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Application of Agilent's PNA-X Nonlinear Vector Network Analyzer and X-Parameters in Power Amplifier Design

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Recent improvements in semiconductor technology, such as laterally diffused metal oxide semiconductor (LDMOS) and gallium nitride high electron mobility transistors (GaN-HEMT), are empowering researchers to develop high-performance microwave circuits and systems. When operated in their nonlinear regions and properly terminated, these devices result in high-efficiency power amplifiers (PA).[1] Such developments underscore the need for accurate nonlinear characterization and modeling of radio frequency (RF) transistors to enable the predictable design of high-performance circuits and systems.

One solution offering an answer to this dilemma is Agilent Technologies' PNA-X vector network analyzer, the world's most integrated and flexible microwave test engine for accurately measuring active devices like amplifiers, mixers, and frequency converters in coaxial, fixtured, and on-wafer environments **(Figure 1)**. The PNA-X features an optional Nonlinear Vector Network Analyzer (NVNA) application for fast, accurate characterization and design of active devices and components.[2] The award-winning Agilent NVNA is the industry's first interoperable measurement and simulation environment for designing nonlinear components. Using the PNA-X's NVNA, X-parameters* are measured and then used to create X-parameter models that can be imported into Agilent's Advanced Design System (ADS), SystemVue, and Genesys to simulate actual linear and nonlinear component behavior. X-parameters represent a new category of nonlinear network parameters for deterministic, high-frequency design, which can be used to characterize both a components' linear and nonlinear behavior. Thanks to the PNA-X and its NVNA application, engineers and scientists can now have the highest level of insight into nonlinear device behavior. Let's take a closer look.

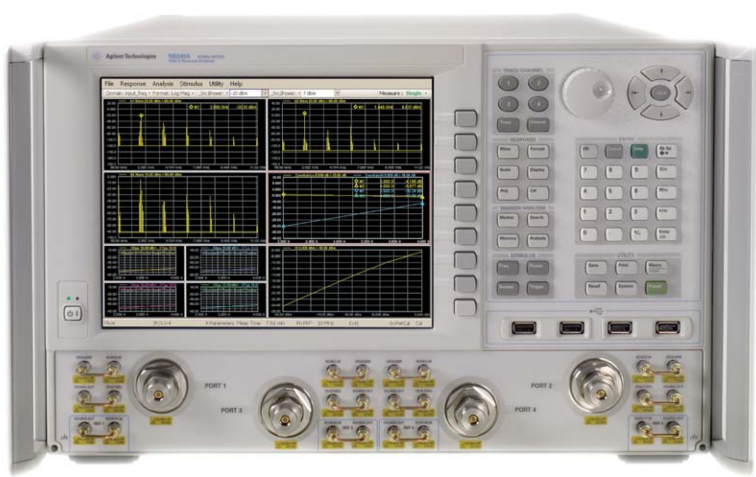

Figure 1. *Built on Agilent's 40-year legacy of technical leadership and innovation in RF network analysis, the PNA-X provides excellent passive measurements, and a variety of active measurements (e.g., nonlinear, gain compression, intermodulation distortion, and noise figure) with an unsurpassed combination of speed, accuracy and flexibility. Available in five frequency ranges: 13.5, 26.5, 43.5, 50, and 67 GHz, it enables today's engineers to realize higher levels of test integration, as well as reduced setup time, measurement complexity, time to make measurements, and test costs.*

** "X-parameters" is a registered trademark of Agilent Technologies. The X-parameter format and underlying equations are open and documented. For more information, visit: http://www.agilent.com/find/eesof-x-parameters-info.*

Wanted: Nonlinear Characterization

When driven with a stimulus that places a component in a nonlinear operating region, the component may generate distorted input and output currents and voltages (or traveling waves) that include multiple spectral components.

While device characterization provides accurate performance information under a given set of operating conditions, extracting a measurement-based simulation model of the transistor offers all-encompassing design insight and flexibility. Two alternative nonlinear device modeling approaches that have been investigated include compact and behavioral models.

Compact models are analytical models generated from device measurement data and are suitable for use in computer-aided design (CAD) simulations for circuit-level design. They are less amenable to system-level simulation where the design may consist of many circuit-level models and where the stimulus involved consists of complex modulated signals. Moreover, they are not always reliable for high powers and non-linear circuit design because they usually lead to intolerable disparities between predicted and measured performance. As a result, microwave circuit engineers —particularly PA designers—have been forced to choose between sometimes inaccurate and simulation-friendly compact models or an explicit measurement-based load-pull technique that does not support a robust simulation. This “broken link” in the design chain dramatically increases the cost and development time required. Bringing accurate device behavioral models into the simulation environment will empower circuit and system designers to develop advanced circuit topologies and system architectures in a systematic manner.

The X-parameter model is a sophisticated behavioral model that describes the linear and nonlinear behavior of the component by describing the relationship between the input-output frequency spectrum on a multi-port device for a given large-signal operation condition.[3-6] The recent integration of X-parameter modeling with load-pull measurements allows PA designers to develop measurement-based behavior models of unmatched devices that can be imported into ADS. [7-8]

