TWO-TONE IMD ASYMMETRY IN MICROWAVE POWER AMPLIFIERS

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ABSTRACT

This paper presents the first study of the relation between the IMD asymmetries, often observed in almost all power amplifiers subject to a two-tone test, and the nonlinear characteristics of their active devices. First, the reasons for the different amplitudes of the two adjacent tones are investigated using a general circuit with frequency dependent embedding impedances, and resistive and reactive nonlinearities. Those theoretical conclusions are then extrapolated for real circuits, and validated by comparing results obtained from nonlinear simulation to laboratory measurements of a microwave power amplifier.

I. INTRODUCTION

Asymmetries in the amplitudes of upper and lower intermodulation distortion (IMD) products of power amplifiers (PA) subject to a two tone test, are often observed [1-3]. This means that the IMD at $2\omega_2$-ω_1 is different from the one at $2\omega_1$-ω_2.

This type of asymmetry can create misjudgments when measuring intermodulation ratios, (IMR), third order intercept point (IP_3) or other type of distortion figures of merit.

The purpose of this paper is to study and explain the origins of such small signal IMD behavior. To carry on the task, first a simple but general nonlinear circuit is analyzed via Volterra series. Using this knowledge, a microwave power amplifier was built, and its experimental and simulated results of IMD asymmetry compared for varying two-tone separation and device bias.

II. SIMPLE GENERAL CIRCUIT ANALYSIS

In order to reveal the causing mechanisms of small signal IMD asymmetry, we begin to study two-tone distortion generation in general mildly nonlinear circuits. For that, the circuit of Fig. 1 was considered, since it represents the best compromise between analysis simplicity – it is composed of a single node - and completeness – its nonlinear elements include resistive, G(v), and reactive nonlinearities, C(v):

$$i_{NL}(t) = G_2 v^2(t) + G_3 v^3(t) + \frac{\partial}{\partial t}\left[C_2 v^2(t) + C_3 v^3(t)\right]$$

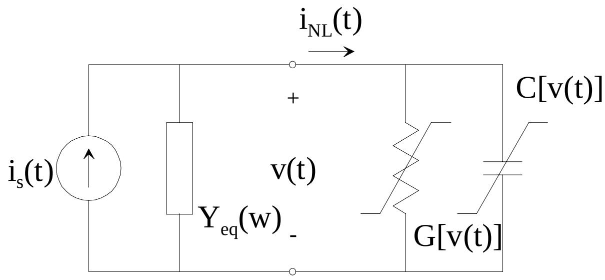

Fig. 1 - Simple general circuit for IMD asymmetry analysis.

The well known Volterra series technique [4] is applied to this simple circuit, and expansions up to third order are considered.

Assuming $i_S(t)$ and v(t) as the system's input and output variables, respectively, the first three Volterra nonlinear transfer functions, $H_1(\omega)$, $H_2(\omega_1, \omega_2)$ and $H_3(\omega_1, \omega_2, \omega_3)$ can be shown to be:

$$H_1(\omega) = \frac{1}{Y_{eq}(\omega)} = Z_{eq}(\omega) \tag{1}$$

$$H_2(\omega_1,\omega_2) = -Z_{eq}(\omega_1+\omega_2)\left[G_2 + j(\omega_1+\omega_2)C_2\right] \left[H_1(\omega_1)H_1(\omega_2)\right] \tag{2}$$

$$H_3(\omega_1,\omega_2,\omega_3) = \frac{-Z_{eq}(\omega_1+\omega_2+\omega_3)}{6}$$
$$\{2[G_2 + j(\omega_1+\omega_2+\omega_3)C_2][H_1(\omega_1)H_2(\omega_2,\omega_3)+$$
$$+H_1(\omega_2)H_2(\omega_1,\omega_3)+H_1(\omega_3)H_2(\omega_2,\omega_1)]+$$
$$+6[G_3 + j(\omega_1+\omega_2+\omega_3)C_3][H_1(\omega_1)H_1(\omega_2)H_1(\omega_3)]\} \quad (3)$$

If a two-tone analysis is undertaken using two ideal elementary amplitude tones of closely spaced frequencies, $i_S(t) = e^{j\omega_1 t} + e^{j\omega_2 t}$, the IMD at ($2\omega_2$-$\omega_1$) and at ($2\omega_1$-$\omega_2$) can be modeled by the 3rd order Nonlinear Transfer Functions:

$$H_3(\omega_1,\omega_1,-\omega_2) = \frac{-Z_{eq}(2\omega_1-\omega_2)}{6}\{2[G_2 + j(2\omega_1-\omega_2)C_2]$$
$$[H_1(-\omega_2)H_2(\omega_1,\omega_1)+2H_1(\omega_1)H_2(-\omega_2,\omega_1)]+$$
$$+6[G_3 + j(2\omega_1-\omega_2)C_3][H_1^2(\omega_1)H_1(-\omega_2)]\} \quad (4)$$

$$H_3(\omega_2,\omega_2,-\omega_1) = \frac{-Z_{eq}(2\omega_2-\omega_1)}{6}\{2[G_2 + j(2\omega_2-\omega_1)C_2]$$
$$[H_1(-\omega_1)H_2(\omega_2,\omega_2)+2H_1(\omega_2)H_2(-\omega_1,\omega_2)]+$$
$$+6[G_3 + j(2\omega_2-\omega_1)C_3][H_1^2(\omega_2)H_1(-\omega_1)]\} \quad (5)$$

