

THIRD ORDER AND FIFTH ORDER INTERCEPT POINT IN RF POWER AMPLIFIER

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ABSTRACT

Two tones test is a method to quantify memory effects in power amplifier (PA) with variable input power levels and frequency. PA is excited with two different radio frequency (RF) signals of equal magnitudes and is equally spaced from centre frequency. Fifth order inter modulation (IM) is significant when the fifth-order IM is relatively high compared to the third-order IM. Using this method, input output intercept point is measured at low side and high side for fifth order and third order.

KEY WORDS

Power amplifier, memory effects, third order intercept point, fifth order intercept point, gain, spectrum etc.

I. INTRODUCTION

It was generally assumed that the effects of the fifth order IM can be ignored. The out-of-band power caused by fifth order IM is significant when the fifth-order is relatively high compared to the third-order. In this study, the simulation and analytical methods are applied to evaluate the TOI and FOI of the RF power amplifier. This analysis also makes it helpful to design RF power amplifiers for other different communication standards [1-4]. A very simple PA input output diagram is shown in fig. 1 in this diagram $V_{in}(t)$ is input voltage, G is a multiplier constant and $V_{out}(t)$ is output voltage [6-7].

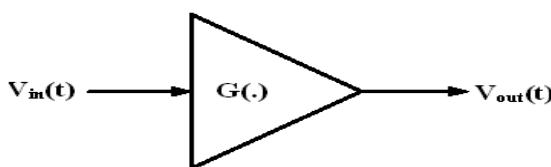


Fig. 1 General PA

In linear PA, the output signal is equal to a constant times the input signal, therefore

$$V_{out}(t) = G \cdot V_{in}(t) \quad (1)$$

Practically PA is non linear, Taylor series (8,9-11) defines the non linear PA in mathematically

$$V_{out}(t) = G_1 V_{in}(t) + G_2 V_{in}^2(t) + G_3 V_{in}^3(t) + \dots + G_n V_{in}^n(t) \quad (2)$$

For analysing above equation $V_{in}(t)$ can be taken as one tone signal or two tones signal. One tone and two tone $V_{in}(t)$ signals are $V \cos \omega t$ and $V_1 \cos \omega_1 t + V_2 \cos \omega_2 t$ respectively. Here

$$f_1 = f_c - \frac{\Delta}{2} \text{ and } f_2 = f_c + \frac{\Delta}{2}, \quad \Delta \text{ is frequency spacing}$$

and f_c is centre frequency [6-7]. When two or more different frequency signals applied at the input of PA then additional signals are also generated with fundamental signals at the output of PA. The new generated signals are inter modulation (IM) products or harmonic components. IM products or harmonic components have frequencies different from the fundamental frequencies [10-13]. IM products can be in band or out of band. Second order sum and difference products i.e.

$f_2 \pm f_1$ are the out of band IM products and the third order products ($2f_1 - f_2$ and $2f_2 - f_1$) are in band products and so on. All even (2^{nd} , 4^{th} etc) order products that occur at far from the fundamental frequency signals are out of band IM products. But all odd order (3^{rd} , 5^{th} etc) products that occur near the fundamental frequency signals are in band IM products [6, 7 and 10]. The even order (out of band) products could be easily filtered out but odd order (in band) products are very challenging IM products in PA. This paper is organized as: Section I introduction, Section II is mathematical analyses of third and fifth order intercept point, Simulation results are presented in section III and Section IV presents summarizing the work with conclusion.

II. THIRD AND FIFTH ORDER

INTERCEPT POINT

The third order intercept (TOI) point corresponds to the fictitious input or output level at which the third order IM product would exhibit the same level as that of the fundamental at the output. Similarly the fifth order intercept (FOI) point corresponds to the fictitious input or output level at which the fifth order IM product would exhibit the same level as the fundamental at the output. Fig 1 shows the TOI and FOI points [14-18].

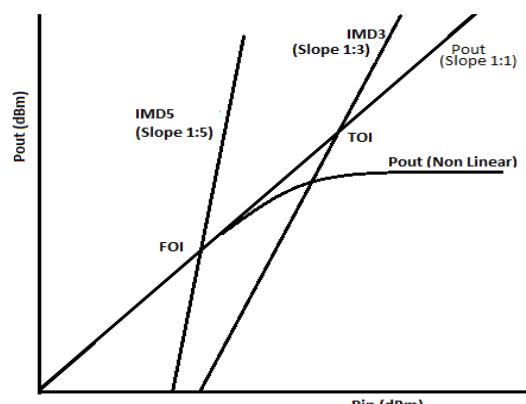


Fig 1 Third and fifth order intercepts points

The equation 2 can be written for odd order distortion component as [7].

$$V_{out}(t) = \sum_{n=1(odd)}^{2n-1} G_n V_{in}^n(t)$$

$$V_{out}(t) = G_1 V_{in}(t) + G_3 V_{in}^3(t) + G_5 V_{in}^5(t) \dots + G_{2n-1} V_{in}^{2n-1}(t) \quad (3)$$