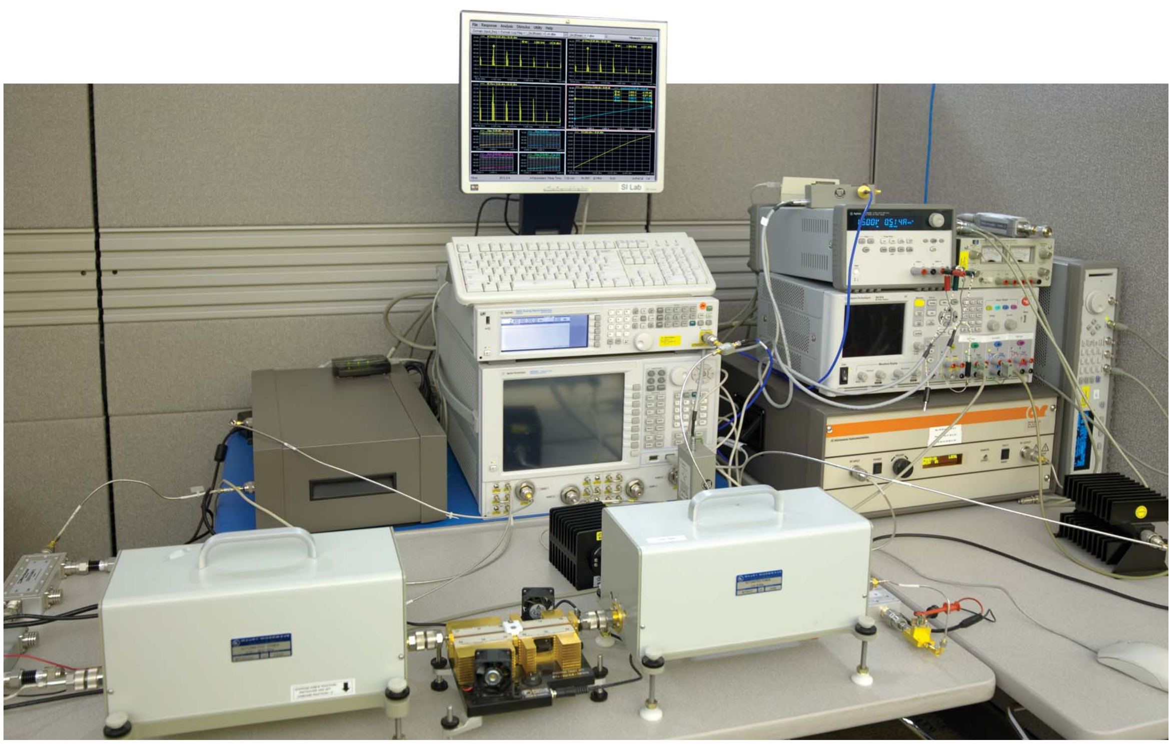

Figure 2. *The PNA-X with NVNA X-parameter high-power load-pull measurement configuration.*

Understanding the X-parameter measurement system

As an example of how to utilize a measurement-based X-parameter model, consider the design of a Class AB 45-Watt GaN amplifier, developed entirely inside the circuit simulator. The measurement system utilized in this example is shown in **Figure 2**. This setup is used to construct the X-parameters of a power transistor. It consists of the PNA-X with the NVNA firmware Option 510 (base NVNA firmware), Option 514 (X-parameters), and Option 520 (load-dependent X-parameter extension). The Agilent U9391C phase reference is also utilized to provide the cross-frequency phase calibration information that is critical to identify the X-parameter coefficients.

In addition to the NVNA, external hardware may be required to measure the X-parameters of a high-power unmatched transistor. [9] Internal signal-routing switches in the PNA-X allow connection of other test equipment to the device-under-test (DUT) via the network analyzer's test-port connectors **(see Figure 3 below)**.

Fundamental frequency	1.2 GHz
Harmonics	3
Gain	15 to 20 dB
Output power	45 Watts
Impedance	Unmatched
Bias	Gate (< 5 Volts, < 100 mA) Drain (< 30 Volts, < 3 Amps)

Table 1. *General transistor measurement characteristics*

To determine the required hardware, the component's general characteristics should be identified (for example, frequency, input power, output power, and DC bias). For the following analysis, the general requirements are listed in **Table 1.**

Since the transistor's output power (approximately 46 dBm) exceeds the maximum input power rating at the PNA-X test ports (typically 30 dBm, or 40 dBm with Option H85), external high power couplers must be connected to the front panel jumpers of the PNA-X to bypass the internal couplers. The external couplers utilized should cover the frequency range of the measurements (1.2 to 3.6 GHz) and handle up to 45 Watts of average power.

Because the transistor under test has a rated small signal gain of 15 to 20 dB, with a typical output power of about 46 dBm, it may require an input stimulus (large-drive) of about 30 dBm (1 Watt) to drive it to saturation. The measurement data is collected with the transistor driven by a pulsed RF signal (carrier frequency = 1.2 GHz, pulse width = 400 µs, and duty cycle = 1%). The NVNA X-parameter measurements, conducted with an input power of 10 dBm to 32 dBm, includes up to the first three harmonics. The X-parameter measurements (refer to the Appendix, *"The NVNA X-Parameter Measurement Sequence" on page 13*) require an additional measurement signal with a frequency up to the 3rd harmonic and therefore, a broadband pre-amplifier that covers up to three times the test frequency (1.2 GHz).

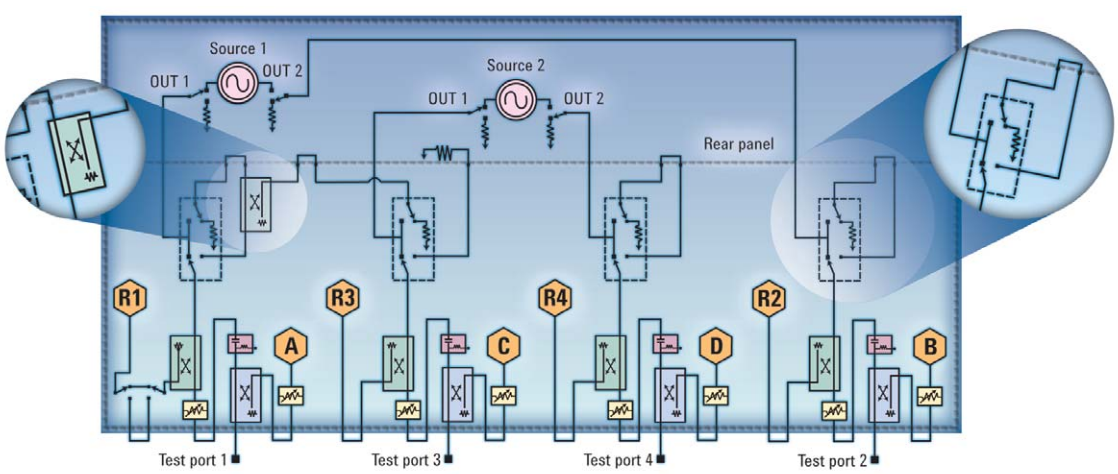

Figure 3. *Internal signal-routing switches in the PNA-X provide increased flexibility for adding signal conditioning hardware or additional test equipment for single connection measurements. They also enable alternate measurement paths, re-routing of signal paths and the addition of amplifiers, filters, and attenuators to optimize system setup.*

The X-parameter measurements also require an RF stimulus to be applied to the output port while the large drive signal is simultaneously provided to the input. This reverse stimulus signal must be approximately 20 dBc below the saturated output power of the transistor. Therefore, the expected saturated output power (approximately 46 dBm) requires a measurement signal on the drain of 26 dBm. If there is any additional attenuation between the drain and the second source of the PNA-X, additional power will be required. In this case, a 60-Watt driver was chosen that operates over the measurement bandwidth.

