APPLICATION NOTE

High Power Amplifier Measurements

Using Nonlinear Vector Network Analyzer

Introduction

High-power devices are common building blocks in RF and microwave communication systems. Mobile phones, base-stations and satellite systems all depend on high-power amplifiers. Characterizing the linear and nonlinear performance of such high-power devices is a critical factor in the design and verification process.

This application note discusses the unique challenges involved in testing high-power devices using the Keysight Technologies, Inc. nonlinear vector network analyzer (NVNA). In this application note, the term “high-power” refers to those cases in which the power levels of the device under test (DUT) exceed the maximum levels of the network analyzer.

Although this application note describes high-power X-parameter characterizations, the techniques used may be applied to any NVNA measurement. This note is focused on testing 50-ohm DUTs and does not describe any special matching networks that might be required to ensure DUT stability. Also, this application note does not address high-power pulse measurements.

KEYSIGHT
TECHNOLOGIES

For further reading, refer to:

- Using a Network Analyzer to Characterize High-Power Components, Keysight Application Note, literature number 5966-3319E.
- Recommendations for Testing High-Power Amplifiers, Keysight application note, literature number 5989-1349EN.
- Keysight Technologies N5242A Option H85 User’s and Service Guide, literature number N5242-90008.
- Polyharmonic Distortion Modeling, literature number 5989-9574EN.
- Keysight Nonlinear Vector Network Analyzer (NVNA) Brochure, literature number 5989-8575EN.

PNA-X Performance

When measuring high-power devices with a network analyzer, one must consider the maximum input and output power limits of the network analyzer. High input power levels can damage the network analyzer and can result in costly repairs. In addition to respecting the damage levels of the PNA-X, the compression levels, noise levels, and output power should also be considered when choosing a high-power setup.

The following block diagram shows the PNA-X N5242A RF test set. This instrument has been configured with Options 400, 419 and 423 which includes four ports, two independent RF sources, source attenuators, receiver attenuators, bias tees, internal combiner and mechanical port switches.

By ordering special Option H85 for the N5242A, the bias tees are removed. The damage level of the bias tees is much lower than that of the test port couplers, so this option is recommended for high-power measurement setups since it allows direct access to all ports of the high-power test coupler, see Table 2.

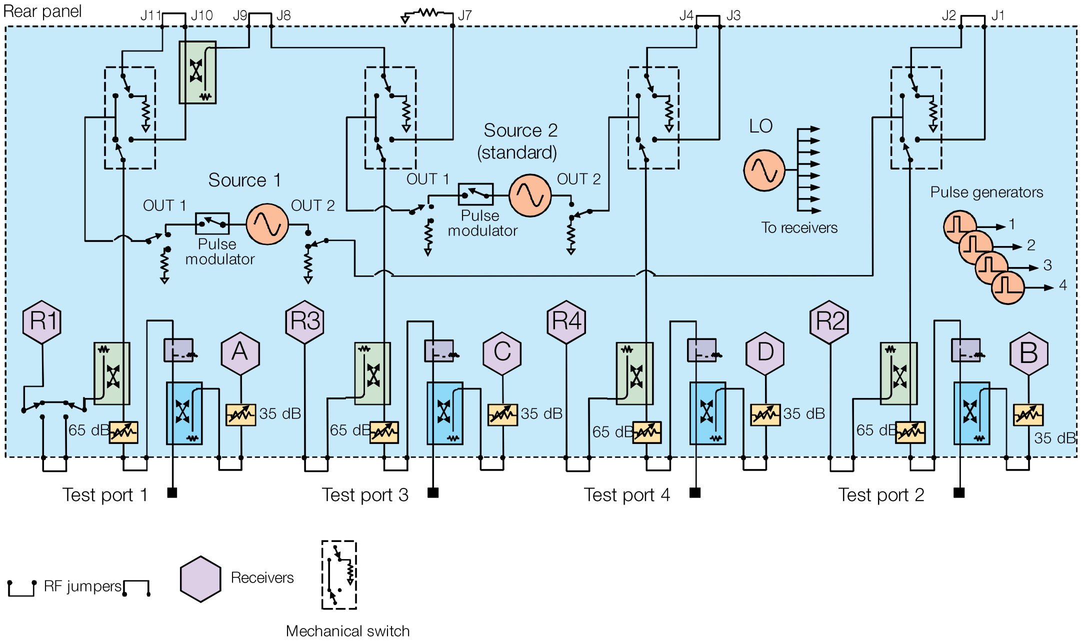


Figure 1. PNA-X N5242A Option 423 Test Set Block Diagram

Each port of the PNA-X network analyzer is associated with six connectors and three jumpers for direct test set access located on the front panel. The port 1 jumpers and connectors for the N5242A are shown below as a reference for position and naming conventions.

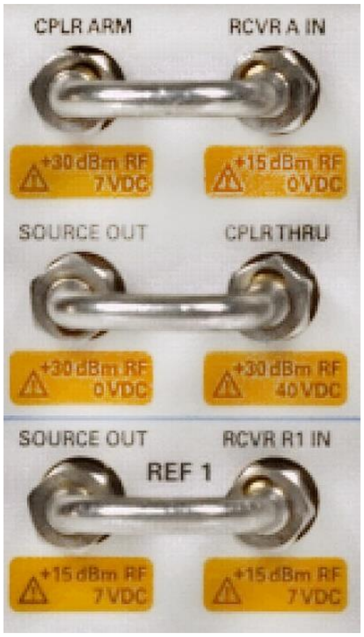


Figure 2. PNA-X N5242A port 1 front panel jumpers

High-power test devices may require very high-power input drive levels from the PNA-X. The following table lists the maximum output power levels of the N5242A Option 423 at the NVNA test ports 1 and 3. If the DUT requires more input power than is indicated in the table, then external pre-amplifiers must be added to the test system.

Table 1. Maximum output power levels of the N5242A Option 423

Maximum Output Power, N5242A Option 423, Typical (dBm)						
Frequency	Src 1, Port 1 Combine Mode Filtered Mode	Src 1, Port 1 Combine ModeHi Pwr Mode	Src 2, Port 1 Combine Mode Filtered Mode	Src 2, Port 1 Combine ModeHi Pwr Mode	Port 3 Filtered Mode	Port 3 Hi Pwr Mode
10 to 50 MHz	7	17	-7	3	9	19
50 to 500 MHz	9	17	-5	4	11	20
.5 to 3.2 GHz	9	10	-5	-4	11	13
3.2 to 10 GHz	15	15	2	2	19	19
10 to 16 GHz	11	11	-2	-2	15	15
16 to 20 GHz	8	8	-4	-4	13	13
20 to 24 GHz	6	6	-6	-6	12	12
24 to 26.5 GHz	2	2	-11	-11	8	8

When testing high-power devices, the power levels may exceed the damage levels of the PNA-X. The following table lists the damage levels of the N5242A Option 423. As a general rule-of-thumb, the power level should be at least 3 dB (ideally 6 dB) below the damage level of the PNA-X connector. If the DUT test setup exceeds these levels, then external components such as attenuators and couplers must be added to the test system.

NOTE: Some ports have no tolerance to non-zero DC voltages, see Table 2.

Table 2. Damage levels of the N5242A Option 423

	Maximum Input Power, N5242A Option 423, Typical		
Connector	**RF damage (dBm)**	**DC max (Volts)**	**Notes**
Front Panel			
Test Port-1 & 3	+30	±40	For special Option H85, DC max = 0 V. For special Option H85, if SOURCE OUT is disconnectedfrom CPLR THRU, then: RF damage = +43 dBm typical DC max = ±40 V
CPLR ARM A & C	+30	±7	
RCVR A IN,RCVR C IN	+15	0	
SRC OUT A & C	+30	0	
CPLR THRU A & C	+30	±40	For special Option H85, RF damage = +43 dBm typical
REF 1 SOURCE OUT	+15	±7	
REF 3 SOURCE OUT	+30	0	
RCVR R1 IN	+15	±7	
RCVR R3 IN	+15	±15	
Rear Panel			
J7, J8, J9, J10, J11	+30	0	

It is often necessary to modify the PNA-X test set when measuring high-power devices. This may include adding external pads or amplifiers. When choosing the components for modifying the test set it is important to know the path losses in the PNA-X. The following table describes the approximate path losses in the N5242A Option 423 test set but is for reference only. Since the values in this table are approximate, if you plan to modify your PNA-X test set then you should measure these paths on your specific PNA-X rather than rely on the values in this table.

Table 3. Path losses in the N5242A Option 423

	Test Set Path Loss, N5242A Option 423, Approximate (in dB)					
Test Set Path	**10 MHz**	**100 MHz**	**1 GHz**	**2 GHz**	**10 GHz**	**20 GHz**
CPLR THRU A to Port-1 (no Option H85)	0	-0.75	-1	-1	-1.75	-2.25
CPLR THRU A to Port-1 (with Option H85)	0	-0.25	-0.5	-0.5	-1	-1.5
CPLR ARM A to Port-1	-52	-32	-15	-15	-15	-14.5
J10 to REF 1 SOURCE OUT	-19	-19	-20	-20	-22.5	-25
J9 to REF 1 SOURCE OUT	-32	-34	-34	-34	-35	-38
J7 to REF 3 SOURCE OUT	-16	-16	-16.5	-16.5	-17	-16.5
J10 to Port-1	-3.5	-4	-5	-5.5	-7.5	-10.5
J9 to Port-1	-18.5	-19	-19	-19.5	-21	-23
J7 to Port-3	-2	-2	-3	-3.5	-5.5	-8

Signal levels at the receivers should be less than -20 dBm to minimize distortion.

