the measurement sweep. External leveling using receiver leveling with the receiver B reduces the variations of output power due to the amplifier gain directly, and provides feedback for compensation of source power from the E5072A. The result is that the output power can be flatter as a function of frequency range of measurements.

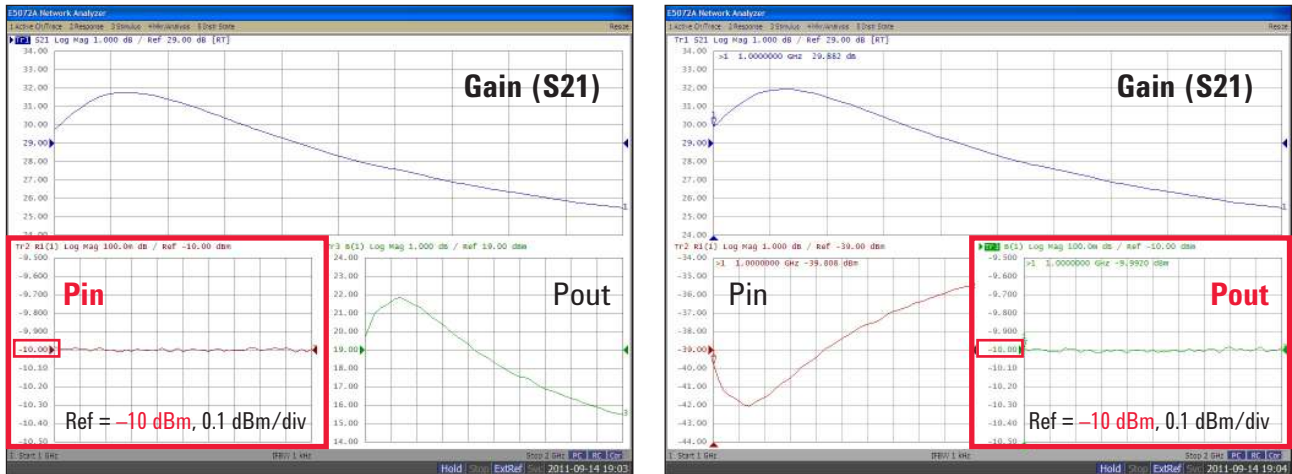


Figure 12. Gain vs. frequency with leveled input power (left), and with leveled output power with receiver leveling (right).

## Gain compression

Gain compression is a common specification for an amplifier that is used to define the transition region between the linear and nonlinear region of operation. The 1 dB gain compression is defined as the input power level where the amplifier gain drops 1 dB relative to the small signal gain in the linear region of operation.

Using the power sweep with the VNA, the gain of the amplifier at the 1-dB compression point can simply be monitored as a function of input power level. This is accomplished by observing the reduction in gain at a continuous wave (CW) frequency as input power is increased as indicated in Figure 13.

When characterizing amplifiers, it becomes more important to know input or output power levels so that the amplifier is operating in its proper power range. If you want to measure non-linear behavior such as the 1 dB compression point or AM-to-PM conversion, it is necessary to know power levels of the DUT more accurately. The E5072A's power calibration techniques are also useful for gain compression measurements where absolute power accuracy is desired.

The power sweep range must be wide enough to drive the amplifier from its linear region of operation to its region of compression. The E5072A provide output power from the test port up to +20 dBm<sup>1</sup> in the frequency range of 300 kHz to 1 GHz, which is great enough to drive most amplifiers into compression. If the output power of the E5072A is not adequate to drive the amplifier under test, it is necessary to have an external booster amplifier to boost the power.<sup>2</sup>

Gain compression is a 2D measurement that consists of power sweep and frequency sweep. The swept frequency gain compression locates the frequency point where compression first occurs. Keysight offers the amplifier measurement wizard for the E5072A that supports swept gain compression measurements. See appendix B "Amplifier Measurement Wizard" for more details.

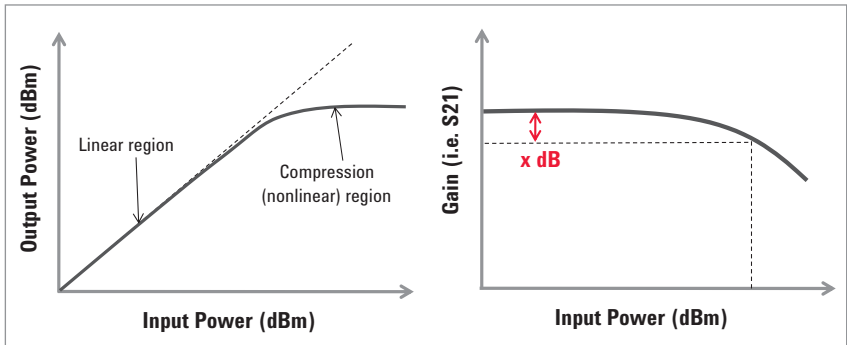


Figure 13. Gain compression measurement.

1. The value is supplemental performance data or SPD that is most likely occur. Not guaranteed by the product warranty.
2. For more details of high-power measurements, refer to Keysight application note, "High-power Measurements Using the E5072A", part number 5990-8005EN. (<http://cp.literature.keysight.com/litweb/pdf/5990-8005EN.pdf>)

## AM-to-PM Conversion

Measurements of AM-to-PM conversion are also useful in characterizing the nonlinear behavior of amplifiers. AM-to-PM conversion is a measure of the undesired phase shifts that occur as a result of any amplitude variations in a system. AM-to-PM conversion can be measured with a power sweep with a VNA and the result data is displayed as the phase of forward transmission ( $S_{21}$ ) versus input power to DUT (Figure 14). The change in amplitude and phase can be easily measured with marker functions of the VNA.

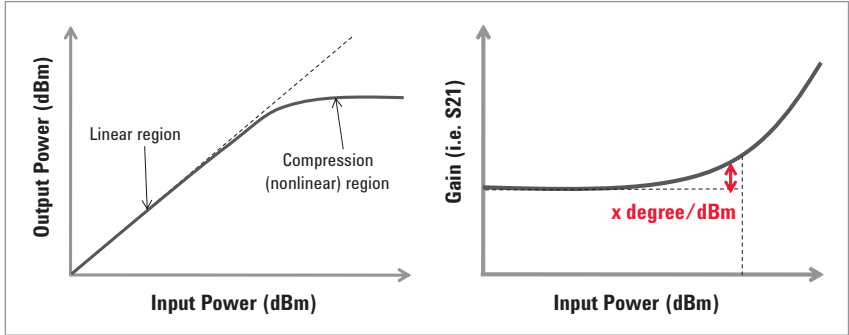


Figure 14. AM-to-PM conversion measurement.

The following describes necessary steps to measure the amplifier's gain compression and AM-to-PM conversion with the E5072A. Also input power and output power of the DUT are monitored by absolute measurements using the E5072A's internal receivers at the same time. The test configuration is the same as illustrated in Figure 8.



