

Carrier to Intermodulation (C/I ratio) Calculations of a GaN 10W Class AB Power Amplifier



S. Elkhaldi, M. Moubadir, N. A Touhami, M. Aghoutane, T. Elhamadi

Abstract – This article presents the analysis and design of a circuit to generate 3rd-order intermodulation (IM3) products for a GaN 10W Class AB power amplifiers (PA). The intermodulation products can't be eliminated by filters. So, it's a critical problem to resolve in RF systems. The circuit has been studied using a two-tone signal at a center frequency of 3.7 GHz. The two tones test is applied to make a large signal analysis of the RF power amplifier. For this paper, the two frequencies are at (3.7 ± 0.005) GHz. The (C/I) ratio, is chosen to investigate the power amplifier non-linearity, and due to various causes, upper_C/I and lower_C/I, can be distinct.

Keywords - Microwave Amplifier; two tones; harmonic balance simulation; Intermodulation distortion; the carrier to intermodulation distortion power ratio (C/I).

I. INTRODUCTION

The RF PA was built at the frequency of 3.7 GHz, an input power of 27.5 dBm, the biasing point in class AB is ($V_{ds}=28$, $V_{gs}=-2.7$). Bias and matching circuits are added to supply DC power to the transistor and to optimize the gain. The distortion generated is both harmonic and non-harmonic. The harmonic distortion is due to the harmonics generated by the power amplifier non-linearities, ie double, triple, etc. of the carrier frequency. The non-harmonic distortion[1], occurs inside and around the frequency band occupied by the modulating signal and is manifested by intermodulation products. The Carrier to Intermodulation (C/I ratio),[2,3], defined as the ratio between the fundamental and the intermodulation output power, can indicate the power amplifier nonlinearity. In real-world, the upper and lower TOI [4], can be different [5].

II. INTERMODULATION DISTORTION

The input signal for a two-tone test[6], is a bi-carrier with two sinusoidal signals of the same amplitude and slightly different frequencies.

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The input signal is given by the following expression:

$$\begin{aligned} V_{in} &= A \cos(\omega_1 t) + A \cos(\omega_2 t) \\ &= 2A \cos\left(\frac{\omega_1 - \omega_2}{2} t\right) \cos\left(\frac{\omega_1 + \omega_2}{2} t\right) \\ &= 2A \cos\left(2\pi \frac{\Delta f}{2} t\right) \cos(2\pi f_0 t) \end{aligned} \quad (1)$$

with

$$\Delta f = f_0 - f_1 \quad (2)$$

and

$$f_0 = \frac{f_1 + f_0}{2} \quad (3)$$

The output signal is given by the following expression:

$$V_{out}(t) = a_1 V_{in}(t) + a_2 V_{in}(t)^2 + a_3 V_{in}(t)^3 \quad (4)$$

The response to a dual-carrier signal will be:

$$\begin{aligned} V_{out}(t) &= a_1 A (\cos(\omega_1 t) + \cos(\omega_2 t)) + a_2 A (\cos(\omega_1 t) + \cos(\omega_2 t))^2 \\ &+ a_3 A (\cos(\omega_1 t) + \cos(\omega_2 t))^3 \end{aligned} \quad (5)$$

The development of this expression gives:

$$\begin{aligned} V_{out}(t) &= a_1 A \cos(\omega_1 t) + a_1 A \cos(\omega_2 t) + \\ &a_2 A^2 \frac{1}{2} a_2 A^2 \cos(2\omega_1 t) + \frac{1}{2} a_2 A^2 \cos(2\omega_2 t) + a_2 A^2 \cos((\omega_1 + \omega_2)t) \\ &+ a_2 A^2 \cos((\omega_1 - \omega_2)t) + 9a_3 A^3 \cos \omega t + 9a_3 A^3 \cos \omega 2t \\ &+ 34a_3 A^3 \cos(2\omega_1 + \omega_2 t) + \frac{3}{4} a_3 A^3 \cos((2\omega_1 - \omega_2)t) + \dots \end{aligned} \quad (6)$$