The input impedance of the unmatched transistor may be different than 50 Ohms. Consequently, obtaining the required input power at the gate of the transistor requires a source tuner. Additionally, a load-dependent X-parameter model requires a load tuner on the drain. Fundamental frequency source-pull is not required during X-parameter model extraction, since a power sweep is performed over a range of input powers at the fixed optimum input impedance (as provided by the source tuner). This measurement process is equivalent to keeping the source power fixed, while sweeping the source impedance provided to the transistor. The tuners also need to cover the bandwidth of the stimulus (up to 3.6 GHz) during the X-parameter measurements because the measurement stimulus must pass through the tuners before reaching the transistor.

Since the X-parameter extraction procedure performs phase-swept measurements at the harmonic frequencies, any variations of the harmonic source and load impedances are implicitly defined inside the X-parameter model. Therefore, independent control of the harmonic impedances may not be necessary for the X-parameter model extraction of the given nonlinear device. As a result, fundamental frequency tuners were chosen and must provide a gamma high enough to match the potential low impedance of the transistor.

The impedance tuners must be characterized using the tuner software and PNA-X before X-parameter measurements are performed. This characterization process provides a pre-computed configurable input impedance and an S-parameter model of the tuner. The S-parameter data is used to de-embed the tuners from the measured results so that the measurement is done at the transistor reference plane. Note that the tuner characterization is performed with a 50-Ohm impedance supplied by the PNA-X at both measurement ports. Based on this calibration, the tuner then provides an impedance transformation from 50 Ohm to an impedance designated by the user, under the assumption that a matched device is presented to the 50-Ohm port of the tuner. If this condition is not satisfied, such as when a poorly matched driver amplifier is connected, the calibration of the tuner is no longer valid and the mismatch of the driver must be characterized and taken into account.

A test fixture connects the transistor to the X-parameter measurement system. It consists of a 50-Ohm microstrip transmission line with the equivalent width of the packaging leads of the transistor so that the insertion loss between the transistor port and the impedance tuner is minimized. This ensures that a transistor without standard measurement connectors can be connected to the impedance tuners without jeopardizing the configurable impedance range of the tuners. Furthermore, this fixture can be calibrated using the PNA-X and the measurements can be de-embedded through the fixture to the package of the DUT.

For the chosen transistor characteristics, a gate voltage of less than 5 Volts (at less than 100 mA) and drain voltage less than 30 Volts (at less than 3 A) is anticipated. External high power bias networks were placed, before the tuners, on the gate and drain sides of the component to apply the necessary voltage and current coupled on the RF ports of the transistor.

Couplers	Mini-Circuits ZGDC10-362HP+
Input pre-amplifier	AR 5S1G4
Output pre-amplifier	AR 60S1G4
Tuners	Maury Microwave MT982
DC supply	Agilent N6705A (with N6752A (gate) and N6754A (drain) modules)

Table 2. *External hardware used for the measurements*

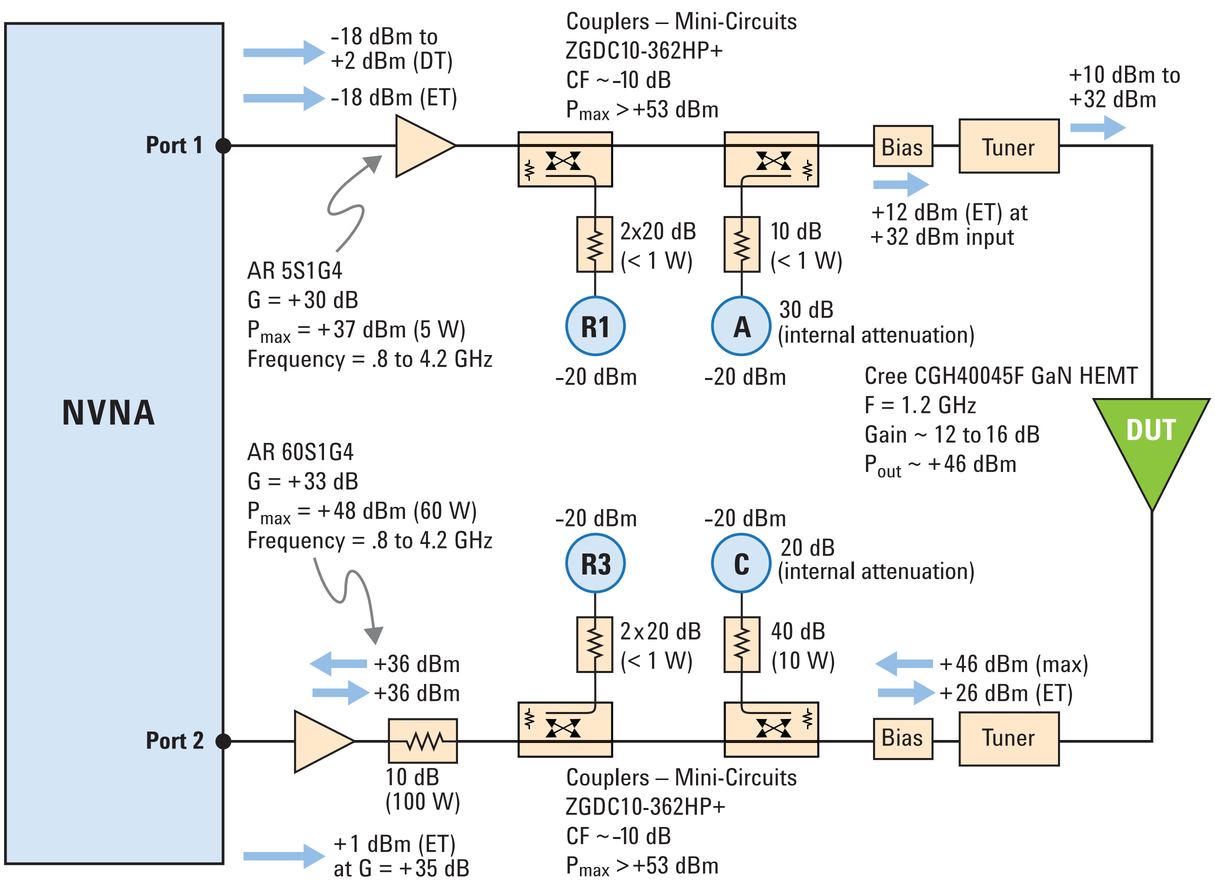

Figure 4. *The NVNA power budget.*

Table 2 lists the external hardware chosen for the measurements. Before measurements are performed, a power budget must be completed **(See Figure 4)**. This is done to ensure instrumentation is not damaged and all system components are operating in their linear range (e.g., no pre-amplifier compression or PNA-X receiver compression at peak powers).

