# Measurement and Modeling of Two Tone Transfer Characteristics of High Power Amplifiers

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*Abstract* - **The high power amplifier with class AB operation has a large memory effect and high nonlinearity. The usual AM-AM and AM-PM data cannot properly describe the large distortion characteristics. We present an accurate block model of the amplifier based on the two tone transfer characteristics. The measurement setup of the two tone transfer characteristics are described. The measured and modeled amplitude and phase data of the two tone harmonics versus input power level are presented. This behavioral model will be very useful for the design of a predistortion linearizer of high power amplifiers and for the nonlinear system simulation with a large memory effect.**

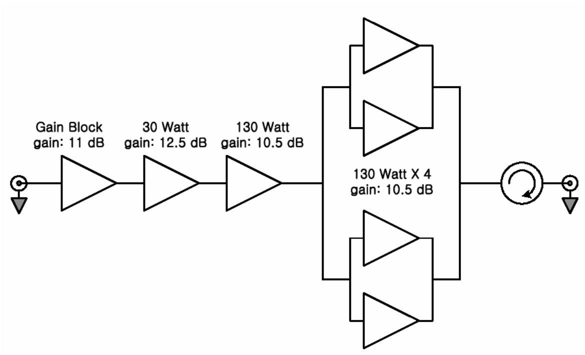



Fig. 1. Class AB high power amplifier module for the measurement and modeling

## I. INTRODUCTION

The behavioral or mathematical model of power amplifiers has been extensively studied. A class A power amplifier has normally been treated with the assumption of a memoryless (representation of AM-AM characteristics only) or quasi-memoryless (complex representation of both AM-AM and AM-PM characteristics) system [1]-[6]. But the characterization and modeling of a very high power amplifier with an output power of over a few hundred watts has not been reported. High power amplifiers with class AB or B operation generally have a large memory effect and strong nonlinearity. The single tone transfer characteristics cannot properly express the nonlinearity of these high power amplifiers. W. Bosch, et al. reported on a case where a predistortion linearized amplifier with improved AM-AM and AM-PM characteristics did not provide any enhancement on the two tone intermodulation nonlinearity [7]. Therefore, an accurate behavioral model based on the two tone characterization with phase information should be developed.

In this paper we present a new, accurate modeling and measurement technique for determining the two tone transfer characteristics of high power amplifiers. For the measurement, the amplifier output is down-converted to an IF frequency and the relative phase is measured by comparing with the reference signal. The relative phases of the harmonic terms of a very low frequency amplifier are 0° or 180°. A small power GaAs MESFET amplifier at 750 KHz is used for the reference IM(Intermodulation) generator. We have fitted the measured two tone data to the conventional model of AM-AM and AM-PM distortion characteristics. A 500 Watts class AB multi-stage power amplifier is used for the measurement and modeling. The measurement setup and sequence are described and the measured and modeled results are also shown.

## II. MEASUREMENT

### 1. *Main Amplifier Under Test*

A four stage amplifier is built for Korea's WLL band of 2.37-2.4 GHz. Its final stage consists of four balanced 130 Watt LDMOSFET (Motorola's RF LD-

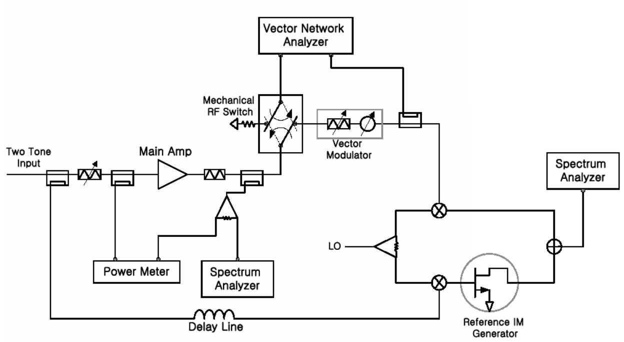



Fig. 2. Measurement setup for two tone transfer characteristics

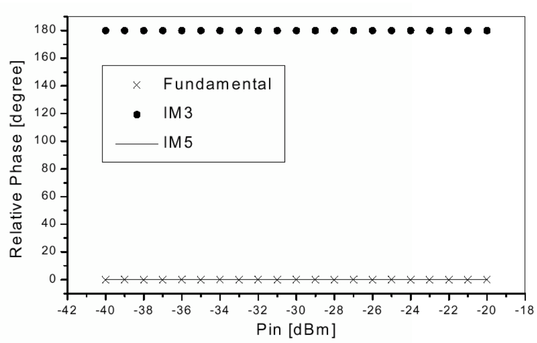



Fig. 3. Simulated relative phases of fundamental, IM3 and IM5 of reference IM generator as two tone input power level at a center frequency of 750 KHz

