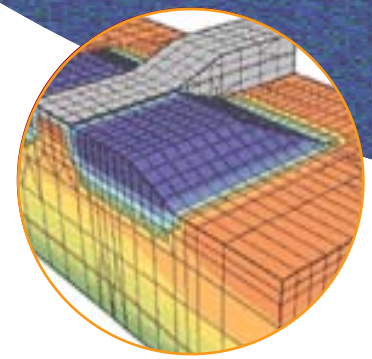
Solutions for

Securing Successful First-Pass Component Design

Understanding X-Parameter Nonlinear Measurements

Application Note



Overview

At one time, linear systems and components were designed using a patchwork of instrumentation and measurements. This approach was quickly replaced by scattering parameters (S-parameters), which unified the multiple instruments and measurements and enabled just one instrument, the network analyzer, to make measurements like gain, isolation and match with a single connection. For more than 40 years, S-parameters have stood as one of the most important of all the foundations of microwave theory and techniques. They are related to familiar measurements such as S_{11} input match, S_{22} output match, S_{21} gain/loss, and S_{12} isolation, and can be easily imported into electronic simulation tools. Today, S-parameters are commonly used to analyze and model the linear behavior of RF and microwave components. Unfortunately, current industry trends toward increasing energy efficiency, higher output power and longer battery life are forcing many linear devices to operate in a nonlinear fashion. Measuring this behavior requires a solution that is much more deterministic in nature.

Problem

While extremely useful and powerful, S-parameters are only defined for small-signal linear systems. With the communications revolution forcing active components like power amplifiers (PAs) into more and more strongly nonlinear regimes of operation, engineers are now forced to use a new set of patchwork solutions for measuring a component's nonlinear attributes. Essentially, they make linear assumptions by taking S-parameters and applying nonlinear figures of merit (e.g., ACPR and gain compression). Relying on this incomplete set of information means that the engineer has to perform extensive and costly empirical-based iteration of their designs, adding substantial time and cost to the design process. To quickly, accurately and more deterministically design nonlinear components at high frequencies, today's engineers require the ability to properly measure nonlinear behavior, as well as a unifying model (similar to an S-parameter, but for nonlinear components) that can take this behavioral information into simulation and design.

Agilent Technologies

Solution

By doing for nonlinear components and systems what S-parameters do for their linear counterparts, X-parameters* offer engineers an answer to this dilemma. X-parameters represent a new category of nonlinear network parameters for deterministic, high-frequency design and are used for characterizing the amplitudes and relative phase of the nonlinear behavior of components. Unlike S-parameters, they are applicable to both large-signal and small-signal conditions, and can be used for linear and nonlinear components. They correctly characterize impedance mismatches and frequency mixing behavior to allow accurate simulation of cascaded nonlinear X-parameter blocks (e.g., amplifiers and mixers), in design.

In contrast to S-parameters, X-parameters represent and analyze the nonlinear behavior of RF/MW components in a much more robust and complete manner. As the logical, mathematical extension of S-parameters under large-signal operating conditions, they are driven into saturation (the real-word operating environment for many components) and then measured under these conditions. When making this measurement, no knowledge is used or required concerning the internal circuitry of the device under test (DUT). Rather, the measurement is a stimulus response model of the voltage waves (Figure 1). In other words, the absolute amplitude and cross frequency relative phase of the fundamental, and the generated distortion products, are accurately measured and represented by X-parameters. Corresponding X-parameter-based behavioral models are created from this information and can be used with calibrated measurement tools to derive different figures of merit (e.g., ACPR, compression and EVM) (Figure 2). These fast, accurate models can take into account a range of different variables including source and load impedance, among other things.

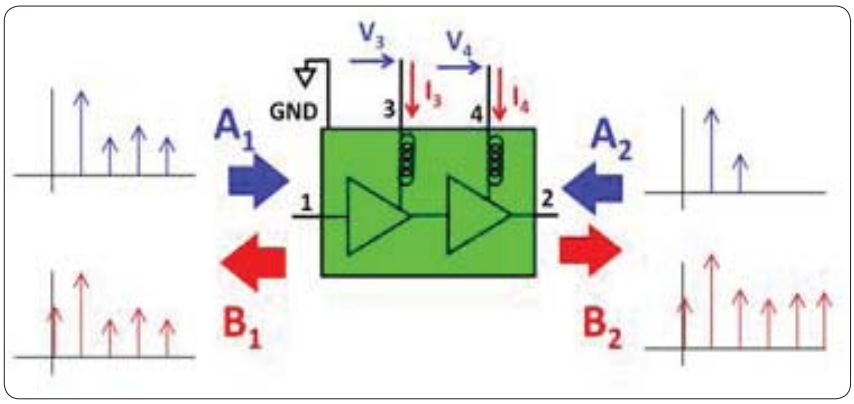


FIGURE 1: *The X-parameter model for the multi-stage amplifier in this example is formulated in the frequency domain and maps incident waves (A) to scattered waves (B). Because the complete knowledge of magnitude and phase of incident and scattered waves at all harmonics is exactly equivalent to complete knowledge of the time-domain waveform, the full nonlinear input-output characteristics of the device are captured.*