Hardware Setup

Measuring the X-parameters of high-power devices is an especially challenging task because the DUT must be driven into its nonlinear region. The stimulus source and extraction-tone source may need to provide more power than the PNA-X can supply. The PNA-X inputs may need to be protected from damage due to high power. The receiver levels may need to be attenuated to avoid compression effects. And finally, the DUT may require special load characteristics to avoid oscillation.

Test Set Changes

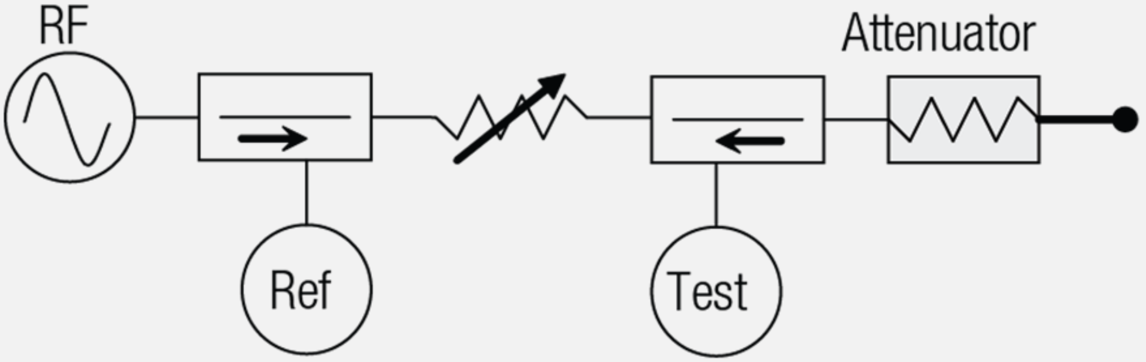
External components may be added to the PNA-X test set in order to avoid the previously described problems. Unfortunately, adding external components may compromise the system performance. Measurement noise may increase, calibration drift may increase, and the calibration procedure may become more complicated. One must carefully consider the tradeoffs before selecting a high-power configuration.

The following block diagrams show various modifications to the test set and the impact of the modifications. When modifying the test set, remember to use short, stable cables in order to minimize system drift.

Adding an attenuator between the couplers

Adding an attenuator between the reference and test couplers will:

- Protect components behind the test coupler from damage and/or compression.
- Improve source and load match at the test port.
- If the output of the DUT is connected to this test port, then the attenuator will reduce active loading effects on the RF source.



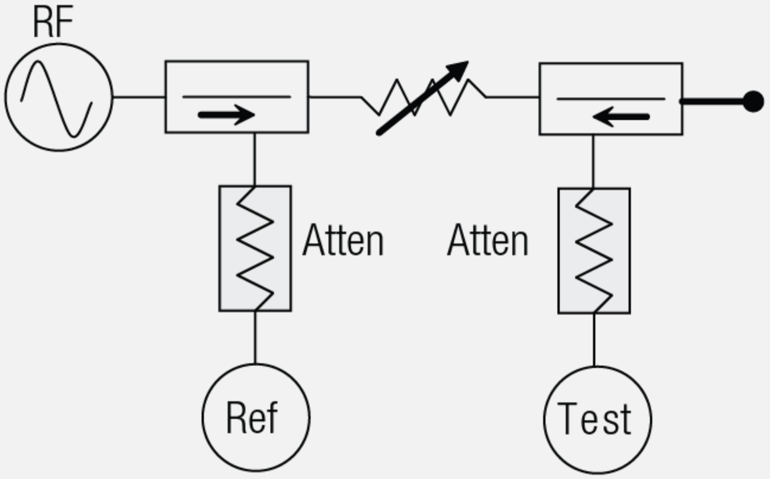
The cables connected to the attenuator should be kept as short and stable as possible to minimize measurement drift.

Often, a high-power test setup will require a pre-amplifier to be added to the PNA-X port 3 in order to drive a large extraction tone into the output of the DUT. In this case, attenuation may be placed between the pre-amplifier and DUT in order to protect the pre-amplifier. Assume that we want the pre-amplifier to provide an extraction tone level X dB below the DUT's maximum output power. If we choose the total attenuation between the pre-amplifier and the DUT to be (X/2) dB, then the maximum power dissipation in the pre-amplifier will be minimized; also, the pre-amplifier output power will equal the DUT output power incident on the pre-amplifier. For example, given a -30 dBc extraction tone level we would like the sum of all attenuation between the pre-amplifier and DUT on port 3 (including coupler and cable losses) to be 15 dB.

Adding an attenuator at test port

Adding an attenuator at the test port will:

- Protect all components in the PNA-X from damage and/or compression.
- Improve source and load match at the test port.
- If the output of the DUT is connected to this test port, then the pad will reduce active loading effects on the RF source.
- Degrade the system raw directivity, resulting in increased calibration drift and noise. Attenuator values of up to 10 dB typically result in good performance. Although useful measurements might be made with a 20 dB attenuator, noise and calibration drift will need to be considered.

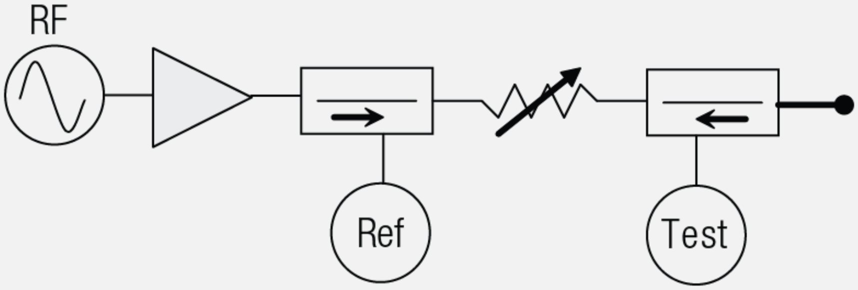


The PNA-X has an internal transfer switch located between the R1 receiver and the coupler arm. When adding a pad to the R1 receiver path, ensure that the internal transfer switch has been set to the "external" mode so that the pad is included in the measurement path.

Adding a pre-amplifier

Adding a pre-amplifier between the RF source and the reference coupler will provide increased output power to stimulate the DUT.

The pre-amplifier must be added behind the couplers. Since the NVNA uses 8-term error correction, this will ensure that any errors introduced by the pre-amplifier will be corrected as long as the pre-amplifier nonlinearities are low enough to be considered small-signal perturbations.

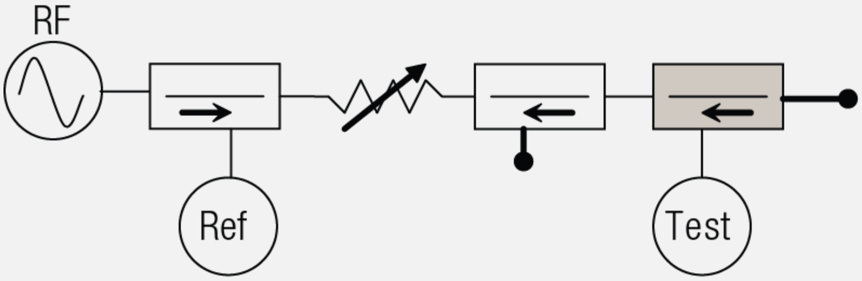


When measuring low gain devices, a pre-amplifier may be added to PNA-X port-1 to increase the DUT input power. As a general rule of thumb, the pre-amplifier's harmonics should be about 20 dB below the maximum main tone at the DUT input to avoid stimulating nonlinear behavior in the DUT which cannot be corrected by the NVNA.

A pre-amplifier added to PNA-X port-3 will increase the extraction tone power applied to the DUT output during X-parameter measurements. A good rule of thumb is to use an extraction tone which is about 20 dB below the maximum level of the main RF tone, but this may be difficult to achieve. In this case, -30 dBc is a good target level and an extraction tone as low as -40 dBc may provide acceptable results, although it may be necessary to reduce the IF bandwidth, increase averaging, or reduce the number of measured harmonics. Distortion generated by this preamplifier is usually not a concern because its output power is much lower than the maximum DUT output power and so it should not stimulate nonlinear behavior in the DUT.

Adding a coupler

The PNA-X internal couplers may be replaced with external couplers by using the front panel access loops or by adding the couplers at the test port. These external couplers may be chosen to have higher power limits or different frequency response than the internal couplers.