Equation 3 is described as odd quintic polynomial:

$$V_{out}(t) = G_1 V_{in}(t) + G_3 V_{in}^3(t) + G_5 V_{in}^5(t) \quad (4)$$

Solving quintic polynomial is very big problem if a two tone signal $V_{in}(t) = V_1 \cos \omega_1 t + V_2 \cos \omega_2 t$ is given to the PA. 1st, 2nd and 3rd terms of equation 1 can be solved separately. 1st term ($G_1 V_{in}(t)$) can be written as [6-7, 19-20]:

$$G_1 V_{in}(t) = G_1 (V_1 \cos \omega_1 t + V_2 \cos \omega_2 t) \quad (5)$$

The 3rd order that is 2nd term ($G_3 V_{in}^3(t)$) of equation 1 will produce $G_3 (V_1 \cos \omega_1 t + V_2 \cos \omega_2 t)^3$, which is equal to $G_3 (V_1^3 \cos^3 \omega_1 t + V_2^3 \cos^3 \omega_2 t + 3V_1^2 V_2 \cos^2 \omega_1 t \cos \omega_2 t + 3V_1 V_2^2 \cos \omega_1 t \cos^2 \omega_2 t)$ $\quad (6)$

Again each term of equation 4 can be expanded one by one as Now

$$\begin{aligned} V_1^3 \cos^3 \omega_1 t &= V_1^3 (\cos^2 \omega_1 t \cos \omega_1 t) = V_1^3 \left[\left(\frac{1}{2} + \frac{1}{2} \cos 2\omega_1 t \right) \cos \omega_1 t \right] \\ &= \frac{1}{2} V_1^3 \cos \omega_1 t + \frac{1}{2} V_1^3 \cos 2\omega_1 t \cos \omega_1 t \\ &= \frac{1}{2} V_1^3 \cos \omega_1 t + \frac{1}{4} V_1^3 [\cos(2\omega_1 t - \omega_1 t) + \cos(2\omega_1 t + \omega_1 t)] \\ &= \frac{1}{2} V_1^3 \cos \omega_1 t + \frac{1}{4} V_1^3 [\cos(\omega_1 t) + \cos(3\omega_1 t)] = \frac{3}{4} V_1^3 \cos \omega_1 t + \frac{1}{2} V_1^3 \cos 3\omega_1 t \end{aligned}$$

Hence

$$V_1^3 \cos^3 \omega_1 t = \frac{3}{4} V_1^3 \cos \omega_1 t + \frac{1}{2} V_1^3 \cos 3\omega_1 t \quad (7)$$

Similarly

$$V_2^3 \cos^3 \omega_2 t = \frac{3}{4} V_2^3 \cos \omega_2 t + \frac{1}{2} V_2^3 \cos 3\omega_2 t \quad (8)$$

Also

$$\begin{aligned} 3V_1^2 V_2 \cos^2 \omega_1 t \cos \omega_2 t &= (3V_1^2 V_2 \cos \omega_2 t) \left(\frac{1 + \cos 2\omega_1 t}{2} \right) \\ &= \frac{3}{2} V_1^2 V_2 \cos \omega_2 t + \frac{3}{2} V_1^2 V_2 \cos \omega_2 t \cos 2\omega_1 t \\ 3V_1^2 V_2 \cos^2 \omega_1 t \cos \omega_2 t &= \frac{3}{2} V_1^2 V_2 \cos \omega_2 t + \frac{3}{4} V_1^2 V_2 [\cos(2\omega_1 t - \omega_2 t) + \cos(2\omega_1 t + \omega_2 t)] \end{aligned} \quad (9)$$

Similarly

$$3V_1 V_2^2 \cos \omega_1 t \cos^2 \omega_2 t = \frac{3}{2} V_1 V_2^2 \cos \omega_1 t + \frac{3}{4} V_1 V_2^2 [\cos(2\omega_2 t - \omega_1 t) + \cos(2\omega_2 t + \omega_1 t)] \quad (10)$$

Combine equations 7 to 10

$$\begin{aligned} G_3 (V_1 \cos \omega_1 t + V_2 \cos \omega_2 t)^3 &= \frac{3}{4} G_3 V_1^3 \cos \omega_1 t + \frac{1}{2} G_3 V_1^3 \cos 3\omega_1 t + \\ &\quad \frac{3}{4} G_3 V_2^3 \cos \omega_2 t + \frac{1}{2} G_3 V_2^3 \cos 3\omega_2 t + \\ &\quad \frac{3}{2} G_3 V_1^2 V_2 \cos \omega_2 t + \frac{3}{4} G_3 V_1^2 V_2 [\cos(2\omega_1 t - \omega_2 t) + \cos(2\omega_1 t + \omega_2 t)] + \\ &\quad \frac{3}{2} G_3 V_1 V_2^2 \cos \omega_1 t + \frac{3}{4} G_3 V_1 V_2^2 [\cos(2\omega_2 t - \omega_1 t) + \cos(2\omega_2 t + \omega_1 t)] \end{aligned} \quad (11)$$

