High-Efficiency Low-IM Microwave PA Design

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***Abstract* — Harmonic terminations effects in microwave power amplifiers on its power and linearity performances is discussed. By a simplified theoretical approach, useful guidelines are inferred to obtain both high efficiency and low intermodulation. The concepts discussed are experimentally validated showing the performances of four hybrid amplifiers, designed using different harmonic manipulation strategies. In particular, using a proper input second harmonic output termination, an improvement both in power added efficiency and intermodulation can be obtained.**

I. INTRODUCTION

The growing demand of new communication systems and services, as the incoming *3G* ones, requires demanding performances to the signal processing units, and in particular the design of the RF output stage become one of the key elements. Such stage must fulfill, at the same time, tight constraints on output power (P_{out}), efficiency (power added efficiency, PAE) and linearity levels; as a consequence, in last years many efforts have been devoted to the development of design strategies for microwave power amplifiers (PAs) satisfying such requirements.

Proposed PAs design solutions have been developed mainly for high efficiency performance [1]-[2], also by the authors using harmonic manipulation approaches [3]-[5]. Even if efficiency improvements is remarkable, limited attention is devoted to the linearity performances, whose main critical effect is represented by the third-order intermodulation product (IM), since it is often an in-band signal, difficult to filter out. To reduce the IM to acceptable levels, many solutions have been proposed based on linearization techniques, often worsening other amplifier performances, as the feedback or back-off approaches, or requiring complex and expensive circuitry, as the feedforward or predistortion strategies [6].

Thus, for a simpler low-IM PA's design, the solution seems to be a trade-off between Pout, PAE and IM performances [7].

The question whether high efficiency design is compatible or not with high linearity is still an open problem; in other words, it is a common sense that harmonic tuning approaches are detrimental for the linearity performances of the amplifiers. Efforts have been devoted to the study of the effects of the harmonic terminations on the IM behaviour. In particular, from published works [8], it is evident that the impact of the fundamental output termination (@f_0, the operating frequency) is remarkable, as well-known, while the other output terminations have negligible effects, as the input fundamental (matching) termination and higher order harmonics; only the effect of the second harmonic input load (@$2f_0$) is not clearly demonstrated [8]-[9].

The aim of this contribution is to discuss the IM generating mechanisms and to clarify the effects of the harmonic loads, demonstrating that the use of a proper second harmonic input termination can simultaneously improve output power, efficiency and IM performances.

II. OVERVIEW OF IM GENERATING MECHANISMS

To predict the active device intermodulation performances, different modeling techniques have been devised [10] and analytic approaches based on Volterra series analysis have been developed [11]. Due to the intrinsic difficulties in the development of an accurate active device model [12], usually too complex to infer useful guidelines, to understand the IM generating mechanisms a simplified model can be considered, in which the active device output nonlinear behavior is simply described by a three-terms power series expansion of the output current:

$$i_{out} = g_m \cdot v_{in} + g_{m,2} \cdot v_{in}^2 + g_{m,3} \cdot v_{in}^3 \quad (1)$$

where v_{in} is the input control signal.

It is to note that in this simplified model the dependence of the output current on the output voltage has been neglected, since its effect becomes relevant for large signal input drive level, i.e. in saturated region [8], where this approach loses its validity. On the other hand, to take into account the input non linear behavior of the active device, ascribed to the non linear gate-source capacitance C_{gs}, the

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input signal can be represented by two input tones and their harmonics, i.e.

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

where A_1 is the amplitude of the two-tones external input signal, and A_2 is the amplitude of the internally generated second harmonic component. It is to note that also the IM input generated signal should be taken into account, but since its contribution is negligible, it has been omitted in eqn.(2) for sake of simplicity.

The simplified and unilateral model considered is depicted in fig. 1.

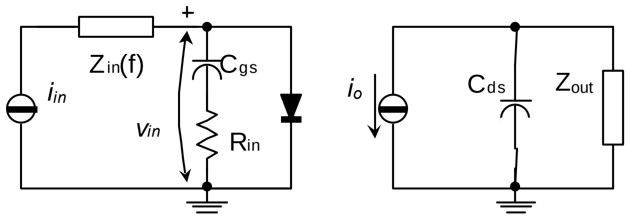

Fig. 1: simplified active device model assumed.