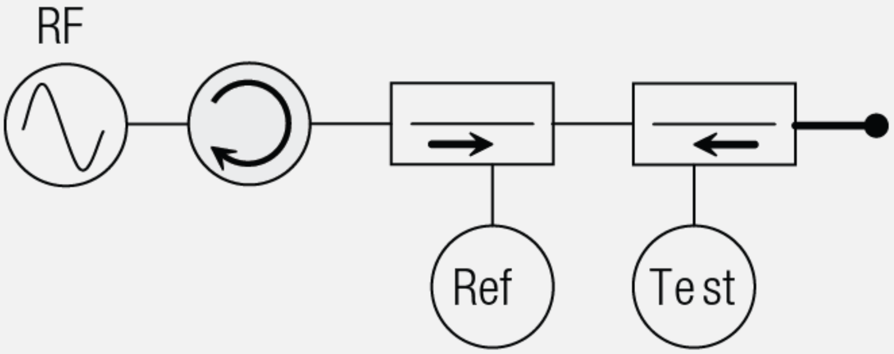


Note that the PNA-X test coupler arm rolls off at 20 dB/decade for frequencies below 700 MHz, so that the typically -15 dB coupling factor is reduced to -52 dB at 10 MHz. If an external test coupler is added which doesn’t exhibit this roll-off, then the dynamic range at low frequencies will be improved.

The PNA-X has an internal transfer switch located between the R1 receiver and the coupler arm. When using an external reference coupler for R1, ensure that the internal transfer switch has been set to the “external” mode so that the coupler is included in the measurement path.

Adding an isolator

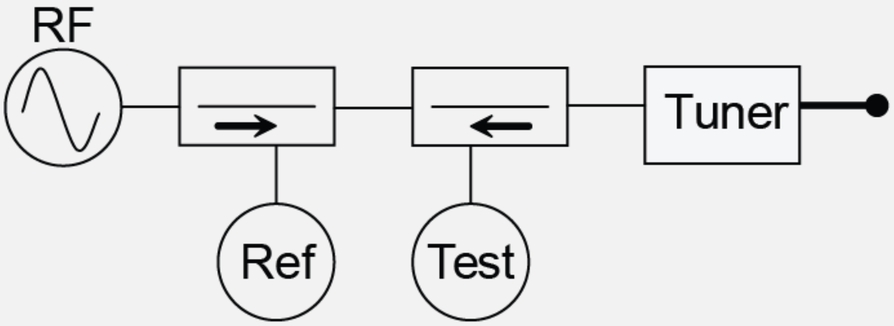
Adding an isolator between the RF source and reference couplers can provide power protection and improve port match. Similar to adding an attenuator, it protects all devices behind the isolator, but unlike an attenuator it does not attenuate the signal from the RF source to the DUT.



Isolators are typically narrowband devices. If an isolator is used in an X-parameter measurement it may not be possible to stimulate the DUT with harmonic extraction tones, however, useful X-parameter information may still be extracted. For example, power supply sensitivity, compression, DUT harmonics, and fundamental match measurements may result in a useful model for simulation.

Adding a tuner

A tuner may be added between the PNA-X port 1 and the DUT input and may be added between the PNA-X port 3 and the DUT output. Programmable tuners allow the NVNA system to perform automated load pull measurements of the DUT. Special calibration software may be required to de-embed the effects of the tuners depending on their placement in the RF path. A tuner that is placed between the couplers and the DUT may need to be de-embedded whereas a tuner placed between the internal sources/loads and couplers does not because it is behind the test and reference couplers, therefore the NVNA error correction utilized remains valid.



The tuners are placed directly at the ports of the DUT in order to provide the widest range of load conditions possible. If low loss couplers are available, then the couplers can be placed between the tuner and the DUT.

Adding tuners to the test system will affect the system performance in the following ways:

- Narrowband tuners will limit the frequency range of the measurement.

- The tuners will add the RF loss to the test set.
- When the tuner is set to a mismatched condition, the signals being measured are attenuated due to the power reflected by the tuner. For example, a 10:1 impedance mismatch results in a 4.81 dB attenuation of the transmitted signal which will increase the measurement noise.

Checking the Hardware Setup

Considering the potential for damaging the DUT and test equipment, it is usually a good idea to check a high-power setup before putting it to use. Here are some ideas for checking the setup:

- Measure the external components before connecting them to the system to verify their performance.
- If the test set is modified with external components, the source power level set by the PNA-X will not be the same as the power at the test ports. Due to variations in the components, it may be difficult to set the power levels with high accuracy without checking the setup with a power meter.
- The PNA-X receiver measurements (A, R1, C, and R3) may be used to check the approximate power levels at the test-ports of the PNA-X if the test set has not been modified. However, modifying the test set will invalidate these readings.
- Set up the test system both with and without the pre-amplifiers.
- Check the power levels at the test ports and the receivers to make sure they look correct.
- Perform a 2-port calibration and check whether the resulting cal looks reasonable.
- Make sure that the power levels used during calibration do not damage the calibration standards.
- Check for oscillations in the pre-amplifiers due to various loading conditions provided by the DUT.
- Check for excessive harmonics in the port 1 pre-amplifier. As a general rule of thumb, the harmonics should be at least 20 dB below the maximum power level of the main tone since higher levels may result in nonlinear behavior in the DUT, which cannot be corrected by the error correction used in the NVNA.
- Of special note is the pre-amplifier added to the PNA-X port 3 which is used to stimulate the DUT in the reverse direction. This pre-amplifier might be operated under extreme load-pull conditions during the test so its performance should be qualified. Similar to the port 1 pre-amplifier, harmonic distortion in this pre-amplifier may cause nonlinear behavior in the DUT and as a general rule of thumb should be at least 20 dB below the maximum power level of the main tone. However, since there will typically be significant attenuation between this pre-amplifier and the DUT output, this is usually not a concern.
- Ensure that all of the external components can safely handle the power that they will encounter during the actual measurements.

Checking the Power Levels

During X-parameter measurements, the PNA-X main source will stimulate the DUT input over a user-defined range of frequencies and powers, it will apply a second extraction tone source to each port at harmonics of the main tone, and it will measure the DUT response.

When selecting the main tone power levels, remember that if the PNA-X test set has been modified then the power level selected may be different from the actual power at the test port. The user must set the main tone power levels to correct for any changes in the test set.

As with the main tones, when setting the extraction tone power levels the user will need to offset any changes made to the test set. It is usually best to set the extraction tone levels using the “manual” method rather than “automatic” to ensure that the power levels are correct and to avoid possible confusion. It is a good rule-of-thumb to set the DUT input extraction tone level to about 20 dB below the main tone maximum level at all ports of the DUT. A -20 dBc extraction tone level is a good choice because it should be small enough to act as a small- signal linear stimulus while still providing sufficient signal-to-noise during the measurements. It may be difficult to provide this level of extraction tone on the output-side of the DUT due to the high power levels involved and any external attenuation added at PNA-X port 3 (the DUT output port). In practice, extraction tone levels at -30 dBc and even as low as -40 dBc may provide reasonable results depending on the frequencies being measured. If the extraction tone power level must be set low, there are several ways to reduce the noise: reduce the number of harmonics being measured, reduce the IF bandwidth, increase the averaging, or increase the number of phase offsets at which the extraction tone is measured.

Setup Examples

The following three examples describe the modifications made to an N5242A network analyzer test set in order to measure high-power amplifiers. These modifications include adding pads, couplers and pre-amplifiers. In each case, the components are selected so that there is enough stimulus power, the components are protected from damage, and the PNA-X receiver distortion is minimized.

Setup 1: Amplifier with +34 dBm output power

In this example, the PNA-X N5242A Option 400, 419 and 423 (without Option H85) is modified to measure an amplifier with the following characteristics:

- Frequency = 1 GHz
- Gain = +14 dB
- P_{out} (max) = +34 dBm

The test setup requires a pre-amplifier and three pads as indicated in the following block diagram by the components shaded in gray.