$$\begin{aligned} G_3 V_{in}^3(t) &= G_3 \left[\frac{3}{4} V_1^3 + \frac{3}{2} V_1 V_2^2 \right] \cos \omega_1 t + G_3 \left[\frac{3}{4} V_2^3 + \frac{3}{2} V_1^2 V_2 \right] \cos \omega_2 t \\ &\quad \frac{1}{2} G_3 V_1^3 \cos 3\omega_1 t + G_3 \frac{1}{2} V_2^3 \cos 3\omega_2 t + \\ &\quad + \frac{3}{4} G_3 V_1^2 V_2 [\cos(2\omega_1 - \omega_2)t + \cos(2\omega_1 + \omega_2)t] + \\ &\quad + \frac{3}{4} G_3 V_1 V_2^2 [\cos(2\omega_2 - \omega_1)t + \cos(2\omega_2 + \omega_1)t] \end{aligned} \quad (12)$$

The 5th order of polynomial that is 3rd term ($G_5 V_{in}^5(t)$) of equation 4 can be written as

$$\begin{aligned} G_5 V_{in}^5(t) &= G_5 (V_1 \cos \omega_1 t + V_2 \cos \omega_2 t)^5 \\ &= G_5 V_1^5 \cos^5 \omega_1 t + G_5 V_2^5 \cos^5 \omega_2 t + \\ &\quad 5G_5 V_1^4 V_2 \cos^4 \omega_1 t \cos \omega_2 t + 5G_5 V_2^4 V_1 \cos \omega_1 t \cos^4 \omega_2 t + \\ &\quad 10G_5 V_1^3 V_2^2 \cos^3 \omega_1 t \cos^2 \omega_2 t + 10G_5 V_2^3 V_1^2 \cos^2 \omega_1 t \cos^3 \omega_2 t \end{aligned} \quad (14)$$

Each term of equation 14 can be expanded one by one, the 1st term ($V_1^5 \cos^5 \omega_1 t$) is

$$\begin{aligned} V_1^5 \cos^5 \omega_1 t &= V_1^5 \cos^3 \omega_1 t \cos^2 \omega_1 t \\ &= V_1^5 \cos^3 \omega_1 t (1 + \cos 2\omega_1 t) \\ &= G_5 V_1^5 \left(\frac{3}{4} \cos \omega_1 t + \frac{1}{2} V_1 \cos 3\omega_1 t \right) \left(\frac{1 + \cos 2\omega_1 t}{2} \right) \\ &= \frac{G_5 V_1^5}{8} (3 \cos \omega_1 t + 2 \cos 3\omega_1 t)(1 + \cos 2\omega_1 t) \\ &= \frac{G_5 V_1^5}{8} (3 \cos \omega_1 t + 2 \cos 3\omega_1 t + 3 \cos \omega_1 t \cos 2\omega_1 t + 2 \cos 3\omega_1 t \cos 2\omega_1 t) \\ &= \frac{G_5 V_1^5}{8} \left(3 \cos \omega_1 t + 2 \cos 3\omega_1 t + \frac{3}{2} (\cos \omega_1 t + \cos 3\omega_1 t) + \cos \omega_1 t + \cos 5\omega_1 t \right) \end{aligned} \quad (15)$$

$$= \frac{G_5 V_1^5}{8} \left(\frac{11}{2} \cos \omega_1 t + \frac{7}{2} \cos 3\omega_1 t + \cos 5\omega_1 t \right)$$

\therefore 1st term $(G_5 V_1^5 \cos^5 \omega_1 t)$ of equation 14 is

$$\frac{11}{16} G_5 V_1^5 \cos \omega_1 t + \frac{7}{16} G_5 V_1^5 \cos 3\omega_1 t + \frac{2}{16} G_5 V_1^5 \cos 5\omega_1 t \quad (16)$$

Similarly 2nd term $(G_5 V_2^5 \cos^5 \omega_2 t)$ can be written as

$$\frac{11}{16} G_5 V_2^5 \cos \omega_2 t + \frac{7}{16} G_5 V_2^5 \cos 3\omega_2 t + \frac{2}{16} G_5 V_2^5 \cos 5\omega_2 t \quad (17)$$

3rd term $(5G_5 V_1^4 V_2 \cos^4 \omega_1 t \cdot \cos \omega_2 t)$ of equation 14 can be expanded as