## Step 1 Setup of stimulus parameters

Stimulus parameters such as CW frequency, power sweep range, IFBW or NOP should be entered before calibration and measurements. Power sweep is selected as a sweep type of measurement. Measurement traces are allocated to measure gain compression, AM-to-PM conversion, input power or output power level with the trace 1, 2, 3 or 4 respectively. The DUT's input power is monitored by absolute measurements using the E5072A's receiver R1, while output power is monitored by measurements of the receiver B. If the "B (1)" (the absolute value at receiver B when port 1 is selected for the source) is selected as a measurement trace, the DUT's output power level in dBm can be monitored after receiver calibration. R1 (1) can be used to monitor input power level.

**[Sweep Setup] > Sweep Type > Power Sweep**  
**[Sweep Setup] > Power > CW Freq** (e.g. 1 GHz)  
**[Start]** (e.g. -15 dBm)  
**[Start]** (e.g. +5 dBm)  
**[Display] > Num Trace** (4)  
**[Display] > Allocate Trace** (x4)  
Activate trace 1 and **[Meas] > S21, [Format] > Log Mag**  
Activate trace 2 and **[Meas] > S21, [Format] > Phase**  
Activate trace 3 and **[Meas] > Absolute > R1** (1)  
Activate trace 4 and **[Meas] > Absolute > B** (1)

## Step 2 Power calibration

Power calibration with a connected a power sensor is performed to get accurate power level from the port 1 at the calibration plane (DUT's input). (Figure 9)

**[Cal] > Power Calibration > Select Port** (1)  
**[Cal] > Power Calibration > Tolerance** (e.g. 0.05 dB)  
**[Cal] > Power Calibration > Max Iteration** (e.g. 10)

## Step 3 Receiver calibration

Receiver calibration is necessary for accurate absolute measurements. A thru is connected between the port 1 and port 2 and receiver calibration for the receiver R1 and receiver B is performed. When an absolute measurement of each receiver is selected as a measurement trace, input or output power level of the DUT is displayed after receiver calibration. (Figure 10)

**[Cal] > Receiver Calibration > Select Receiver > R1 & B**  
**[Cal] > Receiver Calibration > Source Port** (1)  
**[Cal] > Receiver Calibration > Power Offset** (0 dB)  
**[Cal] > Receiver Calibration > Calibrate**

## Step 4 Calibration

Perform calibration with calibration standards under **[Cal]**. (Figure 11)

## Step 5 Receiver leveling

Receiver leveling is enabled to obtain the target power level at the calibration plane. Leveling sweeps are performed at each stimulus data point and the deviation from the target power level is applied to the source power level until the desired target power level is achieved. If the receiver R1 is selected as a receiver for receiver leveling, the DUT's input power level is adjusted within the specified tolerance value or the leveling sweeps continue until the specific number has been reached.

[Sweep Setup] > Power > Receiver Leveling > Port 1 > Receiver > R1  
[Sweep Setup] > Power > Receiver Leveling > Port 1 > Tolerance (e.g. 0.1 dB)  
[Sweep Setup] > Power > Receiver Leveling > Port 1 > Max Iteration (e.g. 10)  
[Sweep Setup] > Power > Receiver Leveling > Port 1 > Leveling > ON

## Step 6 Search compression point

A marker is placed on a small signal gain of gain measurement with S21 of a trace 1. Gain compression point can be found by marker search function relative to a small signal gain.

Select trace 1 and [Marker] > Marker 1  
[Marker] > Ref Marker  
[Marker Search] > Target > Target Value (e.g. -1 dB)  
[Marker Search] > Target > Search Target

The measurement results of gain compression and AM-to-PM conversion are indicated in Figure 15. Note that the DUT's input power is adjusted within 0.1 dB tolerance by receiver leveling using the receiver R1.

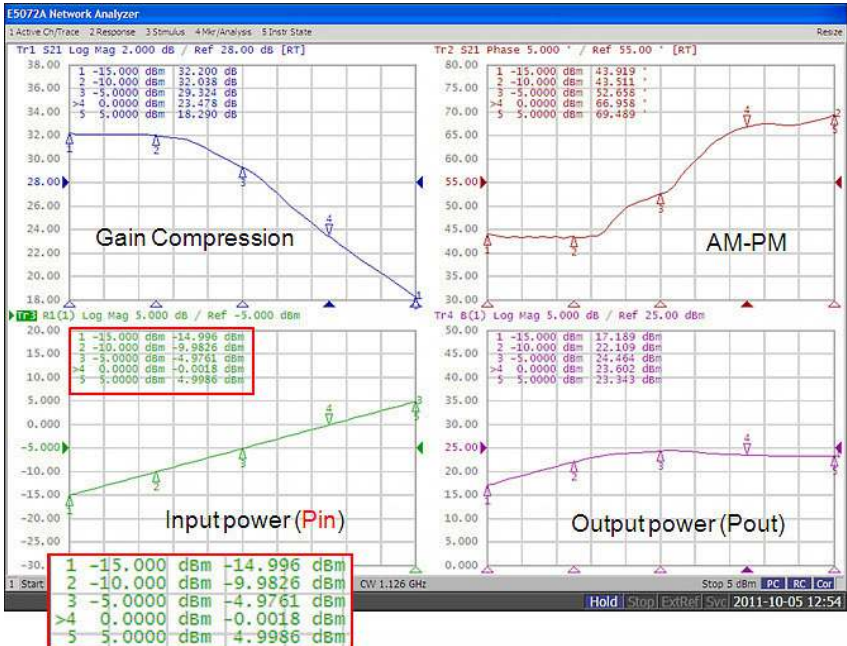


Figure 15. Result of gain compression and AM-to-PM conversion with leveled input power.

Amplifier measurement wizard for the E5072A is available on Keysight's website that guides to measure gain compression point of the amplifier with either CW or swept frequencies. The measurement result of swept gain compression by the wizard is shown in Figure 16. The DUT's input power and output power at 1-dB compression point is measured in the swept frequency range and displayed on the screen. See Appendix B "Amplifier Measurement Wizard" for more details.

