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X-Parameter Measurement and Simulation of a GSM Handset Amplifier

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***Abstract*— X-parameters, also referred to as the parameters of the Poly-Harmonic Distortion (PHD) nonlinear behavioral model, have been introduced as the natural extension of S-parameters to nonlinear devices under large-signal drive [1]-[3]. This paper describes a new approach to X-parameter characterization and nonlinear simulation - including large-signal experimental model validation - of a commercially available GSM amplifier. A specially configured Nonlinear Vector Network Analyzer (NVNA) and procedure for measuring, for the first time, X-parameters under pulsed bias conditions is presented. The measured pulsed bias X-parameters are then used with the PHD framework to enable accurate nonlinear simulation of device behavior, including harmonics (magnitude and phase) under pulsed large-signal conditions with mismatch. Independent NVNA measurements validate the predictions of the X-parameter simulations of output match under drive, and show the inadequacy of "Hot S22" techniques to predict such device performance.**

Introduction

I. INTRODUCTION.

X-parameters have been previously introduced as the parameters of the Poly-Harmonic Distortion (PHD) nonlinear behavioral model [1]-[3], and can be viewed as the natural extension of S-parameters to nonlinear devices. A similar formalism is presented in [4]. While S-parameters are the linearization of the spectral map representing the behavior of a device at a DC operating point, X-parameters are the linearization of the spectral map about a Large Signal Operating Point determined by DC bias conditions and also one or more large RF input tones. X-parameters derived from measurement or simulation can be used in the PHD framework for very accurate simulation under large-signal drive in the presence of small to moderate mismatch, and can predict distortion through cascaded chains of nonlinear components. DC parameters can also be included to accurately predict bias-network interaction and PAE.

Like S-parameters, X-parameters can be easily and unambiguously identified from a set of simple experiments. The hardware required for X-parameter extraction is somewhat more complex, however, since small and large tones must be injected at multiple ports simultaneously, and cross-frequency phase coherence of measurements must be maintained. Due in part to the increased hardware complexity, previous X-parameter measurements have only been measured at fixed DC bias with CW inputs. This paper introduces a system capable of taking the large-signal measurements necessary to extract X-parameters under pulsed bias operating conditions. The system is used to extract X-parameters of a commercially available Skyworks GSM amplifier (SKY77329) [5] under pulsed bias stimulus closely resembling real-world operating conditions, and the measured X-parameters are inserted into the PHD framework for simulation of the device under complex modulated stimulus in Agilent ADS.

II. DEVICE UNDER TEST

The motivation for measuring X-parameters under pulsed bias conditions was to model the behavior of a GSM amplifier under conditions as close as possible to actual GSM applications. The model needs to be able to handle large signal inputs, accurately predict harmonics, and also predict the affects of mismatch at the fundamental and harmonic frequencies. The specific IC considered was the Skyworks SKY77329 Power Amplifier Module, which is commercially available and used as the PA block in the Sony Ericsson W810 quad-band GSM/EDGE mobile phone.

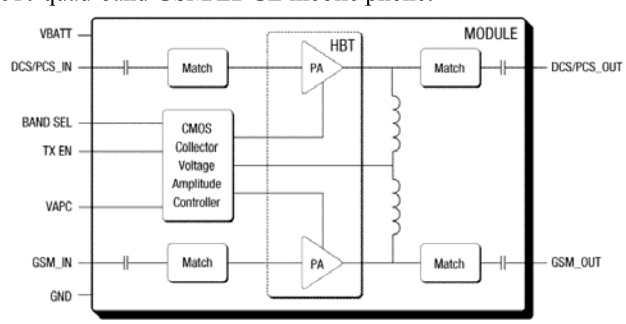

Fig. 1. Block diagram of SKY77329 Power Amplifier Module given on Skyworks Datasheet

The SKY77329 Power Amplifier Module is a multi-chip module (MCM) containing two RF amplifiers together with analog as well as digital control circuitry. The MCM contains a low-band amplifier operating around 900MHz and a high-band amplifier operating around 1800MHz. Each amplifier has its own RF input pins ("GSM_IN" and "DCS/PCS_IN") and RF output pins ("GSM_OUT" and "DCS/PCS_OUT"). These pins are AC coupled. Note that all of the other pins are common to the two amplifiers. The DC power is applied to the "VBATT" pin. The output amplitude is controlled by the voltage applied to the "VAPC" pin. The digital "BAND SEL" pin is used to control whether the low-band or the high-band amplifier is being used. The digital "TX EN" pin controls whether or not the amplifier is turned on.

