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ANALYSIS OF MEMORY EFFECTS AND NONLINEAR CHARACTERISTICS IN RADIO FREQUENCY POWER AMPLIFIER

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ABSTRACT

Radio Frequency (RF) power amplifiers (PAs) have large memory effects and high nonlinearity.It is very important to analyze the system level performance of PAsaccurately using a simple behavioral or mathematical model.This paper proposes a system-level behavioral model for RF PA that exhibit memory effects.This model gives quite accurate results in predicting the behavior of PAs with memory effects.The proposed model is implemented in Agilent software. Description of memory effects and an accurate presentation of highly nonlinear characteristics based on the single-tone transfer characteristics for PA are presented. Gain for circuit level model and behavioral model is calculated.

Keywords: Cross Modulation, Gain Compression, Harmonic Balance, Inter Modulation Distortion, Power Amplifier.

I. INTRODUCTION

Most of the electronic devices are inherently non-linear. Nonlinearity is not desirable in devices like PAs.PA of radio communication system boost up the communication signal to adequate power levels before feeding it to the antenna. When PA operates at saturation, three kinds of nonlinear distortion are produced [1]. First one is harmonics, second one is cross-modulation (CM) and third one is inter modulation distortion (IMD).Harmonics occur at multiples of the carrier frequency f_c. Nonlinear multichannel PAs cause cross-modulation where the modulation of one carrier is transferred to another carrier. IMD produces harmonics close to the carrier frequency. So in this paper, to predict the behavior of PA, a system-level behavioral model for RF PA that exhibit memory effects has been presented. The analysis of memory effects and nonlinear characteristics based on the single-tone transfer characteristics for PA are presented. The paper outlines is as: section 1 is introduction, section 2 presents inter-modulation distortion and the effects of inter-modulation components, section 3 discusses non-linearity analysis of PA using Single-tone stimulus, results and discussions are in section 4 and section 5 is the conclusion.

II. INTERMODULATION DISTORTION

When a single frequency f_1 is fed through a PA ,whose output is not a linear function of its input, harmonics of frequency f_1 are generated, i.e. $2f_1$, $3f_1$, $4f_1$, $5f_1$, etc. Now, if two separate frequencies exist together in a non-linear device, sum and difference frequencies are produced in addition to these harmonics. This means if the two

original frequencies are f_1, f_2 and the higher frequency is f_2, and then we can expect two other components i.e.(f_1+f_2) and (f_2-f_1). These are the IMD, which are frequency components distinct from the harmonic components [1-2].To define the order, we add the harmonic multiplying constants of the two frequencies producing the intermodulationproduct. A typical spectrum produced could be shown asin Fig.1.