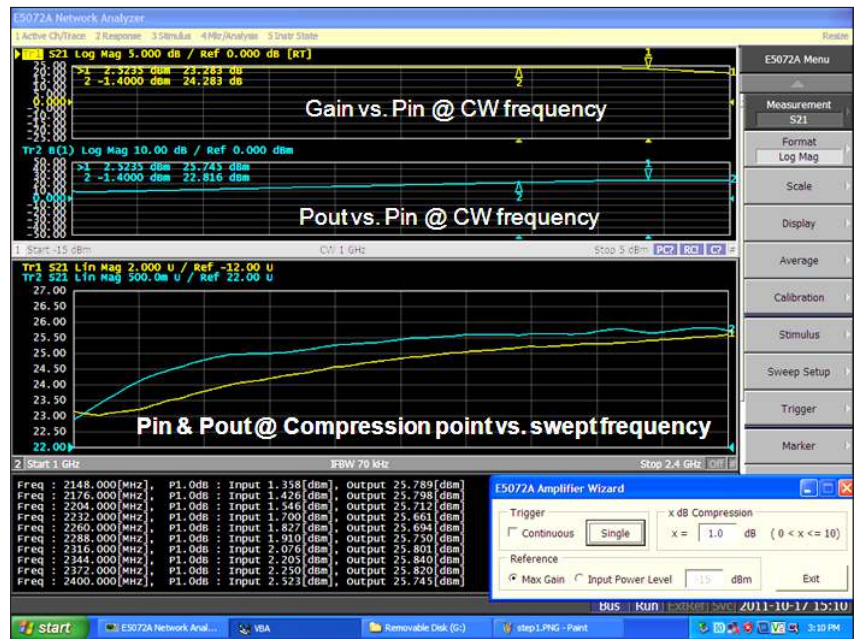


Figure 16. Measurement example of swept gain compression measurement with amplifier measurement wizard.

## Harmonic Distortion

Harmonic distortion is specified to describe nonlinear behavior of amplifier. Harmonic level is defined as the difference in absolute power level between the fundamental and the harmonics, expressed in dBc (dB relative to carrier) for a specified input or output power. (Figure 17)

Many applications require information regarding harmonics performance, as excessive nonlinear distortion of the amplifier causes adjacent channel interference in communication systems. Traditionally, harmonics distortion measurements have been performed with equipments such as a spectrum analyzer and a signal generator. However, the E5072A offers frequency-offset mode option (option 008)<sup>1</sup> which enables the source and receiver to sweep at different frequencies for harmonics measurements. While the source is set to the fundamental frequency, the receivers are tune to the desired harmonics. By combining the frequency offset sweep and power level calibration such as source power calibration and receiver calibration, fast and accurate harmonics measurements can be performed with a single VNA. This can replace the traditional method for measuring harmonic distortion using the combination of a signal generator and spectrum analyzer and provide real-time CW or swept frequency harmonics measurements.

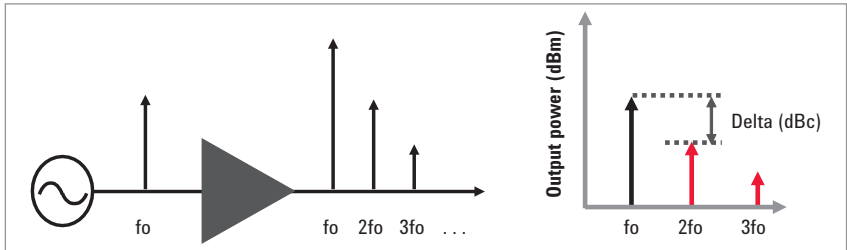


Figure 17. Harmonic distortion of amplifiers.

The following describes necessary steps to measure harmonic distortion using the E5072A. The power of the fundamental tone is measured in channel 1, while the second and third harmonic is measured in channel 2 and 3 respectively. The E5072A's source from port 1 is set to the fundamental frequency for all channels and the receiver B of port 2 is used as a receiver to measure the DUT's output power at fundamental and harmonic frequencies. An optional external attenuator is needed on the port 2 to protect damage or compression of the receiver B. This measurement process is described in the following steps:

**Step 1** Setup of stimulus parameters

**Step 2** Power calibration & receiver calibration in harmonic frequency range

**Step 3** Power calibration in fundamental frequency range

**Step 4** Perform harmonic measurements

In Step 2, receiver calibration with the power-calibrated source is performed for absolute measurements in all channels. The frequency range for this calibration is set in harmonic frequency range. And then, power calibration is performed for the source in fundamental frequency range in Step 3 to get accurate power level at the DUT's input for harmonics measurements.

1. See the E5072A configuration guide, part number 5990-8001EN. (<http://cp.literature.keysight.com/litweb/pdf/5990-8001EN.pdf>) for more detail.

## Step 1 Setup of stimulus parameters

Stimulus parameters such as frequency, IFBW or NOP should be entered for channel 1, 2 and 3.

- (1) Setup channel 1 for fundamental  
Stimulus parameters such as frequency, IFBW or source power level for fundamental signal are entered in channel 1. The absolute measurement using the receiver B is selected for a measurement trace. Three channels are allocated on the screen.

**[Meas] > Absolute > B (1)**  
**[Start]** (e.g. 1.2 GHz)  
**[Stop]** (e.g. 1.5 GHz)  
**[Avg] > IF Bandwidth** (e.g. 1 kHz)  
**[Sweep Setup] > Points** (e.g. 51)  
**[Sweep Setup] > Power > Power** (e.g. 0 dBm)  
**[Display] > Allocate Channel** (x3)

- (2) Setup channel 2 for second harmonic  
Channel 2 is selected and stimulus parameters are entered as the same as channel 1. In addition, Frequency-offset mode (FOM) is enabled and the source and receiver frequency is tuned at second harmonic frequency range (e.g. 2.4 to 3 GHz).

**[Sweep Setup] > Frequency Offset > Port 1 > Multiplier** (2)  
**[Sweep Setup] > Frequency Offset > Port 2 > Multiplier** (2)  
**[Sweep Setup] > Frequency Offset > Frequency Offset** (On)

- (3) Setup channel 3 for third harmonic  
Channel 3 is selected and stimulus parameters are entered as the same as channel 1 or 2. FOM is enabled and the source and receiver frequency is tuned at third harmonic frequency range (e.g. 3.6 to 4.5 GHz).

**[Sweep Setup] > Frequency Offset > Port 1 > Multiplier** (3)  
**[Sweep Setup] > Frequency Offset > Port 2 > Multiplier** (3)  
**[Sweep Setup] > Frequency Offset > Frequency Offset** (On)

## Step 2 Power calibration & receiver calibration in harmonic frequency range

### (1) Perform power calibration

Power calibration is necessary prior to receiver calibration in order to accurately characterize the E5072A's receivers for absolute measurements. A power sensor is connected to the E5072A's port 1 and power calibration is performed at: fundamental frequency ( $f_1$ ) in channel 1, second harmonic frequency ( $f_2$ ) in channel 2 and third harmonic frequency ( $f_3$ ) in channel 3 respectively. (Figure 18)