III. Measurement Setup

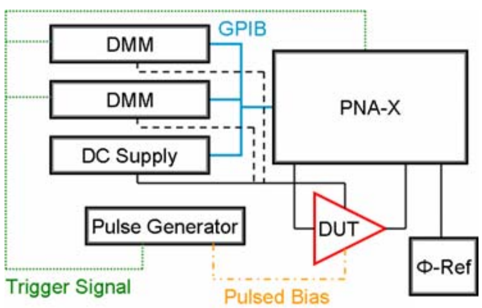

Fig. 2. Block diagram of pulsed bias X-parameter measurement setup.

In order to take the large-signal measurements necessary for X-parameter extraction, a Nonlinear Vector Network Analyzer (NVNA) was configured using the Agilent PNA-X performance network analyzer. By combining the PNA-X with an external phase reference generator and appropriate instrument control and processing software, fully calibrated large-signal measurements were made possible with the high dynamic range, speed, and the feature set of the PNA-X, including triggering and pulsed capabilities. The built-in second source, combiner, and switching capabilities of the PNA-X were particularly useful since X-parameter measurements require multiple simultaneous input tones at harmonically related frequencies and multiple ports.

An Agilent E3631A DC power supply was used to sweep the device bias conditions and Agilent 34411A digital multimeters were used to measure DC current drawn by the device, enabling DC dependence and bias network interaction in simulation as well as PAE prediction. These instruments were controlled from the software running on the PNA-X through the built-in GPIB controller. An Agilent 81110A Pulse-/Pattern Generator was used to provide pulsed bias conditions mimicking actual GSM timing and to provide a trigger signal for measurement synchronization.

In order to model the device behavior under GSM-like operating conditions, the first output of the pulse generator was connected to the enable pin of the DUT and set to a 1/8 duty cycle pulse with a period of 4.615 µs. The second output was set to rise 50 µs after the first for measurement triggering purposes. The multimeters were set to use aperture mode integration, with an aperture of 300 µs to ensure that the measurement was taken entirely during the pulse. The PNA-X was also configured in trigger mode, and the IF bandwidth was set to 10 kHz to meet the timing constraints. Measurement time was also a consideration, since the model was being extracted over a large range of operating conditions (9,720 Large Signal Operating Points per band). With this system, the total time required for measurement and extraction was about 4 hours per band.

IV. Enabling Simulation

The desired end result of these measurements was to produce a working nonlinear simulation model that resembles the DUT as much as possible in structure (including all relevant pins) and functionality, accurately representing the device behavior across its range of operation. Once the X-parameters have been measured, the next step taken toward accomplishing this goal was to generate PHD models for each band of the DUT. This was done using an auto-configuration script that creates and configures a model in Agilent ADS with the appropriate number of ports and harmonics based on the X-parameter measurements. Pins that were not swept in measurement, such as band-select and transmit-enable, were handled through external switching circuitry. This circuitry was combined with the high-band and low-band PHD models into a complete representation of the IC that includes full functionality of all pins and accurate representation of the device behavior across the operating range.