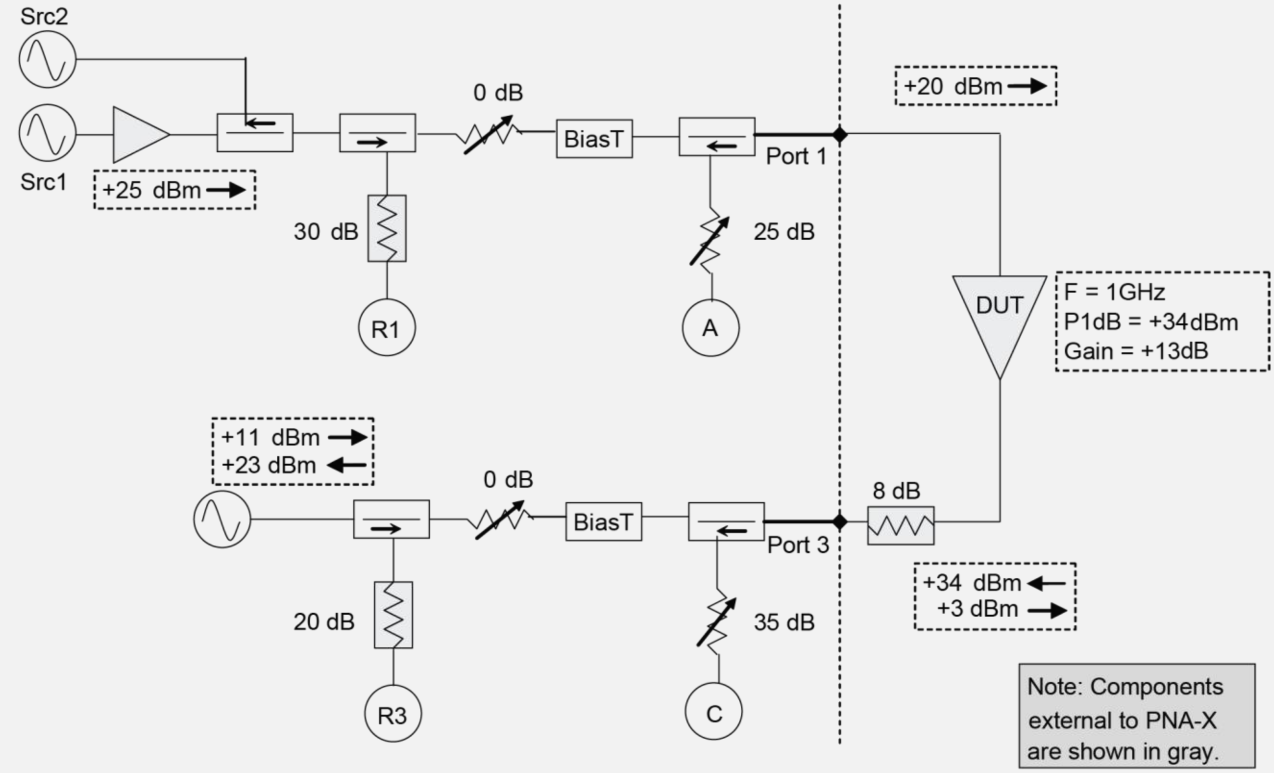


Figure 3. +34 dBm amplifier setup

The component values were chosen with the following constraints in mind:

- The port 1 main tone power is boosted by a +25 dBm pre-amplifier added to the Source 1 Port 1 path at the rear panel.
  - The loss from the rear panel source input to the front panel is approximately 5 dB (from Table 2) at 1 GHz, so the preamp will supply +20 dBm into the DUT.
  - The pre-amplifier should have low distortion at +25 dBm output power[1]. If the DUT is disconnected and Port 1 is open, the maximum signal at the rear panel “COMB THRU IN (J10)” will be the worst case combination of the preamp output (+25 dBm) and the open circuit reflection (+25 dBm -10 dB) resulting in +27.3 dBm. This is 2.7 dB below the +30 dBm damage level of the reference coupler. The 10 dB is from the round trip loss (5 dB forward and 5 dB back).
  - The pre-amplifier should be rated at +27 dBm to withstand an open-circuit condition.
- The port 1 extraction tone is generated by Source 2 passing through the combiner to port 1. This maximum power level is specified as -5 dBm at 1 GHz. Therefore, the extraction tone level is 25 dB below the main tone level (+20 dBm) at port 1 and is sufficiently large[2].

1. A good rule-of-thumb is to keep the harmonics below -20 dBc.
2. Ideally -20 dBc is utilized for the extraction tone level.

- The extraction tone generated at PNA-X port 3 is specified to be a maximum (from Table 1) at 1 GHz. This will result in +3 dBm (+11 dBm – 8 dB) at the DUT output, resulting in an extraction level 29 dB below the main tone level (+34 dBm) and is sufficiently large[2].
- Attenuation levels are set in the A, C, R1 and R3 receiver paths to ensure that the receivers are operating below -20 dBm to minimize distortion.
- The 8 dB attenuator at the DUT output was chosen to avoid power damage to the bias tee and reference coupler.
    - The DUT maximum output power (+34 dBm) passing through the 8 dB attenuator and the test port coupler (approximately 0.5 dB loss at 1 GHz) will result in 25.5 dBm at the bias tee. When added to the source output power (+14 dBm) minus the path loss to the bias tee (3 dB) this will result in 27 dBm at the bias tee, which is 3 dB below the +30 dBm damage level.
    - The DUT maximum output power (+34 dBm) passing through the 8 dB attenuator and the PNA-X components to the reference coupler input (approximately 3 dB loss at 1 GHz) results in +23 dBm at the reference coupler. This may combine with the Source 2 output power level (+14 dBm) to yield a worst case power level of +25.6 dBm at the reference coupler. This is 4.4 dB below the +30 dBm damage level.
    - The 8 dB attenuator must be rated to handle +34 dBm of power.
    - Note that adding an attenuator at this location degrades the coupler's directivity. It is best to minimize the cable length between the attenuator and test port to optimize directivity stability.

Setup 2: Amplifier with +48 dBm output power

In this example, the PNA-X N5242A Option 423 with Option H85 (which removes the bias tees) is modified to measure an amplifier with the following characteristics:

- Frequency = 1 GHz
- Gain = +14 dB
- P_{out} (max) = +48 dBm

Option H85 provides the ability to use the internal components with higher power measurement capabilities thus removing some constraints on the necessary external components.

The test setup requires two pre-amplifiers, two high-power couplers, and six attenuators as indicated in the following block diagram by the components shaded in gray.

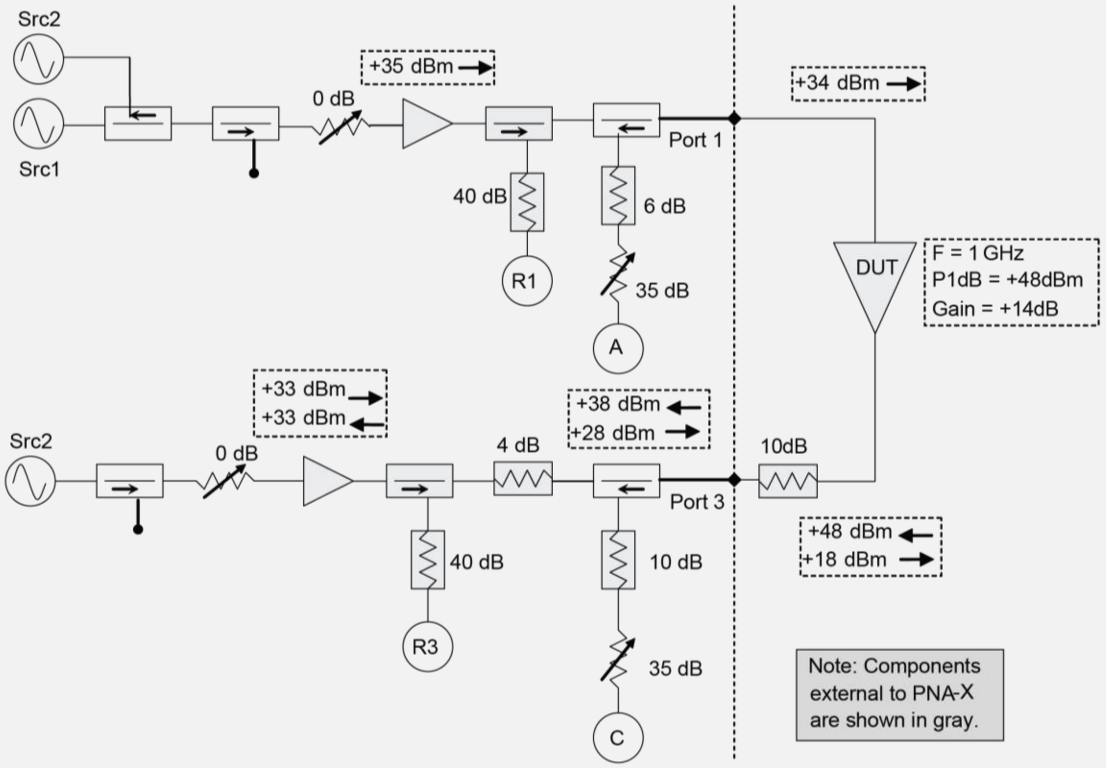


Figure 4. +48 dBm amplifier setup

The component values were chosen with the following constraints in mind:

- The two PNA-X reference couplers are replaced with external high power couplers which have a damage level of +43 dBm (similar to the test port couplers).
- Attenuation levels are set in the A, C, R1 and R3 receiver paths to ensure that the receivers are operating below -20 dBm to minimize distortion.
- The port 1 output power is boosted by a +35 dBm pre-amplifier.
  - Assuming 0.5 dB loss in each coupler, the DUT input power will be +34 dBm.
  - If the DUT is disconnected and port 1 is open, the maximum signal at port 1 will be +40 dBm. This is 3 dB below the +43 dBm damage level of the couplers.
  - The pre-amplifier should have low harmonics at +35 dBm output[1]. The pre-amplifier should be rated at +40 dBm to withstand an open-circuit condition.
- The port 1 extraction tone is generated by Source 2 passing through the combiner to port 1. The maximum output power at port 1 is -5 dBm due to Source 2 and +9 dBm due to Source 1 without the pre-amplifier. Therefore, the extraction tone at port 1 may be set to -14 dBc or lower[2].

