Evaluating and Optimizing High-power Amplifier Designs with X-Parameter Techniques

Application Note

Overview

To meet evolving requirements, today's radar designs are utilizing wider frequency bandwidths and increasingly complex modulation schemes. As one consequence of these changes, power amplifier (PA) designers are pushing to optimize output power while maintaining high efficiency. Whether they're working on aerospace, defense or commercial systems, many designers are investigating and implementing newer technologies such as gallium nitride (GaN). Working with a new technology presents a variety of challenges in design, simulation and testing.

Traditionally, S-parameter measurements have been a used in amplifier design. X-parameters are a relatively new technique that extends the capability of S-parameters to measure and model amplifier nonlinearities. X-parameters can help you overcome three key challenges in RF engineering: nonlinear impedance differences, harmonic mixing, and nonlinear reflection effects that occur when components are cascaded under large-signal operating conditions.

To illustrate the problems and solutions, this application note presents an example PA design that uses a 45-watt GaN transistor. The center operating frequency is 1.2 GHz and the target output power is 45 dBm or more. The device will operate in class AB bias and the desired power-added efficiency (PAE) is greater than 60 percent.

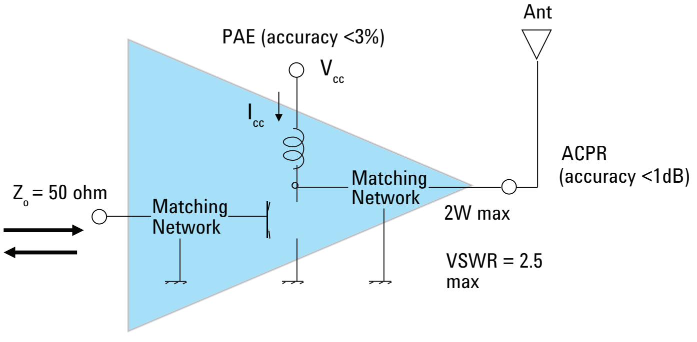
The total PA design was completed using Agilent's Advanced Design System (ADS). ADS was used to simulate the impedance contours of output power and PAE at fundamental and harmonic frequencies at the input (gate) and output (drain) ports. To maximize PAE and output power, simulated impedance contours were used to determine the appropriate termination impedances at the fundamental and harmonic frequencies at the gate and drain ports.

The simulated contours were used to select specific impedances for the appropriate frequency match. From that, a printed circuit board (PCB) was designed to supply the required impedances to the transistor. The final PA was assembled and its actual performance was measured with a nonlinear vector network analyzer (NVNA) and then compared to the simulated PA in ADS.

Problem

For many designers, the first step is to select a transistor based on its potential compatibility with the target specifications for the PA. Example specs include figures of merit such as output power, gain compression, PAE, intermodulation distortion (IMD) and adjacent channel power ratio (ACPR).

Once the transistor is selected the next step is to design input- and output-matching networks that support the target specifications (Figure 1). Potential issues include the design cycle time required to optimize the matching networks and the need to verify design performance through actual measurements.



PAE= Power Added Efficiency • ACPR= Adjacent Channel Power Ratio • VSWR= Voltage Standing Wave Ratio

Figure 1. Optimization of input and output matching networks will help ensure in-spec PA performance

Agilent Technologies

Solution

For PA developers, the ability to easily compare simulated and actual measurement results can help ensure increasingly accurate models and better designs in the future. Agilent offers several simulation platforms that support the needs of PA designers and system architects. On the measurement side, an NVNA equipped with X-parameter[1] characterization capabilities accelerates the process of optimizing the PA design.

The configuration illustrated here used ADS as the simulation environment and the Agilent PNA-X microwave network analyzer as the measurement platform. Through quick and efficient design simulation, ADS reduces the amount of hardware prototyping required to reach a final design. Equipped with the NVNA and X-parameters options, the PNA-X supports traditional source/load-pull systems to provide the measurement knowledge required to work with technologies such as GaN.

