Black-Box Modeling of RFIC Amplifiers for Linear and Non-linear Simulations

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Behavioral modeling of RFIC amplifiers is presented, based on a novel approach that fits complex impedance dependent data for power compression, and Third Order Intercept (TOI) performance. An example, implemented in Agilent ADS, is shown for a commercially available RFIC amplifier operating in the 136 to 174 MHz range. Simulated to measured results are presented that demonstrate the ability to reliably re-create S-parameters, noise parameters, power compression, and intermodulation distortion behavior. The model also predicts noise and non-linear performance variation under source/load pull tuning.

Introduction

Behavioral (black box) models are widely used in system design and evaluation, because they simplify the modeling complexity of the sub-systems (mixers, amplifiers, etc) and cut short the simulation time. This is because behavioral models only considers the input/output relationship of the system under study and use mathematical expressions or data file based models to describe the observation of the system response. In this paper, a behavioral amplifier model will be introduced that characterizes compression and load pull performance using functions that describe large-signal S-parameters.

The concept of large-signal s-parameters was introduced in late 1990s [1], [2], [3]. Large-signal s-parameter is an extension of the small-signal scattering-parameters [4] for the purpose of representing the nonlinear performance of a system that is under large-signal excitation.

Figure 1 illustrates the intrinsic difference between the two concepts. Obviously, small-signal S-parameter describes the linear (small-signal) response of a system while large-signal S-parameter characterizes the nonlinear performance (harmonic generation, intermodulation performance, etc) through complete measurements of vector spectrum at the input/output ports.

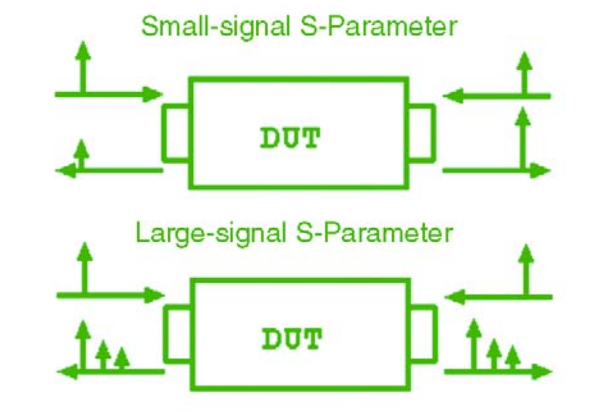

Figure 1: Small-signal and large-signal S-parameter comparison.

Modeling Approach

A simplified comparison of the small- and large-signal S-parameter is illustrated in **Eq. 1** and **Eq. 2**. **Eq. 1** gives the definition of small-signal S-parameters, where A_n and B_n represent the incident/reflected signals at port n and S_{ij} is the reflection coefficient (if i=j) or transmission coefficient (if i≠j). If the S_{ij}'s are dependent on the incident signals, as shown in **Eq. 2**, they become large S-parameters **[3]**. Here in **Eq. 2**, the conjugate part of the A2, which is incorporated in the formulation of the large-signal s-parameter definition, is neglected in the present example implementation.

$$B_1 = S_{11}A_1 + S_{12}A_2$$
$$B_2 = S_{21}A_1 + S_{22}A_2 \qquad \textbf{Eq. 1}$$

$$B_1 = S_{11}(A_1;A_2)*A_1 + S_{12}(A_1;A_2)*A_2$$
$$B_2 = S_{21}(A_1;A_2)*A_1 + S_{22}(A_1;A_2)*A_2 \qquad \textbf{Eq. 2}$$

The impact of the load impedance on the system performance is predicted through the cascade of S-parameter blocks, as shown in **Figure 2**. A_2 is represented with **Eq. 3**, since B_2 is then the incident signal to the load and A_2 is the reflected signal, assuming the external excitation (not shown in **Figure 2**) is applied at port 1. is the reflection coefficient of the load impedance. A similar relationship applies to the source side, for an excitation at port 2.

$$A_2 = B_2 * \Gamma_L \qquad \textbf{Eq. 3}$$

Figure 2: Source and Load Mismatch Effects

A limitation of this simplified large-signal S-parameter representation is that it needs measured datasets of the gain compression and phase compression under different source/load conditions to be able to accurately predict the harmonic and intermodulation performance. It is not trivial to obtain those datasets.

