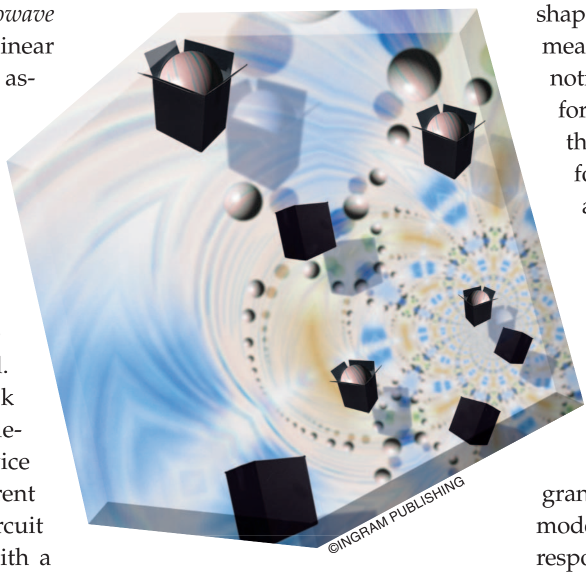
From the Guest Editor's Desk

Nonlinear Vector Measurements and Associated Behavioral Models

■ **Joseph M. Gering**

This issue of *IEEE Microwave Magazine* is focused on nonlinear vector measurements and associated behavioral models. These measurements can be seen as the higher-power extension of small-signal, vector network analyzer (VNA) measurements, where, at higher powers, there is energy transfer from the fundamental to the harmonics, and the signals are no longer sinusoidal. These behavioral models are black box models that empirically describe the behavior of a part or device with a look-up table. (This is different from a conventional equivalent-circuit model, which describes a part with a combination of linear and nonlinear circuit elements.) The field of nonlinear vector measurements is not new. Its roots date back to the late 1980s, and behavioral models have been contemplated even longer. However, this combined field of measurements and models has exploded over the last few years.



Joseph M. Gering (jgering@rfmd.com) is with RFMD in Greensboro, North Carolina.

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The motivation for this can be seen by examining Figure 1. This is a plot of the output power versus input power of a building block in a cellular phone's power amplifier. The inset figures show the current and voltage waveforms at the somewhat saturated power level where this block operates. These waveforms are definitely not sinusoidal, which indicates signal content is present at higher harmonics as well as at the fundamental. The output power, gain, and efficiency all depend on the shape and relative phasing of these waveforms. However, without vector measurements, these shapes and relative phases cannot be measured. Those with keen eyes will notice that there are actually two traces for each curve in Figure 1. These are the measured and simulated curves for this block. The simulation uses a custom, large-signal (nonlinear), equivalent-circuit model for the many transistors making up this block along with electromagnetic simulations of the interconnections. While the agreement is quite good, higher-level simulations incorporating this block can be laborious. Wouldn't it be grand if there were a fast and accurate model for this block that captures the response of the waveforms … such as a nonlinear vector measurement-based behavioral model?

In the past, commercial measurement systems for extracting behavioral model parameters were few and far between. Today, several major equipment suppliers have solutions, and a number of smaller companies have sprung up in this area. As well, major simulation tool providers have incorporated behavioral models using the vector data derived from these measurements systems. This field has also seen significant growth in its conference presence. While VNA measurements have always been a mainstay at the Automatic RF Techniques