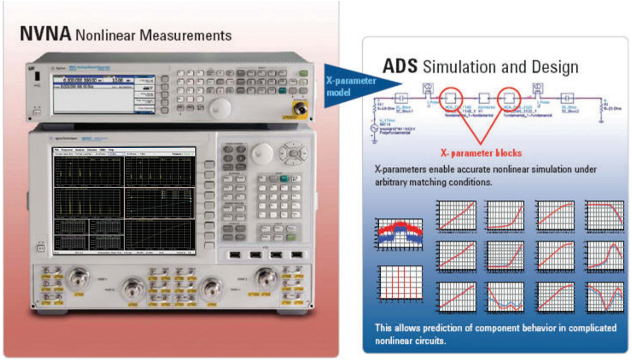


Figure 2. The combination of NVNA, X-parameters and simulation enables rapid optimization of high-power designs

In the paragraphs below, the example shows how to configure a high-power load-pull measurement using the PNA-X in NVNA mode. A measurement of the load-dependent X-parameters will be compared with the original ADS simulations.

Configuring the measurement

Figure 3 shows the NVNA X-parameter system configuration for the PA design based on a 45-watt GaN transistor. The light-blue circles indicate the receiver input ports of the PNA-X network analyzer. All of the items in dark blue are external components that help protect the receiver ports when making high-power measurements: amplifiers, couplers, attenuators and bias tees.

The orange rectangles indicate tuners, which are required for unmatched transistors because their impedance is far from 50 Ω. This requires an X-parameter model that includes dependence on the load impedance present at the output of the component. The output tuner is used to facilitate these load-dependent X-parameter measurements. It is also used to set the output gamma of the tuner.

On the input side of the DUT, the tuner must be tuned as closely as possible to the conjugate match of the input. Depending on the transistor and its class of operation, a multi-harmonic tuner may or may not be required (this is also true for output tuners).

A power sweep can be performed to vary the power available at the input of the component. This is necessary because the X-parameters have a DC bias that is dependent on the large signal at the input of the component.

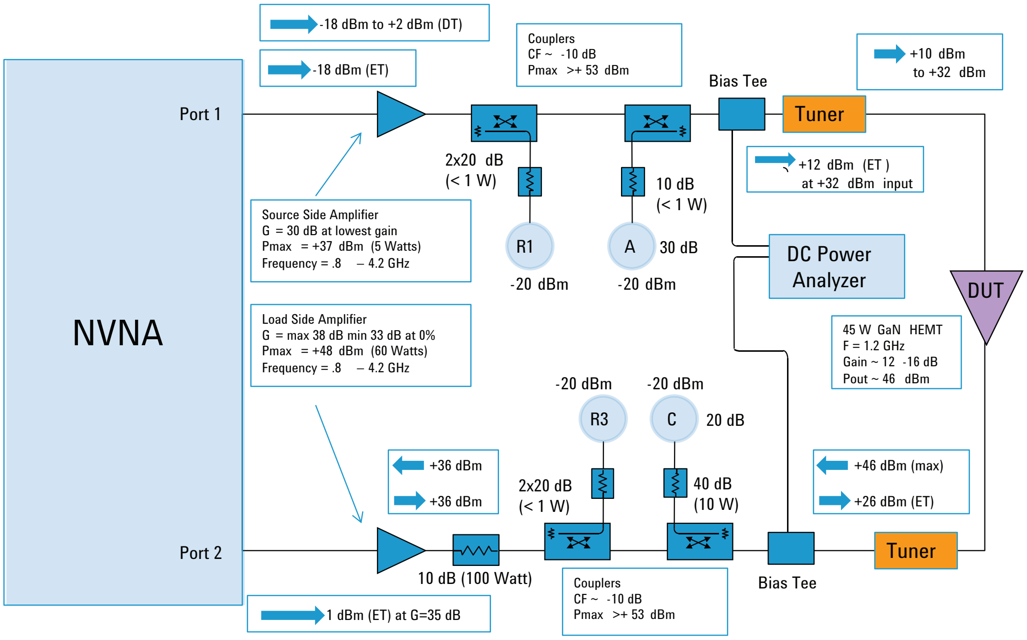


Figure 3. External components protect the receiver inputs while the tuners provide impedance matching