This limitation can be overcome by the use of Sinusoidal Input Describing Functions (SIDFs). SIDFs are used to model nonlinear system behavior under periodic excitation. This is achieved by relating the distortion signals to the fundamental input signals through linear descriptor functions or DFs **[6]**. **Eq. 4** presents a simple representation of the DF for the IM products under two-tone input stimulus signals:

$$IM_{i,j} = f(|A_{n1}|, [A_{n2}], i, j, \Gamma_L) \qquad \textbf{Eq. 4}$$

where A_{n1} and A_{n2} are the two input tones at port n. $IM_{i,j}$ represents the amplitude of the i, j IM product (i^{th} A_{n1} and j^{th} A_{n2}). The function

$$IM_{i,j} = f(|A_{n1}|, [A_{n2}], i, j, \Gamma_L)$$

can be linear or nonlinear (polynomial, etc), depending on the measured relationship between the IM, fundamental tones and the load impedance.

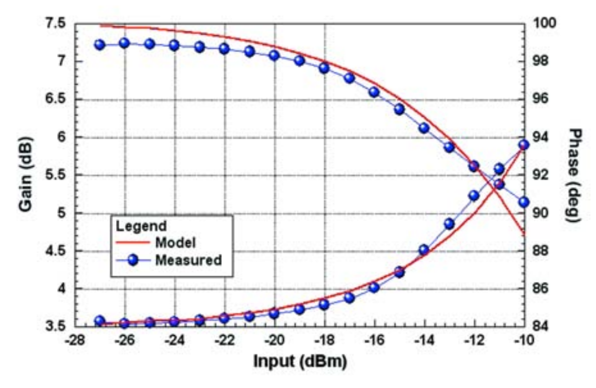

Figure 3: Displayed is a comparison of the 50 Ω gain compression and AM to PM compression for the Maxim 2371 amplifier at 155 MHz. (This was beyond the scope of the original statement of work, as were corresponding measurements.)

Example Results

As an example, a Maxim 2371 low noise amplifier (LNA) **[7]** was measured and characterized based on the method described above. S-parameter, single and 2-tone load pull, and compression measurements were performed. The datasets were then used to develop a non-linear behavioral model for the amplifier. The model was implemented in ADS 2002c using Frequency Dependent Device (FDD) component. The large s-parameter can be easily described using the port voltage/current variables provided by the FDD component. Furthermore, the FDD component enables the implementation of describing functions in the frequency domain, which makes the modeling of output spectrum fairly straightforward.

First of all the non-linear AM/AM (gain) and AM/PM (phase) characteristics are shown for the case of a 50 ohm input and output termination in **Figure 3**. The predicted results follow the measured results closely.

To explore the ability of the model to predict performance variation with load impedance, **Figure 4a** illustrates the gain vs. load impedance index. Each index corresponds to different tuner impedance as shown in **Figure 4b**. The simulated result shows the model tracks the load pull effect on single-tone output power. **Figure 4c** shows the gain compression performance of the LNA for a tuned impedance condition.

Finally, **Figure 5, pg** displays the good correlation achieved between measured and modeled 2-tone intermodulation distortion products for a specified load condition.

