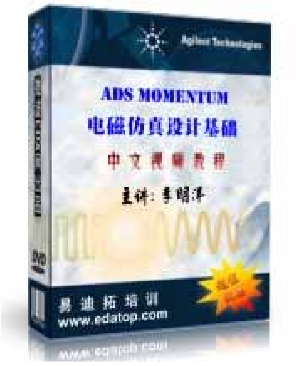
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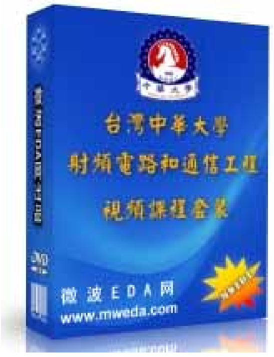
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NONLINEAR MICROWAVE/RF SYSTEM DESIGN AND SIMULATION USING *AGILENT* ADS 'SYSTEM – DATA MODELS'

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Abstract

The successful design of multi-chip modules for microwave systems using EDA tools has been enabled by using behavioral models for the IC components. Data-based models were created from large-signal measurements or simulations of the ICs, and the nonlinear performance of the module, such as gain compression, was simulated accurately.

Keywords

behavioral model, hierarchical design, microwave, multi-chip module, system simulation, grey-box

Introduction

Modern microwave and wireless systems are nowadays too complex to allow complete simulation of the nonlinear behavior at the transistor level of description. A higher level of abstraction of the design is required. This has led to the development of many types of "behavioral models" of the sub-systems and ICs that comprise the overall module. Such behavioral models include "black-box" models, in which the input-output behavior of the IC is described in an abstract mathematical formulation, for example a neural network(1); and "grey-box" models, where the device behavior can be fitted to a template description, for example, a polynomial transfer function, or given circuit topology.

In this paper, we are concerned with grey-box models that are based on look-up tables of data derived from large-signal measurements or nonlinear simulations of the IC. These grey-box models are available in the *Agilent* 'Advanced Design System' (ADS) microwave simulator, as 'System-Data Models'. We shall describe how the models were generated and used in the successful design of a broadband multi-chip microwave module.

Multi-Chip Module Design and Simulation

Challenges in RF/microwave module design include power and gain budgeting through the amplifier chain, and ensuring that no component is driven into saturation, hence creating unwanted harmonic and intermodulation products in the output signal. Because nonlinear simulation of a module using transistor-level models is impossible, due to non-convergence, complexity, etc., much simpler "simulation" tools such as *Microsoft* Excel® are often used to perform gain/power budgeting. This approach can only give an initial guess, since the interactions between the ICs in the module, and any frequency response effects are generally missing from this calculation. Such interactions include linear effects due to mismatch between components, and nonlinear effects leading to harmonic/intermodulation distortion.

It is an advantage to be able to use a single simulation environment for both system and circuit level design. This permits the same types of analyses to be carried out at all levels of hierarchy in the design of the system, and would enable a mixture of transistor-level and behavioral models to obtain optimal design and simulation capability.

Further, the ability to design and simulate with confidence at the behavioral level of hierarchy enables a number of different design alternatives to be explored without the need to build expensive and time-consuming hardware prototypes. This allows a broader aspect of the design space to be studied in an efficient manner.

ADS System – Data Models

A range of models exists in ADS to describe amplifier and mixer components, using measured or simulated large-signal data. These are the 'System – Data Models' In this paper we are primarily concerned with two-port models to describe amplifiers, switches, attenuators, etc. We have used the 'S2D Amplifier' and 'P2D Amplifier' models with the appropriate datafiles to model the ICs: the small- and large-signal behavior of the amplifier is captured in a datafile that is read by the model. The models' behavior, and the generation of the datafiles is described below.

S2D Amplifier

This is essentially a narrow-band amplifier model. It uses the measured S-parameters for matching, and models the large signal amplifier transfer characteristic by fitting a polynomial to the fundamental power out/power in (Gain compression) characteristic. Hence, the polynomial fit is an odd-order polynomial, and only odd-order harmonics are produced by this model. The associated 'S2D' datafile comprises a block of S-parameter data over a range of frequencies, and a 'GCOMP' table, which described the magnitude and phase of the gain compression at a single frequency.