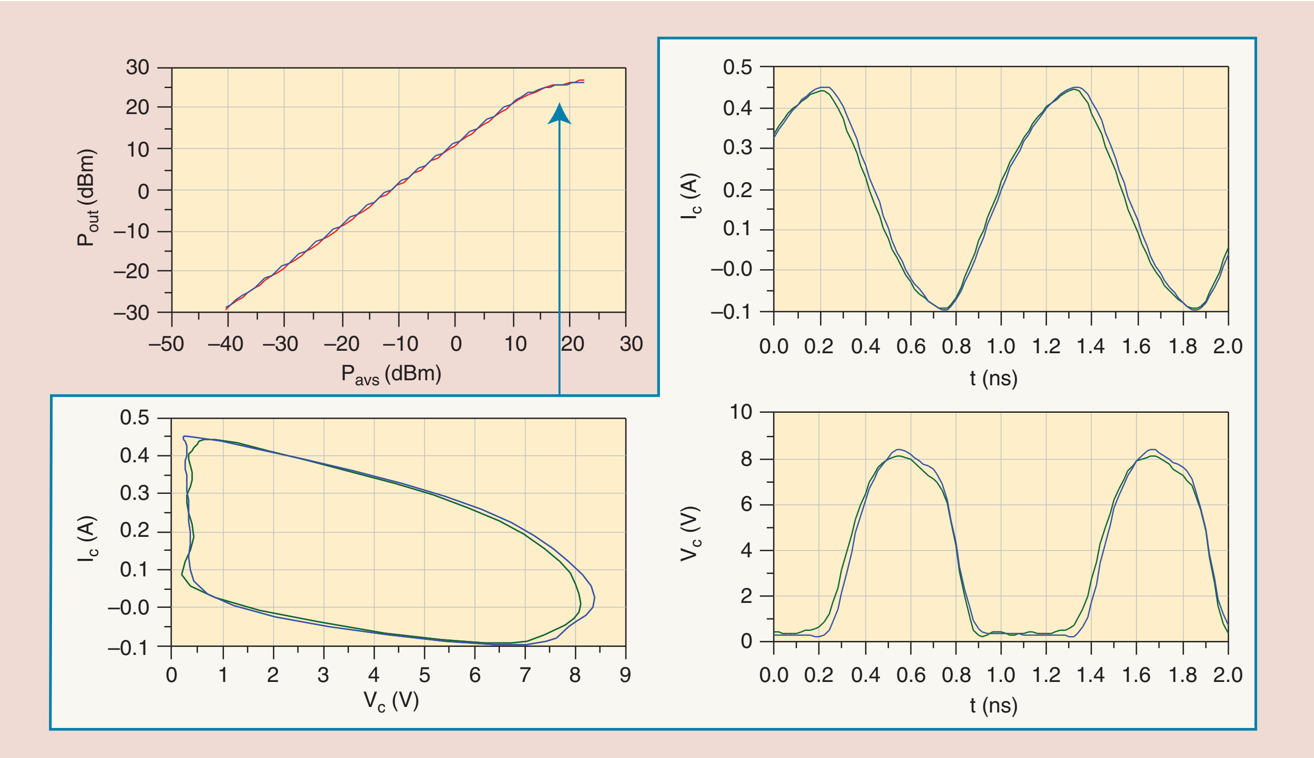

Figure 1. *Measured and simulated output power versus available source power for a building block of a cellular phone's power amplifier. The inset shows the measured and simulated current and voltage waveforms at a typical operating point.*

Group (ARFTG) Microwave Measurements Conference, since 2000 this group has also become a home for nonlinear measurements. Many of the researchers in this field have presented their work at ARFTG over the past several years. This field has also been well represented at the International Microwave Symposium (IMS); however, in recent years, there has been a surge in papers, posters, panel discussions, and presentations at these venues as well as other conferences and publications. To provide the *IEEE Microwave Magazine* reader with an overview of this field and avenues to explore greater depth, this focused issue will delve into this combined area, with articles on measurement techniques and behavioral models with a hint of a power amplifier design perspective.

This special issue has assembled several informative articles from lead researchers in the measurement and behavioral modeling field. In his article, "Get on the Same Nonlinear Page," Michael Heimlich leads things off with an overview of the various models that are being implemented in commercial circuit simulators. He contrasts the Cardiff model, X-parameters (a trademark of Agilent Technologies, Inc.), and S-functions. He also touches upon the nonlinear vector measurements connected with these models. Lastly, he discusses the activities of the OpenWave Forum, a user group striving to promote commonality in these measurements and models.

Paul Tasker and Johannes Benedikt then launch straight into the meat of the subject by discussing efficient ways to measure and utilize waveform data in power amplifier design with their article, "Waveform Inspired Models and the Harmonic Balance Emulator." By taking into consideration the requirements for the desired amplifier class of operation up front, measurement conditions can be synthesized that place the device into its proper operating state. Vector data can be collected at and around this optimal point that feed directly into a behavioral model, which allows design engineers to simulate their amplifier performance. The authors also discuss ways to condense the measured data set, which will speed up these simulations.

Authors Charles Baylis, Robert Marks, Josh Martin, Hunter Miller, and Matthew Moldovan delve into the popular subject of X-parameters and S-functions in their article, "Going Nonlinear." They give a tutorial overview of such nonlinear network parameters. They provide a solid explanation for these parameters, showing how these two formulations are related and tracing their connection back to S-parameters. The authors also explain the on- and off-frequency methods for measuring nonlinear network parameters. This article is accompanied by the sidebar, "X-Parameters Work for Transistors Too," by Loren Betts, Dylan Bespalko, and Slim Boumaiza, which gives a practical example of measuring and simulating with X-parameters. It demonstrates X-parameter measurements and simulations on an unmatched, GaN HEMT, power transistor at 1.2 GHz.

In their article, "NVNA Techniques for Pulsed RF Measurements," Patrick Roblin, Young Seo Ko, Chieh Kai Yang, Inwon Suh, and Seok Joo Doo discuss enhanced vector measurement techniques with sampler-based nonlinear

VNAs. The sampler-based class of instruments directly down-converts all spectral components of the measured waveform/signal. The alternate class of instruments is mixer based and measures individual frequency components one at a time. This article describes some of the pros and cons of these two approaches. It then presents the issues around and a solution for making pulsed, vector RF measurements. Pulsing is often required in device characterization to mitigate the effects of self-heating or dispersive traps. The authors further extend their sampler-based system with pulsed operation to create and demonstrate a real-time active load-pull measurement.

Guillaume Pailloncy, Gustavo Avolio, Maciej Myslinski, Yves Rolain, Marc Vanden Bossche, and Dominique Schreurs round things off with a discussion of an extension of nonlinear VNA measurements to lower frequencies in their article, "Large-Signal Network Analysis Including the Baseband." In modern communication standards, signals are typically modulated to convey the requisite data. Even the simple, analytical case of a two-tone signal can be represented as a single carrier frequency with AM modulation. However, often in these treatments, the impedance and waveforms at the baseband frequencies near dc are ignored. This is an unfortunate oversight because these baseband frequencies represent the "difference" intermodulation products of the RF frequencies in the spectrum around the carrier, and the baseband waveforms can, in turn, influence the unwanted intermodulation products near the carrier frequency. This article discusses measurement system extensions needed to measure these baseband waveforms and to synchronize them to the RF waveforms. It then provides application examples of these measurements in the development of models.

As the reader can see, there is a little something in this issue for the nonlinear enthusiast and lay person alike. Finally, I would be remiss if I didn't acknowledge those who helped make this issue happen. First and foremost, I thank the Editor-in-Chief, Dr. Kate Remley, who has helped with this issue every step of the way. Also, the diligence and support of the outgoing Assistant Editor, Sarah Ohlson, and the incoming Assistant Editor, Sharri Shaw (who has endured a bit of hectic on-the-job training) has been invaluable. My thanks also go to all of the reviewers for their helpful critiques as well as quick response times. This is especially true for the reviewers who also happened to be coauthors on articles. Lastly, to all the authors, thank you for sticking it out and helping to provide what I think is a very nice special issue.