The first step in the power budget is to determine the stimulus/response powers presented at the transistor ports and measurement receivers based on the component's specifications. Next, the required external components can be chosen to satisfy the high-power and receiver linearity requirements. Care should be taken when choosing the pre-amplifier that provides the forward and reverse RF stimulus. If the pre-amplifiers are saturated by the large-drive signal level (which determines the large-signal operating point of the X-parameter model extraction), then adding the extraction signal will result in an invalid model extraction. Therefore, the X-parameters will appear to be incorrect at the higher drive level powers. This is generally seen during a power sweep when there is a divergence between the simulated (X-parameters) and measured results at the higher input power levels. The maximum RF power at the receiver should be limited to –20 dBm for best receiver linearity. Appropriate external and internal attenuation is chosen to meet this requirement based on the power budget shown in **Figure 4.**

Calibration

Once the power budget is computed and the necessary instrumentation is connected, the PNA-X's NVNA can be calibrated. The NVNA calibration consists of three steps: vector calibration using a vector calibration kit or ECal, amplitude calibration using a power sensor and cross-frequency phase calibration using a phase reference.

The pre-amplifiers behind the couplers are often removed during calibration and then inserted back into the measurement system after the calibration procedure is complete. This does not invalidate the calibration since an eight-term error model is utilized in the NVNA. However, adding the pre-amplifiers may affect the tuner characterization. Consequently, the source and load impedances behind the tuners should be measured with the NVNA and must be accounted for to ensure that the impedance presented to the component by the tuners corresponds with the predicted impedance in the tuner characterization file. This process is usually part of the tuner software.

X-parameter verification

When it comes to X-parameter verification, one of the first things to confirm is that the measured X-parameter model is valid in the expected stimulus/response range. This is accomplished by comparing simulated performance using the X-parameter model against the measured performance of the actual component. If the actual measured performance is the same as the simulated one, then the X-parameter model is valid.

When comparing simulated versus measured performance, it is critical that the source and load impedance terminations at the fundamental and harmonic frequencies in the simulation match the impedances that are used during the measurement. The impedances chosen were not the same as those used to create the X-parameter model. As discussed in the previous section and in the Appendix, *"The NVNA X-Parameter Measurement Sequence,"* the component behavior versus harmonic source and load impedances is implicitly defined in the X-parameter model and identified during the application of the measurement signal. At the fundamental frequency, the application of physical impedance from a tuner was used to generate load-dependent X-parameters. Therefore, the X-parameter model is valid over a full gamma at the harmonic source and load impedances, and valid over the fundamental frequency load 'grid' conditions presented by the tuner. The impedances are shown in the simulation network depicted in **Figure 5. Figure 6** illustrates a comparison between the measured and simulated delivered power and thus, validates the behavior of the model.

Designing the power amplifier

To design a Class AB 45-Watt GaN amplifier, the Cree CGH40045F GaN-HEMT transistor was employed. **Table 3** contains a performance overview of the transistor taken from its datasheet.

A design frequency of 1.2 GHz was chosen so that a third-order X-parameter model could be generated using the X-parameter extraction setup described in **Figure 4,** page 5. Before the X-parameters are extracted, the DC quiescent point must be set. A Class AB operation was chosen for the targeted PA. Corresponding supply voltages are listed in **Table 4.**

Frequency	Up to 4 GHz
Gain (small signal)	15 to 20 dB
Psat (typical)	45 Watts
Drain efficiency (typical)	55%