We used this component to model switch and attenuator devices, using a broadband set of measured S-parameters in the datafile, and a gain compression curve measured at a single frequency in the band. With passive components the compression point is generally not the limiting factor in the overall module design, but some indication of when (say) the P_{-1dB} point is reached is a useful flag.

P2D Amplifier

This is a broadband amplifier model based on 'Large Signal S-Parameters'. The LSSP are defined as

$$S_{ij} = \frac{B_i}{A_j}$$

where the incident and reflected waves are defined as

$$A_j = \frac{V_j - Z_0 I_j}{2\sqrt{R_0}} \qquad \text{and} \qquad B_i = \frac{V_i - Z_0^* I_i}{2\sqrt{R_0}}$$

and the *V*s and *I*s are the Fourier coefficients at the fundamental frequency. The P2D Amplifier model reads a 'P2D' datafile that contains:

> a table of small-signal S-parameters over frequency;
>
> a series of tables of Large-Signal S-Parameters: each table is a single frequency, and contains the LSSPs as functions of the power incident at Ports 1 & 2. These tables need not be the same size, nor must the incident powers be identical from table to table: the interpolator in the ADS simulator can take care of this non-uniformity of the data, provided that one of the variables (i.e. frequency) is on a uniform grid.

The P2D Amplifier is monochromatic: works only at a single frequency – it cannot generate the harmonics produced by the nonlinear gain characteristic, but predicts well the gain compression behavior as a function of frequency across the (broad) bandwidth of interest. We used the P2D Amplifier to model the amplifiers in the multi-chip module.

Datafile Generation

The S2D and P2D Amplifier models were chosen because the associated datafiles are in text format – human readable, and can be generated easily from measured data on the actual ICs.

An *Agilent* 8510 Vector Network Analyzer was used with external amplification to generate the large drive signals at the input and output ports of the amplifier IC, and the fundamental tones were measured to determine the magnitude and phase of both Small- and Large-Signal S-Parameters at each input power level. This data was used to create the P2D and S2D files. The system setup is shown in Fig. 1.

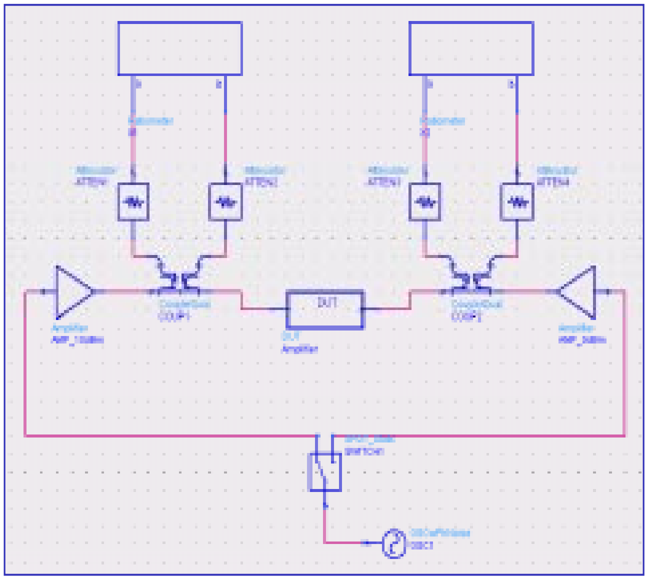


Fig. 1. *Agilent* 8510 VNA with external amplifiers for P2D file extraction.

These and other 'System – Data Models' can also be generated directly from simulation of the transistor level circuit in ADS. The setup shown in Fig. 2 generates the P2D file automatically.

