IMD Performances of Harmonic Tuned Microwave Power Amplifiers

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Abstract

In this paper the linearity performances of harmonic tuned microwave power amplifiers is discussed and analysed, inferring some useful design guidelines. By a simplified active device model, the effects of the amplifier harmonic loads on the intermodulation distortion are investigated and experimentally validated showing the IMD3 performances of four hybrid amplifiers, designed using different harmonic manipulation strategies (i.e. different harmonic input and output terminations).

Introduction

The linearity performance in term of intermodulation (IM) is one of the crucial requirements of microwave power amplifiers (PAs), especially for handy-phone or mobile communication systems. The most troublesome effect of the device nonlinear behaviour is represented by the third order IM product (IMD3), since it is often difficult to filter out or it is even an in-band signal. Thus, many PA's design solutions have been developed to reduce the IMD3 to acceptable levels. The proposed approaches are usually based on linearisation techniques, often requiring complex and expensive circuitry, like the feedforward or predistorsion strategies, or worsening the amplifier performances, like the feedback or back-off approaches. If a simpler low-IM PA's design technique is required, the solution can be in the active device carrier to intermodulation (C/I) load pull characterisation [1]: the active device is measured and characterised for different load values and the resulting amplifier design is a trade-off between output power and IMD3 performances. The main target of published works on the topic is to understand the role of the PA's harmonic loads on the IM behaviour and their effects on the appearance of sweet-spots (i.e. null values) of IMD3.
In this contribution, after a brief discussion on the IMD3 generating mechanisms, the IMD3 performances of four hybrid amplifiers, designed using different operating classes (i.e. harmonic input and output terminations) with the harmonic manipulation strategy, are presented and commented.

Non linear device IMD3 model

In order to obtain a high efficiency PA's, it is well-known that harmonic manipulation design approaches are helpful, and in the past the authors have suggested some strategies [2, 3]. Nevertheless, is a common idea that the use of harmonic terminations could be detrimental for IMD3 performance. This idea is not completely correct, since the role of the harmonic terminations and their effect depend on the harmonic number and the topological position (input or output of the stage).
To understand the IMD3 generating mechanism and to predict the active device intermodulation performances, modelling techniques have been devised [4] or analytic approaches have been developed, based on a Volterra Series analysis, in which the active device is characterised at small signal regimes while its large signal behaviour is approximated using the describing function approach [5].
In particular, the active device nonlinear behaviour could be simplified through a simple three-terms power series expansion for the drain current

$$i_d \approx g_m \cdot v_{in} + g_{m,2} \cdot v_{in}^2 + g_{m,3} \cdot v_{in}^3 \qquad (1)$$

in which v_{in} is the gate-source voltage (in this approach the dependence of i_d on v_{ds} has been neglected).
To infer some useful information about the effect of input signal harmonics on IMD3, an input signal composed by two tones and their second harmonics can be assumed:

$$v_{in} = A_1 \cdot [\cos(\omega_1 t) + \cos(\omega_2 t)] + A_2 \cdot [\cos(2\omega_1 t) + \cos(2\omega_2 t)] \qquad (2)$$

obtaining the IMD3 product given by

$$\left\{ g_{m,2} \cdot A_1 A_2 + g_{m,3} \cdot \left[\frac{3}{4} A_1^3 + \frac{3}{2} A_1 A_2^2 \right] \right\} \cdot \cos(2\omega_2 - \omega_1) \qquad (3)$$

while the fundamental output is

$$\left\{ g_{m,1} \cdot A_1 + g_{m,2} \cdot A_1 A_2 + g_{m,3} \cdot \left[\frac{9}{4} A_1^3 + 3 A_1 A_2^2 \right] \right\} \cdot \cos(\omega_1) \tag{4}$$

Thus, remembering that usually $g_{m,2}$ and $g_{m,3}$ are opposite in sign, the effect of a second harmonic component at the input port is evidenced by the term $g_{m,2}A_1A_2$ that can reduce the overall IMD3 value. Obviously, these is a coarse approximation, but the underlying idea that a proper second harmonic input component can reduce the IMD3 performances is stressed also by Aitchison [6], who has experimentally demonstrated that a second harmonic feedback improves the amplifier linearity.

The simple results in eqn. (3) can be applied to a more realistic device model, in order to compare different harmonic tuning strategies. As an example, if Tuned Load and Class G approaches are considered, the small-signal IMD3 performances are shown in fig. 1, evidencing a remarkable improvement in linearity.

