Analysis and Measurement of Two Tone intermodulation distortion in Wideband Power Amplifier

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Abstract—*Wideband power amplifiers (PAs) generally have large memory effect and high nonlinearity. In non-linearity, Inter modulation distortion (IMD) is an important metric. For a wide range of RF components, the usual AM-AM and AM-PM data cannot properly describe the large distortion characteristics. So an accurate amplifier behavioral modeling method based on two-tone transfer characteristics is presented, which is quite useful to analyze memory effects for third and fifth order harmonic in terms of intercept points, and these are calculated using the harmonic balance test. PA gain for harmonic level simulation and circuit level simulation is calculated. The memory effects are analyzed up to 5th order and the dominance of memory effects in third order has been verified with the simulation results*

Keywords — *Behavioral Model, Gain compression, Inter modulation distortion, Memory effects.*

I. INTRODUCTION

(PA is indispensable component in a communication system and is inherently non-linear. Non-linearity is one of the key issues in design of wideband PA. As the signal bandwidth gets wider, PA begin to exhibit memory effects. Some methods to measure memory effects in PAs are available (Bosch and Gatti, 1989; Ku and Kenney, 2003; Vuolevi et al., 2001). Although wideband signals are spectrally more efficient, but they are subject to severe IMD distortion when the PAs are operated outside of their linear range. Intermodulation distortion analysis can be a tool to measure nonlinear behavior of PA. These signals can be represented by two tone testing which is suitable for showing the non-linear behavior of PA. The effects induced are intermodulation distortion (IMD), which is very dominant in third order. The effects of the IMD is even more significant than harmonic distortions of PA.

Two tone third order IMD is the measure of the third-order distortion products produced by a nonlinear device, when two tones closely spaced in frequency are fed to its input [4]. This distortion product is usually so close to the carrier that it is almost impossible to filter out this distortion. This distortion product can cause interference in multichannel communications. The paper is organized as: section 1 is introduction, section 2 discusses the non-linearity of power amplifier, performance indices upon which the performance of a PA can be evaluated in terms of harmonic distortion, intermodulation distortion and gain compression is in section 3, section 4 describes the results obtained from behavioral and circuit level simulation to model the PA for two tone frequencies and last section 5 concludes the paper.

II. NONLINEARITY OF POWER AMPLIFIER IN TWO-TONE ANALYSIS

Let the two-tone input signal to the power amplifier is

$$Z_{in}(t) = V_{in}\cos_{\omega 1}(t) + V_{in}\cos_{\omega 2}(t) \quad (1)$$

For $\omega_1 < \omega_2$, $\omega_2 - \omega_1 = \Delta\omega$

$$Z_{in}(t) = 2V_{in}\cos\left(\frac{\omega_2 - \omega_1}{2}t\right).\cos\left(\frac{\omega_2 + \omega_1}{2}t\right) \quad (2)$$

Here frequency $\left(\frac{\omega_2 - \omega_1}{2}\right)$ is the modulating frequency ω_m, which is half of the frequency spacing between two tones. $\left(\frac{\omega_2 + \omega_1}{2}t\right)$ is the RF center frequency. So equation 2 can be written as:

$$Z_{in}(t) = 2V_{in}\cos(\omega_m t).\cos(\omega_{cen} t) \quad (3)$$

This two tone signal is recognized as double sideband suppressed carrier signal having carrier frequency ω_{cen} and modulating frequency ω_m [2]. When this signal is applied to power amplifier the output signal can be expressed as

$$Z_o(t) = \sum_{k=0}^{K} a_k.\left[V(t).Cos\omega_1 t + V(t)\cos\omega_2 t\right]^k \quad (4)$$

By expanding equation 4 with the help of trigonometric equations new frequency components will appear, which shows the non-linearity of the device. These new components are called inter modulation distortion [5]. These new frequency components ω_{new} are produced in the output spectrum of the amplifier. In two-tone signal these are computed as

$$\omega_{new} = \left|\pm\alpha.\omega_1 \pm \beta.\omega_2\right| \quad (5)$$

Where new = 1, 2, 3-----------, α and β are positive integers including zero. $\alpha+\beta=k$ denotes the order of the inter modulation distortion.