Comparing expressions (4) and (5), it is obvious that if $\omega = \omega_1 \approx \omega_2$, and thus $2\omega_1$-$\omega_2 \approx 2\omega_2$-$\omega_1$, the only term that is different in the two expressions is the one involving $H_2(-\omega_1,\omega_2)$ or $H_2(-\omega_2,\omega_1)$, since $H_2(-\omega_1,\omega_2) = [H_2(-\omega_2,\omega_1)]^*$ but $H_1(\omega_1) \approx H_1(\omega_2)$. The imaginary parts of $H_2(-\omega_1,\omega_2)$ and $H_2(-\omega_2,\omega_1)$ have opposite signs and so they will add or subtract from the imaginary parts of the other $H_3(\omega_1,\omega_1,-\omega_2)$ terms, as already pointed out in [1].

Therefore, the necessary condition for existence of IMD asymmetry in small signal, is the presence of a reactive part on the difference frequency terminating impedance, provided not all other $H_3(\omega_1,\omega_2,\omega_3)$ terms are real. From (4) and (5) the first thing to note is that if direct 3rd order mixing dominates IMD, no asymmetry will be visible. Therefore and because G_2, G_3 and C_2, C_3 coefficients strongly depends on the bias point, the IMD asymmetry will have an higher value in the zones of G_3=C_3=0, the small signal IMD sweet spots [5].

Now, expressions (4) and (5) are simplified considering that G_3=C_3=0, and the main contributions for the IMD distortion comes from the interaction between 1st and 2nd components. A further simplifying assumption can be made about the terms in expression (2) involving C_2. In normal microwave device operation it should be expected that the nonlinear capacitance is such that the term involving $(\omega_2-\omega_1)C_2$ is negligible when compared to the one of G_2. Therefore, the most important conclusion that can be drawn from expression (2) is that the IMD asymmetry is, indeed, caused by the difference between the reactive part of the base-band and the 2nd harmonic terminating impedances: if the base-band terminating impedance is purely resistive, no asymmetry will be possible because $Z_{eq}(\omega_2-\omega_1)=Z_{eq}(\omega_1-\omega_2)^*$; and if the 2nd harmonic termination is purely resistive, the asymmetry will be mainly created by the difference between the reactive part of $Z_{eq}(\omega_2-\omega_1)$ and the one of $j2\omega C_2 Z_{eq}(2\omega)$.

In the special case where there is no reactive nonlinearity, C_2=C_3=0, the IMD asymmetry will only be created if both, second harmonic and base-band terminations present a significant, and comparable in magnitude, reactive part.

The main conclusions that can be drawn from the above expressions are summarized next:

1 – 3rd degree direct mixing can not be so large that it masks 3rd order IMD generated by 2nd degree coefficients. IMD asymmetry is thus bias sensitive and manifests itself in a great extent in small-signal IMD sweet-spots.

2 – The presence of a significant reactive part on the base-band termination is a necessary condition for IMD asymmetry.

3 – Real parts of 2nd harmonic and base-band terminations can not dominate over reactive parts.

4 – Imaginary parts of base-band and 2nd harmonic terminations should have comparable magnitudes. The interaction between those two determine IMD asymmetry in circuits commonly found in practice.

5 – If 2nd harmonic termination is resistive, IMD asymmetry can still be observed in presence of an important reactive nonlinearity.

In next Section these general conditions will be particularized and validated with a real GaAs MESFET microwave amplifier circuit.

III. Small Signal IMD Asymmetry in a Real Microwave Amplifier

To extrapolate the above conclusions to real microwave power amplifier circuits, and to validate them experimentally, a typical microwave power amplifier was designed and tested. Measurement results of output distortion power and IMD asymmetry were then compared to similar results obtained using a commercial Harmonic Balance simulator [6].

In the first test, the transistor was biased near one of its small signal IMD sweet spots, G_3=0, while the separation, ω_2-ω_1, between the two tones was varied, in order to observe its effect on the IMD asymmetry, Fig. 2.