The output of the power amplifier expressed in Table.1 shows the coefficients corresponding to each degree:

Table.1. Product distortion of bi-carrier signal

Frequency	Aa_1	A^2a_2	A^3a_3	A^4a_4	A^5a_5
0 (DC)		1		9/4	
ω_1	1		9/4		25/4
ω_2	1		9/4		25/4
$2\omega_1$		1/2		2	
$2\omega_2$		1/2		2	
$\omega_1 \pm \omega_2$		1		3	
$2\omega_1 \pm \omega_2$		3/4			25/8
$2\omega_2 \pm \omega_1$		3/4			25/8
$3\omega_1$		1/4			25/16
$3\omega_2$		1/4			25/16
$2\omega_1 \pm 2\omega_2$				3/4	
$3\omega_2 \pm \omega_1$				1/2	
$3\omega_1 \pm \omega_2$				1/2	
$4\omega_1$			1/8		



$4\omega_2$			1/8		
$3\omega_1 \pm 2\omega_2$					5/8
$3\omega_2 \pm 2\omega_1$				5/8	
$4\omega_1 \pm \omega_2$				5/16	
$4\omega_2 \pm \omega_1$				5/16	
$5\omega_1$					1/16
$5\omega_2$					1/16

III. C/I RATIO (CARRIER TO INTERMODULATION RATIO)

The ratio (C/I) can indicate the non-linear behavior of the power amplifier. It is usually measured, using logarithmic units, in decibels below the carrier (dBc):

$$C/I = \frac{P_{out}}{P_{IMD}} \tag{7}$$

It is generally written in the following form:

$$C/I_n (dB) = 10 \log_{10} \left(\frac{P_{f_1, f_2}}{P_{IM_n}} \right) \tag{8}$$

Where n is the number of the IMD under consideration. In general, we define the C/I relationships of order n as the power difference between the line at frequency f_1 or f_2 and the IMD line at $pf_1 + qf_2$ with $p + q = n$. The ratios C/I_3 and C/I_5 are calculated from the following equations:

$$C/I_3 (dB) = -10 \log_{10} \left(\frac{P(2f_1-f_2)+P(2f_2-f_1)}{P(f_1)+P(f_2)} \right) \tag{9}$$

and

$$C/I_5 (dB) = -10 \log_{10} \left(\frac{P(3f_1-2f_2)+P(3f_2-2f_1)}{P(f_1)+P(f_2)} \right) \tag{10}$$

The ratios higher C/I_3^+ and lower C/I_3^- can be calculated by the following relations:

$$C/I_3^- (dB) = -10 \log_{10} \left(\frac{P(2f_1-f_2)}{P(f_1)+P(f_2)} \right) \tag{11}$$

and

$$C/I_3^+ (dB) = -10 \log_{10} \left(\frac{P(2f_2-f_1)}{P(f_1)+P(f_2)} \right) \tag{12}$$

Figure.1 show the 3rd and 5th order intermodulation C/I ratio at the output of a power amplifier:

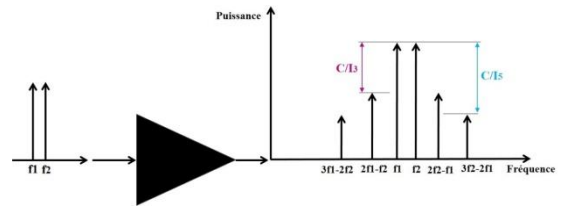


Fig. 1. 3rd and 5th order intermodulation C/I ratio.

IV. POWER AMPLIFIER DESIGN AND HARMONIC BALANCE ANALYSIS

A. Amplifier Design

The Transistor, Cree CGH 40010F GaN operating at 3.7 GHz is selected to design the RF power amplifier. It is a general purpose 10 W transistor. Fig.2 show the schematic of the class AB power amplifier, the biasing, the stability and the matching circuits are presented. Figure.2 show the schematic of the power amplifier.