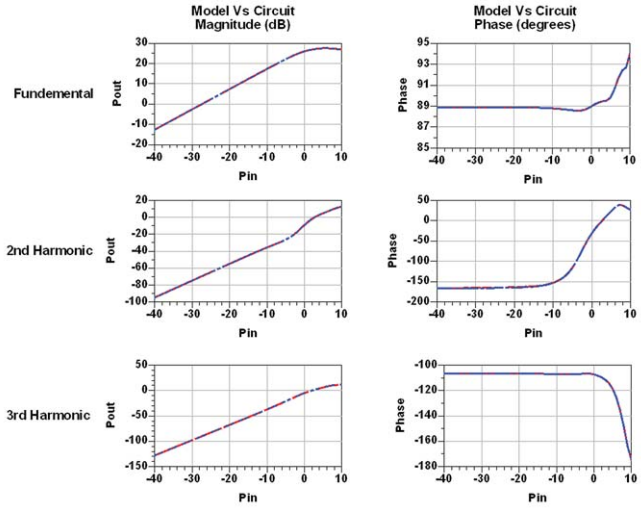


FIGURE 2: *The X-parameters are shown here overlaid on actual circuit-level PA results. As is evident, the X-parameters accurately correlate with the actual circuit.*

Generating X-Parameters

X-parameters can be obtained in one of two ways: generated from a circuit-level design in Agilent Technologies' Advanced Design System (ADS) software or measured using the Nonlinear Vector Network Analyzer (NVNA) software running inside the Agilent Technologies' PNA-X network analyzer (Figure 3).

To generate the X-parameters from a circuit-level schematic, first create the schematic in ADS. Once the schematic is complete, information regarding frequency, bias, temperature, and other important parameters is entered into the X-Parameter Generator. This tool takes the circuit-level design and computes the X-parameters for a component or module that can be used in an ADS, harmonic balance or circuit envelope simulation. The X-Parameter Generator is very flexible and can generate X-parameter models of nonlinear, multi-port components with multi-tone stimulus, as well as simulation under load-pull conditions.

Obtaining quick and accurate X-parameters through measurement requires the use of Agilent's NVNA. It measures the X-parameters of the DUT, which can then be imported into the ADS simulator or displayed like S-parameters. To measure the X-parameters the NVNA uses it's two internal RF sources to drive the DUT with a large signal tone to set the large signal operating point of the device and at the same time applies a small signal tone at the appropriate frequencies and phases.

Careful control of the phase and amplitude of these signals is therefore critical (Figure 4). Measuring the amplitudes and phases of the scattered waves under these conditions allows for the identification of X-parameters. These parameters provide the engineer with information on such things as device gain and match, while the device is operating in either a linear or nonlinear state.

The accurate and robust nature of X-parameters makes them extremely useful for engineers trying to better understand the nonlinear behavior of their active components. Whether created or measured, these X-parameters can be easily imported into ADS and then dropped into a component or system to start the design process or for use with simulation.

Other key features and benefits of X-parameters include:

- Extensible beyond 50 Ω. While netwok analyzers are inherently 50- Ω devices, the extensibility of X-parameters enables components to be measured beyond this point (e.g., a PA at 3 Ω). This can be done by either placing a matching circuit between the network analyzer and the DUT, or by employing a load pull tuner In addition, since the X-Parameter Genertor in ADS has no limits on the number of ports, power or frequency it can handle, it is able to deal with complicated designs involving multiple ports (e.g., 3-port devices), tones and biases (e.g., mixers), as well as arbitrary topology. In the future, such capabilities will also be available in the NVNA to make the physical measurements of X-parameters.

- High power. X-parameters are currently targeted at active devices, like PA's, that commonly exhibit strong nonlinear behavior. The NVNA can make high power X-parameter measurements (e.g., GAN and 10, 100 and 250 watt devices), even if the base network analyzer configuration can only handle 1 watt. The flexibility of Agilent's PNA-X hardware has enabled measurements to be made to 100, and even 250 watts.

