High Linearity and Efficiency Microwave PAs

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***Abstract* — An overview on linearity and efficiency performance optimisation in power amplifier (PA) is presented, stressing the required trade-off demanded to PA designers. For efficiency improvement, the harmonic tuning strategies are discussed, with their advantages and major drawbacks. For linearity improvement, the IMD sweet spot optimisation strategies is presented as a solution to obtain low intermodulation near PA saturated condition, resulting in efficiency enhancement with respect to back-off approaches.**

I. INTRODUCTION

The beneficial effects of advanced modulation schemes allows high spectral efficiency transmission systems, but a highly linear behaviour of the RF components is simultaneously required. From the system level, the transmitter stage is the critical point, being its intrinsic non-linearities the sources of spectral regrowth and adjacent channel intermodulation.

The increase in power supply system operating time is another main aspect, being strongly influenced by the power amplifier (PA): with the same transmitted power, higher conversion efficiency is required. Nevertheless, higher conversion efficiency allows a decrease in dissipated power, with a resulting increase in active device lifetime. The result is a less stressed device and a decrease in heat sink dimensions, with a positive impact on the overall size and weight of the unit.

The PA designer is therefore in front of a difficult trade-off among the contrasting goals of high transmitted power, low power consumption and, for many telecommunication system, linear operation. Given the widespread diffusion of many telecom applications, all of the above specifications have to be fulfilled keeping unit cost to a minimum. Such goals and the resulting compromise may vary depending on the type of radio link to be established and overall system specifications, but their challenge has heavily influenced industrial, technical and research directions of the last decade in the PA field. In the following, possible solutions at the PA design level are presented, focusing on the research activities performed by the authors within the frame of the EU TARGET Network of Excellence.

II. LINEARITY VS. EFFICIENCY OVERVIEW

The maximum output power attainable from a given active device directly depends on its maximum current (I_{max}) and voltage (V_{br}, i.e. breakdown voltage). The limit imposed by the device maximum current may be overcame increasing device gate periphery and/or through the use of device power combining techniques. On the other hand, the limit on drain voltage swings can be surmounted mainly increasing the device breakdown voltage. Unfortunately the latter is an intensive quantity, depending mainly on material properties and device fabrication process. The increasing interest in wide-bandgap materials (mainly GaN and SiC) is in fact motivated from the intrinsic high breakdown field exhibited by such alloys, with typical values in the range of 100 V, as contrasted to the few tens of the traditional GaAs-based FET devices [1]. Therefore, while maximum output power levels can be assumed, at least to a first approximation, practically independent from bias point selection, the latter clearly affects maximum efficiency and linearity performances of PA, as shown in Fig. 1.

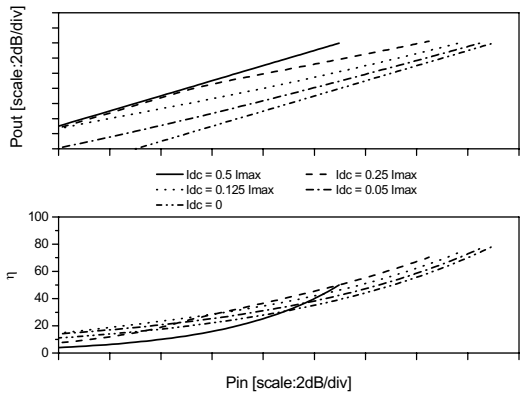

Fig. 1: Theoretical output power (P_{out}) and efficiency (η) vs. input power (P_{in}), for several bias conditions.

From Fig. 1, while maximum output power is practically constant (less than 0.5dB variation), maximum efficiency increases moving form Class A ($I_{DC}=0.5I_{max}$, $\eta=50\%$) towards Class B ($I_{DC}=0$, $\eta=78.5\%$) or C ($\eta\rightarrow100\%$) bias. However, while theoretically in Class A and B there is a linear relation between P_{out} and P_{in}, resulting in a curve with constant slope of 1dB/dB, for intermediate Class AB bias condition the linear behaviour is obtainable for unsaturated condition, e.g. decreasing Pin levels. This means that moving from Class A to Class B, an increasing output back-off (OBO) becomes mandatory to operate in linear condition, resulting in lower efficiency values. For instance, for $I_{DC}=0.25I_{max}$ an OBO of 6dB minimum is necessary for linear PA operation (see Fig. 1).