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[1] A good rule-of-thumb is to keep the harmonics below -20 dBc.
[2] Ideally -20 dBc is utilized for the extraction tone level.

- The high-power 10 dB attenuator is added between the DUT output and PNA-X port 3 to protect the test coupler.
    - The maximum power at PNA-X port 3 is the combination of +38 dBm from the DUT and +28 dBm from the extraction tone, resulting in 40.4 dBm worst case, which is 2.6 dB lower than the +43 dBm damage level of the coupler.
    - Note that adding an attenuator at this location degrades the coupler's directivity. It is best to minimize the cable length between the attenuator and test port to optimize directivity stability.
- A pre-amplifier which outputs +33 dBm was added to PNA-X port 3.
    - The signal from the DUT output (+33 dBm) will combine with this signal, resulting in a worst case power level of +39 dBm at the reference coupler. This is 4 dB lower than the damage level of the coupler (+43 dBm).
    - The pre-amplifier must be able to withstand +39 dBm at its output when driven by the DUT.
- A 4 dB attenuator is added between the PNA-X port 3 couplers to reduce the large signal from the output of the component so that it does not adversely affect the pre-amplifier. This attenuator must be able to withstand +39 dBm.
- The extraction tone at PNA-X port 3 will be +18 dBm (assuming that the couplers have 0.5 dB loss each at 1 GHz). This tone is 30 dB below the main tone level (+48 dBm) and should be sufficiently large[1].

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[1] Ideally -20 dBc is utilized for the extraction tone level.

Setup 3: Amplifier with +60 dBm output power

In this example, the PNA-X N5242A Option 423 (without Option H85) is modified to measure an amplifier with the following characteristics:

- Frequency = 1 GHz
- Gain = +10 dB
- P_{out} (max) = +60 dBm

The test setup requires two pre-amplifiers, four high-power couplers, and six attenuators as indicated in the following block diagram by the components shaded in gray.

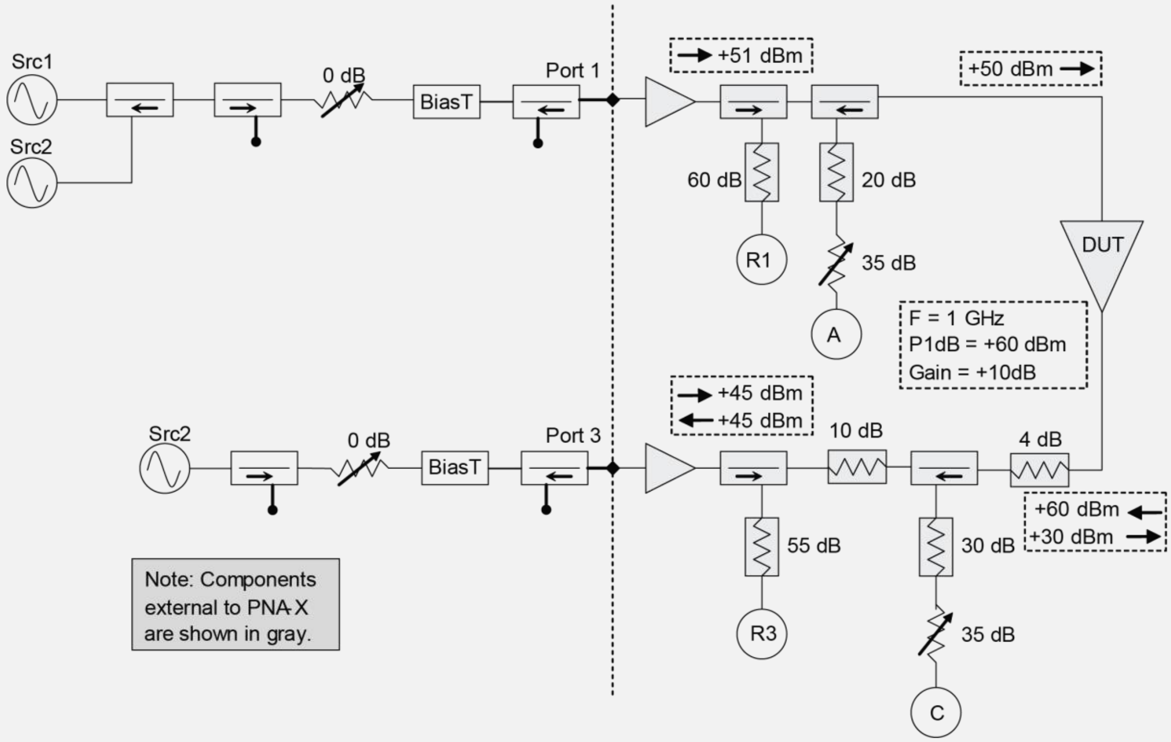

Figure 5. +60 dBm amplifier setup

The component values were chosen with the following constraints in mind:

- All PNA-X couplers are replaced with external high-power couplers with a damage level of at least +60 dBm.
- Attenuation levels are set in the A, C, R1 and R3 receiver paths to ensure that the receivers operated below -20 dBm to minimize distortion.
- The port 1 power is boosted by a pre-amplifier with +51 dBm output power.
  - Assuming 0.5 dB loss in each coupler, the DUT input power will be +50 dBm.
  - If the DUT is disconnected and port 1 is open, the maximum signal at port 1 will be +56 dBm. This is 4 dB below the +60 dBm damage level of the couplers.
  - The pre-amplifier should have low harmonics at +51 dBm output[1]. The pre-amplifier should be rated at +56 dBm to withstand an open-circuit condition.
- The port 1 extraction tone is generated by Source 2 passing through the combiner to port 1. The maximum output power at port 1 is -5 dBm due to Source 2 and +9 dBm due to Source 1. Therefore, the extraction tone at port 1 may be set to -14 dBc or lower[2].

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1. A good rule-of-thumb is to keep the harmonics below -20 dBc.
2. Ideally -20 dBc is utilized for the extraction tone level.

- A high-power (+ 60 dBm) 4 dB attenuator is added between the DUT output and test coupler to protect the test coupler.
  - Note that adding an attenuator at this location may degrade the stability of the directivity term of the calibration. For this block diagram it is best to minimize the cable length between the attenuator and test coupler.
  - The maximum power at the test coupler is the combination of +56 dBm from the DUT and +34 dBm from the extraction tone, resulting in 56.7 dBm worst case, which is 3.3 dB lower than the +60 dBm damage level of the coupler.
- A 10 dB attenuator is added between the PNA-X port 3 couplers to reduce the large signal from the output of the DUT so that it does not adversely affect the pre-amplifier.
- A pre-amplifier which outputs +45 dBm was added to PNA-X port 3.
  - The signal from the DUT output at this point (+45 dBm) will combine with the pre- amplifier output, resulting in a worst case power level of +51 dBm at the reference coupler. This is 9 dB lower than the damage level of the coupler (+60 dBm).
  - The pre-amplifier must be able to withstand +51 dBm at its output.
- The extraction tone at the DUT output will be +30 dBm (assuming that each coupler has 0.5 dB loss at 1 GHz). This tone is 30 dB below the main tone level (+60 dBm) and should be sufficiently large[1].

[1] Ideally -20 dBc is utilized for the extraction tone level.

Testing a 100 W Amplifier

Hardware Setup

The PNA-X N5242A Option 423 was used to make this measurement. The input power level required to drive the DUT is less than +3 dBm so the PNA-X port 1 does not need to be changed. However, since the DUT can output +48 dBm, PNA-X port 3 requires some modification.