---

[1] *X-parameters is a trademark and registered trademark of Agilent Technologies in the US, Europe, Japan, and elsewhere. The X-parameters format and underlying equations are open and documented. For more information, visit http://www.agilent.com/find/eesof-x-parameters-info.*

Establishing a power budget

Before making a measurement, it is necessary to determine a power budget for the NVNA and the X-parameters. This starts with the characteristics of the transistor: operating frequency range, gain, output power, and so on. These values help determine which external components are needed in the actual measurement configuration (e.g., the amps, couplers, attenuators and bias tees shown in Figure 3).

Referring back to the details in Figure 3, the selected devices support measurements up to 120 watts, which provides ample headroom above the 45-watt target. Because the GaN device provides high power and high gain, the driver amplifier must stay in its linear region while delivering enough power to drive the device over its specified operating range. Due to the high output power of the source-side amplifier, the external couplers are needed to measure the incident and reflected waves while also protecting the PNA-X receivers.

In practice, one key point is worth remembering: A high-power amplifier has the potential to damage the front end of the PNA-X receivers. To provide a prominent reminder, a damage specification is affixed to the front panel of the instrument—and the value shown there should never be exceeded. To optimize any X-parameter measurement, it’s best to apply both external and internal attenuation that keeps the maximum power to the receivers below –20 dBm.

Powering the Measurement Configuration

The Agilent N6705A DC power analyzer was used to supply the bias and measure the current at each transistor measurement point. As a result, the model contained actual DC bias information.

One note: The setup was configured for pulsed X-parameter measurements because the device was going to face a pulsed RF signal. Even though the DC bias was kept constant, the peak envelope current was measured by triggering the N6705A. This ensured that the model contained the peak current during the envelope on-time of the pulse.

When making measurements, a signal is also applied in the reverse direction to the output or load side of the transistor. The load-side amplifier needs to operate in its linear region, and its output level needs to be about 20 dBc below the maximum output power of the transistor. (In this example, the signal had to be 26 dBm at the output port of the GaN device.) Adding an attenuator can help manage the power level, and it can also improve the raw impedance match looking into the measurement system, thereby improving long-term measurement stability.

With the necessary protection in place, the X-parameters of the transistor can be measured. When these measurements have been completed, the file can be exported to ADS for independent validation.

Setting up X-parameter models with ADS

Once the X-parameters have been measured, the next step is to verify the measured X-parameter model. This is an indirect process that does not use X-parameter measurements. Instead, the measured parameters include "A" or "B" waves, output power, PAE, or other relevant characteristics based on your experience and design goals. In all cases there are two key steps:

1. For each measurement, record the input power, bias and all impedances—input ports, output ports, fundamental, harmonic.
2. Enter the impedances into the simulator as the terminations of the X-parameter model; sweep the power over that used in the measurement range.