**[Cal] > Power Calibration > Tolerance** (e.g. 0.05 dB)

**[Cal] > Power Calibration > Max Iteration** (e.g. 10)

**[Cal] > Power Calibration > Take Cal Sweep**

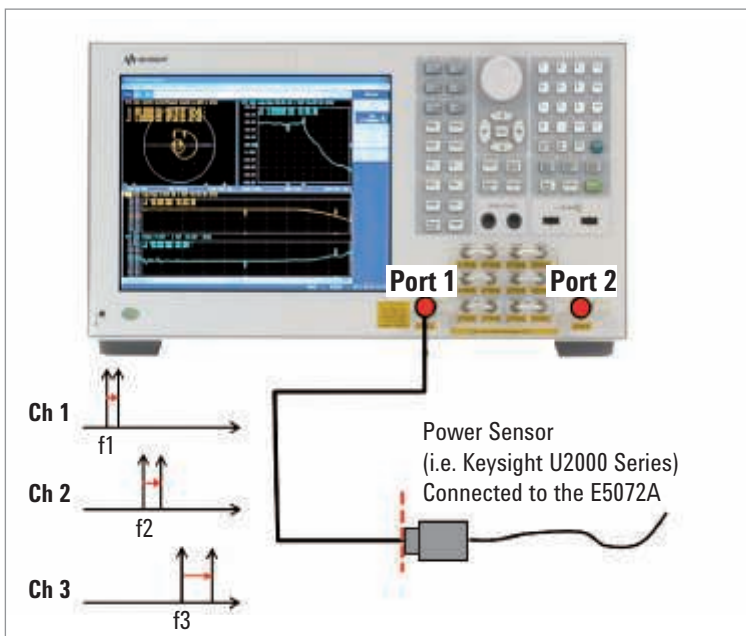


Figure 18. Configuration of power calibration for harmonics frequency range.

(2) Perform receiver calibration

After connecting a thru between the port 1 and port 2, receiver calibration is performed for absolute measurements using the receiver B for all channels. The receiver B is calibrated in the frequency range of the fundamental in channel 1, second harmonic in channel 2, and third harmonic in channel 3 respectively. (Figure 19)

**[Cal] > Receiver Calibration > Select Receiver > B**

**[Cal] > Receiver Calibration > Calibrate**

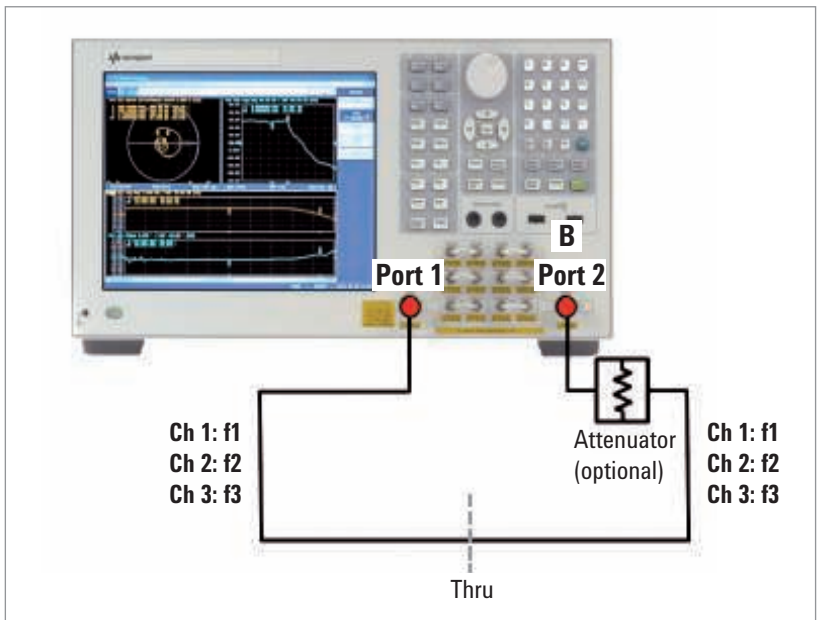


Figure 19. Configuration of receiver calibration for harmonics frequency range.

### Step 3 Power calibration in fundamental frequency range

The E5072A's source generates its own harmonics of typically below 25 dBc at 5 dBm<sup>1</sup>. For accurate harmonics measurement, the source harmonics must be filtered. A low pass filter (LPF) should be placed on the source path of port 1 to reduce the measurement error due to the E5072A's source harmonics.

The purpose of power calibration is to get accurate power level at the cal plane after the LPF in fundamental frequency range for all channels. Source frequency from port 1 is set as the fundamental frequency by selecting 1 as a multiplier for all three channels. (Figure 20)

**[Sweep Setup] > Frequency Offset > Port 1 > Multiplier (1)**  
**[Cal] > Power Calibration > Take Cal Sweep**

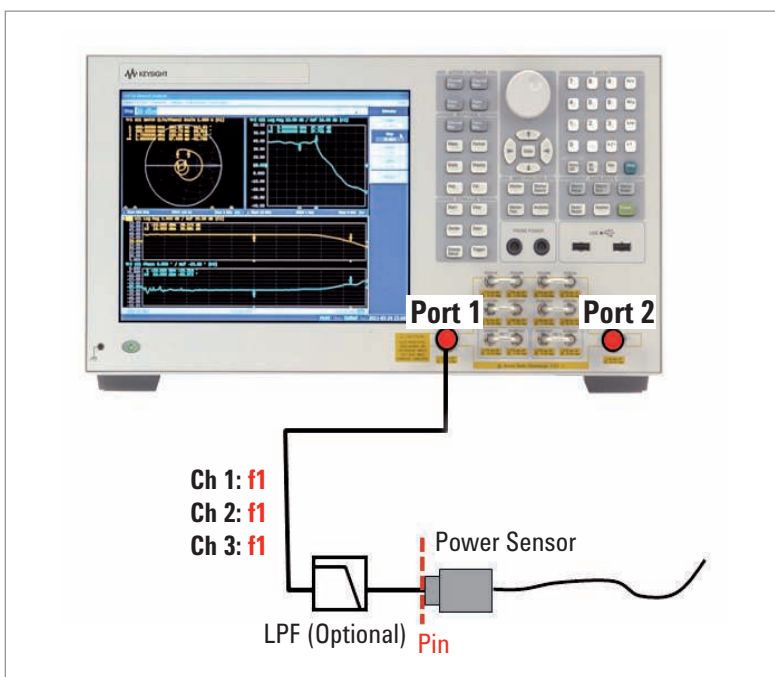


Figure 20. Configuration of power calibration for fundamental frequency range.

1. See the E5072A data sheet, part number 5990-8002EN. (<http://cp.literature.Keysight.com/litweb/pdf/5990-8002EN.pdf>) for more detail.



#### Step 4 Perform harmonic measurements

The DUT is connected and harmonics measurements are performed for all three channels of the E5072A (Figure 21). The harmonics measurement example of an amplifier with swept frequency input is indicated in Figure 22. The fundamental power is monitored with the absolute measurement in channel 1, while second and harmonics are monitored in channel 2 and 3.