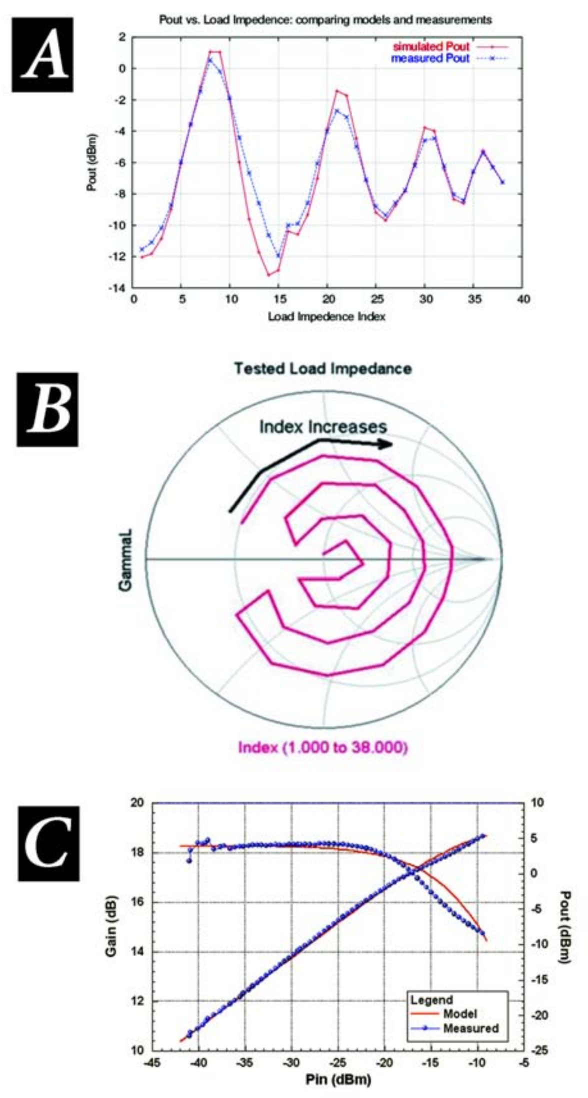

Figure 4: Comparison of simulation and measurement results for the Maxim 2371 amplifier. (a) shows the load pull results and (b) shows the impedances corresponding to the load-pull index (x-axis) of (a). (c) shows a 136MHz gain and power compression simulation compared to measurements, under the impedance conditions. Source = 77.11 + j*105.19 Ω and the Load= 254-j*56.3 Ω.

Conclusions

A behavioral modeling approach has been implemented for use in simulating termination dependent non-linear amplifier performance. The approach uses measured load-pull data and power-dependent S-parameter

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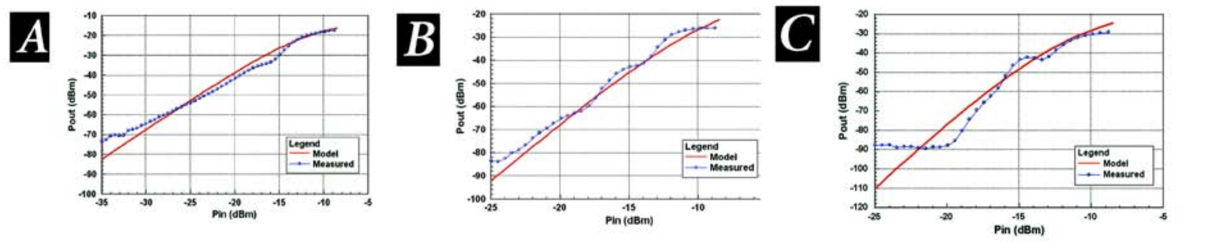

Figure 5: Displayed is a comparison of measured and modeled output power of the third (a) , fifth (b), and seventh (c) order intermodulation terms for a two-tone operation at 100 kHz spacing for the Maxim 2371 amplifier at 174 MHz. The source and load impedances are matched to the conditions specified by the load pull measurement. The source is 58.24+j83.27 Ω load is 287.82+j89.59 Ω.

information. Good measured to modeled agreement is demonstrated for single-tone and two-tone non-linear behavior of a commercial RFIC amplifier. Two device samples were used in the modeling work. If enough samples are available, the statistical distribution of the performance of the device can be derived. New parameters can be added to the model for this statistical analysis, which would be helpful for understanding and evaluation of the products.

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