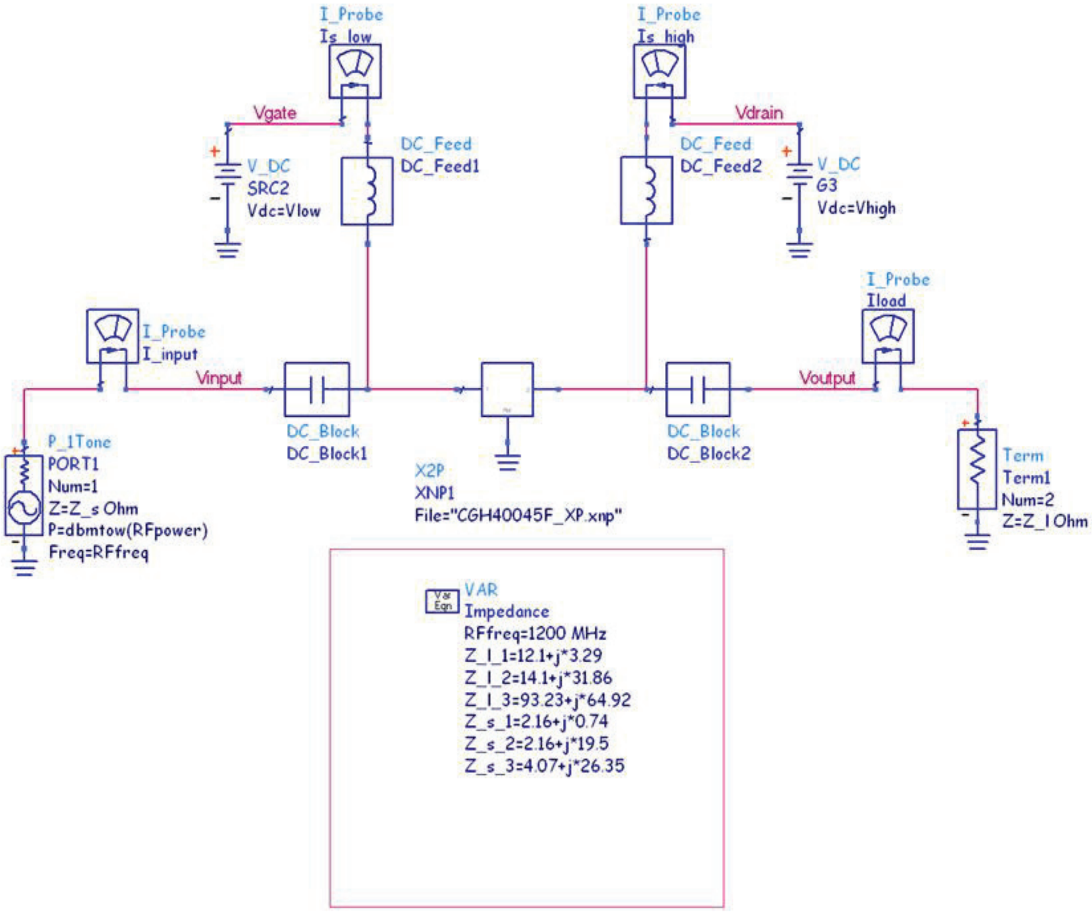
This last step is essential because the X-parameter model will react in the same way the actual device did in response to the physical impedance that was applied.

To compare the actual component measurement to the simulation, be sure that the simulated hardware matches the physical hardware. The simulated hardware is illustrated in the circuit template shown in Figure 4.

The X-parameter model is at the center of the ADS schematic, with the measured impedances at the input and output of the component. These are the impedances of the measurement hardware, not the device, and should be entered as the termination impedances of the model (as mentioned above). At this point, a comparison can be made between the measured characteristics—A wave, B wave, output power, PAE, etc.—and the simulated results in ADS.

Within ADS, the so-called X-Gen capability can be used to convert a circuit-level model into an X-parameters model. X-Gen is easy to set up and use, and simulation speed is fast. Simulations can be run with multi-tone, multi-port and more: there are virtually no limits on frequency, power or number of ports.

The X-Gen capability also helps protect intellectual property. The circuit-level model is literally hidden inside the X-parameter model, which can be easily shared with customers or outside vendors.



VAR
Impedance
RFfreq=1200 MHz
Z_l_1=12.1+j*3.29
Z_l_2=14.1+j*31.86
Z_l_3=93.23+j*64.92
Z_s_1=2.16+j*0.74
Z_s_2=2.16+j*19.5
Z_s_3=4.07+j*26.35

Figure 4. ADS simplifies the creation of circuit-level models and X-parameter models, and enables comparisons between simulated and measured results

Results: Verifying the X-Parameter Model

All of the preceding concepts and techniques were used in an analysis of the 45-watt GaN transistor. Figure 5 shows a comparison of measured and simulated delivered power using the X-parameter model. The results show excellent correlation in two aspects: between measured and simulated delivered power and between measured and simulated drain current (in response to a sweep of the input power level).