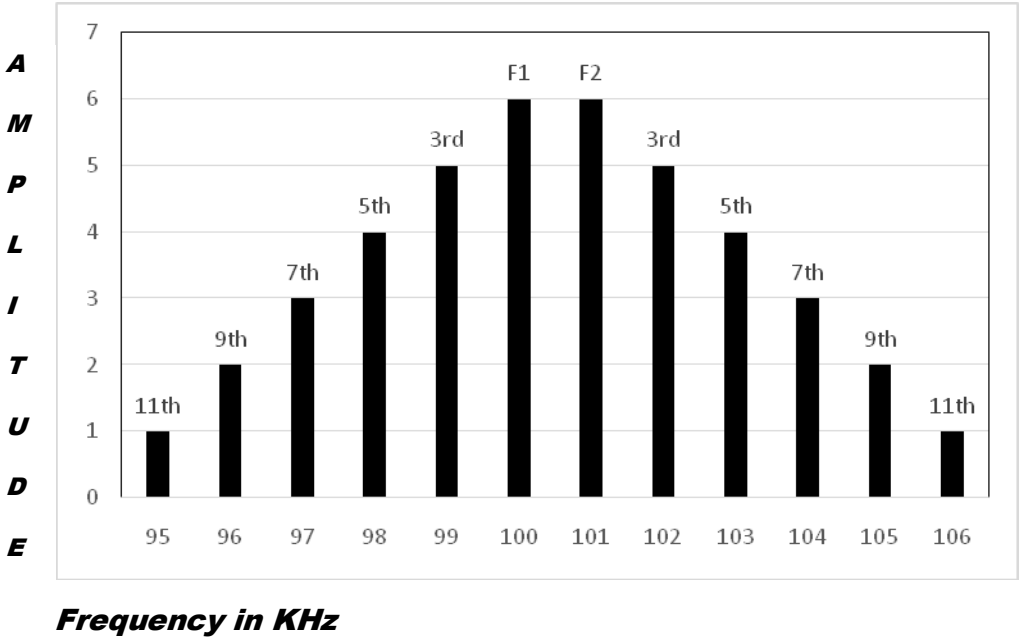


Figure 1: Spectrum of Inter-Modulation Components

The third order components are the closest and also usually the highest in amplitude.

From Fig.1, the odd order components spread out either side of the fundamental components in progression gradually decreasing in amplitude. These odd order, intermodulation components are of considerable concern in the first Mixer stage of a receiver. The function of the mixer stage is to produce some form of non-linearity so that an intermediate lower frequency is formed from the sum or difference between the incoming RF signal frequency and a local oscillator frequency. The mixer stage is, therefore, a prime spot for other undesired intermodulationproducts [3]. The transfer characteristic for an ideal linear PA are as shown in Fig. 2where

$$V_{out}(t) = G.V_{in}(t) \qquad (1)$$

Where, $V_{out}(t)$ is output, $V_{in}(t)$ is input power and G is the gain of the amplifier.The transfer characteristic is not linear up to the saturation point. The amplification decreases as the input power increases.

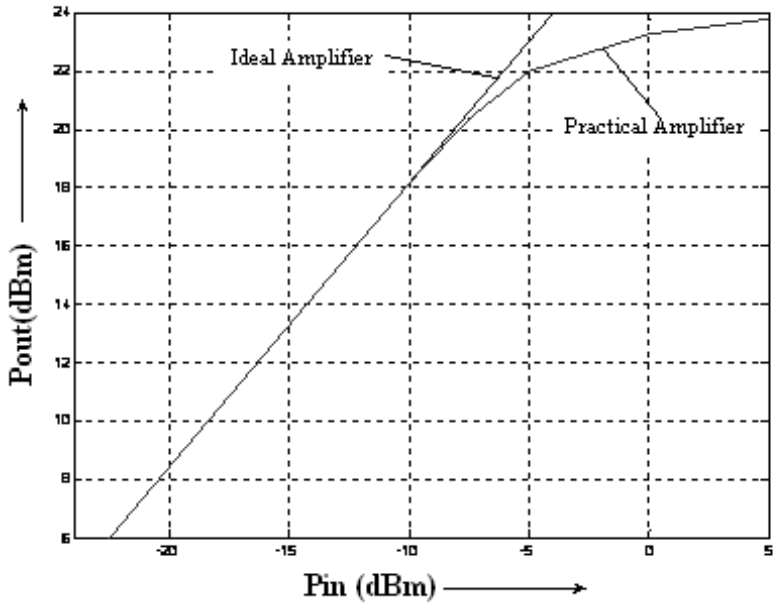


Figure 2: Characteristics of an Ideal and Practical PA

A linear curve is plotted for comparison. The saturating and nonlinear behavior is easily seen as the amplification decreases at higher input levels [4]. There are many methods to express the nonlinear effects in PA mathematically. Polynomial method is one of the important methods to show non-linearity of PA.. In this method, a power series will describe the relationship, i.e.

$$V_{out}(t) = a_1 V_{in}(t) + a_2 V_{in}{}^2(t) + a_3 V_{in}{}^3(t) + ---- \quad (2)$$

The transfer characteristic now includes not only the linear term but also the higherorder terms. In the equation 2, a third order polynomial represents the nonlinear transfer function. The second-order coefficient is positive and the third-order coefficient negative, which result in a compressive characteristic of the curve [5]. The more the input signal grows, the larger the influence of the higher-order powers. Feeding an amplifier with a signal of some frequency, the output signal will include unwanted frequency components. This is referred as AM/AM distortion, since the output amplitude will be distorted in relation to the input amplitude.The conversion of input power to output phase is called AM/PM response. The amplitudeof the input signal affects the output signal phase. Increasing amplitude levels willintroduce an increasing phase distortion on the output signal.