Table 3. *Cree CGH40045F transistor specifications*

Frequency	1.2 GHz
VGS	-2.87 V
VDS	28.0 V
IDS_Q	400 mA

Table 4. *Class AB bias conditions for X-parameter model extraction*

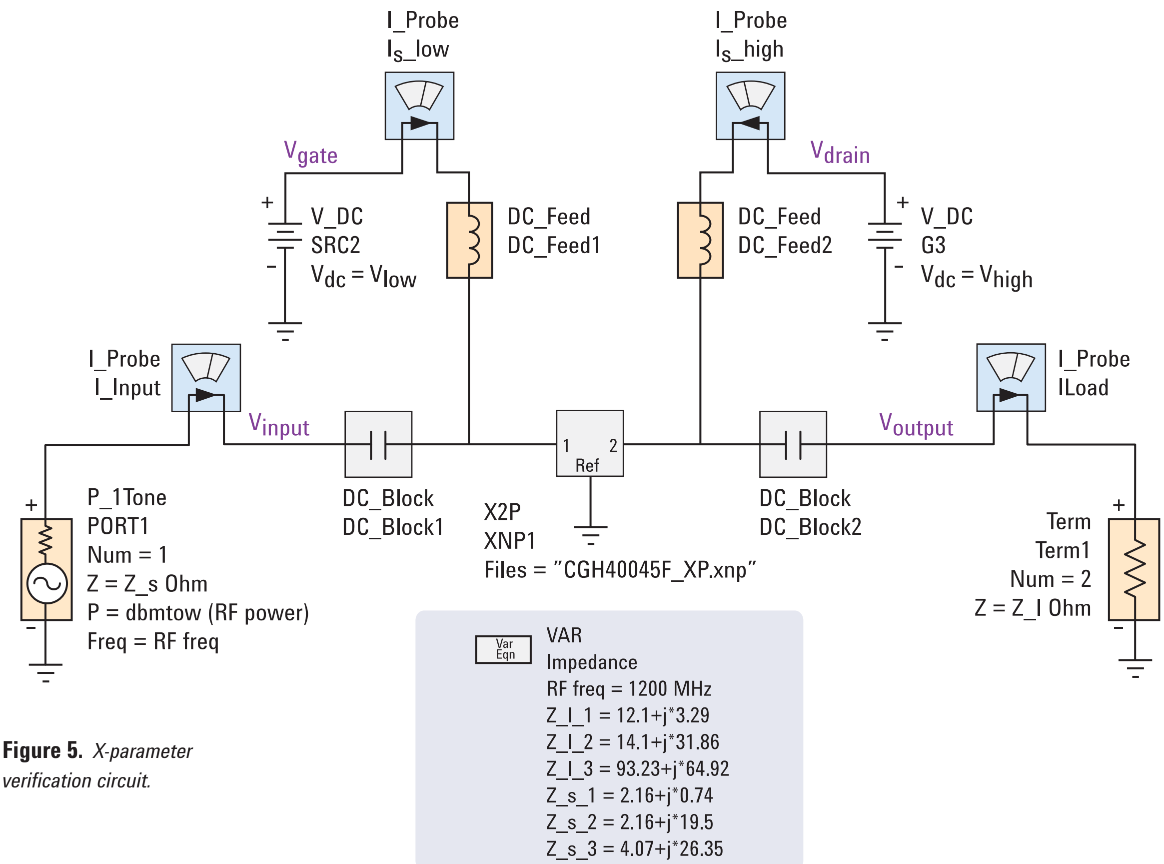

Figure 5. *X-parameter verification circuit.*

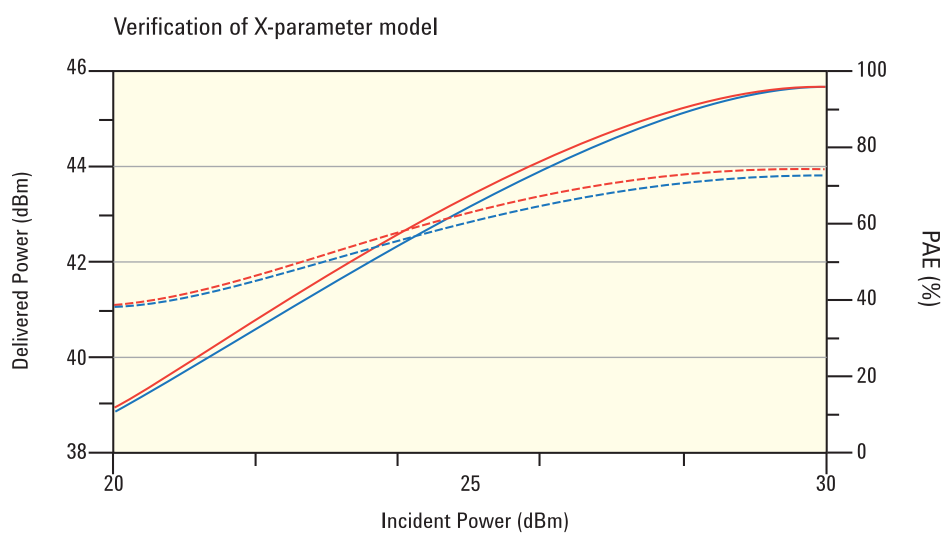

Figure 6. *X-parameter verification results.*

Source/load-pull X-parameter simulations

Source and load-pull simulations were conducted based on the measured X-parameter model to determine the optimal impedance matching conditions. The X-parameter model provides an implicit prediction of the harmonic source and load impedance variations. The simulated source and load-pull contours for the first three harmonics are presented in **Figure 5**. In this case, a compromise was struck between maximizing output power and maximizing power-added-efficiency (PAE) to ensure that suitable output power, greater than 45 dBm, would be obtainable. Given this trade-off, the results in **Figure 7** demonstrate the maximum PAE and output power that can be achieved with harmonic matching networks that have explicit control over the 2nd and 3rd harmonic impedance at the source and the load of the transistor.

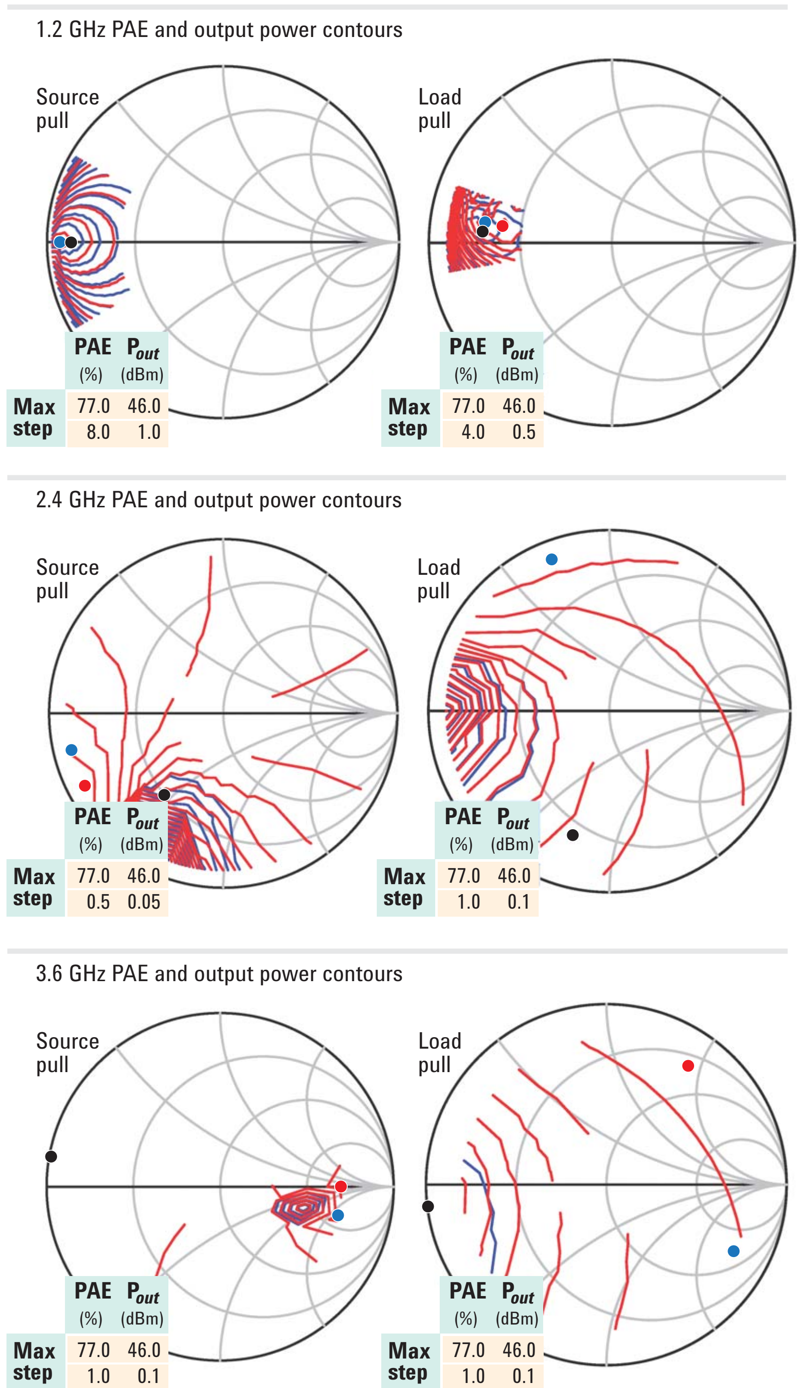

Figure 7. *Source and load-pull simulated contours of the first three harmonics.*

Legend

- Power added efficiency contours (red line)
- Output power contours (blue line)
- Maximum power added efficiency impedance condition (red dot)
- Maximum output power impedance condition (blue dot)
- Matching network impedance condition (black dot)

Matching networks and simulation results

The matching networks for the PA were designed using a variable-width, sequential transmission line topology and were simulated using the RF-ADS harmonic balance simulator, followed by electromagnetic (EM) simulations that were run in Momentum-ADS. This type of matching network guarantees optimal matching at the fundamental frequency; however, it provides limited control over the source and load impedance that is presented to the device at the harmonic frequenci es. Therefore, this simple matching network cannot provide the maximum efficiency predicted in the harmonic source/load-pull simulations of **Figure 7**. Instead, a more sophisticated harmonic matching network would be required.