With the model verified, it can now be used in the design of the PA. The simulator can be used to plot PAE and output power contours, as shown in Figure 6. These results show that the two key design goals—output power ≥45 dBm and efficiency ≥60 percent—can be achieved through careful selection of impedances. In this case, efficiency greater than 70 percent can be achieved if the transistor is terminated with optimum impedances in the matching networks. Table 1 provides a detailed comparison.

Table 1. Comparing simulated and measured results for the power amplifier (courtesy of the University of Waterloo)

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

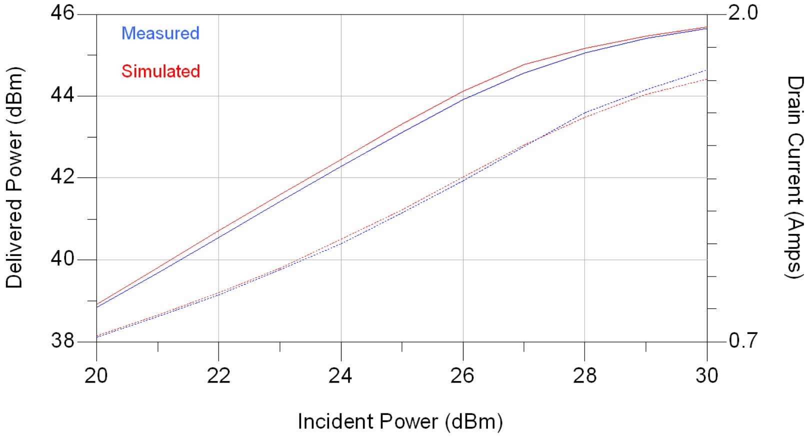


Figure 5. A plot of delivered power (left) and drain current (right) versus incident power shows excellent agreement between measured and simulated results