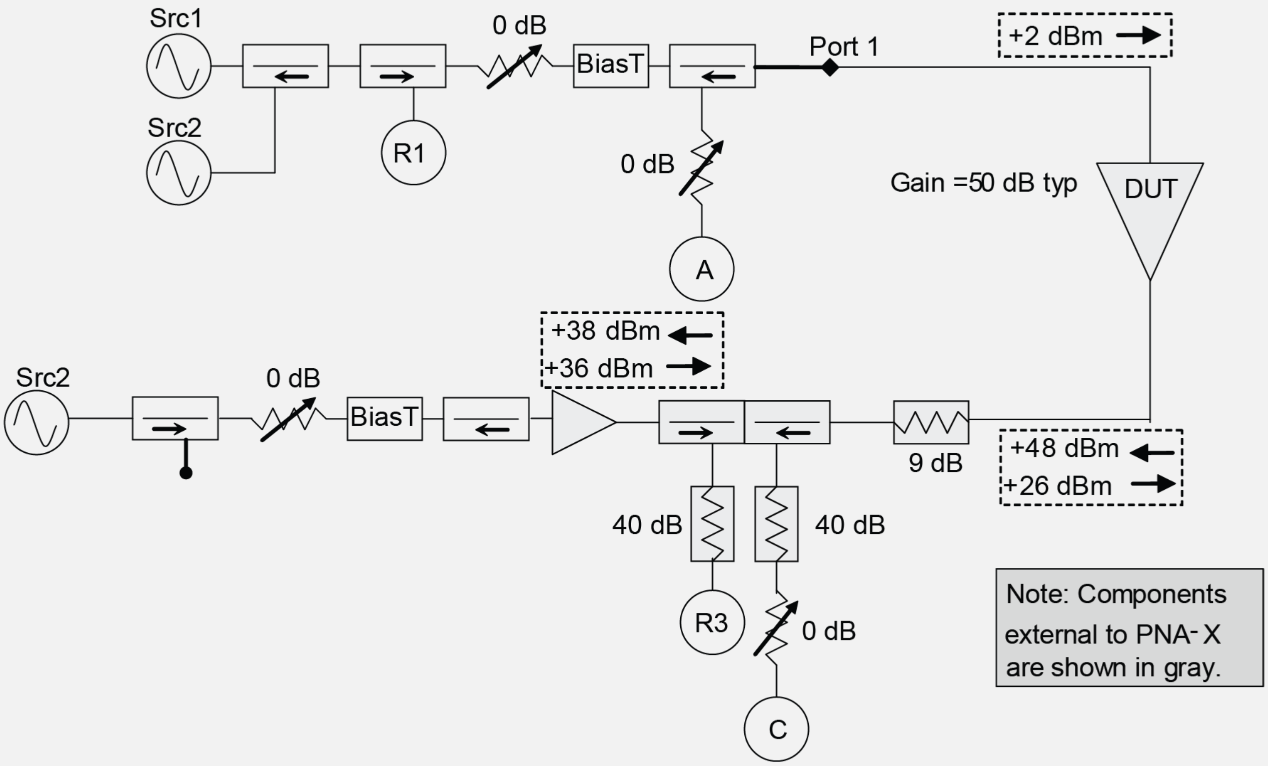

Figure 6. 100 Watt amplifier setup

Parameter	Description
Part Number	HP 778D12
Frequency	10 MHz to 2 GHz
Coupling Factor	-20 dB
P_{max}	+50 dBm

Six external components were added to the PNA-X for this setup.

- An external dual coupler (HP 778D12) is connected at PNA-X port 3. An external coupler was used because the N5242A did not have Option H85 (which removes the bias tees) so the internal test coupler couldn't be used at its maximum power level. The dual coupler has the following performance in the table to the left:
- A 150 W/3 dB attenuator (from Narda) and a 50 W/6 dB attenuator (from Trilithic Inc.) were combined to create a 100 W, 9 dB attenuator at the output of the DUT. This provides over-power protection for the coupler and a good load match for the DUT.

- Two 40 dB attenuators were added in front of the two PNA-X port 3 receivers to reduce the receiver power levels to approximately -20 dBm. External attenuators were used instead of internal ones because of the power levels.
- A Mini-Circuits ZHL-20W-13 pre-amplifier was added between the PNA-X port 3 RF source and the reference coupler. This provides enough power to provide an extraction tone level at the DUT output which is -20 dBc below the DUT maximum output power. The preamplifier operates over 20 MHz to 1000 MHz with a typical gain of 50 dB and P1 dB = +41 dBm.

Power level calculations

The power levels of the test setup are calculated in order to ensure that they are high enough, maximum power limits are not exceeded, and that the receivers are not operating in their nonlinear region.

- The PNA-X port 1 must provide -2 dBm input to the DUT so that given a typical 50 dB gain it will output +48 dBm. This is well within the PNA-X specifications.
- The PNA-X port 1 must provide a second RF extraction tone, ideally -20 dBc below the -2 dBm main tone. Using the internal 2nd source and combiner, this is well within the PNA-X specifications.
- The DUT output attenuator must withstand +48 dBm from the DUT. This attenuator is rated at +50 dBm maximum operating power, so is within specifications.
- The PNA-X port 3 pre-amplifier is used to drive the extraction tone into the output of the DUT. Given a +36 dBm output power, a dual coupler loss of 1 dB and an attenuator loss of 9 dB, the extraction tone level will be +26 dBm at the DUT output. This is -22 dBc below the DUT maximum output power of +48 dBm, so it is a reasonable extraction tone level. The maximum power level experienced at the output of the preamp is the worst case combination of +36 dBm and +38 dBm from the DUT, resulting in +43 dBm. Since the pre-amplifier may output +43 dBm at 3 dB compression, this should be an acceptable condition.
- The coupler will experience the same power levels as the pre-amplifier output. As mentioned previously, the worst case power level expected during extraction tone measurements at the coupler is +43 dBm which is 7 dB below the coupler's maximum power rating.

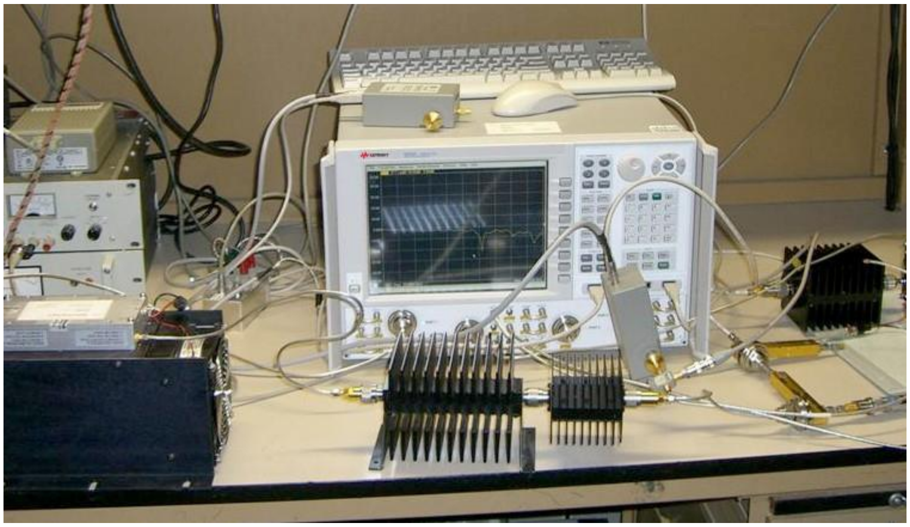

Figure 7. Photograph of test setup for 100 W amplifier

Software Setup

- The two U9391C 26.5 GHz phase reference units were driven by the 10 MHz reference output of the PNA-X. These are used for the system phase reference and phase calibration. The phase reference internal dividers were set to 1.
- Main Stimulus Tone Setup:
  - Set measurement frequencies: 50 MHz to 200 MHz, 4 frequencies.
  - Set measurement powers: -10 dBm to 0 dBm, 15 powers, using a voltage sweep.
  - Set measured harmonics: 5
  - Set resolution bandwidth: = 100 Hz
- X-parameter Setup:
  - Number of harmonics for extraction: 3
  - Manual level setup:
    - DUT port 1 extraction tone power level: -20 dBm. (This results in -20 dBm extraction tones at the input, which are -20 dBc below the main tone.)
    - DUT port 2 extraction tone power level: -12 dBm. (Due to the 50 dB gain and 10 dB loss in the RF path, this results in +26 dBm extraction tones at the output, which are -22 dBc below the main tone.)
- Calibration details:
  - Remove the pre-amplifier from the test setup during calibration. Add back after the complete NVNA calibration is finished.
  - Set power calibration level: -5 dBm (both ports)
  - Perform the phase and power calibrations at port 1. The test receiver has minimal attenuation on port 1 so the phase calibration will work best on that port.

Test Results

Voltage vs. time

The following plot shows the DUT output wave (B2) versus time at 200 MHz for P_{out} = +50 dBm. The waveform is approximately 180 Vp-p and exhibits compression effects.

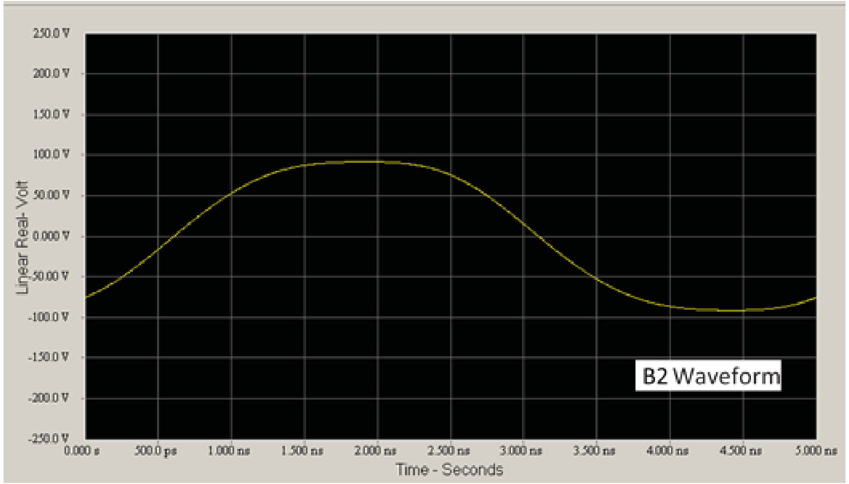

Figure 8. B2 (DUT output) waveform versus time, at 200 MHz, P_{out} = +50 dBm

Gain compression vs. power

The following plot shows the DUT gain versus input power at 200 MHz. 1 dB gain compression occurs near 0 dBm input power. It is of interest that the gain appears to be fairly linear at low powers but is slightly higher at -10 dBm than at -8 dBm. As the input power is swept from -10 dBm to 0 dBm, the DUT reaches its compression point and the DUT power supply begins to limit. When the next sweep starts (at -10 dBm) the power supply hasn't had time to recover, so the DUT gain measurement is in error. This problem could be solved by using a better power supply or by adding some measurement delay.

