DESIGN STRATEGIES FOR EFFICIENT AND LINEAR RF POWER AMPLIFIERS

Paolo Colantonio, Franco Giannini, Rocco Giofrè, Ernesto Limiti, Antonio Nanni
University of Roma Tor Vergata, Dept. Electronic Engineering

Abstract

In this contribution, research activities and trends in the field of RF and microwave power amplifiers design are discussed. Design strategies for high efficiency and linearity amplifiers are focused and the results attained in three years of TARGET NoE activities are presented, showing interesting and state-of-the-art power amplifier design, employing GaAs or GaN technologies.

Introduction

The power amplifier (PA) is a key element in transmitter systems, whose main task is to increase the power level of signals at its input up to a predefined level. PA's requirements are mainly related to the absolute achievable output power levels, in conjunction with highest efficiency and linearity performances.

Nowadays, the increasing demand for portable apparatuses, whose main characteristic is battery duration and overall size, naturally translates into a low power electronic system.

Since the main power supply consumer is the PA, the low power feature is directly translated to PA specifications. Moreover, due to the widespread diffusion of communication applications, the PA designer has usually to trade-off among the contrasting goals of high transmitted power, low power consumption and highly linear operation. The relative weight of the above goals and the resulting compromise may vary depending on the radio link to be established and overall system specifications [1]. The resulting challenge has however heavily influenced, in the last decade, industrial, technical and research directions in the PA field.

From the PA designer point of view, both the selection of the active devices composing the PA and especially the exploration of their non-linear operating regions, to fully exploit the output power capabilities become critical [2]. Dedicated and non linear design methodologies to attain the highest available performance become therefore crucial for successful results [2].

In this contribution, moving from an overview of the available technologies for PA realisation and related performances, PA design strategies for high efficiency and high linearity performances are revisited and established through several experimental results carried out in the first three years of TARGET NoE activities.

Design Approaches

PA design strongly depends on operating frequency and application, as well as on the available device technology. Available approaches are not therefore not unique. Moreover, the design is further complicated by active device non linear behaviour, even if simplified approaches are often adopted to infer preliminary device figures [3]. For high frequency applications however, two broad PA design methodologies classes are available: Switching-Mode (SM) amplifiers [4] and transconductance-based amplifiers with Harmonic Tuned terminations (HT) [5].

Switching-Mode Power Amplifiers

This class of amplifiers is featured by the assumption of an ideal switching-mode behaviour of the selected active devices, which are therefore driven by a large-signal input to act as a switch, rather than a current source, as in HT amplifiers. For this reason, the resulting SM amplifier is often considered as a *dc*/*rf* converter rather than a RF amplifier.

Starting from the early Class E configuration proposed by Sokal in 1975 [6], several approaches and design solutions were proposed later [7, 8]. The approach is widely adopted, especially in RF wireless systems, due to its relatively simple scheme and availability of closed form expressions for its circuit components [7]. The basic amplifier schematic is depicted in Fig. 1, even if slightly different topologies have been proposed [8, 9].

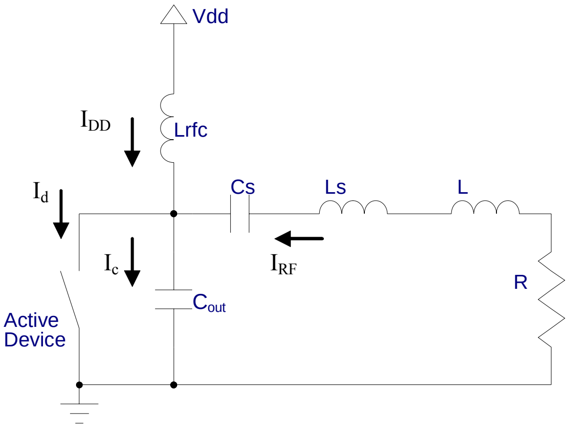


Fig. 1: Class E amplifier scheme.

The L_S-C_S components synthesise a filter for the operating frequency f, while the L-R load has to be selected to terminate the device output on the impedance

$$Z_{E,1} = \frac{0.28 \cdot e^{j49°}}{2\pi f \cdot C_{out}} \qquad (1)$$

C_{out} being the device output capacitance (eventually increased by an external capacitor to fulfil design relationship for the low frequency range [7]).

In such amplifiers the high efficiency condition is achieved by minimizing the overlap between output voltage and current waveforms, and therefore dissipated *dc* power. A 100% drain efficiency for switching-mode amplifiers may be theoretically reached, and although many loss mechanisms, such as ohmic and capacitive discharge losses, degrade efficiency in actual realisation, high values have been demonstrated. A 90% has been recorded at HF [10], decreasing up to 70% at microwave frequencies [11].