III. HIGH EFFICIENCY APPROACHES

While technological progress can achieve higher power performances, acting in order to increase I_{max} and V_{br} values, suitable design strategies are mandatory to attain highest efficiency performances. Two PA design strategies

can be evidenced, based on switched mode active device operating conditions or on the selection of proper device harmonic loading conditions. In order to generalize such approaches and to introduce high-efficiency operating classes, a simplified theory based on Power Balance consideration has been proposed in [2] and experimentally confirmed in [3]. As a result, 100% drain efficiency is obtained if two conditions are simultaneously fulfilled. On one hand dissipated power on the active device has to be nulled, (accomplished by properly shaping voltage and current waveforms to have a null overlapping, i.e. current on the device must vanish for a non-zero voltage and vice-versa). Secondly, harmonic *active* power from the device has to be nulled, thus implying either the zeroing of current (I_n) or voltage (V_n) harmonic components or their proper phasing ($atan(V_n/I_n)= \varphi_n = \pi/2$). The designer's task is therefore in the proper shaping of current and voltage waveforms with the selection of appropriate harmonic terminations, thus leading to the fulfillment of the above conditions.

Switching-mode Power Amplifiers

In this category a number of different approaches can be grouped, characterized by the assumption that the active device(s) in the power stage operate as switches, commuted between the two "on" (i.e. short-circuit-like) and "off" (i.e. open-circuit-like) states (see chapter 14 in [4] for a detailed list). As compared to classical PA operating condition, in which the active device is represented as a controlled current source replying with good fidelity the input stimulus, switching-mode PAs exhibit highly non linear characteristics. Such inherent lack of linearity is not an issue for constant-envelope modulations, in which switched-mode operation may infer the benefit of high efficiency operation of the transmitter, while preventing their adoption if amplitude-modulated signals are considered. On the other hand, techniques consisting in the envelope elimination and restoration [5], outphasing [6] or other high linearity modulating schemes, may alleviate the linearity drawback. The most popular and effective switched mode configuration is the Class E amplifier, introduced and patented by Sokal in 1975 and recently resurrected with the expiration of the patent. The success of Class E amplifier is related to closed form design expressions for its circuit components, together with the attainable high efficiency [7]. Nevertheless, constraints imposed on the output circuit high-Q operation may be severe if high-frequency operation is considered. The result of a low quality factor for the output series resonant circuit is a non zero harmonic current flowing into the output, implying a non-optimum drain voltage waveform, with possible ringing phenomena. Moreover, since the Class E amplifier has to be over-driven by a driver stage well into device compression regions, its large-signal gain may be well below the level of a comparable linear power amplifier (say 3-5 dB lower [8]). Given the typical frequency roll-off of power devices, this poses an intrinsic frequency limitation to the applicability of the Class E scheme. The frequency limit is further decreased by the intrinsic reactive behavior of the device output (dominated by the device output capacitance C_{ds}).

Harmonic Tuning Approaches

Harmonic tuning (HT) approaches represent indeed a hot discussion topic given the beneficial effect on stage efficiency attainable by a proper selection of harmonic terminations. Starting from ideal Class F design approach proposed by Snider in [9], a huge number of contributions have been proposed, ranging from experimental observation of performances to introduction of novel topologies, from systematic investigations of experimental performances to design methods for special harmonic configurations [10]. However, as the operating frequency enters the microwave region, the theoretical Class F approach exhibits a degradation in performances, due to the lack of harmonic impedances control. In fact, as frequency increases (e.g. > 20 GHz), the control of both the 2nd and 3rd harmonic terminations becomes troublesome, since the active device output capacitive behavior practically short-circuit higher components, not allowing the desired wave shaping. Moreover, for low voltage applications a Class F strategy is not the best solution, since different methodologies (based on 2nd harmonic output impedance tuning) have demonstrated better performances [2]. In Fig. 2 the measured results are reported for the power performances of four single-device PA stages, designed utilizing Tuned Load approach (TL, e.g. short circuits for harmonic frequencies), 2nd harmonic tuning, 3rd harmonic tuning and 2nd and 3rd harmonic together [11].

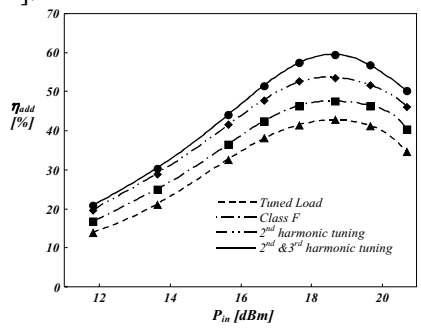

Fig. 2: Power-added efficiency measured performances of four single-device PA stages designed utilizing different HT strategies [11].