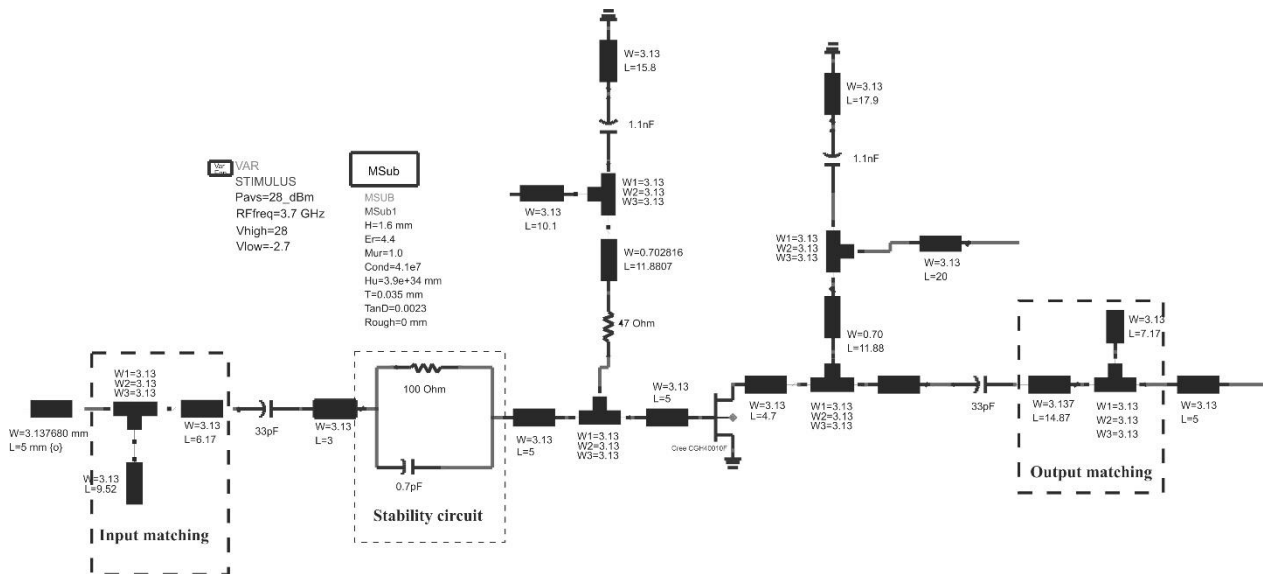


Fig. 2. Circuit schematic of the Class-AB PA.

B. The one Tone Test

we make a one tone test [7], to the power amplifier and we can find the P1dB, the Power Added Efficiency (PAE), and the power gain. Fig.3 show the Output spectrum with the one-tones test.



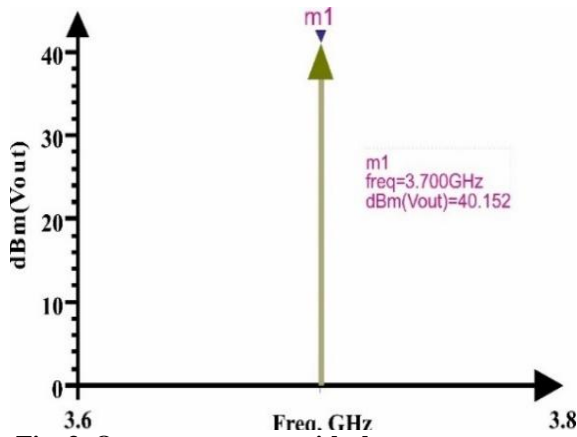


Fig. 3. Output spectrum with the one-tones test.

C. The 1-dB and Gain

The P1dB [8], is the output power value at which the gain decline 1 dB from its straight line . Once a PA reaches its P1dB it becomes a non-linear component, and product harmonics and IM products.