Since the purpose of this article is to demonstrate the application of X-parameters modeling tech nology in PA design it was beneficial to use a simple matching network topology to minimize fabrication related errors. Furthermore, the size of the input and output tab of the transistor (0.22″ x 0.25″) behaves as a capacitance that effectively short-circuits the third harmonic impedance on the gate and drain. For these practical reasons, it was impossible to design a matching network that has the same harmonic impedances as the simulated source and load-pull analysis.

The matching networks shown in **Figure 8** below include integrated microstrip bias networks that are constructed from a bank of capacitors, and a quarter-wavelength transmission line, which ensure that RF leakage does not occur through the bias network. The source and load impedance presented by the matching networks are listed in **Table 5** and are indicated by the black dots in **Figure 7**.

Frequency	Source impedance (Ω)	Load impedance (Ω)
1.2 GHz	3.03 - j0.07	8.85 + j2.42
2.4 GHz	16.5 - j23.4	12.7 + j36.1
3.6 GHz	0.08 + j4.53	0.20 + j2.85

Table 5. *Matching conditions provided by the impedance matching networks*

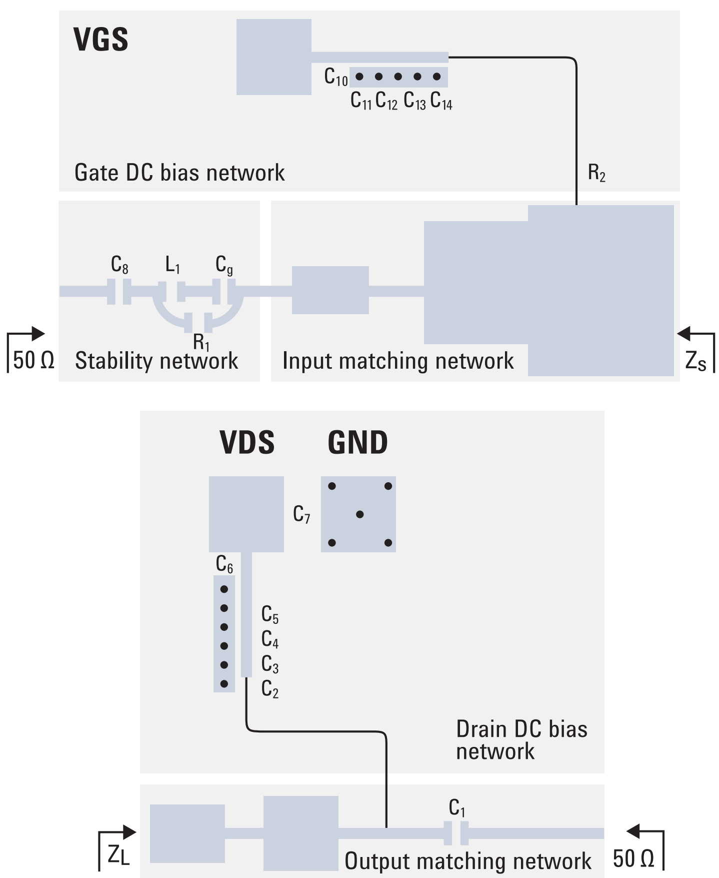

Figure 8. *Input and output matching network design.*

To predict the effects of connecting the input and output matching networks to the transistor ports, a PA simulation design was created by combining the matching networks (as a Momentum-ADS component) and the X-parameter model inside a single simulation. From this simulation, the overall performance of the PA was simulated at the reference plane outside of the matching networks as shown in **Figure 9**. The final simulation results of the PA are listed in **Table 6**

Figure of merit	Value
Input power	30 dBm
Drain efficiency	64.1%
PAE	62.3%
Output power	45.3 dBm

Table 6 *Power amplifier simulation results*

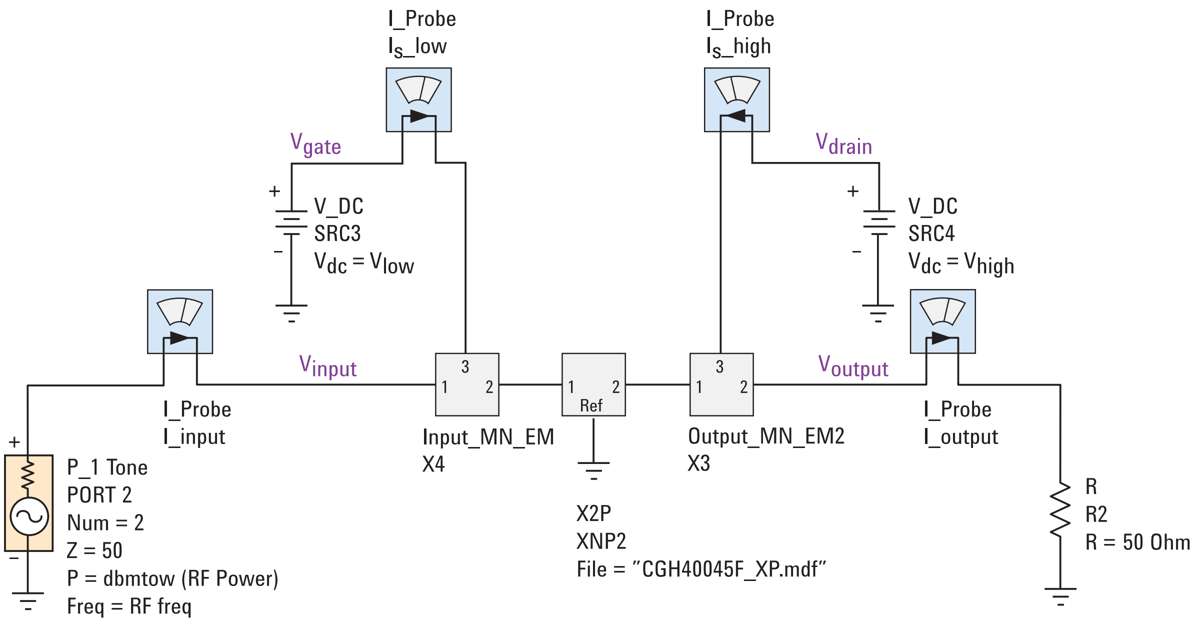

Figure 9. *Power amplifier simulation schematic.*

Comparing the results

The PA was fabricated **(Figure 10)** and measured using the NVNA. **Table 7** compares the simulated results to the measurement results at a fixed input power at 30 dBm.