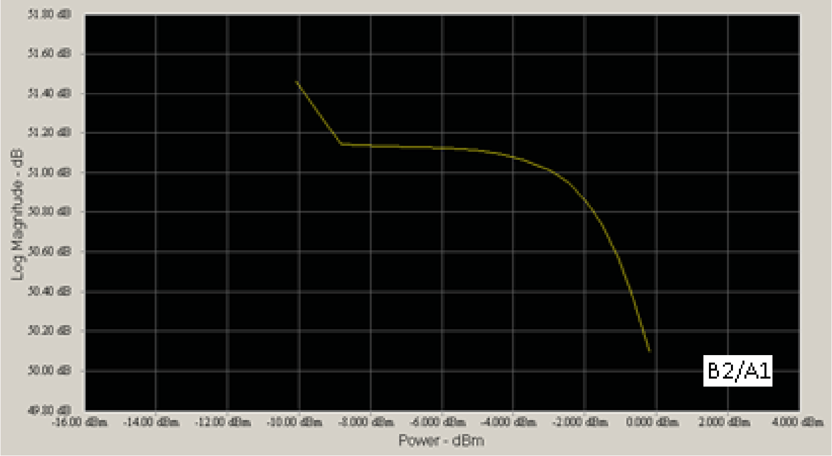

Figure 9. B2/A1 (DUT gain) versus power input, at 200 MHz for 1st harmonic

Harmonics vs. power

The following plots show the DUT output power wave (B2) at the 1st and 3rd harmonic versus the DUT input power. Note that as the input power approaches 0 dBm, the slope of the 1st harmonic output decreases whereas the slope of the 3rd harmonic output increases, which indicates compression.

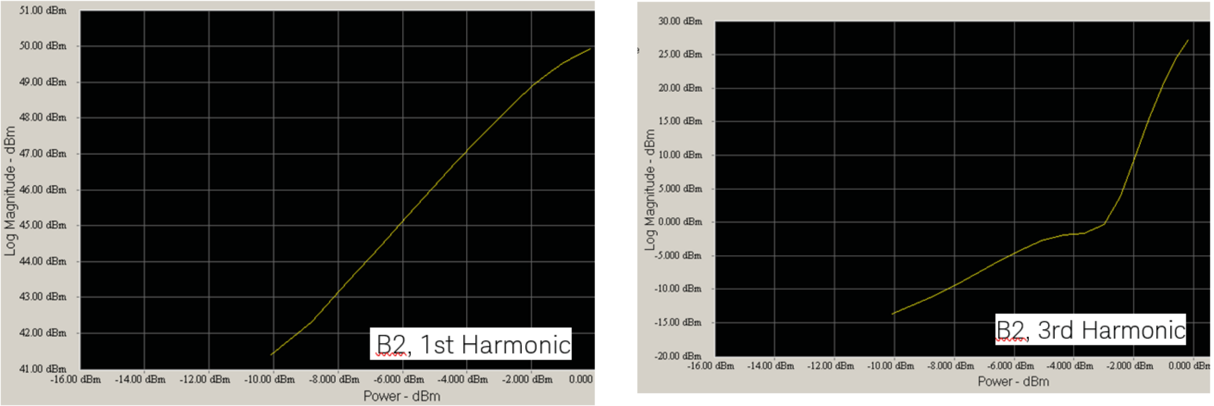

Figure 10. B2 (DUT output) power out versus power input, at 200 MHz for 1st and 3rd harmonics

XS and XT parameters

The following plots measure the output match of the DUT and are analogous to measuring S_{22} for standard S-parameters. The input main tone is swept at the DUT input from -10 dBm to 0 dBm at 200 MHz. The extraction tone is applied to the DUT output at 200 MHz.

The terms $XS_{21,21}$ and $XT_{21,21}$ measure the ratio of the reflected 200 MHz signal to the incident 200 MHz signal at DUT port 2. As the input power level increases, we expect $XS_{21,21}$ to be constant (and equal to S_{22}) until the DUT becomes nonlinear. We also expect the term $XT_{21,21}$ to be small at low powers and to increase as the nonlinearities increase. Neither parameter appears noisy, which is a good indication that the extraction tone level is high enough.

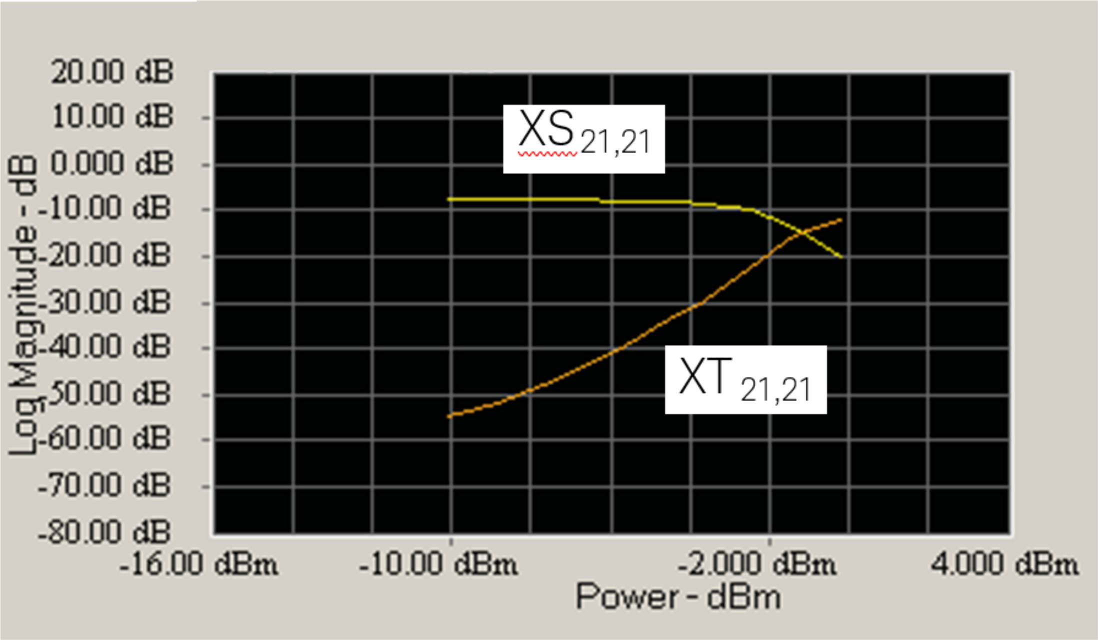

Figure 11. $XS_{21,21}$ and $XT_{21,21}$ versus power input at 200 MHz

The terms $XS_{23,21}$ and $XT_{23,21}$ measure the ratio of the reflected 600 MHz signal to the incident 200 MHz signal at DUT port 2. Ideally these values will be very small, indicating low harmonic distortion. Note that as the input power increases, both terms increase, as is expected for a nonlinear device.

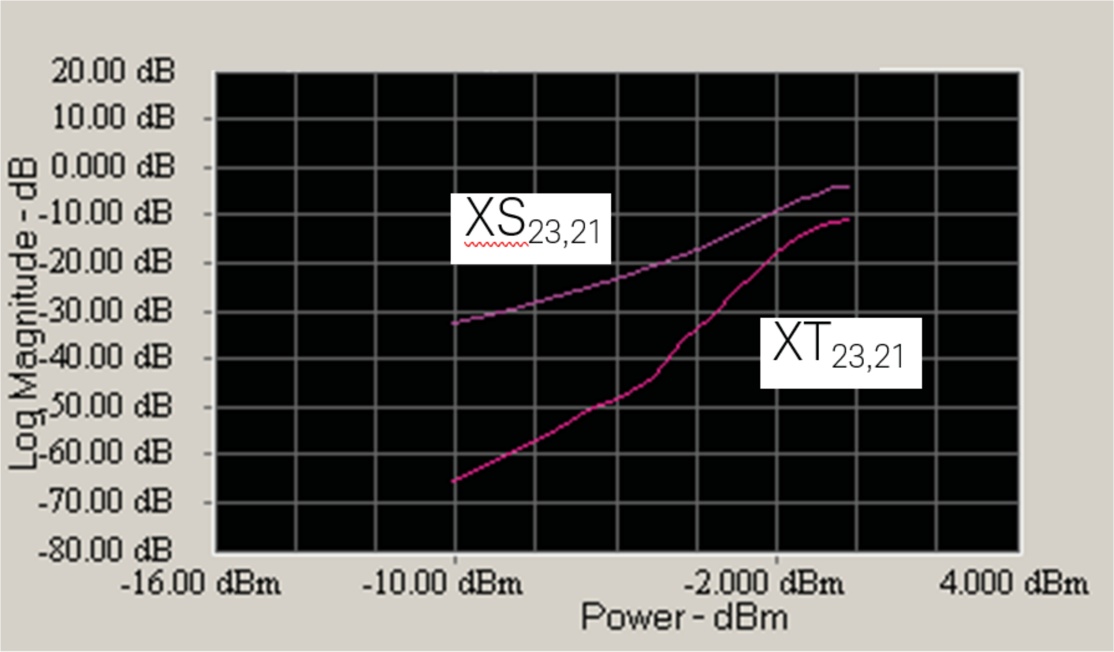

Figure 12. $XS_{23,21}$ **and** $XT_{23,21}$ **versus power input at 200 MHz**

Load-pull simulation

The X-parameters from this measurement were imported into the Keysight microwave simulation software package ADS. This was used to simulate load-pull data for the DUT at -2 dBm input power and at 200 MHz.