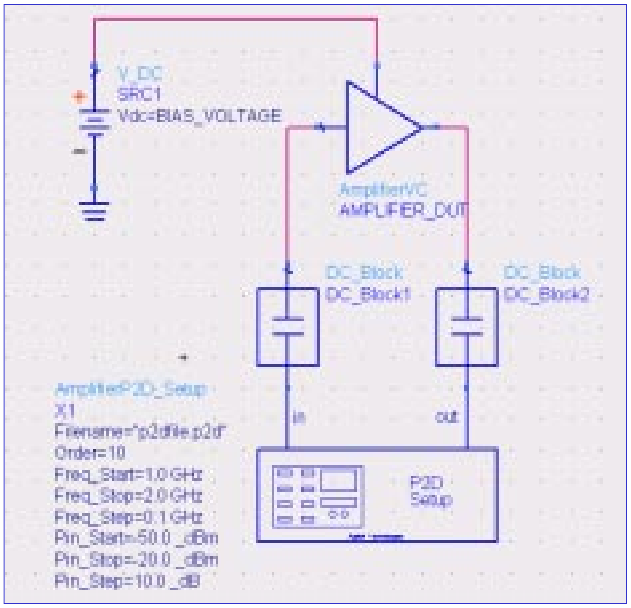


Fig. 2. *Agilent* ADS Setup for P2D file extraction.

An excerpt of a P2D file for a broadband amplifier, generated directly from measured data, is shown in Fig. 3. Further details of the file structures can be found in the ADS documentation(2).

```
BEGIN           ACDATA
#AC( GHZ        S     DB   R     50    FC    1      0 )
!Freq S11m      S11ph      S21m        S21ph        S12m          ...
![GHz][dBm]     [Deg]      [dBm]       [Deg]        [dBm]         ...
%F    n11x      n11y       n21x        n21y         n12x          ...
1     -18.3825  -99.2072   11.8947     138.8001     -59.1892      ...
1.5   -20.9719  -124.826   11.3667     130.0363     -58.8555      ...
2     -23.6244  -142.497   11.2236     120.0527     -53.9049      ...
2.5   -27.2905  -151.965   11.1670     109.9809     -52.6143      ...
3     -31.2688  -159.010   11.1751      98.9049     -54.8310      ...
.
.
.
!Large signal Sparameters Begin
%F
1
%P1       P2        n11x      n11y      n21x      n21y...
-2.6676   -6.6932   -18.2882  -100.292  11.8505   138.7...
-1.6483   -5.6746   -18.3437  -100.610  11.8476   138.7...
-0.6472   -4.6766   -18.3104  -100.877  11.8347   138.8...
 0.3686   -3.6554   -18.2969  -100.644  11.8233   138.8...
 1.3660   -2.6606   -18.3104  -100.783  11.8083   138.9...
 2.3590   -1.6623   -18.3385  -100.439  11.7885   138.9...
.
.
.
```

Fig. 3. Excerpt from P2D Data File

Model Verification

The models for each IC were compared against measured and simulated data, under small- and large-signal conditions. The table-data is interpolated between the measurement points using cubic spline functions, and extrapolated linearly outside the measurement data bounds. This yields a robust model in the simulator. The power compression characteristics of a broadband amplifier, comparing behavioral model and transistor-level circuit model, are presented in Fig. 4. The behavioral model is simulated on a finer grid than the original data, and can be seen to exhibit good interpolation and extrapolation characteristics. The grey-box model simulation ran about 300 times faster than the circuit level simulation.

Modeling the Multi-Chip Module

The multi-chip module for the broadband power source comprises amplifiers, switches, filters, attenuators and includes a frequency doubler. It is constructed on an RF printed circuit. In the ADS simulation, the module was constructed from behavioral models of amplifiers, switches, attenuators, and a circuit-level model for a frequency multiplier, as shown in Figure 5.