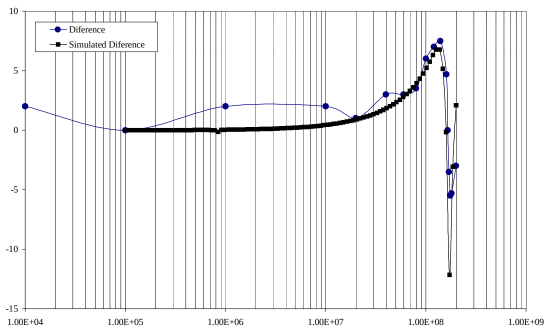

Fig. 2 – a) Asymmetry variation vs tone separation, experimental and simulated results.

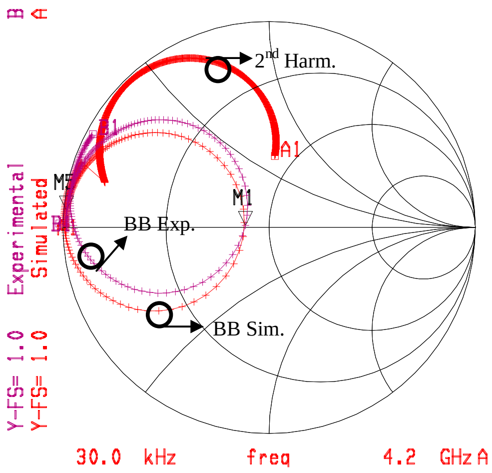

Fig.2 - b) Experimental and Simulated Base-band Load, and simulated 2nd Harmonic Load Impedance.

It can be seen that when the base-band is near a short circuit, asymmetry can hardly be noticed. When this base-band component faces an impedance larger than the one referred by marker 5, (M5, 30MHz, Fig. 2b), the asymmetry starts to get worse. Then, the base-band load tends to an open circuit, (M1, 165MHz), and a minimum in the asymmetry appears again, changing its sign when the imaginary part of the base-band impedance becomes negative, Fig. 2b. The 2nd harmonic load presents an imaginary part in all the tone separation range, which permits the asymmetry, as above explained. If those results are now compared with similar ones obtained from measurements, Fig. 2a, a good agreement between these two data sets is clear. The slight differences can be attributed to a small deviation in the base-band load impedance modelling, as is depicted in Fig. 2b.

To validate the conclusions drawn about the dependence of IMD asymmetry on changes of the Taylor series expansion coefficients, the amplifier was then tested with a constant tone separation of 100MHz, while its active device quiescent point was varied within the $-1.6<V_{GS}<0$ range.

As previously concluded from the general simple circuit analysis, the worst case of IMD asymmetry is verified when $G_3=0$, proving that only there the asymmetry is not masked by this 3rd order coefficient's contribution.

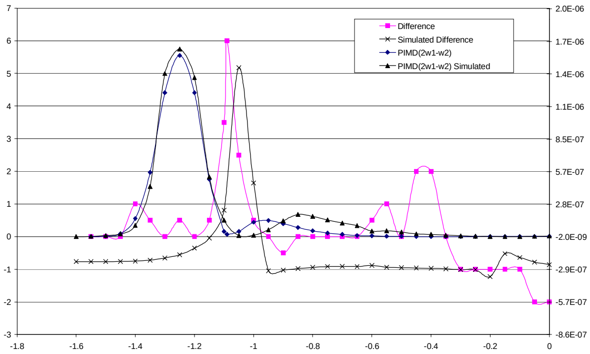

Fig. 3 - Asymmetry changing with bias point and IMD vs bias point, simulated and experimental results.

As can be seen in Fig. 3, there is again a good agreement between measured and simulated results of IMD asymmetry versus bias, validating the above conclusions. The differences in the first asymmetry maximum can be attributed to a slight imprecision in the modeled small signal IMD sweet spot, which is about 0.1 V higher than the measured one. The differences in the second maximum were attributed to a problem in the model prediction of the second small signal IMD sweet-spot. In the remaining points the differences are inside a 1dB error, and can be considered a very good approximation.

IV. Conclusions

In this paper small signal IMD asymmetry normally observed in PAs was studied and related to the amplifier's mild nonlinear device characteristics and base-band termination impedance.

First, a simple, but general circuit was studied, and used for explain the main sources of IMD asymmetry that appears in usual nonlinear circuits. The main conclusion drawn with this study is that for the small signal asymmetry generation the nonlinear device must have a reactive base-band load impedance and the 3rd Taylor expansion coefficient, G_3, should not over role nonlinear distortion.

In the third section, a real PA was built and its small signal IMD asymmetry studied. Measurements and small signal results gathered with that prototype were then used to experimentally validate the previously drawn theoretical predictions.

With this explanations in mind it is now possible to built a PA without IMD asymmetry, (changing the bias points, or the base-band impedance), which may help in measuring IP_3, or IMR.

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