The measurements show excellent correlation with the simulation results and demonstrate that the X-parameter model prediction is accurate to within 1% of the measured drain efficiency and 0.4 dB of the measured output power. Consequently, the measurement results prove that the X-parameter model is a viable solution for modeling high-power unmatched nonlinear devices.

Figure of merit	Simulation results	Measurement results
Input power	30 dBm	30 dBm
Drain efficiency	64.1%	64.6 %
PAE	62.3%	62.6 %
Output power	45.3 dBm	44.93 dBm

Table 7. *Power amplifier measurements versus simulation results*

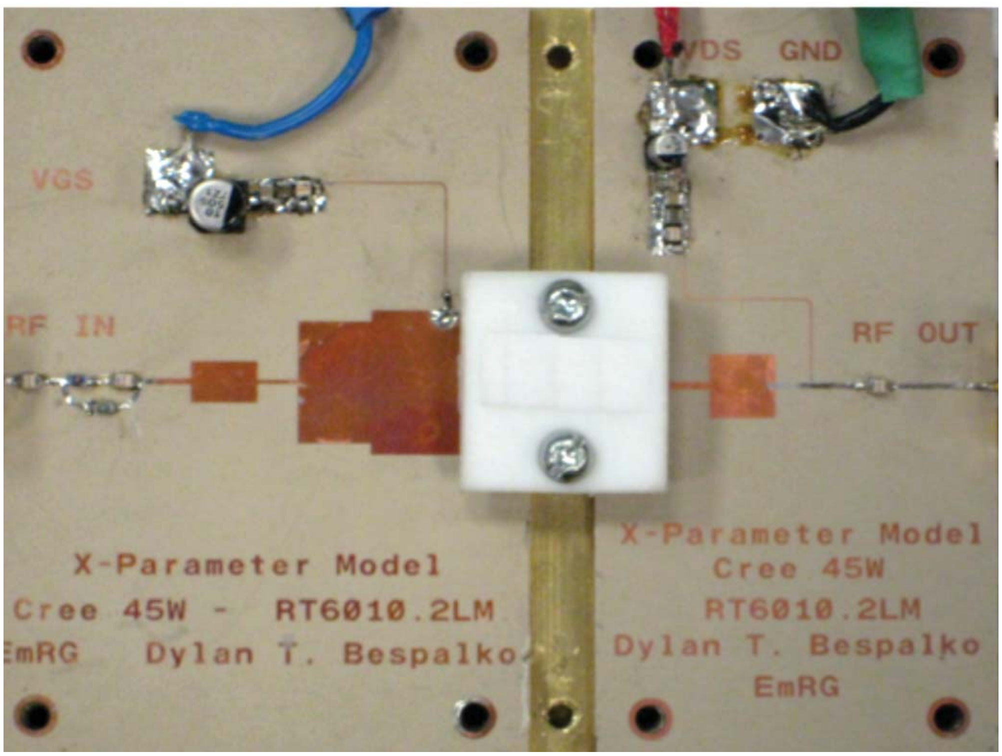

Figure 10. *A 45-Watt Class AB power amplifier.*

Conclusion

Traditionally, barriers have existed between device characterization and modeling and microwave circuit design. Luckily, a new approach to bridging this gap has now been proposed that can be extremely helpful in streamlining the high-power amplifier design process.

Using the example of a Class AB 45-Watt GaN amplifier, the first step of this process combines load-pull characterization with the advantages of Agilent's NVNA application for the PNA-X network analyzer to generate an X-parameter model of an unmatched 45-Watt GaN device that is imported into the ADS simulation software. The resulting model is used to identify adequate source and load matching networks to be presented to the transistor. In this article, the design was simulated using the RF-ADS harmonic-balance analysis and the ADS dynamic link with the accurate EM simulator Momentum, to accurately synthesize the biasing and matching networks. When compared to the simulation results, the measurement results for the fabricated PA prototype were in excellent agreement. Consequently, this example demonstrates the true power of bringing accurate device behavioral models into the simulation environment to systematically develop advanced circuit topologies and system architectures.

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Appendix

The NVNA X-Parameter Measurement Sequence

Linear scattering parameters (S-parameters) describe the linear behavior of a component and can be used to design predictable linear systems **(Figure A)**. They relate the incident independent 'a' waves to the reflected dependent 'b' waves at the component input and output ports. For a two-port component, the S-parameter can be written as two independent equations with four unknowns (S_{11}, S_{21}, S_{12}, and S_{22}). A vector network analyzer (VNA) is utilized to measure the 'a' and 'b' waves at the component to determine a solution for the S-parameters. This is typically done by performing a forward and reverse stimulus sweep on the component, which provides a set of four independent equations for the four unknowns. The S-parameters, by definition, cannot change versus the stimulus drive direction when determining the solution. This is often the case for a component that exhibits nonlinear behavior.

When measuring a component that exhibits nonlinear behavior, the definition of the linear scattering model is no longer valid. Examples of nonlinear component behavior are multiple input and output frequencies (harmonics) generated by the component, or changes in the linear scattering parameters as previously discussed. A new model must be generated that accurately encompasses both the linear and nonlinear characteristics of the component.