MOSFET MRF21120). It is a push-pull type with class AB operation. The other three stages are arranged to drive the final stage amplifier. The peak output power at the 1 dB gain compression point is about 500 Watts and the overall gain is 44.5 dB. The operational average output power is 45 Watts for the WCDMA signal with a chip rate of 8.192 Mcps. Fig. 1 is a line-up diagram of the main amplifier used for the measurement and modeling.

### 2. *Measurement Setup*

The measurement setup is shown in Fig. 2. This setup requires many measurement instruments: a two tone signal generator, a vector network analyzer, a two-input power meter, and two spectrum analyzers. The reference IM generator is a small power MESFET of HP's ATF21186 and is operated at a very low center frequency of 750 KHz. In the low frequency, the memory effect of the device can be ignored because its nonlinear capacitances are nearly open-circuited and the propagation delay is negligible. Hence, the device has no AM-PM characteristics and its fundamental, IM3 and IM5 show no phase variations with the input power level. This characteristic is verified by the two tone harmonic balance simulation using the large signal model of the device. Fig. 3 shows the results of this simulation. The phases of fundamental, IM3 and IM5 are constant throughout the input power level up to the 1 dB gain compression point. Fundamental and IM5 have an equal phase and IM3 is 180° out of phase because the third order volterra series coefficient (gm3) has a negative sign.

The two tone input signal, which has a tone spacing of 100 KHz, is tapped to the reference path. The main path signal passes through the step attenuator for input power level control and is then coupled to power meter A for monitoring input power. The main amplifier output signal is attenuated and coupled to power meter B for monitoring output power and to the spectrum analyzer for the relative power measurement of IM3 and IM5. The vector modulator, which consists of a variable attenuator and variable phase shifter, is used to adjust the amplitude and phase of the fundamental, IM3 or IM5 component of the output signal in order to cancel the corresponding reference signal component at the adder.

Finally, the output signal and the reference signal are down-converted to a very low frequency (around 750 KHz). The down-converted reference signal is amplified by the reference IM generator and the reference IM terms are generated. The output and reference signals are canceled using an analog adder circuit. This low frequency part may well be shielded to block out environmental noise. The vector network analyzer measures the required phase variation of the vector modulator for the cancellation by reading the phase of S21. The mechanical RF switch connects and disconnects the loop without breaking calibration.

### 3. *Measurement Sequence*

For the initialization, the vector network analyzer port 1 is connected to 50 Ω load and the main path is connected to the vector modulator by a mechanical RF switch, the two tone input is ON, and the input step attenuator is set to an appropriate starting power level. The input and output powers are read from the power meter and the relative amplitudes of fundamental, IM3 and IM5 are acquired from the spectrum analyzer. Then the vector modulator is adjusted to cancel the fundamental, IM3 or IM5 components. After the adjustment has been done, the two tone input is OFF at the signal generator and the RF switch changes the connection of vector network analyzer port 1 to the vector modulator and the main path to 50 Ω load in order to measure the relative phase variation of the vector modulator. After reading the phase of S21 from the vector network analyzer, the RF switch connects the main path to the vector modulator, the two tone input is ON, and input step attenuator is set to increase the input power level.

This sequence is repeated for the measurement of fundamental, IM3 and IM5 phases until the output power of the main amplifier is saturated. The measured data provide the relative phase variations of the fundamental, IM3 and IM5 components of the main amplifier. The reference IM3 phase offset of 180° is deembeded from the measured relative phase of IM3.