III. NONLINEARITY ANALYSIS OF PA USING SINGLE-TONE STIMULUS

For a linear amplifier output can be described as

$$Z_o(t) = G_{Lin}.Z_{in}(t) \quad (3)$$

Here G_{Lin} is a time independent linear amplifier gain.Practically due to non-linearity the output of amplifier saturates at some value as the input signal amplitude is increased.Due to non-linearity amplifier has a non-constant gain and non-linear phase.These amplifiers are called quasi-memoryless amplifiers and described by the polynomial as

$$Z_o(t) = \sum_{k=0}^{K} a_k . Z_{in}(t)^k \quad (4)$$

$$Z_o(t) = a_0 + a_1 . Z_{in}(t) + a_2 . Z_{in}(t)^2 + \ldots . a_k . Z_{in}(t)^k \quad (5)$$

In equation (5), k is the maximum polynomial order which shows the non-linearityof the amplifier. a_0, a_1, a_2, $\ldots a_k$ are complex polynomial coefficients,which determine the exact shape of the input-output characteristics[6-7].For memory-less case,these polynomials have only real values. By using trigonometric formulas, the quasi-memory-less PA will produce new frequency components which are located at the harmonics $2\omega, 3\omega, -----K\omega$ of the input signal.

$$Z_{in}(t) = V(t).Cos\left[\omega_c t + \theta(t)\right] \quad (6)$$

By substituting this value in equation 4, we get

$$Z_o(t) = \sum_{k=0}^{K} a_k . \left[V(t).Cos(\omega_c t + \theta(t))\right]^k \quad (7)$$

When time constant of the PA is very small compared to the amplitude $V(t)$ and phase $\theta(t)$,then for narrow band application i.e <1.2 MHz ,these amplitude and phase variations can be neglected and we assume it to be constant. But for high PAs, it comes in the form of memory effects[8-9]. Memory effects can be described as changes in the amplitude and phase of the output signal as function of the input signal amplitude and can be expressed as:

$$Z_o(t) = V_0(V_{in}).\cos\left[\omega_c t + \theta + \phi_{out}(V_{in})\right] \quad (8)$$

Whose complex envelop will be

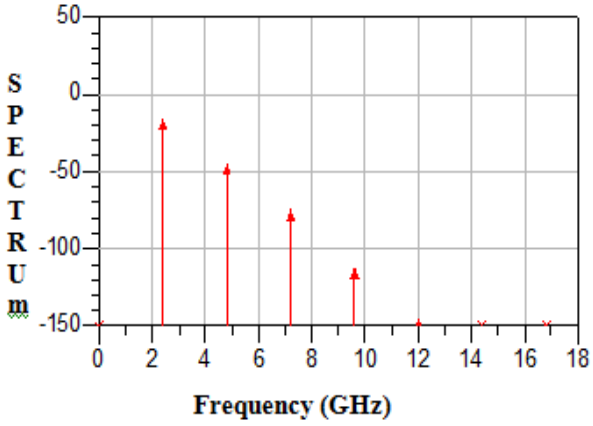
$$A_{out}(t) = V_{out}(V_{in}).e^{j[\theta + \phi_{out}(V_{in})]} \quad (9)$$

Here $V_{out}(V_{in})$ and $\phi_{out}(V_{in})$ represent the AM/AM and AM/PM conversions of the output signal at fundamental frequency. Both AM/AM and AM/PM conversions depend upon the amplitude V_{in} of the input signal.