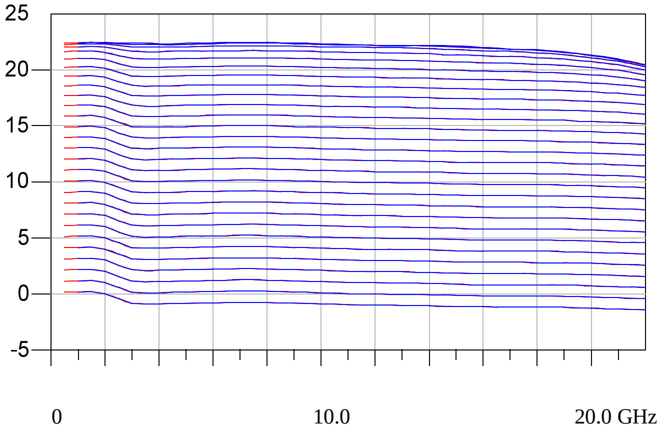


Fig. 4. Power output in dBm vs frequency, parameterized by input power, for a transistor-level circuit model (blue curves) and P2D Amplifier model (red curves)

S-parameter and power budget/compression analysis over the range of frequencies could be performed over the whole module, and each component's behavior examined, in a matter of seconds. As an example, the module power output is shown over the complete frequency range in Fig 6. These simulation results would be impossible to obtain by using full circuit-level models for every IC.

This simulation and analysis capability provided the designers with greater insight into the module behavior than was possible previously. For example, to obtain the good agreement between the measured and modeled output power shown in Fig 6 required more accurate models of the passive components in the module, such as the board connectors, on/off chip interconnects, etc.

Further, in the simulated structure we have the ability to 'probe' the module and investigate the interactions between the ICs, and study power levels and compression inside the module. Such a facility is not possible with the completed module: as with ICs, we cannot physically probe the circuit to measure these interactions.

For example, the module prototype exhibited higher harmonic levels than was expected, indicative of running an amplifier at higher compression than anticipated in the original design. By probing the power at every point in the amplifier chain, we can see in Fig. 7 that the Driver Amplifier to the output PA is running in compression. This would be difficult to identify from measured data alone: it might be expected that the final stage, the PA itself, is the device in compression. Here, with the aid of grey-box modeling, we are able to diagnose the problem, and hence determine a solution.