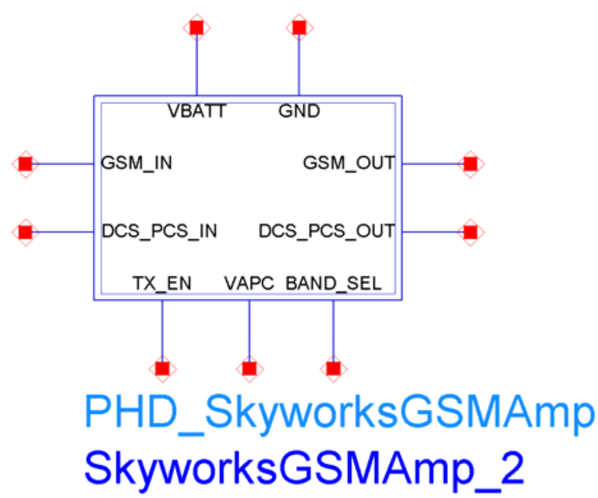

Fig. 3. ADS block representing the SKY77329 IC with full functionality of all relevant input/output pins, enabling pulsed simulation.

V. Results

The measured X-parameters were used in simulation under a variety of conditions, and accurately reproduce the device behavior. The IC was characterized across a wide range of bias conditions, so we chose a few specific points of interest at which Skyworks had provided data on the IC and compared the simulation results to the specified behavior. Output power was predicted as a function of VAPC, and results agreed very well with the provided data.

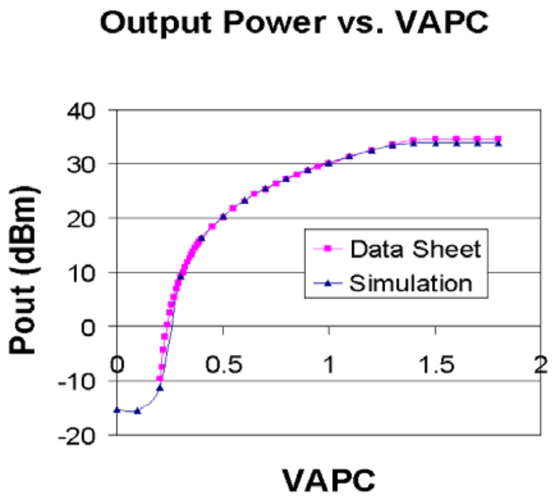

Fig. 4. Pout vs. VAPC comparison of simulation results and data provided with the IC.

Simulations sweeps were also run to verify the consistency of the measurements. Since the X-parameters for each large signal operating point are extracted from independent measurements, the smooth curves and consistent behavior of the DUT with respect to load changes, even on sensitive terms like the third harmonic phase, verify measurement consistency and repeatability.

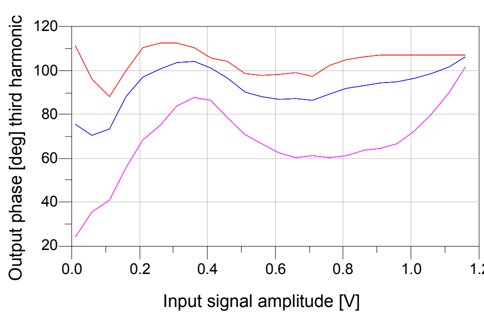

Fig. 5. Third harmonic phase vs. input power at fixed VAPC and VBATT. 25 ohm load shown in red, 50 in blue, and 100 in magenta.

To verify the accuracy of the X-parameters and illustrate their importance in characterizing a device like this, additional measurements were taken with tones injected at both the input and output ports of the DUT. The magnitude of the input tone at the output port was set such that the device saw an effective reflection coefficient of magnitude 0.5, and the phase was swept to cover a circular region on the smith chart. The measured b-waves of the device were then compared to the X-parameter predicted results, as well as traditional Hot S22 predicted results for comparison. The actual measured b-waves are very close to the predictions from the X-parameter measurements. Hot S22 predictions are not close to the actual measurements.