VI. REULTS AND DISCUSSIONS

For simulation setup, parameters for PA are set as SP 12=0,SP 22=0.234+j0.005,SP 11=0.365-j0.419.Tone P1 is selected, which provides a single frequency sinusoid at a specified power. The available source power is set to 30 dBm, Signal Frequency is taken as 2.4GHz and the non- linear order is set to 7.The output voltages and current waveforms are observed by the harmonic balance simulation. Output waveform contains various frequency components as shown in Fig. 5. At 0 GHz, only DC term is present. There are three solutions to solve this scenario, one is auto select which is a linear solver, second one is direct solver when problem is too small i.e. few non-linear components are present and third one is Krylov solver, which is used for large number of non-linear components.

Fig.3 illustrates the results of the simulation, showing the fundamental and higher order harmonics, amplitude decreasing with increasing frequency. Fig. 4 shows the load voltage with time. The output response to RF power input has been shown in Fig. 5.The results for different harmonic components have been shown in Fig.6, 7, 8, and 9. The blue color represents circuit level behavior whereas red color shows behavioral response. Thus overall memory effects and nonlinear characteristics are represented with the help of single-tone transfer characteristics for PA to predict the PA behavior. From measurements Fundamental frequency is computed as 2.4 GHz, available source power is 10dBm, output power is -17.138dBm, transducer power gain is -27.138dBm, second harmonic is computed as -28.5 dBc, third harmonic is computed as -58.488dBc, fourth harmonic is computed as -128.693dBm. Low signal power at fifth, sixth and seventh harmonics have very less significance.