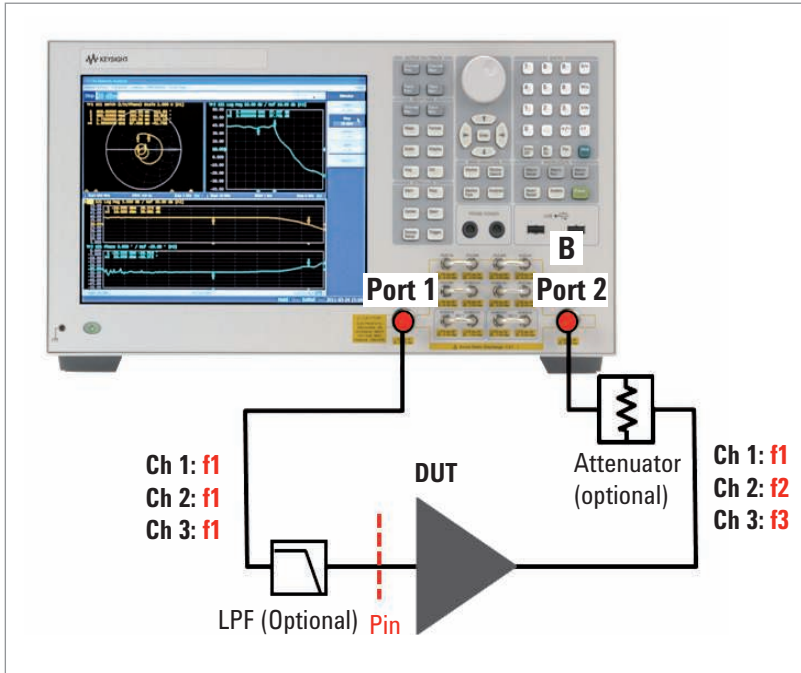
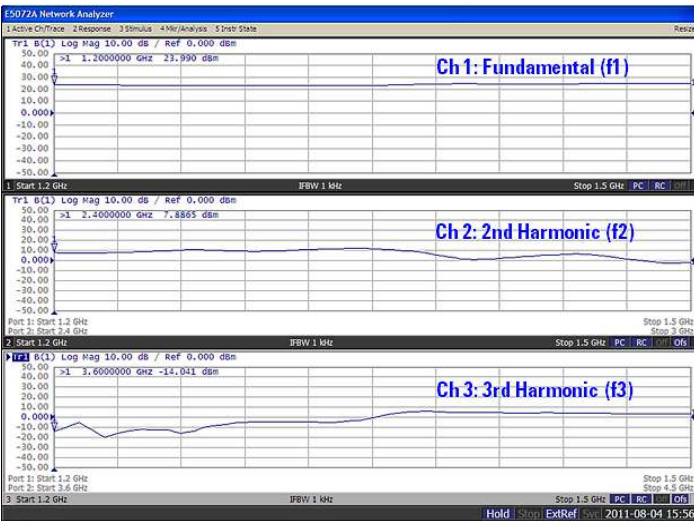


Figure 21. Configuration of harmonic measurements with the E5072A.



→  
Fundamental Frequency (1.2 to 1.5 GHz)

Figure 22. Measurement result of swept harmonic measurement.

Amplifier measurement wizard for the E5072A guides you through swept-frequency harmonics measurements. The measurement example of swept frequency harmonics by the wizard is shown in Figure 23. The power level of fundamental and up to 5th harmonics (in dBm), and harmonics relative to carrier (in dBc) can be monitored by with the utility wizard. See Appendix B “Amplifier Measurement Wizard” for more details.



Figure 23. Measurement example of swept harmonic measurement with amplifier measurement wizard.

## Pulsed 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 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 VNAs have trigger functionality to make such measurements. The VNA is the common tool for characterizing RF components in both CW and pulsed operation.

Figure 24 shows a typical test setup of making pulsed-RF measurements for an amplifier with the E5072A. The pulsed RF signal from a pulse generator such as Keysight 81150A pulse generator is used as an external trigger for measurements in the E5072A. This trigger signal must be synchronized with the RF pulse that drives a pulse modulator such as a solid-state switch inserted in the signal path. The pulse-modulated RF signal drives the DUT in pulsed-RF operation and the E5072A captures the RF signals by synchronizing trigger input of measurements. The minimum pulse width for pulsed measurements with the E5072A is about 5 microseconds when IFBW is set at 500 kHz.

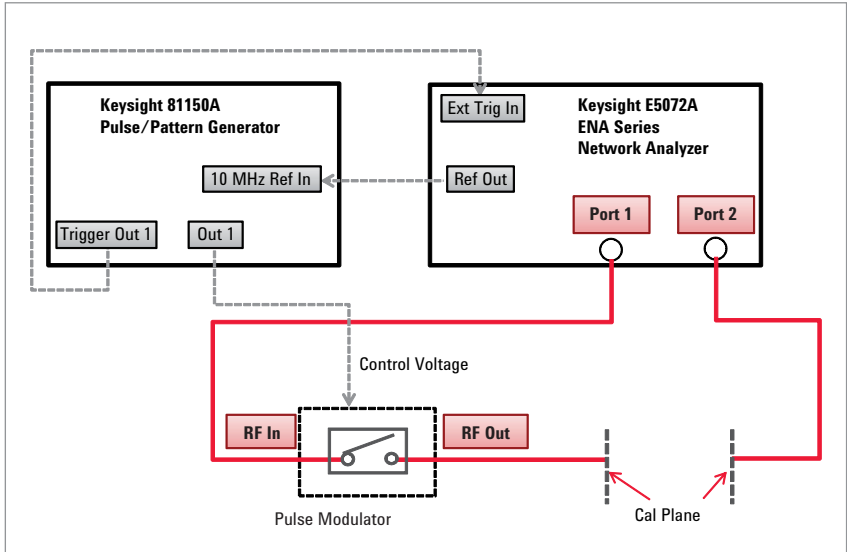


Figure 24. Typical test configuration of pulsed-RF measurements with the E5072A.

The typical timing chart for pulsed measurements is shown in Figure 25. Sampling or data acquisition in the E5072A must take place during the RF pulse, and this is achieved by externally triggering the analyzers to measure the appropriate points in time. 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 E5072A (indicated as “Td” in Figure 25). This means the E5072A must be triggered before the RF pulse is applied from a pulse generator. Note that there is some inherent settling time on the E5072A before the setup of parameters such as sweep frequency, IFBW, or power level. The typical delay time of the E5072A is about 12.3 microseconds.