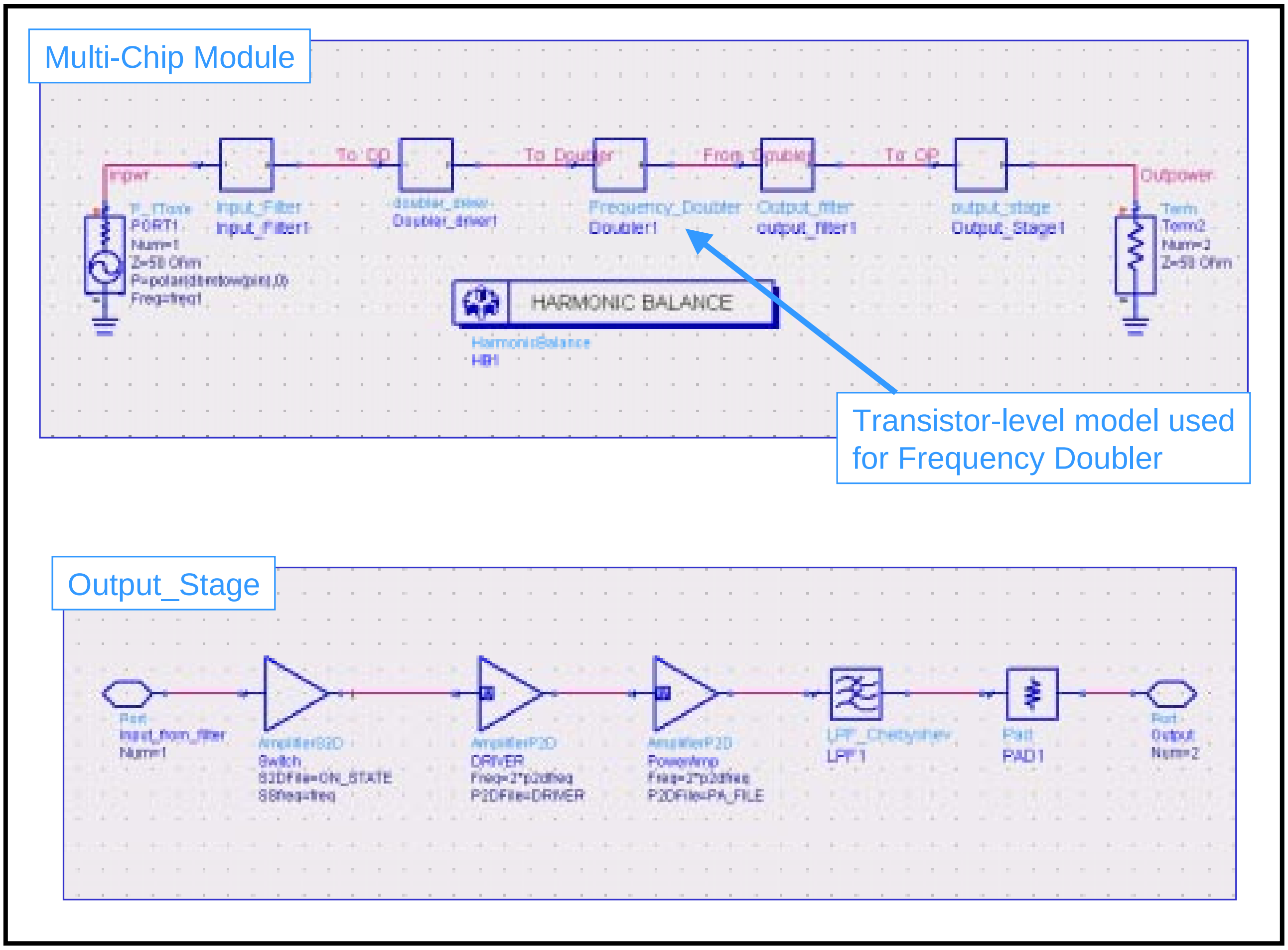


Fig. 5. Multi-Chip Module high-level schematic, and details of the sub-circuit containing the Amplifier Behavioral Models, in ADS.

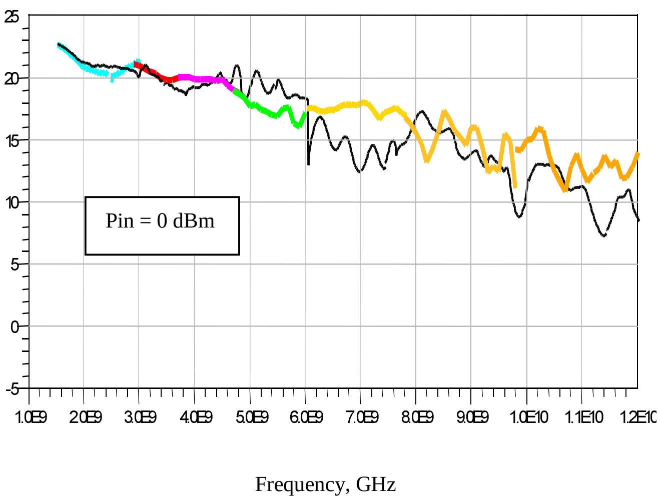


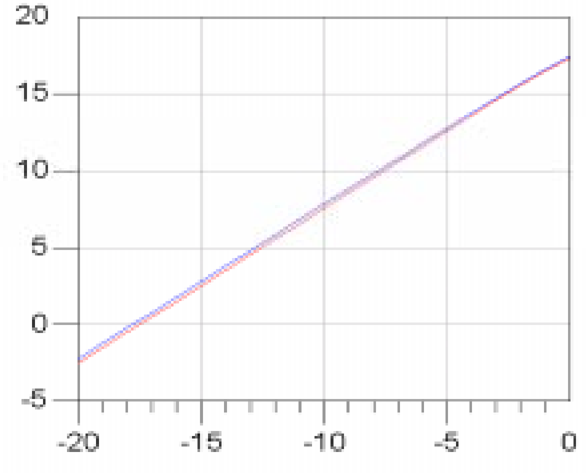
Fig. 6 Measured and modeled power output in dBm versus frequency for the Multi-Chip Module. The black trace is the measured data, the colored traces are the model predictions.