Substituting eqn.(2) into eqn.(1), and rearranging, the IM output signal obtained is

$$IM = \left\{ \begin{array}{l} g_{m,2} \cdot A_1 A_2 + \\ g_{m,3} \cdot \left[\frac{3}{4} A_1^3 + \frac{3}{2} A_1 A_2^2 \right] \end{array} \right\} \cdot \cos[(2\omega_2 - \omega_1) \cdot t] \quad (3)$$

while the fundamental output signal is

$$OUT = \left\{ \begin{array}{l} g_m \cdot A_1 + g_{m,2} \cdot A_1 A_2 + \\ g_{m,3} \cdot \left[\frac{9}{4} A_1^3 + 3 A_1 A_2^2 \right] \end{array} \right\} \cdot \cos(\omega_1 t) \quad (4)$$

Since usually $g_{m,2}$ and $g_{m,3}$ are opposite in sign, the effect of the second harmonic component at the input port ($g_{m,2}A_1A_2$) is to reduce the overall IM value. This observation has been also experimentally demonstrated in [13].

To validate the above results and to compare different harmonic tuning strategies, the results predicted by this simple small-signal model are compared with measurements for a Tuned Load (i.e. without harmonic manipulation) and a Class G (i.e. properly terminating the load @$2f_0$) realized PA's [14], showing a good small signal agreement, as reported in fig. 2.

In this figure IMD represents the ratio between IM and fundamental output power and the results confirm the predicted linearity improvement obtainable using a proper second harmonic input termination, as will be discussed in the next section.

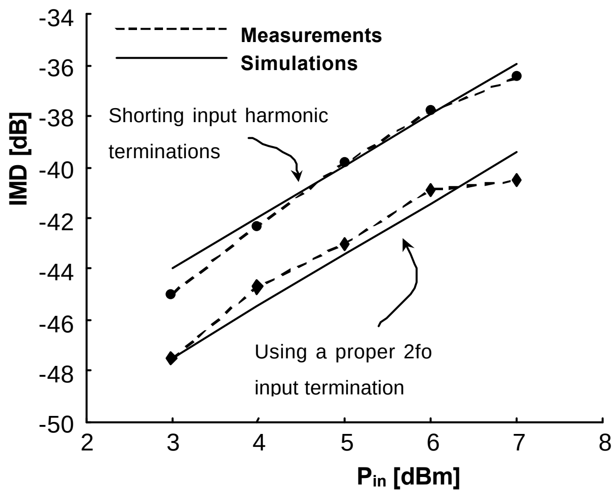

Fig. 2: comparisons between simulation (continuos lines) obtained with model shown in fig. 1 and measured (dotted lines) IM performances for two different input harmonic termination approaches.

II. DESIGN CRITERIA

For sake of simplicity only the rationale of the design approaches will be presented, while the theoretical details can be found in [3]-[5].

The basic assumption of high efficiency power amplifier design approaches is that the active device operates as a voltage controlled current source, i.e. the output current is imposed by a proper input drive signal, according to fig.1, while the output voltage can be properly shaped to minimize the dissipated power and consequently assuring an efficiency improvement. This waveform shaping can be obtained properly terminating the output current harmonic components: the fundamental output termination is chosen to assure a pure resistive load, maximizing the output power, while the harmonic ones to control the voltage waveshaping, taking into account practical limitations since only the first few harmonics can be fruitfully employed. Thus, the design approaches ranging from the Class F strategies (3rd harmonic control only) [3], to Class G (2nd harmonic control only) [4] to Class FG (2nd and 3rd harmonics control) [5]. In fig.3 the simulated output current and voltage waveforms are shown for amplifiers designed with these different approaches, as will be described in the next section. From fig.3 it can be noted that the output voltage waveform exhibits an overshoot, due to the use of a second harmonic component, that must be accounted even if it is not critical for low voltage applications, as handy-phone systems.

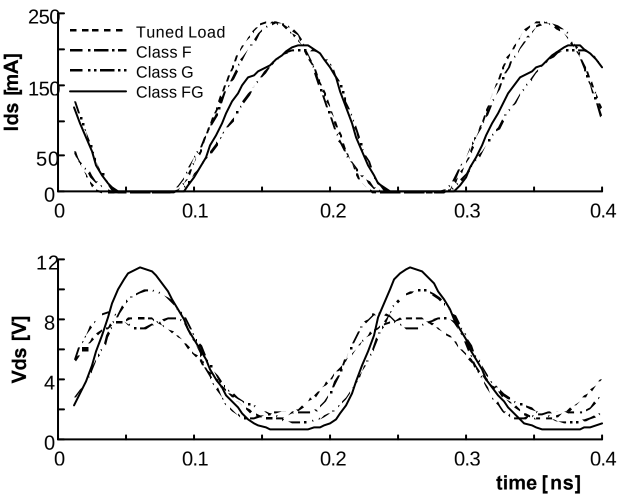

Fig. 3: simulated output current and voltage for PAs realized using different harmonic terminating strategies.