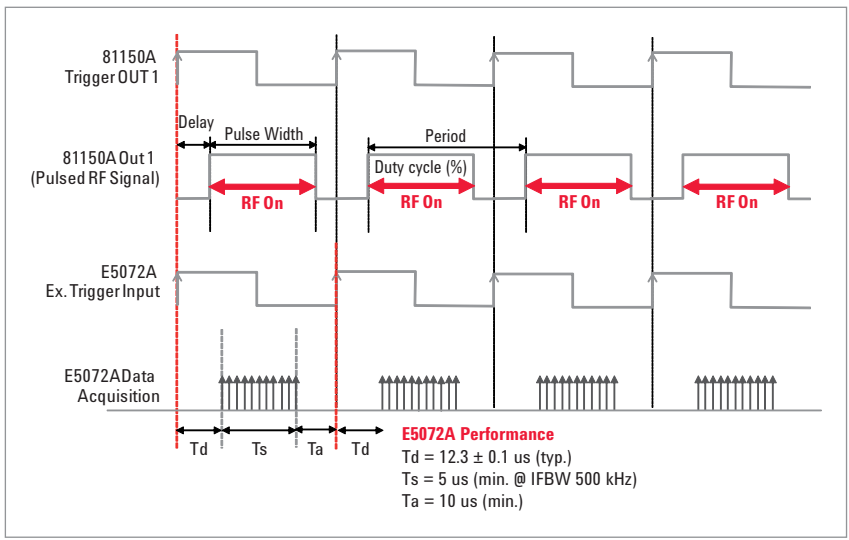


Figure 25. Timing chart of pulsed-RF measurements with the E5072A.

As many devices under pulsed condition are active devices and the characteristics including compression and distortion are typically sensitive to input power level. Inaccurate stimulus power may introduce considerable measurement errors and it is critical to employ the appropriate techniques for accurately leveling the stimulus power. Power level calibration techniques such as receiver leveling are recommended for pulsed measurements with the E5072A.

The following describes the necessary steps for the pulsed RF measurement using the E5072A. Input and output power of the DUT in pulsed operation are monitored by absolute measurements with the E5072A. The output signal of the pulse modulator is measured by the receiver R1, and temperature drift of the modulator is eliminated by the receiver leveling with the E5072A to get accurate power level at the DUT's input. The DUT's output power is monitored by absolute measurements using the receiver B. The test configuration of the measurement with the E5072A is shown in Figure 26.

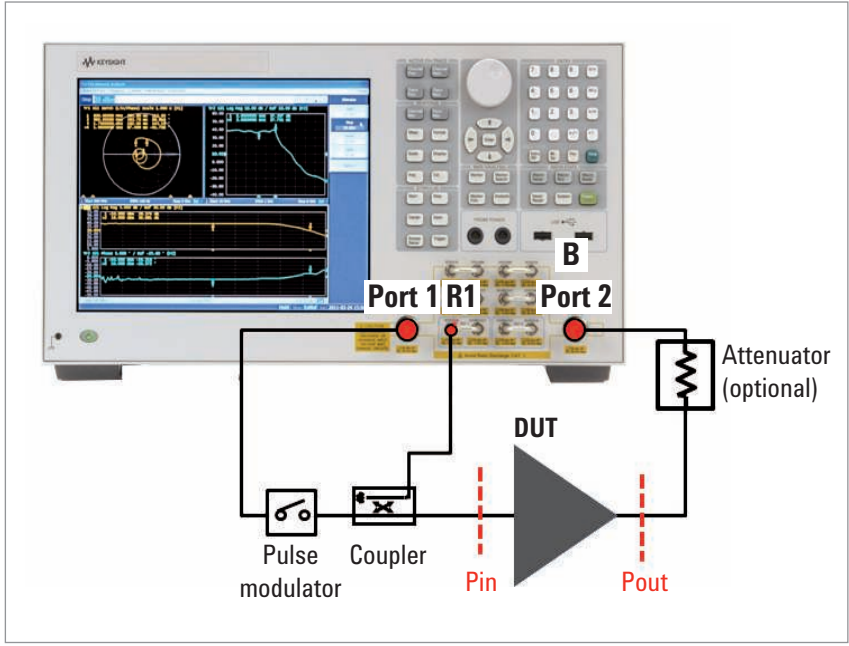


Figure 26. Test configuration of pulsed-RF measurements using receiver leveling of the E5072A.

## Step 1 Setup of a pulse generator

Pulse width, pulse period or signal levels of pulse signals are setup by a pulse generator such as Keysight 81150A pulse generator. The trigger delay can be setup by a pulse generator with accurate resolution. The pulsed signals are supplied to a pulse modulator in the signal path and the external trigger input of the E5072A.

## Step 2 Setup of stimulus parameters

Stimulus parameters such as frequency, IFBW or NOP should be entered on the E5072A before calibration and measurements. Note that IFBW should be wide enough for data acquisition when narrow pulse width is required for the measurement. The minimum pulse width for the E5072A is about 5 microseconds when 500 kHz is selected for IFBW.

**[Avg] > IF Bandwidth** (e.g. 500 kHz)

## Step 3 Power calibration

Power calibration with a power sensor connected at the calibration plane is performed to get accurate power level at the DUT's input by compensating the loss of the pulse modulator or coupler in the signal path. Note that cycle time of a pulse generator should be set at 100% when the average power sensor is used for power calibration.

**[Cal] > Power Calibration > Select Port** (1)

**[Cal] > Power Calibration > Tolerance** (e.g. 0.05 dB)

**[Cal] > Power Calibration > Max Iteration** (e.g. 10)

**[Cal] > Power Calibration > Take Cal Sweep**

## Step 4 Receiver Calibration

Receiver calibration is necessary for accurate absolute measurements. A thru is connected between the port 1 and port 2 and receiver calibration for the receiver R1 and receiver B is performed. When an absolute measurement of each receiver is selected as a measurement trace, input or output power level of the DUT is displayed after receiver calibration.

**[Cal] > Receiver Calibration > Select Receiver > R1 & B**

**[Cal] > Receiver Calibration > Source Port** (1)

**[Cal] > Receiver Calibration > Power Offset** (0 dB)

**[Cal] > Receiver Calibration > Calibrate**

## Step 5 Calibration

For S-parameter calibration in pulsed condition, external trigger input must be selected as a trigger source for the calibration. To minimize the variation of the delay time between trigger input and data acquisition for accurate timing setup, it is recommended that the low-latency external trigger mode be turned on with the [Low Latency] soft key.

**[Trigger] > Trigger Source > External**

**[Trigger] > Trigger Event > On Point**

**[Trigger] > Low Latency** (On)

Calibration using mechanical cal kits is required for synchronized calibration measurements with external trigger input. An appropriate calibration technique under [Cal] hard key is selected and calibration is performed with pulsed-RF signals. Note that duty cycle of pulsed signals from the pulse generator should be set before calibration measurements to apply pulsed RF signals to a pulse modulator and the E5072A.

### Step 6 Receiver leveling

To remove the temperature drift of a pulse modulator, receiver leveling using the receiver measurement is useful. The source power from the E5072A is adjusted to get accurate targeted power level at the DUT's input.