FIGURE 3: *Agilent's NVNA software, for use with the PNA-X network analyzer, establishes a new industry standard in RF/MW nonlinear network analysis from 10 MHz to 50 GHz. It allows the engineer to deterministically measure X-parameters.*

FIGURE 4: *The NVNA requires a simple procedure using a power meter, phase reference and vector calibration standard to analytically remove the systematic errors from the measurements.*

Summary of Results

With active components continuing to be driven into nonlinear operation, the need for fast and accurate measurement of that nonlinear behavior becomes all the more urgent. As a logical extension of S-parameters to include nonlinear effects, accurate and robust X-parameters represent the ideal solution to this dilemma. Whether created from measurement or ADS simulation, they offer speed and convenience analogous to the well-known linear S-parameters. Resulting X-parameter-based behavioral models can be quickly and easily dropped into simulation and used to deterministically design the most robust components and systems in the shortest amount of time and with the highest degree of accuracy.

The Power of X

The Agilent X-Parameters and PNA-X Microwave Network Analyzer with the NVNA software are key products in Agilent's comprehensive Power of X suite of products. These products grant engineers the power to gain greater design insight, speed manufacturing processes, solve tough measurement problems, and get to market ahead of the competition.

Offering the best combination of speed and scalability, and created and supported by renowned worldwide measurement experts, Agilent's X products are helping engineers bring innovative, higher performing products to emerging markets around the globe.

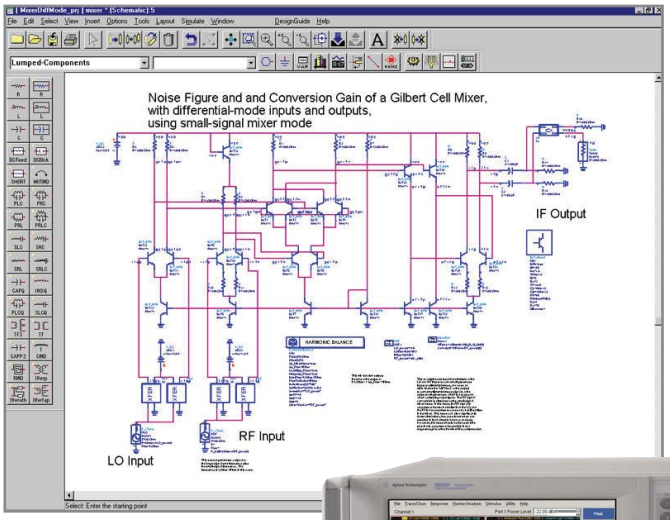
To learn more about Agilent's suite of X products please visit:
www.agilent.com/find/powerofx.

Related Applications

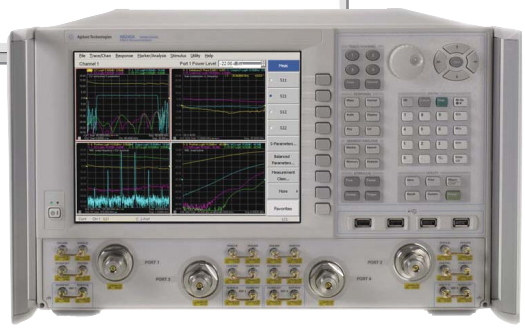
- Semiconductor process design
- Semiconductor IC design and validation of active components
- Base station PA design and validation
- Military active component design and validation

Related Agilent Products

- W2305 X-Parameter Generator
- W2200 ADS Core
- Nonlinear Vector Network Analyzer



Gilbert cell mixer circuit in ADS



PNA-X network analyzer

Remove all doubt

For more information on repair and calibration services, go to:

www.agilent.com/find/removealldoubt

Agilent Email Updates

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

Agilent Channel Partners

www.agilent.com/find/channelpartners
Get the best of both worlds: Agilent's measurement expertise and product breadth, combined with channel partner convenience.

www.agilent.com
www.agilent.com/find/powerofx

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
Latin America	305 269 7500
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
Thailand	1 800 226 008

Europe & Middle East

Austria	43 (0) 1 360 277 1571
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
Switzerland	0800 80 53 53
United Kingdom	44 (0) 118 9276201

Other European Countries:
www.agilent.com/find/contactus

Revised: October 1, 2009

Product specifications and descriptions in this document subject to change without notice.
© Agilent Technologies, Inc. 2010
Printed in USA, January 6, 2010
5990-5151EN

Agilent Technologies