III. PERFORMANCE INDICES WITH TWO TONE TEST

If a single tone signal with frequency f is applied to a nonlinear device, the output will include signals of frequencies of the form $(n.f)$, where, $n=2,3,4,\ldots$ is harmonic distortion and it will be always greater than one. If a two tone signal with frequencies f_1 and f_2 is applied to a nonlinear device, the output will include frequencies of the form $mf_1 \pm nf_2$, where m and n are integers greater than zero. Theses frequencies are called inter modulation products. The order of a given inter modulation product is defined as $|m|+|n|$. Two-tone test is used to assess the amplitude and phase distortions present in a PA. In the two-tone test, the envelope of the input signal is varied throughout its complete range so the PA is tested over its whole transfer characteristics [5]. Let input signal be represented by:

$$V_i(t)=v\cos f_1(t)+v\cos f_2(t) \tag{6}$$

Then the output voltage is

$$\begin{aligned} V_o(t) &= a_1 v\left[\cos(f_1 t) + \cos(f_2 t)\right] + \\ & a_2 v^2\left[\cos(f_1 t) + \cos(f_2 t)\right]^2 + \\ & + a_3 v^3\left[\cos(f_1 t) + \cos(f_2 t)\right]^3 + \\ & a_4 v^4\left[\cos(f_1 t) + \cos(f_2 t)\right]^4 + \\ & + a_5 v^5\left[\cos(f_1 t) + \cos(f_2 t)\right]^5 + \\ & a_6 v^6\left[\cos(f_1 t) + \cos(f_2 t)\right]^6 + \ldots\ldots \end{aligned} \tag{7}$$

When viewing the nonlinear response of the amplifier in the frequency domain, a number of extra frequencies will be present as shown in equation 7. The output signal consist of a DC term, which is the wanted signal, the original cosine signal, a cosine signal with double frequency and a cosine signal with three times the original frequency [6]. The frequencies which are multiples of the original frequency are referred as over tone or harmonics. Second harmonic is twice the original frequency, third harmonic is three times etc. The sign of a1 and a3 determine whether the distortion product adds or subtracts from the fundamental. Additive means gain expansion, subtraction means gain compression [7]. With multicarrier modulation schemes, even harmonic components could be filtered out, but 3rd and 5th order distortion component will exist with the fundamental channel [8]. The most serious inter modulation product is the 3rd order inter modulation product, because it is usually close to the desired frequency and cannot be completely filtered out [9]. These distortions can be measured in terms of harmonic distortion, inter modulation distortion, adjacent channel power ratio, error vector magnitude, crest factor which is a measure of peak to average power ratio (PAPR), third order intercept point etc.

IV. RESULTS

IMD occurs when more than one input frequency component is present in the PA input. Two-tone simulations are generally performed with two closely spaced input frequencies. In two tone test the frequency spacing is swept between the input tones. Here fundamental RF signal of 2.4 GHz is taken as input, F spacing is taken as 20 MHz and RF power is 10 dBm. So the two frequencies are:

$$f_1 = RFfrequency - \frac{Fspacing}{2}$$

$$f_2 = RFfrequency + \frac{Fspacing}{2}$$

So $f_1 = 2400 - {}^{20}\!/_{2} = 2.39$ GHz and

$f_2 = 2400 + {}^{20}\!/_{2} = 2.41$ GHz.

Frequency order specifies the number of harmonic frequencies to be calculated, here maximum IMD order is 7. It is same for both frequencies f_1 and f_2. Behavioral modal of PA is shown in Fig 1.