Figure B shows an example realization of this model consisting of scattering coefficients called X-parameters. Like S-parameters, X-parameters relate the incident independent 'a' waves to the reflected dependent 'b' waves, but across the full linear and nonlinear component behavior.

$$b_i = \sum_k S_{ik} \cdot a_k$$

$$b_1 = S_{11} a_1 + S_{12} a_2$$

$$b_2 = S_{21} a_1 + S_{22} a_2$$

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$\begin{bmatrix} b_1^{fwd} & b_1^{rev} \\ b_2^{fwd} & b_2^{rev} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1^{fwd} & a_1^{rev} \\ a_2^{fwd} & a_2^{rev} \end{bmatrix}$$

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} b_1^{fwd} & b_1^{rev} \\ b_2^{fwd} & b_2^{rev} \end{bmatrix} \begin{bmatrix} a_1^{fwd} & a_1^{rev} \\ a_2^{fwd} & a_2^{rev} \end{bmatrix}^{-1}$$

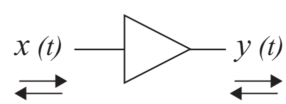

Figure A. *Scattering parameters—linear systems S-parameters.*

Definitions

i = Output port index
j = Output frequency index
k = Input port frequency
l = Input frequency index

$$b_{ij} = X^{(F)}_{ij}(DC, |A_{11}|, \Gamma_2)\, P^{j} + \sum_{k,l \neq (1,1)} \left(X^{(S)}_{ij,kl}(DC, |A_{11}|, \Gamma_2)\, P^{j-l} \cdot a_{kl} + X^{(T)}_{ij,kl}(DC, |A_{11}|, \Gamma_2)\, P^{j+l} \cdot a^{*}_{kl} \right)$$

For example: $X^{T}_{21,21}$

Means: Output port = 2
Output frequency = 1 (fundamental)
Input port = 2
Input frequency = 1 (fundamental)

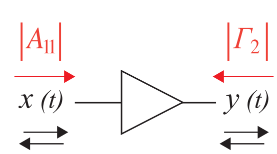

Figure B. *Scattering parameters—nonlinear systems X-parameters.*

Definitions

i = Output port index
j = Output frequency index
k = Input port frequency
l = Input frequency index
$|A_{11}|$ = Large signal drive to the amplifier input port (port #1) at the fundamental frequency (#1)
$|\Gamma_2|$ = Load dependent X-parameters with variable gamma at port #2

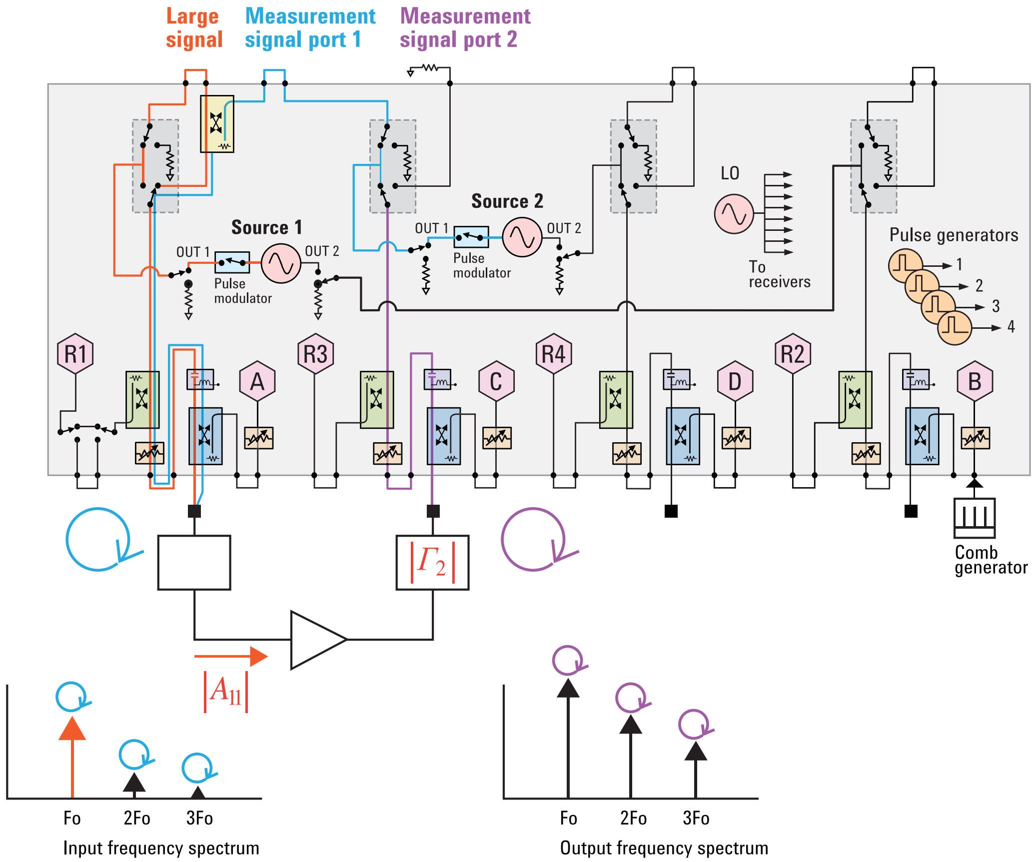

Figure C. *The sequence used by the Agilent PNA-X with NVNA application to measure X-parameters.*

As an example, consider that an amplifier is stimulated with a large-drive signal from one source on its input port that sets a specific large-signal-operation-point (LSOP). The X-parameters are measured utilizing a second source. The input power of the large-drive signal is then swept across the linear and nonlinear range of the component. At each input power point, a set of X-parameters is generated that are mathematically and analytically correct over the full linear and nonlinear range of the component.

The Agilent PNA-X network analyzer with the NVNA software application is used to measure the X-parameters following the sequence illustrated in **Figure C.** To simplify the analysis, the input large signal is assumed to be set at a single frequency and power level. During the measurement process, the following steps are taken:

Step 1:
A large drive signal is applied only to the PNA-X's port 1.

Step 2:
Simultaneously with the large signal on port 1, the measurement signal is applied to port 1 sequentially to all fundamental and harmonic frequencies. At each frequency, the phase is rotated at steps around 360 degrees.

Step 3:
Simultaneously with the large signal on port 1, the measurement signal is applied to the PNA-X's port 2 sequentially to all fundamental and harmonic frequencies. At each frequency, the phase is rotated at steps around 360 degrees.

The 'a' and 'b' waves are measured at each stimulus change (e.g., port, frequency and phase) in the large drive and measurements signals. Once all the sequences are complete, the resulting waves are utilized to identify the X-parameters.

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The authors would like to thank the following vendors for use of their equipment: AR RF/Microwave Instrumentation, Maury Microwave Corporation, and Mini-Circuits.

Nonlinear Reference Website

Get the latest nonlinear reference information, download a free copy of *"High Power Amplifier Measurements Using Agilent's Nonlinear Vector Network Analyzer,"* (App Note 1408-19), and find pertinent X-parameter and nonlinear technical papers at:
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Revised: October 14, 2010

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Printed in USA, May 1, 2011
5990-7768EN

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