The operating frequency of Class E amplifiers is however intrinsically limited by the active device switching behaviour, limited by the device frequency roll-off. Moreover, device intrinsic output reactive behaviour (dominated by the output capacitance C_{out}), further decreases the frequency range of Class E amplifiers, according to the expression [12]:

$$f_{\max} = 0.063 \frac{I_{\max}}{V_{BD} \cdot C_{out}} \qquad (2)$$

where I_{max} and V_{BD} are device maximum output current and breakdown voltage respectively.

Class E design has been extended at relatively high frequency applications, taking into account the aforementioned practical frequency limitation, resulting in a decrease in the $Z_{E,1}$ magnitude in (1) of 13.5% together with an increase of 5° in its phase [12].

The proposed methodology has been successfully applied for the design of a S-Band power amplifier, based on the innovative GaN technology, obtaining the results summarised in Fig. 2.

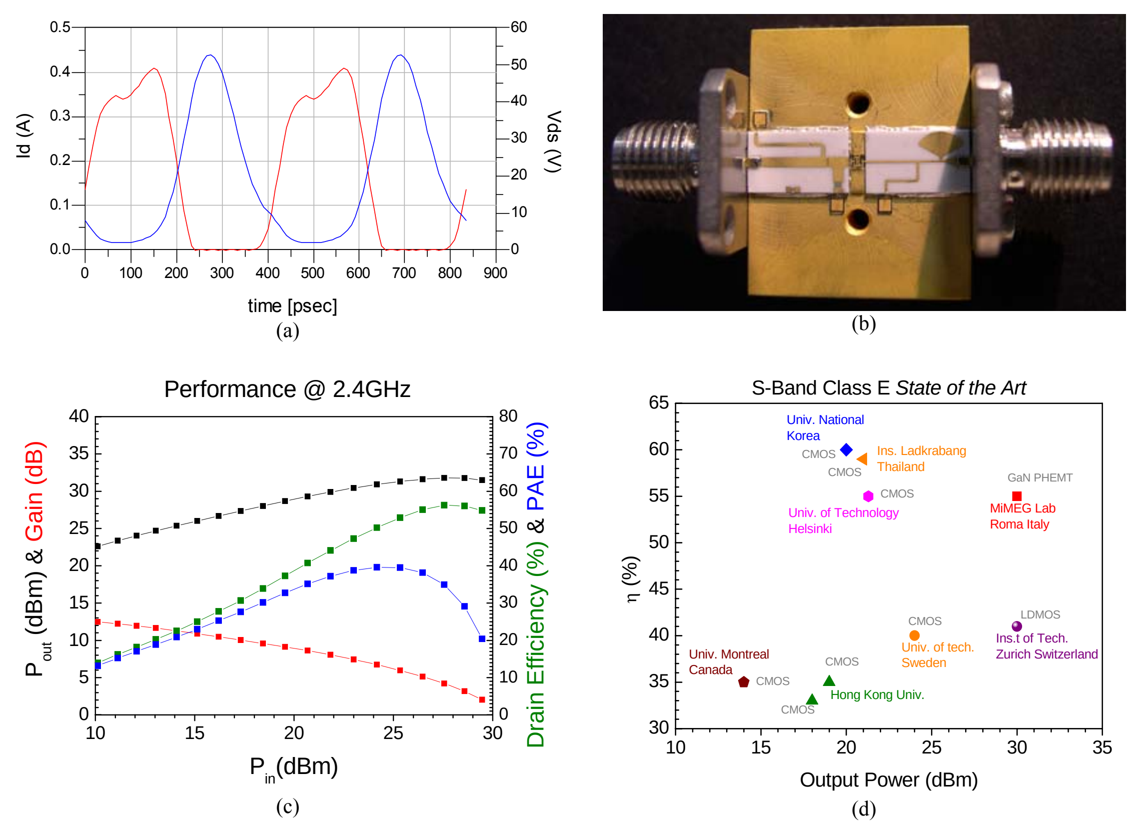


Fig. 2: Performance of realised S-Band GaN Class E amplifier: a) I-V simulated waveforms; b) photo of the realized ibrid PA; c) measured performance; d) comparison with state of the art Class E S-Band PA (mainly based on CMOS technology)

From a linearity point of view, SM amplifiers usually do not exhibit satisfactory performance, since output power is not directly related to input power, which is only responsible to drive the device in on-off states. Consequently, SM amplifiers are commonly adopted for constant-envelope modulation schemes, requiring less stringent linearity performance, or in complex architectures like EER (Envelope Elimination and Restoration) and LINC (LInear amplification using Nonlinear Components) [1], where a high efficiency and constant envelope amplifier is required. Recent results shown that a Class E amplifier can be successfully applied in transmitter with time-varying envelope operating at X-Band [13].