$$\begin{aligned} & \therefore 3^{\text{rd}} \text{ term} \\ & = 5G_5 V_1^4 V_2 (\cos^2 \omega_1 t \cdot \cos^2 \omega_2 t) \\ & = \frac{5G_5 V_1^4 V_2}{2.2} ((1 + \cos 2\omega_1 t)^2 \cos \omega_2 t) \\ & = \frac{5G_5 V_1^4 V_2}{4} ((1 + \cos^2 2\omega_1 t + 2\cos 2\omega_1 t) \cos \omega_2 t) \\ & = \frac{5G_5 V_1^4 V_2}{4} ((1 + \cos^2 2\omega_1 t + 2\cos 2\omega_1 t) \cos \omega_2 t) \\ & = \frac{5G_5 V_1^4 V_2}{4} \left(\left(1 + \frac{1 + \cos 4\omega_1 t}{2} + 2\cos 2\omega_1 t \right) \cos \omega_2 t \right) \\ & = \frac{5G_5 V_1^4 V_2}{8} ((3 + \cos 4\omega_1 t + 4\cos 2\omega_1 t) \cos \omega_2 t) \\ & = \frac{5G_5 V_1^4 V_2}{8} (3\cos \omega_2 t + \cos 4\omega_1 t \cdot \cos \omega_2 t + 4\cos 2\omega_1 t \cdot \cos \omega_2 t) \\ & = \frac{5G_5 V_1^4 V_2}{8} \left(3\cos \omega_2 t + \frac{1}{2} (\cos(4\omega_1 + \omega_2)t + \cos(4\omega_1 - \omega_2)t) + \frac{4}{2} (\cos(2\omega_1 + \omega_2)t + \cos(2\omega_1 - \omega_2)t) \right) \\ & = \frac{5G_5 V_1^4 V_2}{16} (6\cos \omega_2 t + \cos(4\omega_1 + \omega_2)t + \cos(4\omega_1 - \omega_2)t + 4\cos(2\omega_1 + \omega_2)t + 4\cos(2\omega_1 - \omega_2)t) \end{aligned}$$

$(5G_5 V_1^4 V_2 \cos^4 \omega_1 t \cdot \cos \omega_2 t)$ of equation 14 is

$$\begin{aligned} & \frac{30}{16} G_5 V_1^4 V_2 \cos \omega_2 t + \frac{5}{16} G_5 V_1^4 V_2 \cos(4\omega_1 + \omega_2)t + \frac{5}{16} G_5 V_1^4 V_2 \cos(4\omega_1 - \omega_2)t \\ & + \frac{20}{16} G_5 V_1^4 V_2 \cos(2\omega_1 + \omega_2)t + \frac{20}{16} G_5 V_1^4 V_2 \cos(2\omega_1 - \omega_2)t \end{aligned} \quad (18)$$

Similarly 4th term $(5G_5 V_2^4 V_1 \cos \omega_1 t \cdot \cos^4 \omega_2 t)$ of equation 14 can be written as

$$\begin{aligned} & \frac{30}{16} G_5 V_2^4 V_1 \cos \omega_1 t + \frac{5}{16} G_5 V_2^4 V_1 \cos(4\omega_2 + \omega_1)t + \frac{5}{16} G_5 V_2^4 V_1 \cos(4\omega_2 - \omega_1)t \\ & + \frac{20}{16} G_5 V_2^4 V_1 \cos(2\omega_2 + \omega_1)t + \frac{20}{16} G_5 V_2^4 V_1 \cos(2\omega_2 - \omega_1)t \end{aligned} \quad (19)$$

5th term $(10G_5 V_1^3 V_2^2 \cos^3 \omega_1 t \cdot \cos^2 \omega_2 t)$ of equation 14 can be expanded as

Putt the value of $(\cos^3 \omega_1 t)$ from 7 and $(\cos^2 \omega_2 t)$

$$\begin{aligned} & = 10G_5 V_1^3 V_2^2 \left(\frac{3}{4} \cos \omega_1 t + \frac{1}{2} \cos 3\omega_1 t \right) \left(\frac{1 + \cos 2\omega_2 t}{2} \right) \\ & = \frac{10}{8} G_5 V_1^3 V_2^2 (3\cos \omega_1 t + 2\cos 3\omega_1 t)(1 + \cos 2\omega_2 t) \\ & = \frac{10}{8} G_5 V_1^3 V_2^2 (3\cos \omega_1 t + 2\cos 3\omega_1 t + 3\cos \omega_1 t \cos 2\omega_2 t + 2\cos 3\omega_1 t \cos 2\omega_2 t) \\ & = \frac{10}{8} G_5 V_1^3 V_2^2 \left(3\cos \omega_1 t + 2\cos 3\omega_1 t + \frac{3}{2} (\cos(2\omega_2 + \omega_1)t + \cos(2\omega_2 - \omega_1)t) + \frac{2}{2} (\cos(3\omega_2 + 2\omega_1)t + \cos(3\omega_2 - 2\omega_1)t) \right) \\ & = \frac{10}{16} G_5 V_1^3 V_2^2 (6\cos \omega_1 t + 4\cos 3\omega_1 t + 3(\cos(2\omega_2 + \omega_1)t + \cos(2\omega_2 - \omega_1)t) + 2\cos(3\omega_2 + 2\omega_1)t + 2\cos(3\omega_2 - 2\omega_1)t) \end{aligned}$$

\therefore 5th term $(10G_5 V_1^3 V_2^2 \cos^3 \omega_1 t \cdot \cos^2 \omega_2 t)$ of equation 14 is

$$\begin{aligned} & \frac{30}{8} G_5 V_1^3 V_2^2 \cos \omega_1 t + \frac{20}{8} G_5 V_1^3 V_2^2 \cos 3\omega_1 t + \frac{15}{8} G_5 V_1^3 V_2^2 \cos(2\omega_2 + \omega_1)t + \frac{15}{8} G_5 V_1^3 V_2^2 \cos(2\omega_2 - \omega_1)t \\ & + \frac{10}{8} G_5 V_1^3 V_2^2 \cos(3\omega_2 + 2\omega_1)t + \frac{10}{8} G_5 V_1^3 V_2^2 \cos(3\omega_2 - 2\omega_1)t \end{aligned} \quad (20)$$