## III. MODELING

The measured two tone characteristics are fitted to the general quadrature AM-AM, AM-PM nonlinearity model. The nonlinear transfer function of the power amplifier is formulated as

$$v_{out}(t) \;=\; A[v_{in}(t)]\cdot \exp\{j\cdot \Phi[v_{in}(t)]\}$$

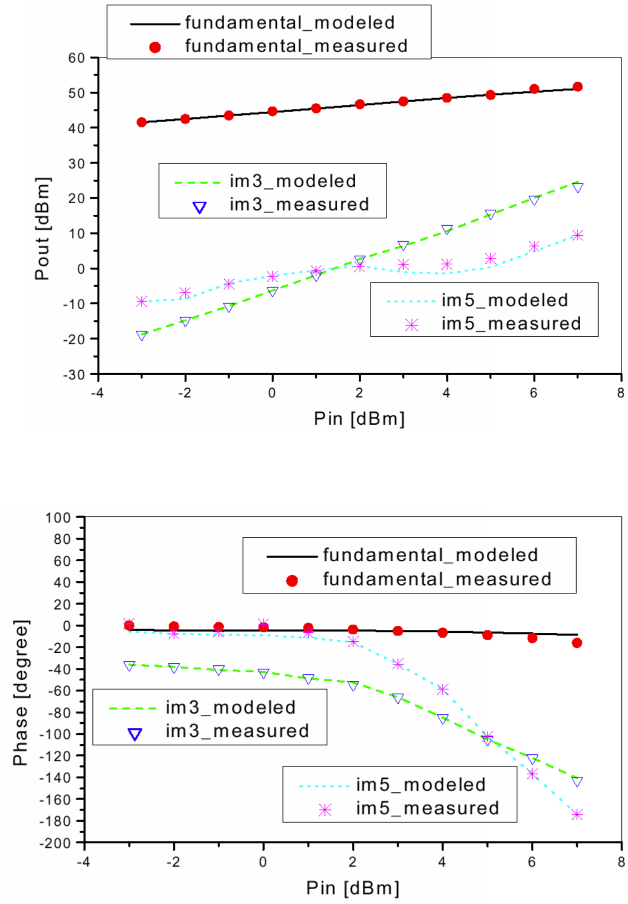
where $v_{in}(t)$ and $v_{out}(t)$ are the input and output envelope signals of power amplifier, respectively. In this experiment, AM-AM distortion function is modeled using a Fourier sine series and AM-PM distortion function is a rational polynomial. AM-AM and AM-PM functions used in this experiment are represented as

$$\begin{aligned} A[v_{in}(t)] \;&=\; a_0\cdot v_{in}(t) \\ &+ \sum_{n=1,2,3\cdots} a_n\cdot \sin[(2n-1)\cdot\xi\cdot v_{in}(t)] \end{aligned} \qquad (2)$$

$$\Phi[v_{in}(t)] \;=\; \frac{\sum_{n=0,1,2\cdots} b_n\cdot v_{in}(t)^n}{1+c_0\cdot v_{in}(t)^2+c_1\cdot v_{in}(t)^4} \qquad (3)$$

where $\xi$ is a input scaling factor. $a_n$'s are the AM-AM expansion parameters and $b_n$'s, $c_0$, and $c_1$ are AM-PM expansion parameters.

To extract the model parameters, we optimize all the AM-AM, AM-PM coefficients to fit the measured amplitudes and phases of fundamental, IM3 and IM5 simultaneously throughout the input power level. As the nonlinearity and memory effect of the amplifier increase, more amplitude and phase modulation coefficients are required to fit the measured data. We have used 27 parameters to represent amplitude modulation and 16 parameters to represent phase modulation of the class AB 500 Watts high power amplifier. Behavioral model is built and model parameters are optimized in HP ADS using SDD(Symbolic Defined Device).



(b)

Fig. 4. Measured and modeled two tone transfer characteristics of high power amplifier: (a) amplitudes and (b) phases

## IV. RESULTS

Fig. 4 shows the measured and modeled amplitude and phase characteristics of the high power amplifier under test. The two tone average output powers of fundamental, IM3 and IM5 are plotted in Fig. 4(a). The measured and modeled relative phases are plotted in Fig. 4(b). The first measurement point of fundamental is set to zero phase and the others are calculated to have relative values. The phases of IM3 and IM5 vary rapidly as the power level approaches saturation. The measured and modeled two tone characteristics are in good agreement.

To verify this model, the measured and modeled ACPRs of a WCDMA signal are compared. A WCDMA signal with a chip rate of 8.192 Mcps and average output power of 45 Watts, is used for the measurement. The measured data are compared with the simulated data in the WCDMA co-simulation of the

ADS. As shown in Fig. 5, the measured and modeled ACPRs have very similar trend.