In the following, measurements of four PA's designed with different harmonic tuning approaches will be shown, given a practically confirmation of this property and demonstrating that the harmonic manipulation PA's design approaches can be helpfully used both to increase power performances and improve IMD3.

Experimental Results

Four amplifiers were realised implementing different tuning approaches, ranging from the classical Tuned Load (TL) strategy, in which the output voltage harmonic components are shorted, to Class F [2], Class G [3] and Class FG[7] strategies, where respectively 3rd, 2nd and 2nd&3rd harmonics are properly terminated. The active device used is a medium power GaAs MESFET by Alenia Marconi Systems, and the amplifiers have been designed to operate at 5GHz, with a 5V drain bias and a quiescent drain current of 30% $\mathbf{I_{dss}}$.

The PA's matching networks have been realised on a Allumina substrates (25mil thick) with different criteria.

For TL and Class F approaches, the input matching networks were synthesised to fulfil fundamental frequency conjugate matching and to minimise the input distortion, i.e. zeroing the harmonic components of driving signal represented by the voltage across the gate-source capacitance C_{gs}. Such a function, as represented in table 1, has been accomplished by means of an external input termination that, at the internal terminals, actually synthesise a short-circuit starting from the reported values. For Class G and Class FG strategies, the input networks were designed, besides to fulfil the matching conditions again, to manage the output current harmonic components (2nd and 3rd) to obtain the proper phase relationships, allowing purely resistive output loads [7].

The synthesised external loads are reported in tab.1, where their base-band values are also shown, practically independent from harmonic loads choice and correlated to the dc bias.

The IMD3 measurement have been performed by a spectrum analyser, driving the amplifiers with two equal-amplitude input signal at 5 and 5.05GHz respectively. The scheme of the measurement set-up is depicted in fig. 2.

The measured performances of the four realised PA's are reported in fig. 3, evidencing the improvement due to the harmonic manipulation approach, both in terms of output power and power added efficiency, as expected when a harmonic tuning strategy is applied. Finally, in fig. 4 are depicted the measured IMD3 performances.

Some interesting observation can be made from the results shown; it can be noted from fig. 4 that with a Class F approach, the use of a third harmonic actually degrades the IM3 behaviour, even if its effects is not so relevant, as predicted with Volterra Series analysis. On the other hand, the use of a second harmonic component, as made for Class G and FG PA's decrease the IMD3 distortion, according to the observations made in the previous section.

In particular, Class G amplifier exhibit the lower IMD3, and its different behaviour with respect to Class FG amplifier can be ascribed to two reasons. Firstly, from eqn (3), the second harmonic components A_2 changes the IM3 sign, in any case reducing the overall amplitude: in the case of Class G the amplitude obtained is less than for Class FG, due to the lower second harmonic contribution. Secondly, the presence of an input third harmonic component in the Class FG amplifier, necessary to obtain the output in-phase third harmonic voltage component, not taken into account in eqn (1), actually increase the overall IMD3.

Finally, from the measured results, the sweet-spot position (the null in IMD3) is basically unchanged by the different harmonic manipulation strategies, evidencing its major dependence on the choice of the bias point only .

Conclusions

The intermodulation generating mechanisms has been discussed and the role of the amplifier harmonic termination, both at the input and at the output has been clarified by a simplified model. Measured performances of four realised PA's, implementing different harmonic terminating solutions, have been confirmed the assertion made in this paper.

Moreover, the presented results evidencing the improvement due to the harmonic manipulation approach, both in terms of output power and power added efficiency, as expected when a harmonic tuning strategy is applied.

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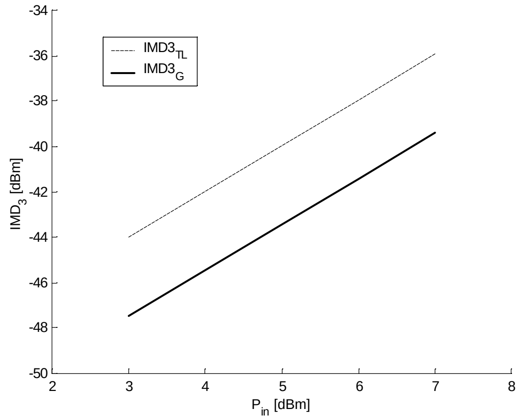


Fig. 1: IMD3 small signal comparisons between Tuned Load and Class G approaches derived from eqn. (3)