The following plot displays the load match contours resulting in constant output power from the power amp. A contour is generated for each 0.4 dB step in output power. Note that the contours are nearly circular, indicating a fairly linear response when the input to the amp is set to -2 dBm.

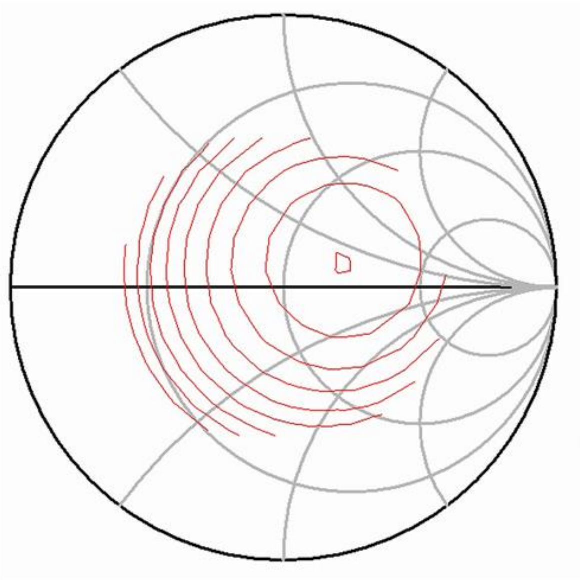

Figure 13. Load match contours for constant delivered power

NVNA Calibration

Calibrating a PNA-X high-power test setup has its own set of challenges. Pre-amplifiers added to the test set may compress or damage the calibration standards, while attenuators added to improve power handling capability in the test system may result in a noisy calibration.

It may be advantageous to calibrate the test system after removing the pre-amplifiers or increasing source attenuation to avoid possible damage to the calibration standards, however this may result in a noisy calibration. Assuming that the pre-amplifiers and attenuators are located between the RF source and reference coupler, then adding the pre-amplifiers or changing attenuation after a complete NVNA calibration will not affect the S-parameter and power measurement accuracy because the NVNA uses 8-term error correction. However, source power levels will be affected.

If the test setup includes tuners located between the DUT and the PNA-X test ports, then the NVNA calibration must be performed without the tuners in place. External software must then be used to characterize the tuners, de-embed the results, and perform automated load pull measurements.

An NVNA calibration involves three steps: vector calibration, phase calibration, and power calibration. The calibration wizard leads the user through these steps.

Vector Calibration

- Before performing the calibration, the user should set the calibration power levels.
- The calibration power level is set at the test port of the PNA-X assuming that the test set has not been changed. Any attenuators or amplifiers added to the RF path will change the power level at the ports of the test system. This must be accounted for when calculating the true calibration power level.
- When using an electronic calibration unit (ECal), remember that it cannot “auto-orient” if its calibration power level is below -18 dBm. The following table lists the suggested maximum calibration power levels for various Keysight ECals to avoid compression during calibration:

Model	Compression level (dBm)	Damage level (dBm)
N469x series	-5	+10
N4432A series N4433A series	-7	+20
N4431x series	+7	+20
8509x series	+9	+20

- When using an SOLT mechanical calibration kit (with Type-N, APC-7, 3.5 mm or 2.4 mm connectors), the maximum power level is between +27 dBm and +33 dBm due to dissipation in the load standard. It is best to keep the calibration power level below +20 dBm to avoid heating effects.
- When using a TRL mechanical calibration kit without a load standard, the maximum power levels are determined primarily by the voltage breakdown and heating characteristics of the devices. Therefore, a TRL cal kit without a load standard may be used at higher power levels than an SOLT cal kit.

Phase calibration

The NVNA will perform a phase calibration on one port by using a phase reference standard. It is usually best to perform the phase calibration on port 1. The port 1 test receiver will usually have less attenuation than the PNA-X port 3 test receiver and low receiver loss results in a better phase calibration.

As a general rule-of-thumb, the phase reference output power should be at least 20 dB above the noise floor of the test receiver. The output power of the 26.5 GHz phase reference (U9391C) is -80 dBm per tone for 10 MHz tone spacing. Given a typical noise floor of -128 dBm (IFBW = 10 Hz) in the N5242A for direct receiver access between 0.1 GHz and 20 GHz and given a test coupler coupling factor of 15 dB at 1 GHz, this implies that the attenuator between the coupler and receiver should be less than 23 dB for a 10 Hz IFBW at 1 GHz. There are several strategies for handling high receiver attenuations:

- Increase the average factor to reduce the noise.
- Increase the frequency driving the phase reference to increase its output power. For example, increasing the frequency from 10 MHz to 100 MHz will increase the output power level by 20 dB. The spectral levels follow a 20log (Freq2/Freq1) response. It is always good practice to drive the phase reference with a signal that is high in frequency while still maintaining spectral content at the measurement frequencies of interest.
- Don’t measure the harmonics of the DUT. If no harmonics are characterized, then the phase reference data will not be used. Note that it is possible to extract useful X-parameter information even without measuring harmonics. For example, power supply sensitivity, compression and fundamental match may result in a useful model for simulation.
- Remove the port 1 test receiver attenuator during the complete NVNA calibration. Connect the attenuator after the NVNA calibration is done, then de-embed an S2P file representing the test set change from port 1. This S2P file is measured by the following process:
  - Perform a 2-port vector calibration between PNA-X port 1 and port 3 without the attenuator
  - Add the attenuator to the PNA-X port 1 test receiver
  - Connect a zero-length thru between PNA-X port 1 and PNA-X port 3
  - Measure the thru and save the resulting S2P file

Amplitude calibration

The NVNA will perform an amplitude calibration on one port using a power sensor. This will calibrate the PNA-X receivers to measure absolute power and will correct for any changes made to the test set. Note that this does not calibrate the PNA-X source output power levels. Following a calibration, the PNA-X will set the power levels assuming that there have been no changes to the test set.

Since the port 1 RF path will usually have the lowest power, performing a power calibration on port 1 is often the best choice.

Phase calibration

The S-parameter calibration and the power calibration define their calibration power levels very differently. For S-parameter calibrations, the power levels are set in the calibration power dialog box. During an S-parameter calibration the PNA-X sets the power levels assuming that no changes have been made to the test set. In contrast, for power calibrations the power level is defined in the power meter setup dialog. If the offset value in this dialog is set to 0 dB, then the calibration power level will equal the value chosen for the S-parameter calibration. Entering a non-zero offset will change the calibration power level for the power calibration. During the power calibration, the PNA-X output power level will be adjusted until the power sensor measures the specified calibration power level. Therefore, even if the PNA-X test set has been changed, the specified power will be set and measured at the DUT test port.

Conclusion

When measuring high-power devices with the NVNA, a certain degree of caution is required to avoid damaging the network analyzer, test components, and even the device under test.

- The maximum DC voltage allowed on some ports of the PNA-X is 0V.
- Of special note is Option H85 in which the RF test ports require 0V DC. Use AC coupling if possible.
- The RF power applied to the PNA-X ports should be at least 3 dB below the RF damage levels of those ports and should ideally be at least 6 dB lower.
- When calculating the power levels at a given point in the test setup, make sure to determine the worst-case levels. For example, if two 0 dBm signals combine together at the same frequency, the resulting signal levels may be equivalent to +6 dBm worst case.
- The DUT and pre-amplifiers may have specific input and output load match requirements which must be met before being powered-up to avoid oscillation or damage. Beware of open-circuit conditions.
- The DUT and pre-amplifiers may be sensitive to power-on sequencing. This typically involves first providing the correct source and load match, next turning on the DC power, and then finally turning on the RF power. Make sure that you know your pre-amplifier and DUT requirements before turning on the system.
- If the setup uses the PNA-X test port coupler at high power levels (near +40 dBm), make sure that the PNA-X has Option H85 (which removes the bias tees) because the bias tee damage level is +30 dBm.
- Presetting the PNA-X will set the outputs to a pre-determined level and may result in system or DUT damage. You may consider saving a “user preset” condition which sets the power to lower levels than the preset condition.
- After the NVNA has finished making measurements the PNA-X RF source power is on. It is a good idea to turn off the source power following the measurement to avoid overheating in the DUT.

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