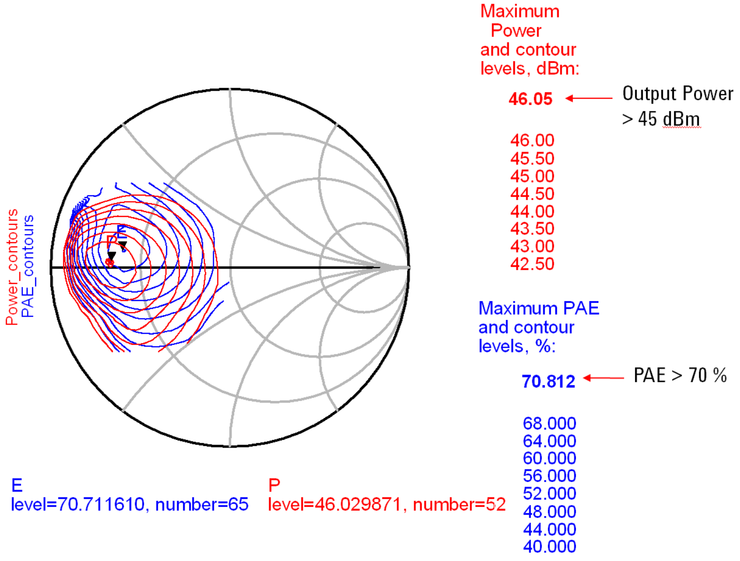
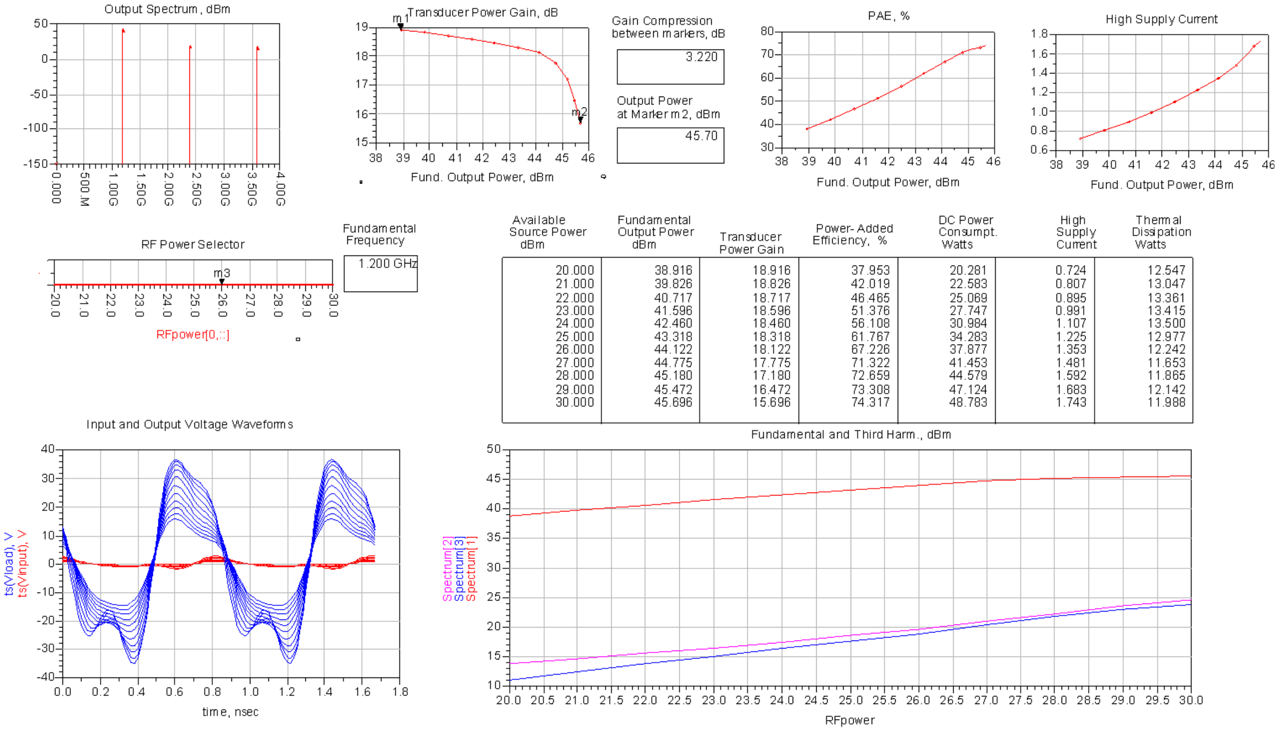


Figure 6. A plot of PAE and output power contours shows that the two key design targets (output power ≥45 dBm and efficiency ≥60 percent) can be achieved if appropriate impedances are selected

The ADS software offers an amplifier design guide (Figure 7), which provides a template that can be applied to an X-parameters model to simulate figures of merit for an amplifier:

- Output power spectrum
- Input and output waveforms versus drive power
- Gain versus fundamental output power
- PAE versus output power
- Drain current versus output power
- Fundamental and harmonic output spectrum versus RF input power



Available Source Power dBm	Fundamental Output Power dBm	Transducer Power Gain	Power-Added Efficiency, %	DC Power Consumpt. Watts	High Supply Current	Thermal Dissipation Watts
20.000	38.916	18.916	37.953	20.281	0.724	12.547
21.000	39.826	18.826	42.019	22.583	0.807	13.047
22.000	40.717	18.717	46.465	25.069	0.895	13.361
23.000	41.596	18.596	51.376	27.747	0.991	13.415
24.000	42.460	18.460	56.108	30.984	1.107	13.500
25.000	43.318	18.318	61.767	34.283	1.225	12.977
26.000	44.122	18.122	67.226	37.877	1.353	12.242
27.000	44.775	17.775	71.322	41.453	1.481	11.653
28.000	45.180	17.180	72.659	44.579	1.592	11.865
29.000	45.472	16.472	73.308	47.124	1.683	12.142
30.000	45.696	15.696	74.317	48.783	1.743	11.988

Figure 7. To potentially reduce the number of prototyping cycles, the ADS DesignGuide provides a practical, end-to-end single-stage PA design using an X-parameters model

Tips: Best Practices for X-Parameter Measurements

A few best practices will help ensure good results when performing X-parameter measurements on high-power devices. The first is to leave enough preamplifier linear gain for extraction and drive tones. If the preamp is saturated with the drive signal then adding the extraction signal will degrade the X-parameters.