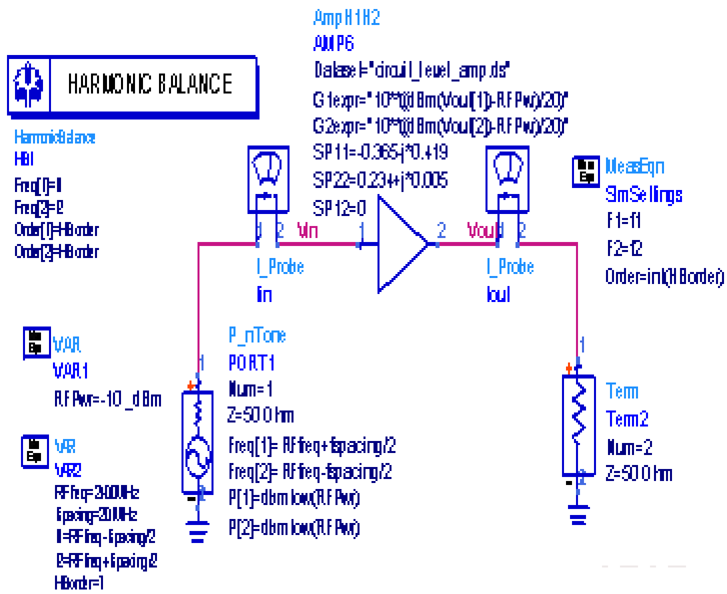

Fig. 1 Behavior model of power amplifier

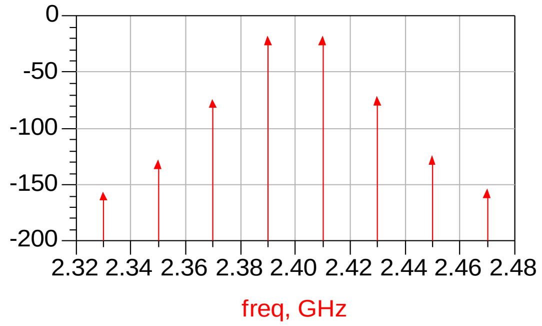

Fig. 2 Intermodulation products of two tone test

Fig. 2 shows inter modulation products up to the 7th order. Here (f_1+f_2) is second order, $(2f_1-f_2)$ is third order, $(3f_1-2f_2)$ is fifth order, & so on. Frequencies f_1 and f_2 of 2.39 GHz and 2.41 GHz respectively are 20 MHz apart from each other. Fig. 2 and Table 1 represents the inter modulation products.

Table I Intermodulation products

First order	f_1 = 2.39 GHz	f_2 = 2.41 GHz
Second order	f_1+f_2 = 4.8 GHz	f_2-f_1 = 0.02 GHz
Third order	$2f_1-f_2$ = 2.37 GHz	$2f_2-f_1$ = 2.43 GHz
	$2f_1+f_2$ = 7.19 GHz	$2f_2+f_1$ = 7.21 GHz
Fourth order	$2f_1+f_2$ = 9.6 GHz	$2f_2-2f_1$ = .04GHz
	$3f_1-2f_2$ = 2.35 GHz	$3f_2-2f_1$ = 2.45 GHz
Fifth order	$3f_1+2f_2$ = 11.99 GHz	$3f_2+2f_1$ = 12.01 GHz
Seventh order	$4f_1-3f_2$ = 2.33 GHz	$4f_2-3f$ = 2.47 GHz

From Table 1, it can be seen that only the odd order inter modulation products are close to the two fundamental frequencies f_1 and f_2. First one of third order product $(2f_1-f_2)$ is 2.37 GHz lower in frequency than f_1 and another $(2f_2-f_1)$ is 2.43 GHz above f_2. First one of fifth order product $(3f_1-2f_2)$ is 2.35 GHz below f_1 and another $(3f_2-2f_1)$ is 2.45 GHz above f_2. In fact the odd order products are closest to the fundamental frequencies f_1 and f_2. Let's expand further the odd order products of table 1. The series of odd order products can be seen to descend and ascend progressively in increments of 20MHz from the two fundamental frequencies f_1 and f_2 respectively. For circuit level simulation, input voltage and frequencies are taken as same.

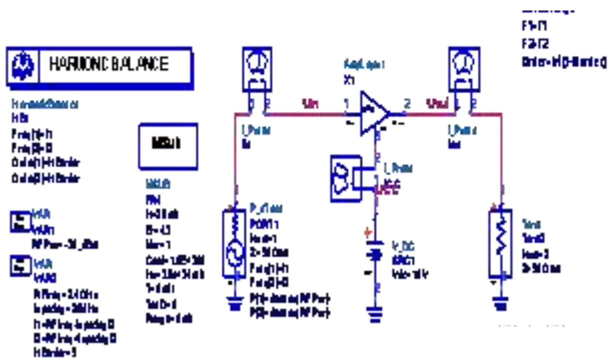

Fig. 3 Circuit level model of power amplifier

Combined effect of Behavioral model and circuit level model is shown in Fig. 4. Effect of inter modulation products at frequencies f_1 =2.39 GHz and f_2 =2.41 GHz is shown in Fig. 5.