- [Sweep Setup] > Power > Receiver Leveling > Port 1 > Receiver > R1
- [Sweep Setup] > Power > Receiver Leveling > Port 1 > Tolerance (e.g. 0.1 dB)
- [Sweep Setup] > Power > Receiver Leveling > Port 1 > Max Iteration (e.g. 10)
- [Sweep Setup] > Power > Receiver Leveling > Port 1 > Leveling (ON)

### Step 7 Pulsed measurement

The pulsed measurement example on an RF amplifier's gain is presented in Figure 27. While the internally triggered measurement shows the intermittent trace (with memory trace) indicating that the analyzer fails to capture the data, the externally triggered synchronous measurement result (with data trace) shows the correct frequency response of the DUT in pulsed operation.

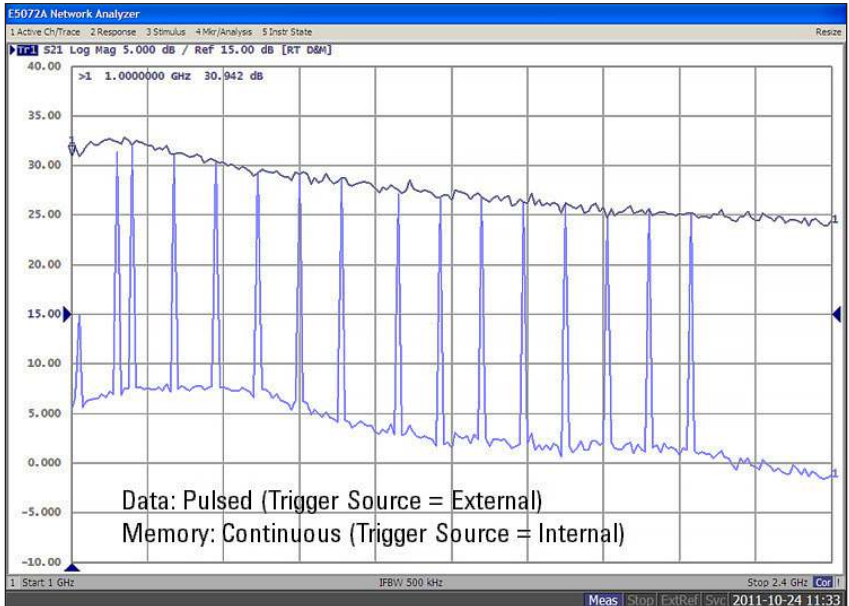


Figure 27. Measurement result of pulsed-RF measurement.

Figure 28 shows the comparison of measurement results when receiver leveling using the receiver R1 is turned on (data trace) and off (memory trace). When receiver leveling is enabled, input power ( $P_{in}$ ) in pulse mode at the DUT's input is adjusted within the tolerance. This gives more accurate result especially when the DUT is operating in nonlinear region. As the short-term drift of the pulse modulator is eliminated, receiver leveling is useful for characterization of power-dependent performance or nonlinear operation of active devices.

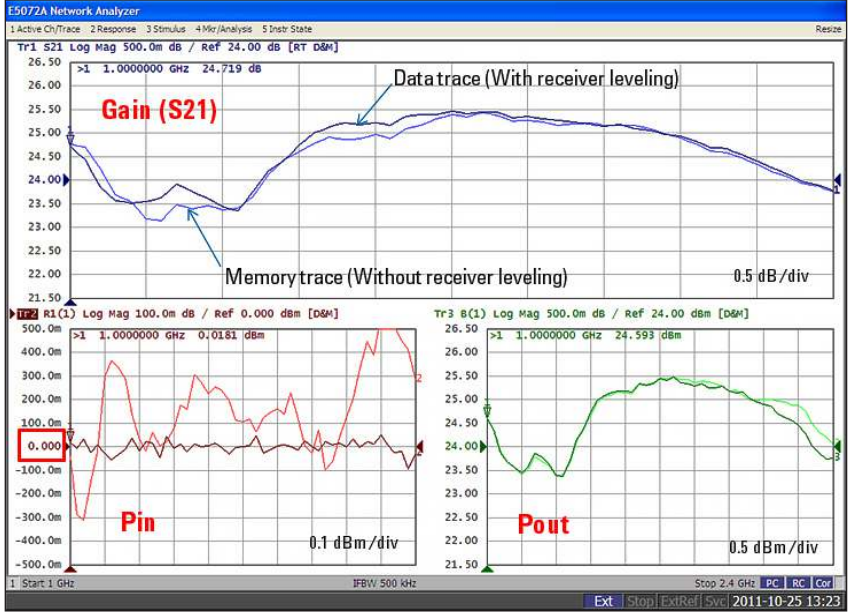


Figure 28. Receiver leveling makes more accurate pulsed measurements for the amplifier in nonlinear operation.

## Summary

The modern VNA such as the E5072A has many useful functions for accurate characterization of amplifiers, which enables you to reconfigure test system eliminating complexity and simplifying time-consuming measurement procedures.



## Appendix A. Power Handling Consideration

Special care has to be taken to protect instruments by considering for power handling capability of the internal components of the VNA. High power levels can damage the VNA, and it is costly to repair the internal components of the analyzer. It is important to understand how the analyzer works and the power handling capability of each component in the signal path. The block diagram of the E5072A is shown in Figure 29.

Each test port (port 1 and port 2) of the E5072A is associated with six SMA connectors for direct receiver access on the front panel. The damage level and compression level are listed in Table 1. Be sure not to exceed these levels and add external attenuating components such as attenuators or couplers to the test system if necessary. The input power level should be at least 3 dB below the damage level of the connectors on the E5072A (ideally at least 6 dB lower).

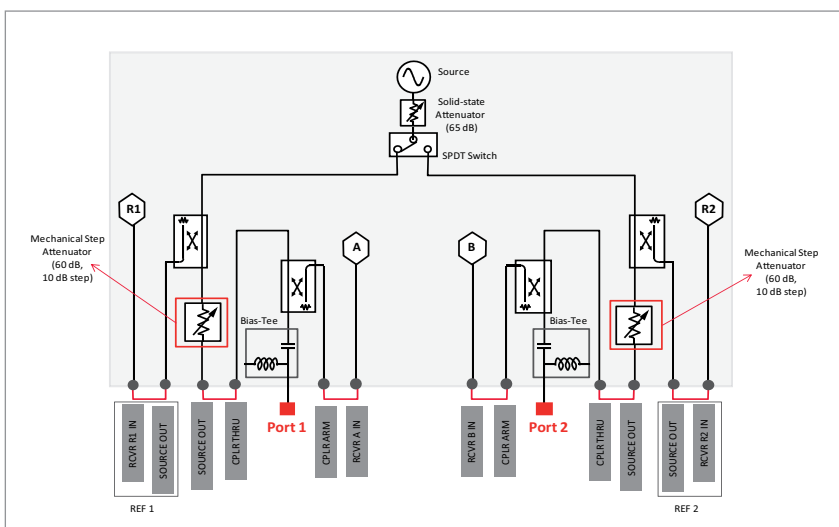


Figure 29. Block diagram of the E5072A.