Harmonic Tuned Power Amplifiers

In this class of amplifiers the active device is operated (and modelled) as a current source, whose output waveform is mainly controlled by the input driving signal, at least to a first approximation [3]. Starting from different quiescent active device biases, resulting in different output current conduction angles (from 2π to 0) and related nomenclature (from Class A, AB, B to C respectively), the high efficiency condition is achieved exploiting the device non linear behaviour through a suitable selection of both input and output harmonic terminations, to properly shape the device output current and voltage waveforms [5].

In this case the most famous solution is the Class F approach [14,15], while for high frequency applications and taking into account practical limitations on the control of harmonic impedances, several solutions have been successfully proposed [16].

The general scheme of a HT amplifier is reported in Fig. 3, where in practical realisation the idlers are usually replaced by matching networks designed to fulfil well-identified frequency constraints at harmonic frequencies.

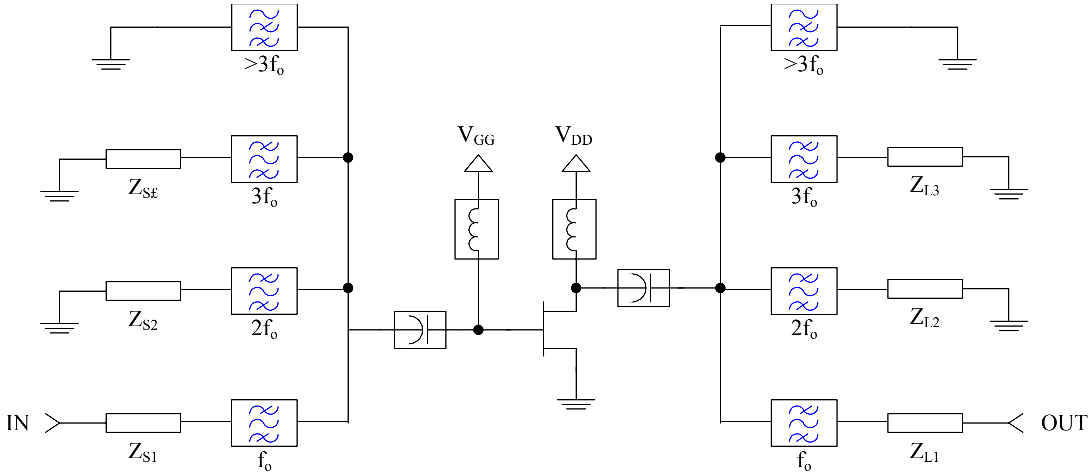


Fig. 3: Theoretical scheme for HT amplifiers.

The disadvantage of HT amplifiers, as compared as to SM ones, is related to the lack of closed-form design expressions, even if a theoretical formulation and useful design guidelines have been proposed in [5] and experimentally validated in [17], stressing also the relevance of input harmonic terminations. The HT methodology aims to shape the output voltage waveform to fulfil device physical constraints, while assuring an higher fundamental component as compared as to a standard Class A amplifier. Such amplifiers are classified according to the terminations controlled, like Class F (or 3rd HT), 2nd HT or 2nd&3rd HT amplifiers.

HT approaches have been applied to design several state-of-the-art amplifiers within TARGET frame. As an example, Class F strategy has been adopted for the design of monolithic microwave integrated circuits (MMIC) PA based on PHEMT GaAs devices, for X-Band application (9.6 GHz), investigating and demonstrating the possibility to adopt innovative design criteria to combine active devices, to further increase output power levels, fulfilling HT conditions [18, 19, 20]. Measured performance of the realised Class F amplifiers are reported in Fig. 4 (photo in the box).