A simplified theory to generalise HT approaches has been presented in [2], stressing also the relevance of input harmonic terminations. The exploitation of the device input non linearities and therefore the input terminations to the active device has been the subject of a series of investigations, leading to experimental and theoretical studies [12]. In Fig. 3 the efficiency contour plots for a 1mm PHEMT are reported, by varying input 2nd harmonic termination using an harmonic load/source pull [3].

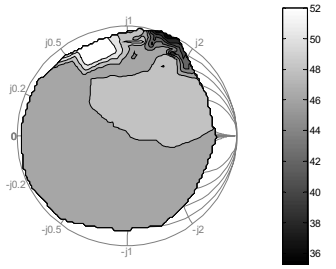

Fig. 3: Measured contour plot of drain efficiency vs. second harmonic input impedance.

A final consideration regards the linearity performances of harmonic-controlled PAs: high-efficiency tuning leaves in fact some open questions on the resulting linearity. The proper trade-off among such requirements is not clearly evidenced to date, even if experimental results demonstrate that high efficiency tuning do not necessarily imply detrimental linearity effects [13]. Moreover, harmonic injection techniques have been proposed to optimise linearity performances [14]. In any case however, proper subsystem linearization techniques can be adopted in the case of harmonic tuned PA stages, adopting predistortion, feedback or feedforward approaches.

IV. Linearity Issues

Linearity of PAs is an issue of primary concern in telecommunication applications where the signal format involves non-constant envelopes. That is the case in modern pulse-shaped QPSK digital transmission or in any multi-carrier systems. There, intermodulation distortion (IMD), noise and spectral efficiency determine a "linear" PA operating mode, typically unsaturated class A or AB, in detriment of the highly efficient class B or C or, mostly, the saturated classes E, D or F. This choice has an high cost in PA efficiency: the basic target of PA design is to get class B efficiency with class A distortion. Although this is in general not possible, there are some particular PA features that provide a way to escape from this apparent dead end. One of such PA characteristics, which has recently seen an increased interest, resides in the so-called large-signal IMD sweet-spots [15,16]. They are particular points of the IMD vs. Pin characteristic (Fig. 4) where only a few dBs of output-power back-off (and thus a few percent of efficiency degradation) can lead to astonishingly high levels of power-to-IMD ratio, (IMR).

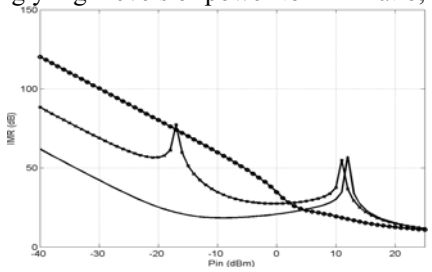

Fig. 4: Typical *IMR vs.* P_{in} plots for three operation classes: C (-), AB (x) and A (o).

Those curious nonlinear effects can be qualitatively explained as opposite phase interactions of small and large-signal IMD components, typically arising from the mild $i_{DS}(v_{GS})$ nonlinearities of FETs (or $i_C(v_{BE})$ in bipolar usually associated to the on-set of saturation). While the former are mainly determined by the device's soft turn-on followed by a region of quasi-linear input-output transfer characteristic, the latter are imposed by gate-channel junction conduction or breakdown, or, more commonly, saturation-to-triode region transition. Mild nonlinearities are characterized by a gain expansion (class C quiescent point) or gain compression (class A or AB quiescent points) distortion characteristic, whereas strong nonlinearities always imply a gain compression type of IMD. Hence, depending on the quiescent point, we can have a very slight small-signal gain compression followed by strong gain compression, as in usual class A PAs, or a moderate gain expansion followed by, again, the strong compression. Any time the nonlinear distortion contributions reverse their phase, they pass through a theoretically null amplitude, i.e. a deep in the IMD *vs* Pin plot, the mentioned large-signal IMD sweet-spot. Moreover, if the device is biased slightly above turn-on, usually identified as class AB operation, the PA shows again a very shallow gain compression. Hence, similarly to what was concluded for class A operation, no IMD sweet-spot is expected. Nevertheless, depending on the abruptness of turn-on and succeeding linearization of the $i_{DS}(v_{GS})$ characteristic (typical in LDMOS, MOSFETs or even in some HEMTs), it can be shown that as the signal excursion grows, entering more and more into the gain expansion region, the PA ceases to exhibit gain compression and tends to behave as in class C [17], generating another IMD sweet-spot for moderate signal levels. At this stage, the circuit starts behaving as a class C PA with the corresponding gain expansion. Consequently, a new IMD sweet-spot will occur at large-signal when gain compression will finally take place. Depending on the actual device transfer characteristic and on the adopted bias point, class AB may be significantly different from class A: it may even present two IMD sweet-spots, for small to moderate levels of input power and for the on-set of saturation. In summary, low IMD is either achieved through a largely backed-off class A PA, or through the sweet-spots of a class C or AB PA at the on-set of saturation. Despite this is accomplished in a pre-determined zone of excitation level, its efficiency is comparably so high that, unless extremely good figures of carrier-to-IMD ratio are required, the latter solution exhibits a much better IMD versus efficiency compromise. Given this large-signal sweet-spot origin, it becomes clear that the parameters controlling the on-set of saturation (namely the biasing voltages and the load termination) can be effectively used to produce a sweet-spot at the desired operating power level [16]. Lowering the gate-to-source DC voltage in a class C FET amplifier would move the point of optimum linearity to higher input power levels, as shown in Fig. 5. An accurate description of such behavior opens the possibility of automatically conforming Pin-IMD profiles with a wide or multiple sweet-spots. Two actions are required: sensing the long-time RMS value of the excitation envelope and using this quantity to modify the device operating conditions.