Similarly 6th term $(10G_5 V_2^3 V_1^2 \cos^2 \omega_1 t \cdot \cos^3 \omega_2 t)$ of equation 14 can be written as

$$\begin{aligned} & \frac{30}{8} G_5 V_2^3 V_1^2 \cos \omega_2 t + \frac{20}{8} G_5 V_2^3 V_1^2 \cos 3\omega_2 t + \frac{15}{8} G_5 V_2^3 V_1^2 \cos(2\omega_1 + \omega_2)t + \frac{15}{8} G_5 V_2^3 V_1^2 \cos(2\omega_1 - \omega_2)t \\ & + \frac{10}{8} G_5 V_2^3 V_1^2 \cos(3\omega_1 + 2\omega_2)t + \frac{10}{8} G_5 V_2^3 V_1^2 \cos(3\omega_1 - 2\omega_2)t \end{aligned}$$

Combine 16 to 21 3rd term

$(G_5 (V_1 \cos \omega_1 t + V_2 \cos \omega_2 t)^5)$ of equation 4 is

$$\begin{aligned} & \frac{11}{16} G_5 V_1^5 \cos \omega_1 t + \frac{7}{16} G_5 V_1^5 \cos 3\omega_1 t + \frac{2}{16} G_5 V_1^5 \cos 5\omega_1 t + \\ & \frac{11}{16} G_5 V_2^5 \cos \omega_2 t + \frac{7}{16} G_5 V_2^5 \cos 3\omega_2 t + \frac{2}{16} G_5 V_2^5 \cos 5\omega_2 t + \\ & \frac{30}{16} G_5 V_1^4 V_2 \cos \omega_2 t + \frac{5}{16} G_5 V_1^4 V_2 \cos(4\omega_1 + \omega_2)t + \frac{5}{16} G_5 V_1^4 V_2 \cos(4\omega_1 - \omega_2)t \\ & + \frac{20}{16} G_5 V_1^4 V_2 \cos(2\omega_1 + \omega_2)t + \frac{20}{16} G_5 V_1^4 V_2 \cos(2\omega_1 - \omega_2)t + \\ & \frac{30}{16} G_5 V_2^4 V_1 \cos \omega_1 t + \frac{5}{16} G_5 V_2^4 V_1 \cos(4\omega_2 + \omega_1)t + \frac{5}{16} G_5 V_2^4 V_1 \cos(4\omega_2 - \omega_1)t \\ & + \frac{20}{16} G_5 V_2^4 V_1 \cos(2\omega_2 + \omega_1)t + \frac{20}{16} G_5 V_2^4 V_1 \cos(2\omega_2 - \omega_1)t + \\ & \frac{30}{8} G_5 V_1^3 V_2^2 \cos \omega_1 t + \frac{20}{8} G_5 V_1^3 V_2^2 \cos 3\omega_1 t + \frac{15}{8} G_5 V_1^3 V_2^2 \cos(2\omega_2 + \omega_1)t + \frac{15}{8} G_5 V_1^3 V_2^2 \cos(2\omega_2 - \omega_1)t \\ & + \frac{10}{8} G_5 V_1^3 V_2^2 \cos(3\omega_2 + 2\omega_1)t + \frac{10}{8} G_5 V_1^3 V_2^2 \cos(3\omega_2 - 2\omega_1)t + \\ & \frac{30}{8} G_5 V_2^3 V_1^2 \cos \omega_2 t + \frac{20}{8} G_5 V_2^3 V_1^2 \cos 3\omega_2 t + \frac{15}{8} G_5 V_2^3 V_1^2 \cos(2\omega_1 + \omega_2)t + \frac{15}{8} G_5 V_2^3 V_1^2 \cos(2\omega_1 - \omega_2)t \\ & + \frac{10}{8} G_5 V_2^3 V_1^2 \cos(3\omega_1 + 2\omega_2)t + \frac{10}{8} G_5 V_2^3 V_1^2 \cos(3\omega_1 - 2\omega_2)t \end{aligned} \quad (21)$$