The intrinsic difficulty on the design of a second harmonic controlled PA is related to the hard control of the proper fundamental to second voltage harmonic components phase relationship [4]; in fact, since the output current harmonics are usually out-of-phase, it could be necessary to resort to a complex termination, both @f_0 and $2f_0$, so loosing the benefits of the waveshaping. Then the solution proposed is to choice a second input harmonic termination ensuring the proper phase relationships of the output current harmonics [15], and terminating the latter ones on resistive loads. In the case of the designed amplifiers, figure 4 shows the amplitudes of the fundamental and second harmonics generated at the device input intrinsic control terminal.

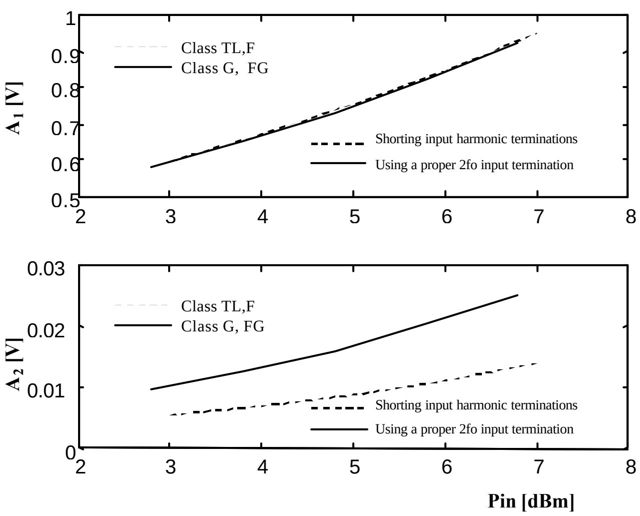

Fig.4: Input fundamental and second harmonic generated voltage components for the four design approaches

As a consequence, a second input harmonic signal A_2 is generated [eqn.(2)]. A qualitative interpretation is possible. It is obvious that the input termination @$2f_0$ can be designed trading-off between the optimum value for PAE maximization and the optimum value minimizing IM. Moreover, since the input generated signal A_2 is related to the input drive signal, then there will be a combination of load and input power values zeroing the IM level, i.e. producing a sweet spot on IMD measurements.

In the next section the measurements of four realized amplifier will be presented to validate the concepts inferred in this section.

III. EXPERIMENTAL RESULTS

The realized amplifiers have been designed implementing different harmonic strategies, ranging from the simplest Tuned Load (TL), to Class F [3], Class G [4] and Class FG [5], all operating @5 GHz. The active device is a medium power GaAs MESFET by Alenia Marconi Systems, with @5V drain bias and 30% I_{dss}. In Table I the measured and expected power performances are reported at -1dB output compression level.

TABLE I

Amplifier	P_{out} [dBm] Measured	PAE [%] Measured	PAE [%] Simulated
Tuned Load	25.0	42	39
Class F	25.2	47	44
Class G	25.3	54	53
Class FG	25.6	60	61

For the tuned Load and Class F approaches, the input matching networks were synthesized to fulfill fundamental frequency conjugate matching and to minimize the input distortion, i.e. zeroing A_2 of eqn. (2). For Class G and Class FG strategies, the input networks were designed both to fulfill the matching conditions again and to manage the output current harmonic components obtaining the proper phase relationships; in this case an equivalent A_2 was generated.

IMD measurements are reported in fig. 4, performed with two equal-amplitude input signal @5 and 5.05GHz, as a function of the output back-off (OBO).

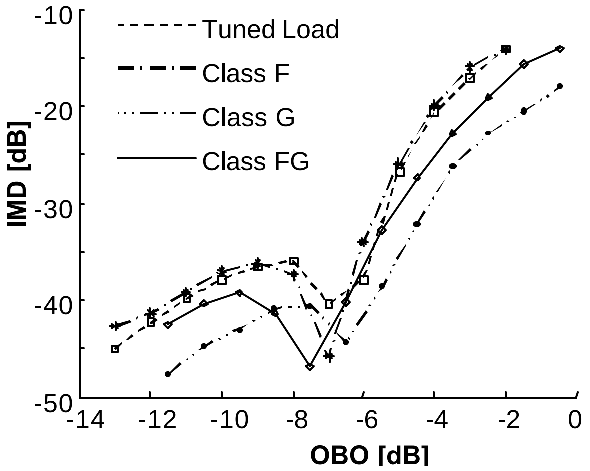

Fig. 4: IMD measurements *vs.* Output Back-Off (OBO).