Table 1. level and compression level of test ports.

Connector	RF Damage Level (Typ.)	DC Damage Level (Typ.)	0.1 dB Compression Level (SPD)
Test Port 1 & 2	+26 dBm	± 35 VDC	+6 dBm (30 to 300 kHz) +16 dBm (300 k to 2 GHz) +14 dBm (2 G to 6 GHz) +10 dBm (6 G to 8.5 GHz)
CPLR ARM	+15 dBm	0 VDC	—
RCVR A IN, RCVR B IN	+15 dBm	± 16 VDC	-15 dBm (30 to 300 kHz) -10 dBm (300 k to 8.5 GHz)
SOURCE OUT (Port 1 & 2)	+26 dBm	0 VDC	—
CPLR THRU (Port 1 & 2)	+26 dBm	± 35 VDC	—
REF 1/2 SOURCE OUT	+15 dBm	0 VDC	—
RCVR R1 IN, RCVR R2 IN	+15 dBm	± 16 VDC	-15 dBm (30 to 300 kHz) -10 dBm (300 k to 8.5 GHz)

## Appendix B. Amplifier Measurement Wizard

The ENA Series includes Microsoft VBA Macro programming capability, a time-saving tool for test automation. You can customize your interface easily to optimize the operating environment at no additional cost and you can also add automation processes. Many VBA sample programs for the ENA series are available on Keysight's website ([www.keysight.com/find/enavba](http://www.keysight.com/find/enavba)) to help you create your own program library for your applications.

Amplifier measurement wizard for the E5072A is provided for basic amplifier measurements. (Figure 30) This utility program supports the following measurements of amplifiers with the E5072A:

### **S-parameters / K-factor**

### **Swept-frequency harmonic distortion**

### **Gain compression and AM-to-PM Conversion (CW)**

### **Swept-frequency gain compression**

It guides you through measurement procedures to setup parameters and perform necessary calibration for measurements, so that you can minimize the time spent on measurement setup. High-power amplifier measurements with the E5072A using an external booster amplifier are also supported by the wizard.

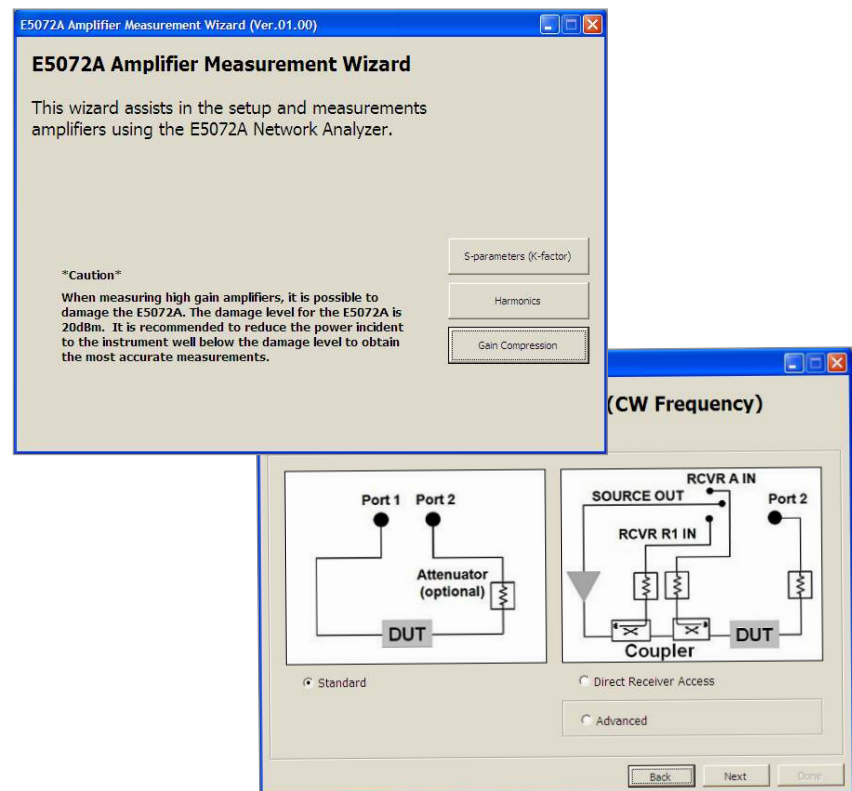


Figure 30. Amplifier measurement wizard for the E5072A.

## Appendix C. Comparison with E5071C

The comparison of the Keysight E5071C and E5072A ENA Series Network Analyzer is shown in table 2. The E5072A is a more suited solution for RF amplifier characterization.

Table 2. Comparison with the E5071C ENA series network analyzer.

Features/ Functions	E5071C 2-port RF Options(opt.24x, 26x, 28x)	E5072A
Configurable test set (Direct receiver access)	No	Yes (standard)
Uncoupled power (with source attenuators)	No	Yes
Max output power	+10 dBm (up to 5 GHz)	+16 dBm (spec, up to 3 GHz) +20 dBm (SPD <sup>1</sup> , 300 k to 1 GHz)
Power calibration	Yes	Yes (More accurate with tolerance and max iteration)
Receiver calibration	Yes	Yes (with four independent receivers)
Receiver Leveling	No	Yes
Harmonic distortion	Yes (with FOM option)	Yes (with FOM option)
Pulsed-RF	Yes (wide pulse width)	Yes (wide pulse width)
Amplifier measurement wizard	Yes	Yes (High-power measurement is also supported.)
Equation Editor	Yes	Yes

1. The value is supplemental performance data or SPD that is most likely occur. Not guaranteed by the product warranty.

### References

E5072A Configuration Guide, part number 5990-8001EN

<http://literature.cdn.keysight.com/litweb/pdf/5990-8001EN.pdf>

E5072A Data Sheet, part number 5990-8002EN

<http://literature.cdn.keysight.com/litweb/pdf/5990-8002EN.pdf>

E5072A Quick Fact Sheet, part number 5990-8003EN

<http://literature.cdn.keysight.com/litweb/pdf/5990-8003EN.pdf>

E5072A Technical Overview, part number 5990-8004EN

<http://literature.cdn.keysight.com/litweb/pdf/5990-8004EN.pdf>

High-power Measurement Using the E5072A, part number 5990-8005EN

<http://literature.cdn.keysight.com/litweb/pdf/5990-8005EN.pdf>

7 Reasons to update from the 8753 to the ENA, part number 5989-0206EN

<http://literature.cdn.keysight.com/litweb/pdf/5989-0206EN.pdf>

ENA series web page: <http://www.keysight.com/find/ena>

E5072A web page: <http://www.keysight.com/find/e5072a>

Keysight 81150A and 81160A Pulse Function Arbitrary Noise Generators Data Sheet

<http://literature.cdn.keysight.com/litweb/pdf/5989-6433EN.pdf>

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