\therefore 3rd term $(G_5 V_{in}^5(t))$ of equation 4 is

$$\begin{aligned}
 & \left(\frac{11}{16} G_5 V_1^5 + \frac{30}{16} G_5 V_2^4 V_1 + \frac{30}{8} G_5 V_1^3 V_2^2 \right) \cos \omega_1 t + \\
 & \left(\frac{11}{16} G_5 V_2^5 + \frac{30}{16} G_5 V_1^4 V_2 + \frac{30}{8} G_5 V_2^3 V_1^2 \right) \cos \omega_2 t + \\
 & \left(\frac{7}{16} G_5 V_1^5 + \frac{20}{8} G_5 V_2^3 V_1^2 \right) \cos 3\omega_1 t + \left(\frac{7}{16} G_5 V_2^5 + \frac{20}{8} G_5 V_1^3 V_2^2 \right) \cos 3\omega_2 t + \\
 & \frac{2}{16} G_5 V_1^5 \cos 5\omega_1 t + \frac{2}{16} G_5 V_2^5 \cos 5\omega_2 t + \\
 & \left(\frac{20}{16} G_5 V_1^4 V_2 + \frac{15}{8} G_5 V_2^3 V_1^2 \right) \cos (2\omega_1 + \omega_2) t + \left(\frac{20}{16} G_5 V_1^4 V_2 + \frac{15}{8} G_5 V_2^3 V_1^2 \right) \cos (2\omega_2 - \omega_1) t + \\
 & \left(\frac{20}{16} G_5 V_2^4 V_1 + \frac{15}{8} G_5 V_1^3 V_2^2 \right) \cos (2\omega_2 + \omega_1) t + \left(\frac{15}{8} G_5 V_1^3 V_2^2 + \frac{20}{16} G_5 V_2^4 V_1 \right) \cos (2\omega_2 - \omega_1) t + \\
 & \frac{10}{8} G_5 V_1^3 V_2^2 \cos (3\omega_2 + 2\omega_1) t + \frac{10}{8} G_5 V_1^3 V_2^2 \cos (3\omega_2 - 2\omega_1) t + \\
 & \frac{10}{8} G_5 V_2^3 V_1^2 \cos (3\omega_1 + 2\omega_2) t + \frac{10}{8} G_5 V_2^3 V_1^2 \cos (3\omega_1 - 2\omega_2) t + \\
 & \frac{5}{16} G_5 V_1^4 V_2 \cos (4\omega_1 + \omega_2) t + \frac{5}{16} G_5 V_1^4 V_2 \cos (4\omega_1 - \omega_2) t + \\
 & \frac{5}{16} G_5 V_2^4 V_1 \cos (4\omega_2 + \omega_1) t + \frac{5}{16} G_5 V_2^4 V_1 \cos (4\omega_2 - \omega_1) t
 \end{aligned} \tag{23}$$

Odd quintic polynomial

$$(G_1 V_{in}(t) + G_3 V_{in}^3(t) + G_5 V_{in}^5(t)) \text{ output } (V_{out}(t))$$

after Combine equation 5, 12 and 23 is.

$$\begin{aligned}
 & \left(G_1 V_1 + \frac{3}{4} G_3 V_1^3 + \frac{3}{2} G_3 V_1 V_2^2 + \frac{11}{16} G_5 V_1^5 + \frac{30}{16} G_5 V_2^4 V_1 + \frac{30}{8} G_5 V_1^3 V_2^2 \right) \cos \omega_1 t + \\
 & \left(G_1 V_2 + \frac{3}{4} G_3 V_2^3 + G_3 \frac{3}{2} V_1^2 V_2 + \frac{11}{16} G_5 V_2^5 + \frac{30}{16} G_5 V_1^4 V_2 + \frac{30}{8} G_5 V_2^3 V_1^2 \right) \cos \omega_2 t + \\
 & \left(\frac{1}{2} G_3 V_1^3 + \frac{7}{16} G_5 V_1^5 + \frac{20}{8} G_5 V_2^3 V_1^2 \right) \cos 3\omega_1 t + \left(\frac{1}{2} G_3 V_2^3 + \frac{7}{16} G_5 V_2^5 + \frac{20}{8} G_5 V_1^3 V_2^2 \right) \cos 3\omega_2 t + \\
 & \frac{2}{16} G_5 V_1^5 \cos 5\omega_1 t + \frac{2}{16} G_5 V_2^5 \cos 5\omega_2 t + \\
 & \left(\frac{3}{4} G_3 V_1^2 V_2 + \frac{20}{16} G_5 V_1^4 V_2 + \frac{15}{8} G_5 V_2^3 V_1^2 \right) \cos (2\omega_1 + \omega_2) t + \\
 & \left(\frac{3}{4} G_3 V_2^2 V_1 + \frac{20}{16} G_5 V_2^4 V_1 + \frac{15}{8} G_5 V_1^3 V_2^2 \right) \cos (2\omega_2 - \omega_1) t + \\
 & \left(\frac{3}{4} G_3 V_1 V_2^2 + \frac{20}{16} G_5 V_2^4 V_1 + \frac{15}{8} G_5 V_1^3 V_2^2 \right) \cos (2\omega_2 + \omega_1) t + \\
 & \left(\frac{3}{4} G_3 V_1 V_2^2 + \frac{15}{8} G_5 V_1^3 V_2^2 + \frac{20}{16} G_5 V_2^4 V_1 \right) \cos (2\omega_2 - \omega_1) t + \\
 & \frac{10}{8} G_5 V_1^3 V_2^2 \cos (3\omega_2 + 2\omega_1) t + \frac{10}{8} G_5 V_1^3 V_2^2 \cos (3\omega_2 - 2\omega_1) t + \\
 & \frac{10}{8} G_5 V_2^3 V_1^2 \cos (3\omega_1 + 2\omega_2) t + \frac{10}{8} G_5 V_2^3 V_1^2 \cos (3\omega_1 - 2\omega_2) t + \\
 & \frac{5}{16} G_5 V_1^4 V_2 \cos (4\omega_1 + \omega_2) t + \frac{5}{16} G_5 V_1^4 V_2 \cos (4\omega_1 - \omega_2) t + \\
 & \frac{5}{16} G_5 V_2^4 V_1 \cos (4\omega_2 + \omega_1) t + \frac{5}{16} G_5 V_2^4 V_1 \cos (4\omega_2 - \omega_1) t
 \end{aligned} \tag{24}$$