## V. CONCLUSION

To adequately consider the memory effect of high power amplifiers, we have presented a new, accurate method for measuring and modeling two tone transfer characteristics. For the phase measurement, we have used a reference IM generator at a very low frequency. The two tone harmonic balance simulation shows the accuracy of the relative phase of the reference IM generator. The complete measurement setup and sequence have been described. For the experiment, we have employed a multi-stage high power amplifier with 500 Watt PEP and 44.5 dB gain. We measured the relative phases of fundamental, IM3 and IM5. The measured data of IM3 and IM5 are very smooth and continuous, and vary rapidly as the power level approaches the output power saturation.

These measured two tone amplitudes and phases have been modeled. The model could accurately represent high nonlinearities and rapid phase variations of a high power class AB amplifier. A WCDMA measurement and simulation have been conducted for verification. The measured and modeled ACPRs are in good agreement. This nonlinear behavioral model of a high power amplifier is very useful for the design of predistortion linearizer and various high power amplifiers.

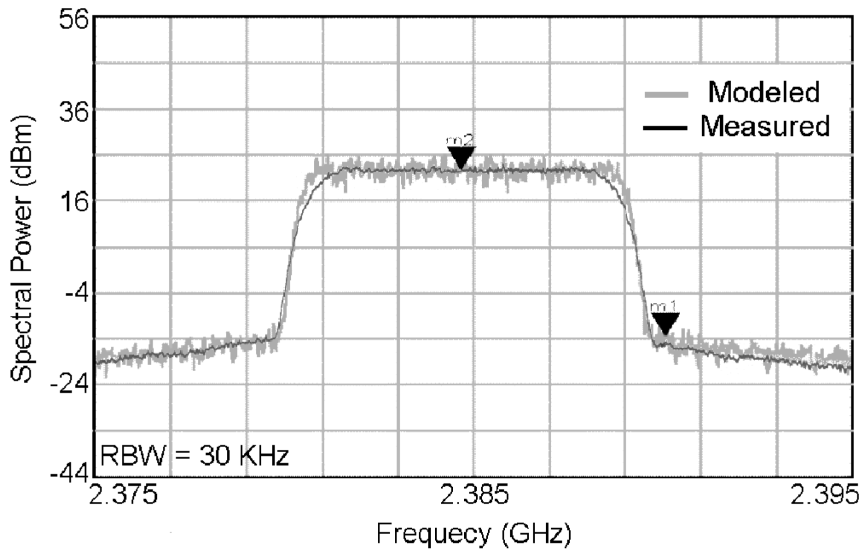



Fig. 5. Measured and modeled WCDMA responses with a chip rate of 8.192 Mcps and average output power of 45 Watts

## REFERENCES


[1] K. G. Gard, H. M. Gutierrez, and M. B. Steer, "Characterization of Spectral Regrowth in Microwave Amplifiers Based on the Nonlinear Transformation of a Complex Gaussian Process," *IEEE Trans. Microwave Theory Tech.,* vol. 47, No. 7, pp. 1059-1069, July 1999.

[2] H. Gutierrez, K. Gard, and M. B. Steer, 'Spectral Regrowth in Microwave Amplifiers Using Transformation of Signal Statistics," *IEEE MTT-S Int. Microwave Conf. Dig.,* pp. 985-988, Jun. 1999.

[3] Q. Wu, H. Xiao, and F. Li, "Linear RF Power Amplifier Design for CDMA Signals: A Spectrum Analysis Approach," *Microwave Journal,* pp. 22-40, Dec. 1998.

[4] C. J. Clark, G. Chrisikos, M. S. Muha, A. A. Moulthrop, and C. P. Silva, "Time-Domain Envelope Measurement Technique with Application to Wideband Power Amplifier Modeling," *IEEE Trans. Microwave Theory Tech.,* Vol. 46, No. 12, pp. 2531-2540, Dec. 1998.

[5] A. Leke and J. S. Kenny, "Behavioral Modeling of Narrowband Microwave Power Amplifiers with Applications in Simulating Spectral Regrowth," *IEEE MTT-S Int. Microwave Conf. Dig.,* pp. 1385-1388, 1996.

[6] S. Chen, W. Panton, and R. Gilmore, "Effects of Nonlinear Distortion on CDMA Communication Systems," *IEEE Trans. Microwave Theory Tech.,* Vol. 44, No. 12, pp. 2743-2750, Dec. 1996.

[7] W. Bosch and G. Gatti, "Measurement and Simulation of Memory Effects in Predistortion Linearizers," *IEEE Trans. MTT,* Vol. 37, No. 12, pp. 1885-1890, Dec. 1989.