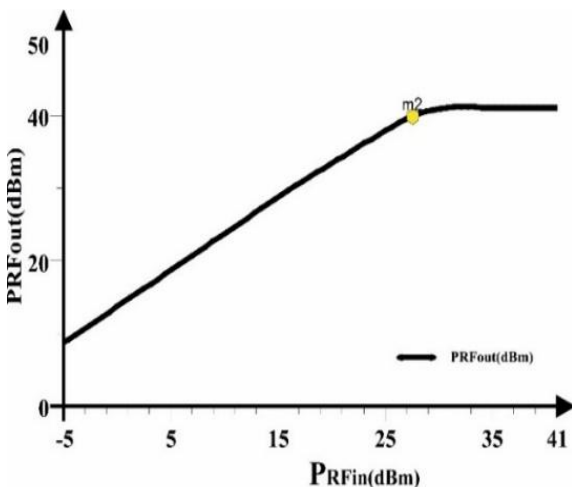


Fig. 4. Simulated power gain of the power amplifier.

From Figure.4 we notice that the P1dB corresponded to an input power of about 27.5 dBm, and the output power is about 40.15 dBm.

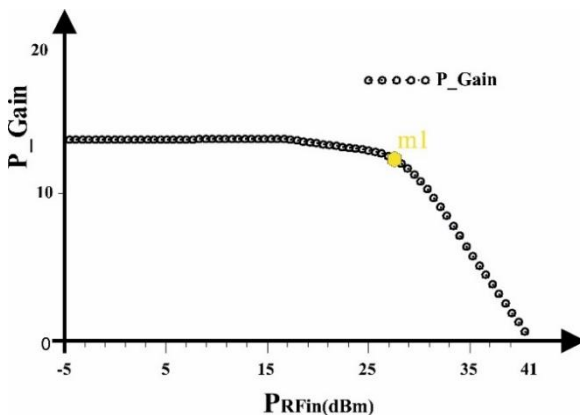


Fig. 5. Simulated values of the gain.

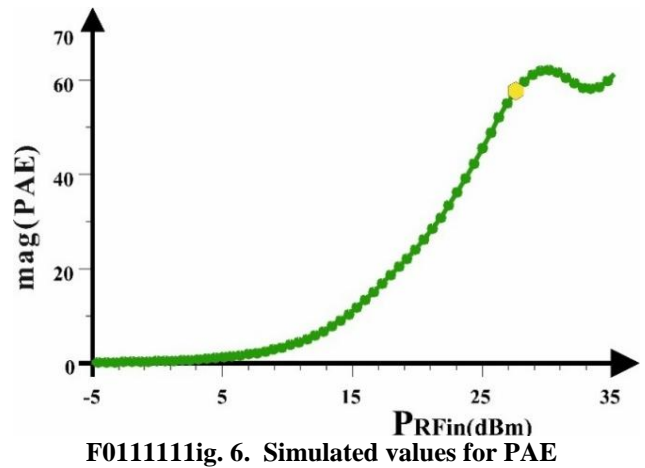
In Figure.5 we notice that the gain corresponding to the P1dB is about 13.5 dBm.

D. The Power Added Efficiency (PAE)

The PAE , is the efficacy of the PA, to transform the input DC power to the output power. The equation that describes the power added efficiency is as follows:

$$PAE = \frac{P_{RFout} - P_{RFIn}}{P_{dc}} \quad (13)$$

The plot of the PAE is given in Figure.6:



The plot in Fig. 6 show the curve representing the PAE of the power amplifier, we read a PAE about 58 %.

E. The Two Tones test

The two input frequencies used to make the two tones harmonic balance simulation are at (3.7 ± 0.005) GHz.

V. RESULTS AND DISCUSSION

For the GaN 10W Class AB Power Amplifier. Fig. 3 show the Simulated output spectrum at the saturated power with the one-tone test, we observe that P_{out} is about 10W, the Simulated values of the two-tones test is given in Fig.7, we note that the lower and the upper IM3 is about 25.63 dBm and 21 dBm respectively. In Fig.8, we observe that the lower and the upper TOI is about 46 dBm and 53 dBm successively. The Fig.9 show the simulated upper and lower C/I, at these conditions, the values are 16.7 dBc and 14 dBc, respectively, the power amplifier is highly non-linear and can be used in non-linear applications. Finally, The Layout of the RF PA is shown in Figure.10.