From equations 24, the odd quintic polynomial gives the results in the frequency components

$$\omega_1, \omega_2, 3\omega_1, 3\omega_2, 5\omega_1, 5\omega_2, 2\omega_1 + \omega_2, 2\omega_1 - \omega_2, 2\omega_2 + \omega_1, 2\omega_2 - \omega_1, 3\omega_1 + 2\omega_2, 3\omega_1 - 2\omega_2, 3\omega_2 + 2\omega_1, 3\omega_2 - 2\omega_1, 4\omega_1 + \omega_2, 4\omega_1 - \omega_2, 4\omega_2 - \omega_1, 4\omega_1 + \omega_2$$

are at the output of PA. In this work f_C and Δ are 2.6GHz and 20 MHz respectively then

$f_1 = 2.59\text{GHz}$ and $f_2 = 2.61\text{GHz}$. These frequency components are calculated and found that;

$$2\omega_1 + \omega_2, 2\omega_2 + \omega_1, 3\omega_1 + 2\omega_2, 3\omega_2 + 2\omega_1, 4\omega_2 + \omega_1,$$

$$4\omega_1 - \omega_2, 4\omega_2 - \omega_1, 4\omega_1 + \omega_2, 3\omega_1, 3\omega_2, 5\omega_1, 5\omega_2$$

are the out of band products. These can be easily filtered out.

But $2\omega_1 - \omega_2, 2\omega_2 - \omega_1, 3\omega_1 - 2\omega_2, 3\omega_2 - 2\omega_1$ are in-band components, these contribute for the in-band distortion at the output of PA. After filtered the out of band products the equation 24 is

$$\begin{aligned}
 & \left(G_1 V_1 + \frac{3}{4} G_3 V_1^3 + \frac{3}{2} G_3 V_1 V_2^2 + \frac{11}{16} G_5 V_1^5 + \frac{30}{16} G_5 V_2^4 V_1 + \frac{30}{8} G_5 V_1^3 V_2^2 \right) \cos \omega_1 t + \\
 & \left(G_1 V_2 + \frac{3}{4} G_3 V_2^3 + G_3 \frac{3}{2} V_1^2 V_2 + \frac{11}{16} G_5 V_2^5 + \frac{30}{16} G_5 V_1^4 V_2 + \frac{30}{8} G_5 V_2^3 V_1^2 \right) \cos \omega_2 t + \\
 & \left(\frac{3}{4} G_3 V_1^2 V_2 + \frac{20}{16} G_5 V_1^4 V_2 + \frac{15}{8} G_5 V_2^3 V_1^2 \right) \cos (2\omega_1 - \omega_2) t + \\
 & \left(\frac{3}{4} G_3 V_2^2 V_1 + \frac{20}{16} G_5 V_2^4 V_1 + \frac{15}{8} G_5 V_1^3 V_2^2 \right) \cos (2\omega_2 - \omega_1) t + \\
 & \left(\frac{3}{4} G_3 V_1 V_2^2 + \frac{20}{16} G_5 V_2^4 V_1 + \frac{15}{8} G_5 V_1^3 V_2^2 \right) \cos (2\omega_2 + \omega_1) t + \\
 & \left(\frac{3}{4} G_3 V_1 V_2^2 + \frac{15}{8} G_5 V_1^3 V_2^2 + \frac{20}{16} G_5 V_2^4 V_1 \right) \cos (2\omega_2 - \omega_1) t + \\
 & \frac{10}{8} G_5 V_1^3 V_2^2 \cos (3\omega_2 - 2\omega_1) t + \frac{10}{8} G_5 V_2^3 V_1^2 \cos (3\omega_1 - 2\omega_2) t
 \end{aligned} \tag{25}$$

Equation 25 can be re-written as

$$\begin{aligned}
 & K_{11} \cos \omega_1 t + K_{12} \cos \omega_2 t + K_{31} \cos (2\omega_1 - \omega_2) t + K_{32} \cos (2\omega_2 - \omega_1) t + \\
 & K_{51} \cos (3\omega_2 - 2\omega_1) t + K_{52} \cos (3\omega_1 - 2\omega_2) t
 \end{aligned} \tag{26}$$

K_{11}, K_{12} are coefficients of 1st order, K_{31}, K_{32} are coefficients of 3rd order and K_{51}, K_{52} are coefficients of 5th order. Intercept points by K_{31}, K_{32} and K_{51}, K_{52} coefficients with fundamental coefficients K_{11}, K_{12} are called third order intercept (TOI) point and fifth order intercept (FOI) point respectively. The ratio of the n order IM product component to the fundamental frequency component is n order IM Distortion (IMD_n), subscript n denotes the order of the IM product [1, 20-22].