Conclusions and Further Work

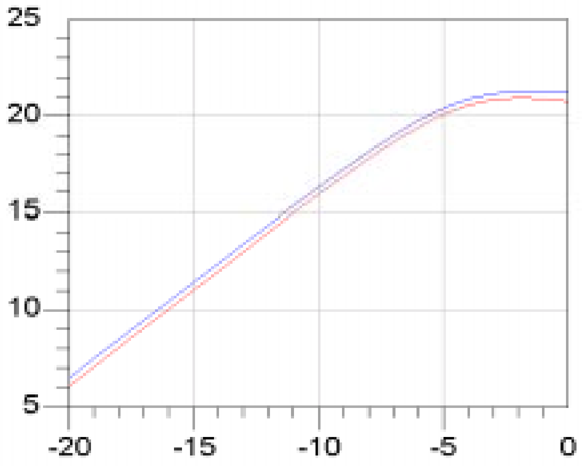
A complex microwave module has been modeled and simulated in *Agilent* ADS using grey-box System – Data Models. Excellent agreement between the modeled and measured data for the individual models and the overall module was obtained. Using the models enabled the identification of design issues that would have been otherwise impossible to correct.

The use of grey-box modeling as an integral part of module and system design enables the investigation of alternative design scenarios without requiring costly and time-consuming hardware prototypes.

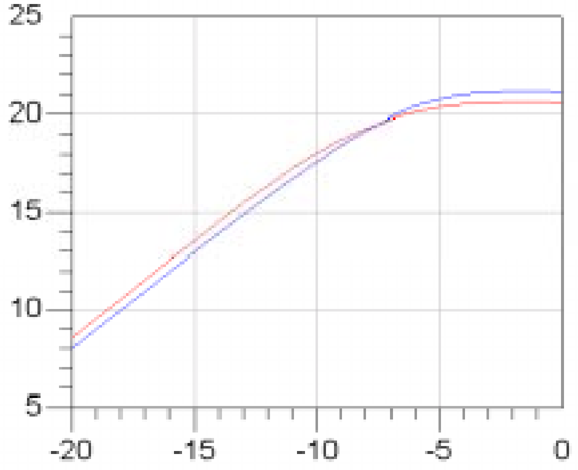
There are more sophisticated amplifier models in the ADS 'System – Data Models' portfolio. These models can be generated from simulation of the transistor-level circuit, using a built-in setup, producing an ADS dataset binary file that can be read by the model. These models can also be generated from measurement, by using an *Agilent* PNA-series E8364A Vector Network Analyzer, which can output its measured data in the ADS dataset format.



(a) Line Amplifier



(b) PA Driver Amplifier



(c) Module Output at PA stage

Fig. 7. Modeled Power Out versus Power In Compression Characteristics of the output stages of the Multi-Chip Module, showing compression occurring at the PA driver stage.

Further behavioral modeling development will focus on black-box modeling techniques, such as Non-Linear Time Series (NLTS), as described in Ref (1). This technique is founded in the principles of nonlinear dynamics and offers a more general and powerful approach to the transportable modeling of nonlinear circuits and systems.

References

(1) D. Root, J. Wood, N. Tufillaro, D. Schreurs, A. Pekker, 'Systematic behavioral modeling of nonlinear microwave/RF circuits in the time domain using techniques from nonlinear dynamical systems', this Workshop.

(2) ADS Documentation: 'Circuit Simulation, Appendix A'

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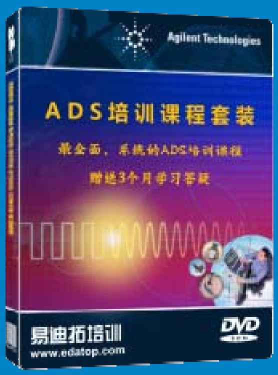

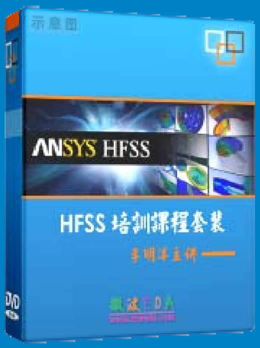

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