Tab. 1: synthesised external load values

	Base-Band (0.05GHz)	**Fo (5GHz)**	**2Fo (10GHz)**	**3Fo (15GHz)**
	Input			
TL	17.8-6.0j	14.4+25.9j	42.9-223.4j	23.9-130.4j
Class F	17.8-6j	14.4+25.9j	42.9-223.4j	23.9-130.4j
Class G	17.8-6.2j	14.5+25.9j	0.4+14.7j	15.2+117.8j
Class FG	17.8-6.1j	14.5+25.8j	0.5+14.8j	2.0+26.8j
	Output			
TL	4.0-13.1j	22.3+6.1j	1.6-4.6j	1.3-7.2j
Class F	3.7-12.4j	25.1+8.3j	1.4-4.6j	0.5+36.7j
Class G	4.3-13.6j	29.7+15.5j	18.0+151.6j	1.0-6.2j
Class FG	4.2-13.5j	32.6+20.5j	3.4+68.1j	42.9-469.2j

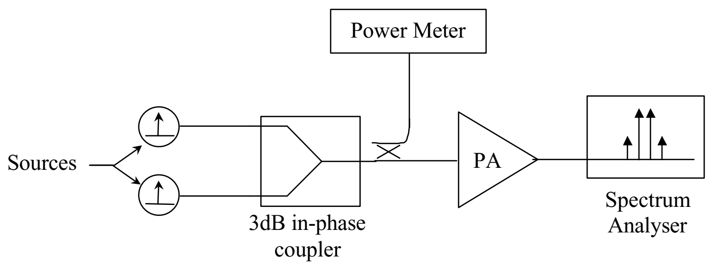
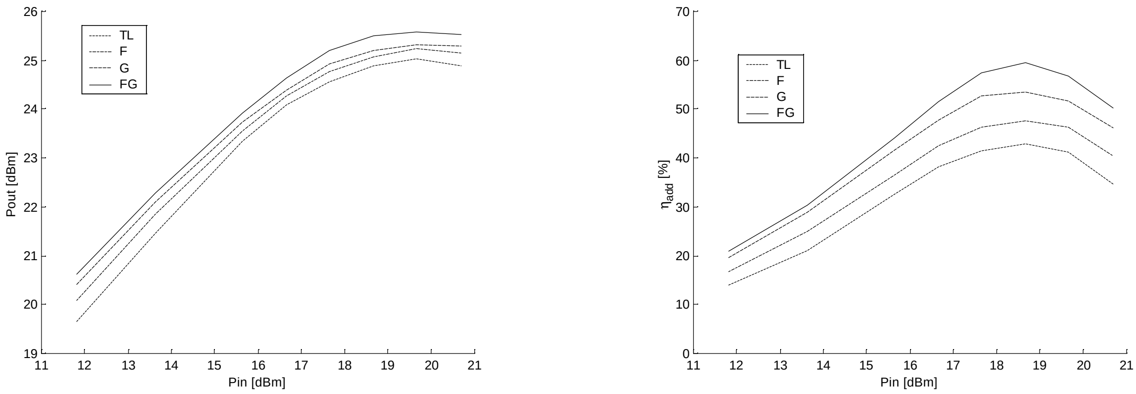


Fig. 2: IMD3 measurement set-up



(a) (b)

Fig. 3: Measured output power (a) and power added efficiency (b) of the four realised PA's .

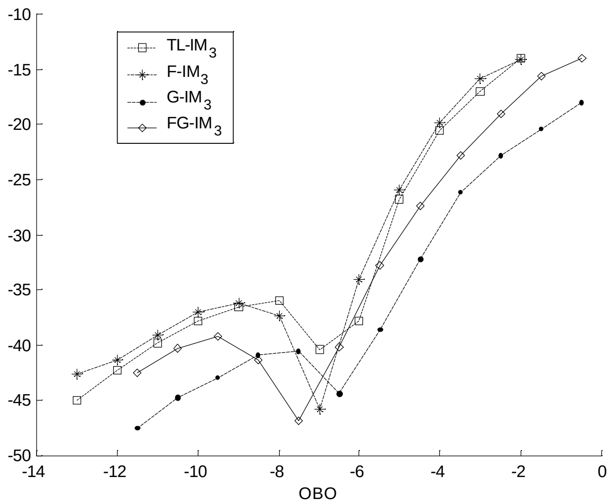


Fig. 4: IM3 measures performances of the four PA's realised.