III. TWO TONES ANALYSES

Two tones simulation set up is shown in fig. 2, in this work f_C and Δ are 2.6GHz and 20 MHz respectively then $f_1 = 2.59\text{GHz}$ and $f_2 = 2.61\text{GHz}$. Maximum IMD order = 11 and RF power is 46 dBm.

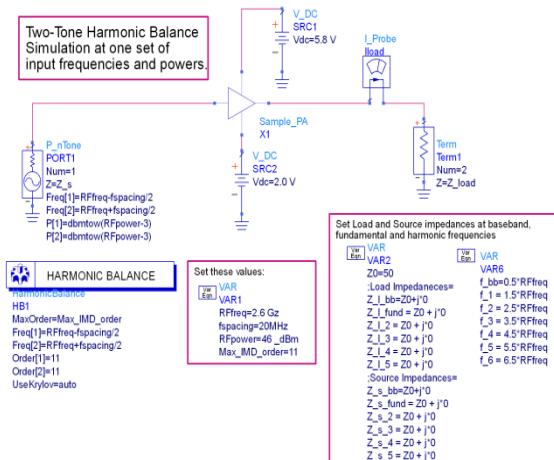


Fig. 2 Two tone simulation set up.

The output spectrum for 0 to 30GHz and zoomed output spectrum 2.52 to 2.68GHz is shown in fig 3(a) and 3(b)

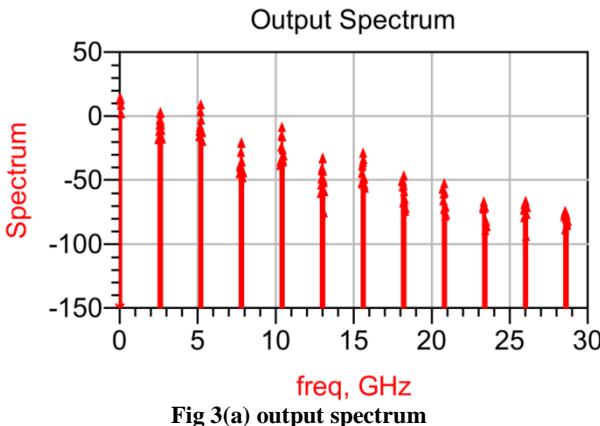


Fig 3(a) output spectrum

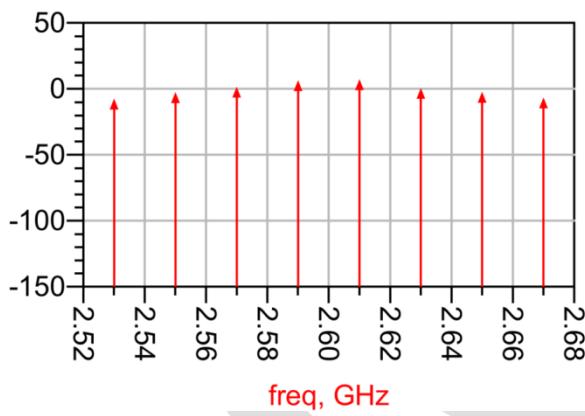


Fig 3(b) Zoomed output spectrum

Two tones analysis for single value input frequency and power:

The single value ($f_1=2.59\text{GHz}$, $f_2=2.61\text{GHz}$, and RF power 46 dBm) of two tones signal produce the fundamental output power of both tones 8.219dBm and transducer power gain-37.781. Input Output TOI and Input Output FOI for single value at low side and high side are calculated as given in table 1.

Table 1: TOI and FOI of Input and Output for single value

Intercept Point	Input Intercept Point (dBm)		Output Intercept Point (dBm)	
	Low Side	High Side	Low Side	High Side
Third Order	7.192	9.032	44.973	46.813
Fifth Order	6.972	8.055	44.753	45.836

Two tone single value with power added efficiency (PAE):

The single value of two tones signal produce the fundamental output power of both tones 10.136dBm and transducer power gain is -35.864, when high supply current is 0.453, DC power consumption 2.627watts, thermal dissipation 7.667watts and

PAE is -195.564%. The input output TOI and input output FOI for single value with PAE are calculated in table 2

Table 2: TOI and FOI of Input and Output for single value with PAE

Intercept Point	Input Intercept Point (dBm)		Output Intercept Point (dBm)	
	Low Side	High Side	Low Side	High Side
Third Order	9.696	9.870	45.560	45.734
Fifth Order	9.425	9.400	45.289	45.264

IV. CONSLUSION

In this paper, the simulation and analytical approaches has been used to evaluate the TOI and FOI of the RF power amplifier. In a simulation, a method based on two tone input approach has been analyzed for the determining of TOI and FOI in RF power amplifier circuits. From table 1 and table 2, it has been concluded that input intercept point and output intercept point are improved for TOI and FOI with PAE.

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