As it can be noted, for a Class F approach the manipulation of the 3rd output harmonic has a detrimental effect on IMD levels, also predicted by a Volterra analysis, but its impact is negligible with respect to the Tuned Load case, since the input networks are the same. Instead, for the Class G and Class FG approaches the generation of the input 2nd harmonic A_2 decrease the IM distortion, according to the observations made in the previous section. In particular, the Class G amplifier exhibits the lower IMD3. Its different behavior with respect to Class FG amplifier can be ascribed to two reasons. Firstly, the signal A_2 generated both for Class G and Class FG changes the IM sign, to assure the proper output harmonic phase relationships, but the obtained amplitude for Class G is less than for Class FG, reducing the IM levels. The second reasons is the presence of an input 3rd harmonic component for the Class FG amplifier, not taken into account in eqn. (2), whose effect is an increase of IM level.

A final observation regards the presence of the sweet spots, i.e. the null IMD values, that are basically unchanged by the different harmonic manipulation strategies. It seems to be dependent of the bias point chosen, but further investigation are necessary.

IV. CONCLUSION

In this contribution the intermodulation generating mechanisms has been discussed and the role of the amplifier harmonic terminations, in particular at the input port, has been clarified by a simplified unilateral model. The assertion made in this contribution has been verified by the measured performances of four hybrid amplifiers, designed implementing different harmonic tuning approaches.

REFERENCES

[1] N.O.Sokal, "Class E High-Efficiency Power Amplifiers, from HF to Microwave," *1998 IEEE MTT-S Int. Microwave Symp.* pp. 1109-1112.

[2] F.H.Raab, "Class-F Power Amplifiers with Maximally Flat Waveforms," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-45, no. 11, pp. 2007-2012, Nov. 1997.

[3] P.Colantonio, F.Giannini, G.Leuzzi, E.Limiti, "On the Class-F Power Amplifier Design," *Int. Journal on RF and Microwave Computer-Aided Engineering*, vol. 9, no. 2, pp. 129-149, March 1999.

[4] P.Colantonio, F.Giannini, G.Leuzzi, E.Limiti, "High Efficiency Low-Voltage Power Amplifier Design by Second Harmonic Manipulation," *Int. Journal on RF and Microwave Computer-Aided Engineering*, vol. 10, no. 1, pp. 19-32, June 2000.

[5] P.Colantonio, F.Giannini, G.Leuzzi, E.Limiti, "RF versus Microwave High Efficiency PA Design," *Proc. Of the European GAAS2000 Symp*, Paris, France, pp. 132-135, Oct. 2000.

[6] Nick Pothecary, *Feedforward Linear Power Amplifiers*, Artech House, Norwood, MA, USA 1999.

[7] F.N.Sechi, "Design Procedure for High_Efficiency Linear Microwave Power Amplifiers," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-28, no. 11, pp. 1157-1163, Nov. 1980.

[8] R.A.Minasian, "Intermodulation Distortion Analysis of MESFET Amplifiers Using the Volterra Series Representation," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-28, no. 1, pp. 1-8, Jan. 1980.

[9] R.S.Tucher, C.Rauscher, "Modelling the third-order intermodulation-distortion properties of GaAs FET," *Electronics Letters*, vol. 3, pp. 508-510, Aug. 1977.

[10] S.A.Maas, D.Neilson, "Modelling MESFET's for Intermodulation Analysis of Mixers and Amplifiers," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-38, no. 12, pp. 1964-1971, Dec. 1990.

[11] J.J.Bussgang, L.Herman, J.W.Graham, "Analysis of Nonlinear Systems with multiple Inputs," *IEEE Proceedings*, vol. 62, no. 8, pp. 1088-1119, Aug. 1974.

[12] S.A.Maas, "How to Model Intermodulation Distortion," *1991 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 149-151.

[13] M.R.Moazzam, C.S.Aitchison, "A Low Third Order Intermodulation Amplifier with Harmonic Feedback Circuitry," *1996 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 827-830.

[14] P.Colantonio, F.Giannini, E.Limiti, G.Saggio, "Experimental performances of 5GHz harmonic-manipulated high efficiency microwave power amplifiers," *Electronics Letters*, vol. 36, no. 9, pp. 800-801, April 2000.

[15] P.Colantonio, F.Giannini, E.Limiti, G.Saggio, "Input/Output Optimum 2nd Harmonic Terminations in Low-Voltage High-Efficiency Power Amplifiers," *Proc. Of the 10th MICROCOLL*, Budapest, Hungary, pp. 401-406, March 1999.

[16] P.Colantonio, F.Giannini, G.Leuzzi, E.Limiti, "IMD Performances of Harmonic Tuned Microwave Power Amplifiers," *Proc. Of the European GAAS'2000 Symp*, Paris, France, pp. 132-135, Oct. 2000.