One caution: If the fundamental frequency is driven out of the preamplifiers—and if they are completely compressed at the fundamental frequency during the measurement—then the amplifier will not generate any additional power at the fundamental frequency when the second measurement source is activated. This problem will surface when comparing measured and simulated results from a power sweep. At the low-power end of the sweep, correlation will be excellent; however, the responses will begin to deviate as power increases. This is due to saturation of the power amp at higher drive power.

Harmonic distortion is less problematic when measuring X-parameters. If the preamplifiers are generating any harmonic distortion that is at least 20 dBc down from the fundamental, the X-parameter measurement technology will remove those distortion components from the resulting X-parameter model. The net result is a model of an amplifier with no harmonic distortion.

The second best practice focuses on the terminating impedances. When comparing simulated X-parameter results to actual measurements, the impedances used in the simulator must match those used in the independent measurements. To ensure accurate measurement results, be sure to use proper calibration and de-embedding techniques (where applicable).

As a final point, tuners (when used) are typically characterized separately in the measurement system. In that process, the preamplifiers are removed from behind the couplers during calibration; they are placed back in line after calibration is complete. One note: Because this technique may affect the tuner characterization, the source and load impedances behind the tuners should be determined using the NVNA. Tuner software can perform this function. These values can be used to ensure the tuner applies the proper impedance to the component.

Conclusion

The use of new technologies often drives the need for new techniques in design, simulation and measurement—and the thoughtful application of such new approaches can help reduce design cycle time. This is the case when designers use components such as GaN transistors in the design of high-power amplifiers. As shown here, a combination of accurate X-parameter models and precise NVNA measurements can lead to better models and improved PA performance.

www.agilent.com
www.agilent.com/find/AD

Agilent Email Updates

www.agilent.com/find/emailupdates
Get the latest information on the products and applications you select.

Agilent
Advantage
Services

Agilent Advantage Services is committed to your success throughout your equipment's lifetime. We share measurement and service expertise to help you create the products that change our world. To keep you competitive, we continually invest in tools and processes that speed up calibration and repair, reduce your cost of ownership, and move us ahead of your development curve.

www.agilent.com/find/advantageservices

Agilent Electronic Measurement Group
KEMA Certified
ISO 9001:2008
Quality Management System

www.agilent.com/quality

For more information on Agilent Technologies' products, applications or services, please contact your local Agilent office. The complete list is available at:
www.agilent.com/find/contactus

Americas

Canada	(877) 894 4414
Brazil	(11) 4197 3500
Mexico	01800 5064 800
United States	(800) 829 4444

Asia Pacific

Australia	1 800 629 485
China	800 810 0189
Hong Kong	800 938 693
India	1 800 112 929
Japan	0120 (421) 345
Korea	080 769 0800
Malaysia	1 800 888 848
Singapore	1 800 375 8100
Taiwan	0800 047 866
Other AP Countries	(65) 375 8100

Europe & Middle East

Belgium	32 (0) 2 404 93 40
Denmark	45 70 13 15 15
Finland	358 (0) 10 855 2100
France	0825 010 700* *0.125 €/minute
Germany	49 (0) 7031 464 6333
Ireland	1890 924 204
Israel	972-3-9288-504/544
Italy	39 02 92 60 8484
Netherlands	31 (0) 20 547 2111
Spain	34 (91) 631 3300
Sweden	0200-88 22 55
United Kingdom	44 (0) 118 9276201

For other unlisted Countries:
www.agilent.com/find/contactus

Revised: October 14, 2010

Printed in USA, April 28, 2011
5990-7528EN

Agilent Technologies