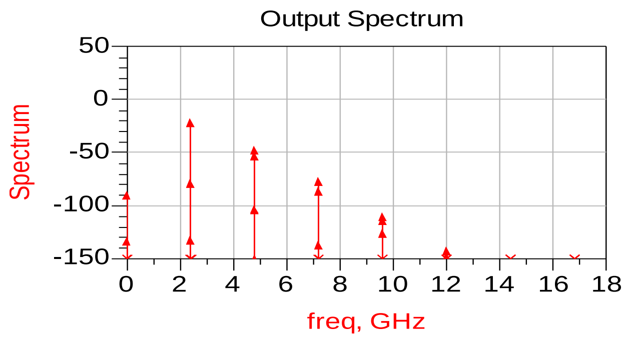

Fig. 4 Combined inter modulation products

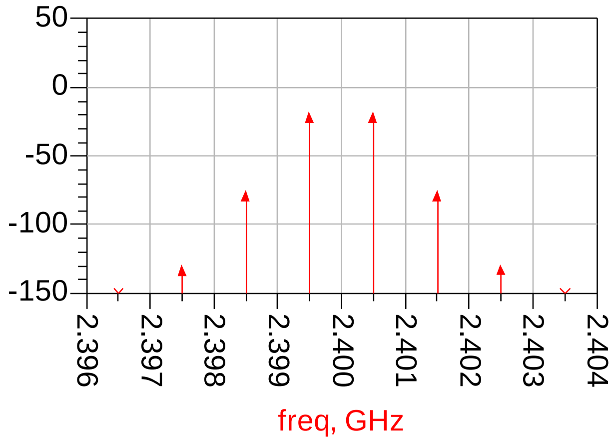

Fig. 5: Inter modulation products generated by two tone test

In behavioral model for two fundamental frequencies f_1 (2.39 GHz) and f_2 (2.41 GHz), for source power 10 dBm, output power is calculated for both tones is -17.141 dBm. Transducer power gain calculated is -27.141. From circuit level simulation for two frequencies f_1 (2.39 GHz) and f_2 (2.41GHz), and source power of 10 dBm, output power for both the tones is -17.139 dBm, transducer power gain is -27.139. From circuit level and behavior level simulation, output power and the transducer gain is almost same for both the tones. The odd order products have more effect than even order harmonics. The amplifier third order intercept values appear almost symmetrical as shown in Fig. 5. Output third order intercept points for third order output intercept is calculated as 8.392 dBm on lower side and 8.305 dBm on higher side. Output third order intercept points for fifth order output intercept is calculated as 7.606 dBm on lower side and 7.538 dBm on higher side. Input third order intercept point for third order output intercept is calculated as 35.531 dBm on lower side and 35.444 dBm on higher side. Input third order intercept points for fifth order output intercept is calculated as 34.744 dBm on lower side and 34.677 dBm on higher side.

V. Conclusion

A two tone distortion analysis was presented for nonlinear power amplifier. Linearity and linearization can be considered from both a fundamental signal and IMD product. The two tone signal producing intermodulation is quite useful to represent the behavior of a PA. A behavioral model of PA was built and its small signal IMD asymmetry is analyzed in terms of gain and IMD products. From results, it has been concluded that Input third order intercept points of third order and Output third order intercept points of fifth order are almost identical and third order IMD products have more influence on PA output as compare to fifth order products. Memory effects can be measured with the help of two-tone signal analysis.

References

[1] Hyunchul Ku, J. Stevenson Kenney, "Behavioral modeling of nonlinear RF power amplifiers considering memory effects", *IEEE transactions on microwave theory and techniques*, vol 51, pp. 2495-2503, 2003.

[2] P. B. Kenington, *High-linearity RF amplifier design*, Artech House, Boston, London, 2000.

[3] F. H. Raab, P. Asbeck, S. Cripps, P. B. Kenington, Z. B. Popovic, N. Pothecary, J.F. Sevic, N. O. Sokal, *"Power amplifiers and transmitters for RF and microwave," IEEE Transactions on Microwave Theory and Techniques,* vol. 50, pp. 814–826, Mar. 2002.

[4] Singla, R., & Sharma, S., "Digital predistortion of power amplifiers using look-up table method with memory effects for LTE wireless systems," *EURASIP Journal on Wireless Communications and Networking*, pp. 1-8, 2012.

[5] H. Ku, M. D. McKinley, and J. S. Kenney, "Quantifying memory effects in RF power amplifiers," *IEEE Trans. Microwave Theory Tech*., vol. 50, pp. 2843–2849, Dec. 2002.

[6] N. Borges De Carvalho and J. C. Pedro, "Two-tone IMD asymmetry in microwave power amplifiers," *IEEE MTT-S Int. Microwave Symp. Dig*, pp. 445–448, 2000.

[7] H. Ku, M. D. Mckinley, and J. S. Kenney, "Extraction of accurate behavioral models for power amplifiers with memory effects using two-tone measurements," *IEEE MTT-S Int. Microwave Symp. Dig*., pp.139–142, 2002.

[8] D. Wisell, M. Isaksson and N. Keskitalo, "*A general evaluation criteria for behavioral power amplifier modeling*," in ARFTG 69, Honolulu, USA, pp. 251-255, 2007.

[9] S. C. Cripps, *RF Power Amplifiers for Wireless Communications*, 2nd ed. Boston: Artech House, 2006.