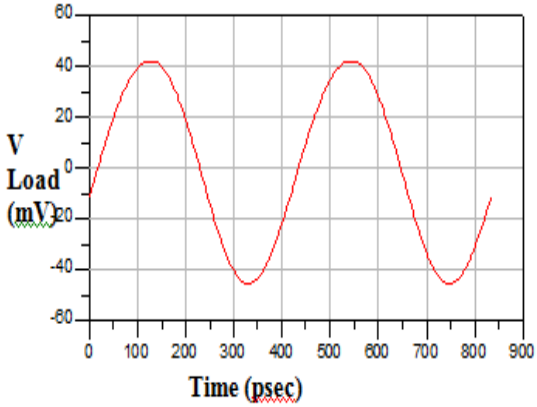


Figure3: Harmonics at PA Output **Figure 4: Output power of Power Amplifier**

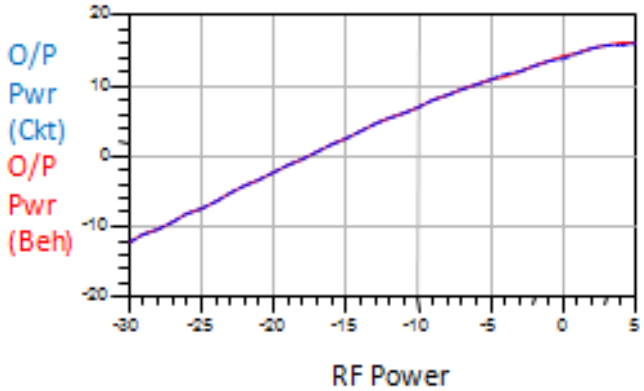


Figure 5: First Harmonic Component of Behavioral Model and Circuit Model

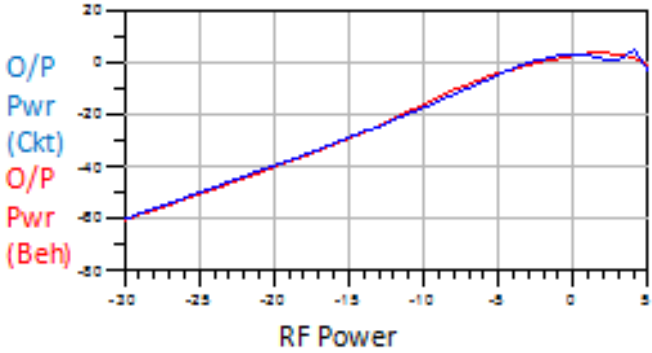


Figure 6: Second Harmonic Component of Behavioral Model and Circuit Model

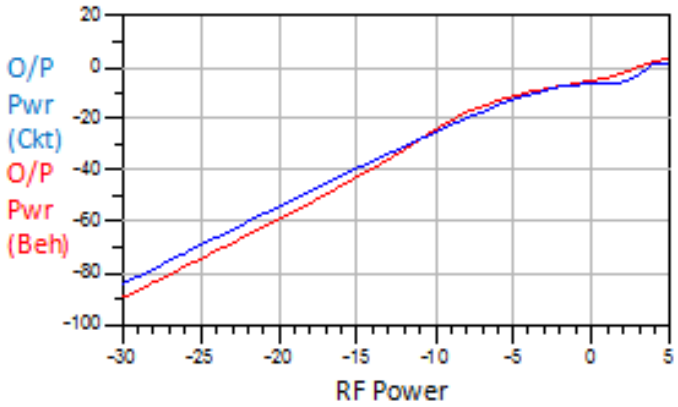


Figure 7: Third Harmonic Component of Behavioral Model and Circuit Modal

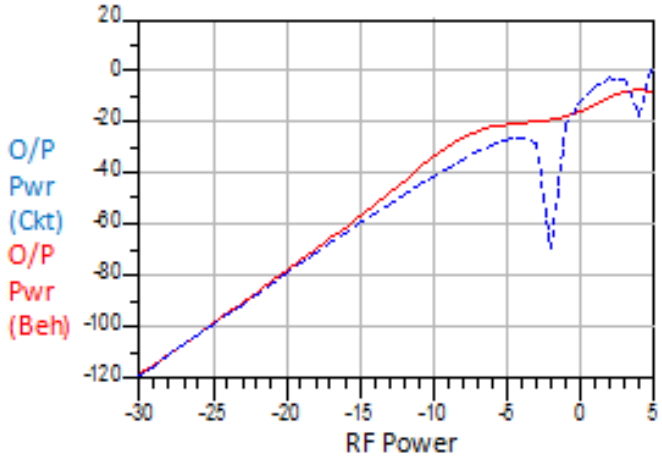


Figure8: Fourth Harmonic Component of Behavioral Model and Circuit Model

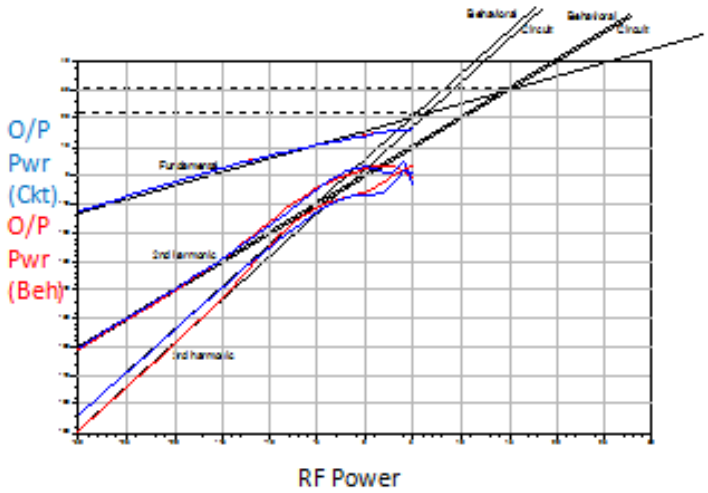


Figure9: Tangents for Fundamental, Second and Third Harmonics of Behavioral Model and Circuit Model

V. CONCLUSION

A new, accurate method for measuring and modeling single-tone transfer characteristics has been presented to take into account the memory effect of high power amplifiers. The dependence of the inter-modulation

distortion components on single tone signal is presented to discover memory effects in PA.In this paper memory is predicted in terms of first and second harmonics accurately i.e modal constructed match first and second harmonics accurately.The third and fourth harmonics are predicted less accurately.These measured single-tone amplitudes have been modeled. The model accurately represents high nonlinearities of a high power amplifier. A LTE signal measurement and simulation have been conducted for verification. This nonlinear behavioral model of a high power amplifier is very useful for the design of various predistortion linearizers.

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