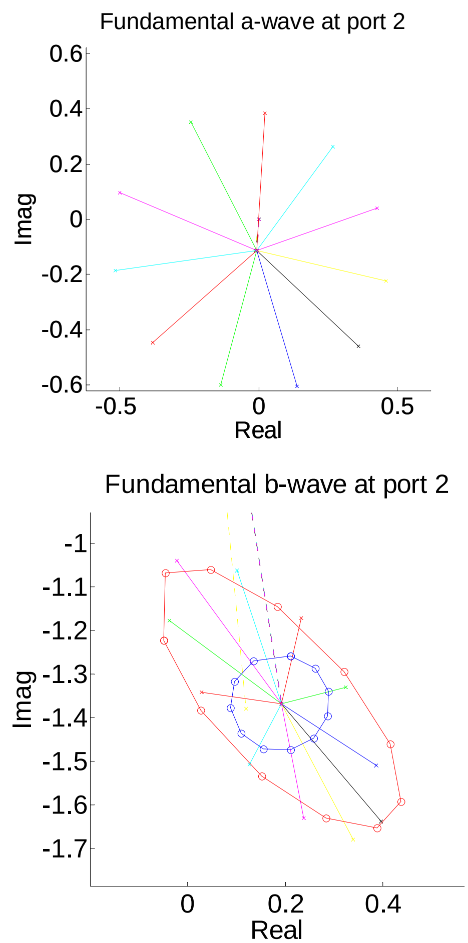

Fig. 6. **Top:** Measured complex amplitudes of injected tones at fundamental frequency at output DUT port, $a_{2,1}$ (colored "X"s at end of radial solid lines). **Bottom:** measured complex amplitudes of fundamental responses at output port, $b_{2,1}$ (colored "X"s at end of radial solid lines), X-parameter predictions (red circles) and classic Hot-S22 predictions (blue circles).

The inclusion of PHD blocks for both the upper and lower bands and additional switching circuitry in a single block in ADS allows correct simulation under pulsed conditions. The Envelope simulator can be used to accomplish this and much more with the resulting simulation block, including simulation with complex modulated stimulus. This allows simulation of the PA block under GSM-like conditions including the interaction effects with surrounding circuitry.

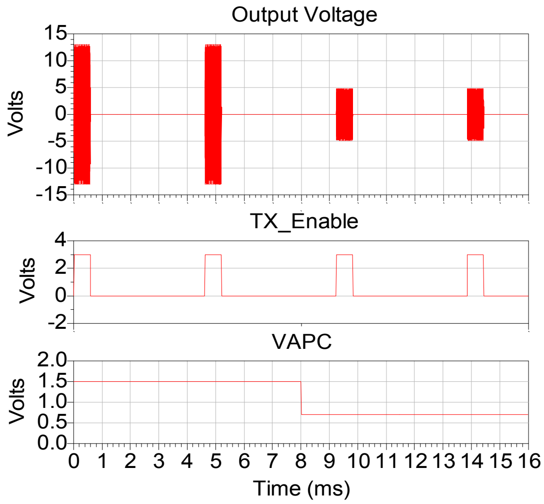

Fig. 7. Envelope simulation results under pulsed bias conditions.

The envelope simulation results include time domain waveforms at input and output ports of the DUT. In other words, the full magnitude and phase information at the fundamental and harmonics, as well as DC information, is predicted within each pulse. This model inherits the properties given in [1]-[3] of the PHD model, but since the X-parameters are measured under pulsed bias conditions closely resembling the actual application, the resulting model is more faithful to the device in pulsed applications.

VI. Conclusion

X-parameters, which have previously been shown to enable accurate simulation of nonlinear devices under large-signal stimulus in a mismatched environment, were measured on a commercially available GSM handset amplifier under pulsed bias conditions that closely mimic real-world operating conditions. The measurements were done efficiently on state-of-the-art equipment, enabling the rapid extraction necessary to meet the demands of the short product development cycle in the mobile wireless industry. The measured X-parameters were then packaged into a virtual representation of the IC with functionality at all relevant pins that accurately reproduces the device behavior in simulation. In particular, the output match under large-signal operating conditions is demonstrated to be in excellent agreement with the simulation model based on automated X-parameter measurements. This has practical implications for designers, who can directly use the model as a design tool to help integrate the IC into a handset, and for IC manufacturers, who can distribute such a model as an electronic datasheet for their product.

Acknowledgement

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