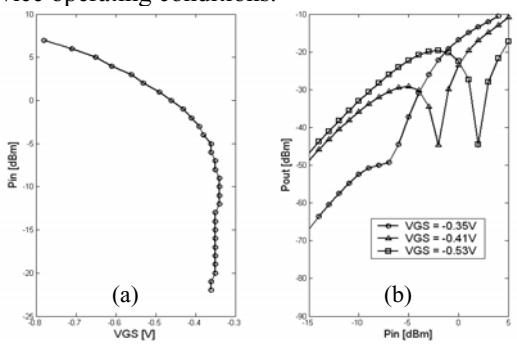

Fig. 5: Typical sweet-spot evolution plots with V_{GS} and P_{in}. (a) P_{in} at which an IMD sweet-spot takes place for each V_{GS} bias. (b) A family of IMD *vs* P_{in} profiles when V_{GS} bias is used as a parameter.

A resistor can be added in the gate DC path to reduce the sensitivity of the sweet-spot to input power variations in a simple amplifier. On the other hand, a complete bias adaptation topology can be implemented, if one were interested in assuring a good linearity versus efficiency tradeoff with constant gain in the output stage of a transmitter with power control capability [18].

The biasing or output impedance condition influence over the large-signal intermodulation distortion is also finding application in the development of power amplifier linearization techniques at the device-level. Taking advantage of the distortion current control in amplitude and sign around the sweet-spot, large-signal forms of the derivative superposition have been suggested [19, 20].

Finally, let us mention some issues that may jeopardize the linearity characteristics of these IMD nulls, and thus should deserve particular attention during the PA design and implementation phases. As seen above, large-signal IMD sweet-spots are based on the cancellation, at a given signal level, of small-signal and large-signal IMD components. Such linearization method has a reduced effectiveness if some of its pre-conditions are not met.

In fact, if the handled signal has a wide varying amplitude envelope, cancellation is perfect at the given amplitude, but degrades outside. The overall effect is likely to depend on the statistics of the signal amplitude distribution [21]. Furthermore, the IMD sweet-spot no longer reflects a deep IMD null, but becomes a more or less smooth valley [16]. Also, perfect cancellation requires that the IMD components arising from the device's mild and strong nonlinearities are opposite in phase. If the condition is not met, the sweet-spot will again be converted in a smooth valley. A phase deviation from the required 180º arises because the intrinsic load impedance at the fundamental components is not a pure resistance, or because there are out-of-band reactive effects at the base-band and the even harmonics [16]. The first condition refers to a phase shift between the pure in-phase compression due to the hypothetical resistive output and the actual phase of the IMD in case of a significant output reactive mismatch [16]. The second condition concerns the odd order IMD generated by remixing even order components with odd order ones. For example, the IMD components at $2\omega_1$-ω_2 that arise by the output remixing of $2\omega_1$ with the fundamental ω_2 have a phase that is obviously dependent on the $2\omega_1$ output termination. Finally, as even the difference frequency components can be remixed with the fundamentals to create new in-band distortion products, care should be taken to prevent dynamic effects induced by bias networks, low frequency dispersion of the active device or self-heating [22].

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