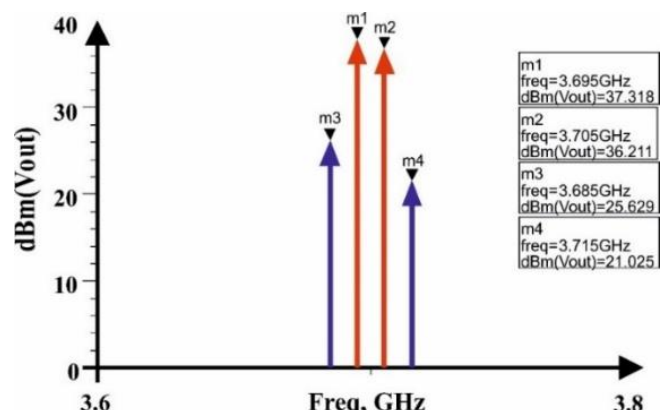


Fig. 7. The two-tones test, Output spectrum.

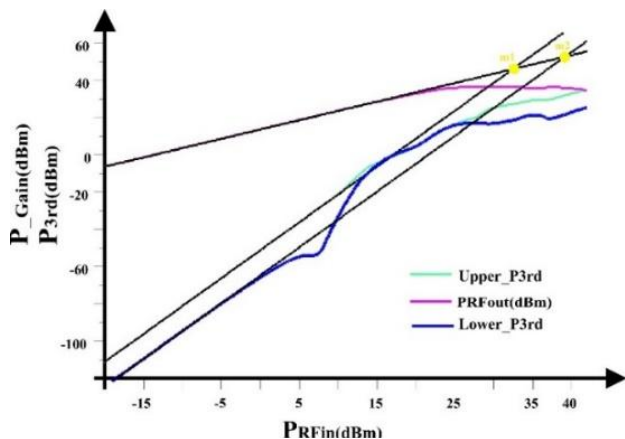


Fig. 8. Simulated TOI values.

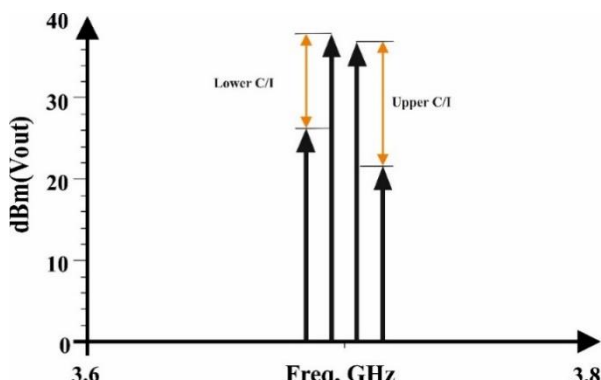


Fig.9. The upper and lower C/I values .

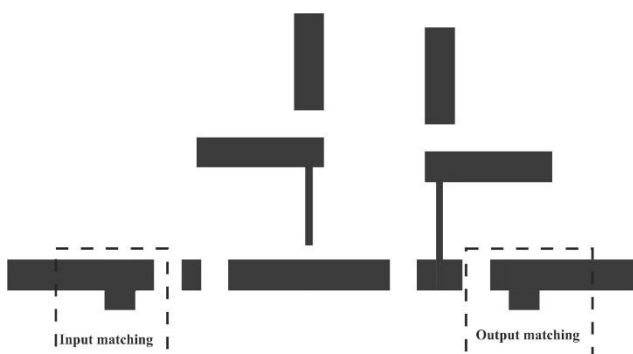


Fig.10. Layout of the power amplifier

VI. CONCLUSION

In this article, the design and the harmonic balance analysis of a RF power amplifier operating at 3.7 GHz has been presented. The PA delivered about 40 dBm with about 59% PAE. The lower_TOI and the upper_TOI are about 46 dBm and 53 dBm successively. The upper C/I in this condition is about and lower C/I is 14 dBc, respectively. In order to improve the PA non linearity.

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