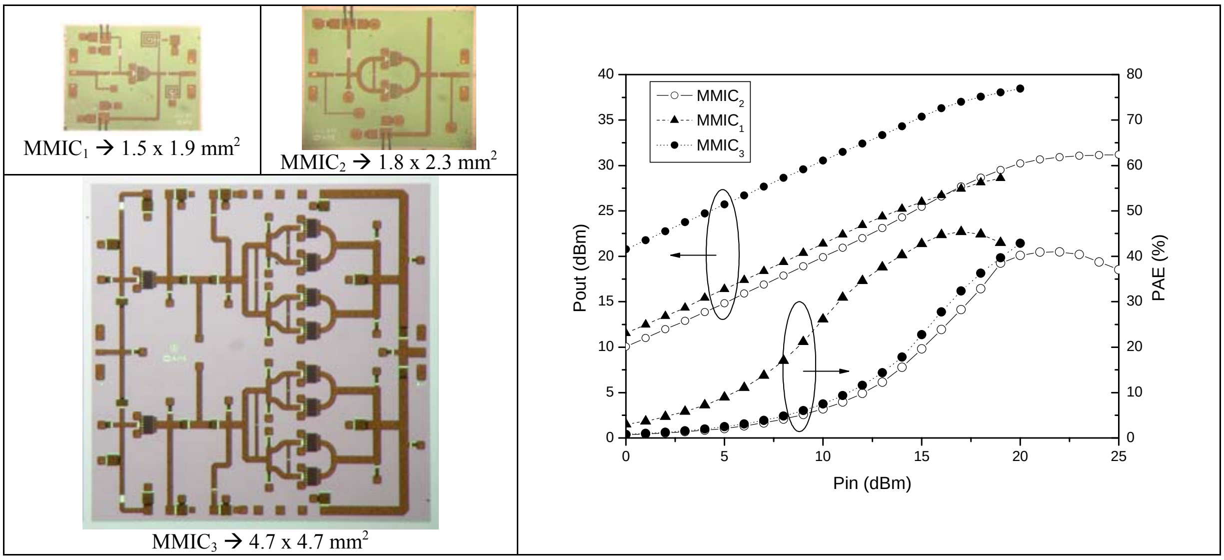
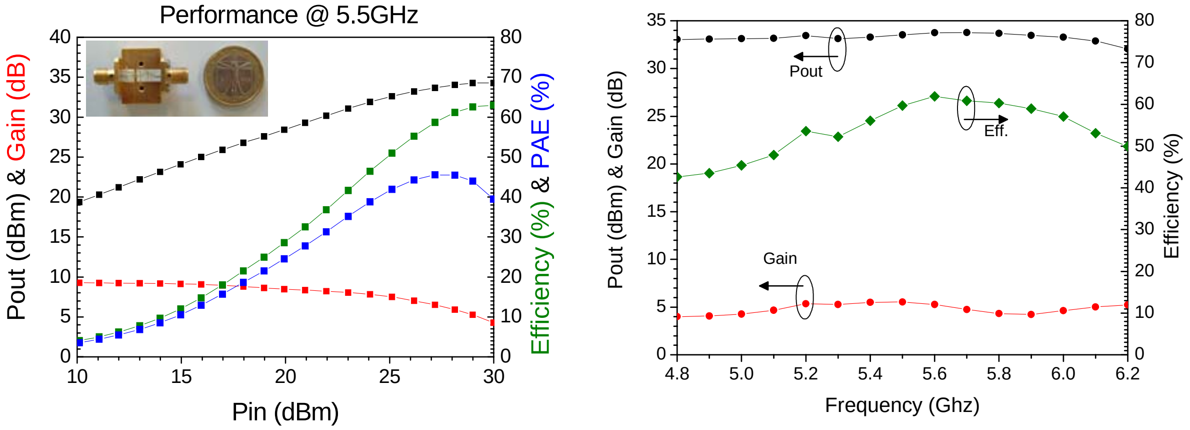


Fig. 4: Measured performance of realised Class F PA, based on single GaAs PHEMT device (MMIC1), coupled devices (MMIC2) and the complete 7W 2-stage PA.

For the design of PA based on combined active devices, stability conditions have to be carefully accounted, including odd-mode oscillations which are forecasted using the approach proposed in [21] and prevented using suitable resistors in the combiner branches (as shown in $MMIC_2$ and $MMIC_3$ in Fig. 4).

With the advent of GaN devices, characterised by a very high breakdown voltage, the use of a 2nd HT strategy becomes very attractive, due to the huge improvements assured, as compared to a Class F (e.g. 3rd HT) approach. For instance, a C-Band 2nd HT amplifier has been designed in hybrid technology utilising a GaN device, whose measured performance at 5.5GHz is reported in Fig. 5 [22].



(a)

(b)

Fig. 5: C-Band GaN 2nd HT amplifier (photo in the box) measured performance at 5.5GHZ and frequency behaviour (c).

Linearity Issues in PA

The realisation of a PA simultaneously maximising output power level (P_{out}), efficiency (η) and linearity performance (in terms of carrier over third-order intermodulation product, C/I_3), is a crucial challenge in transmitter systems design. Unfortunately, such goals are contrasting since η (or PAE) exhibits an opposing behavior respect to C/I_3 (the former increases when the latter decreases, as depicted in Fig. 6 for a sample case), resulting in a trade-off for the final PA operating level.

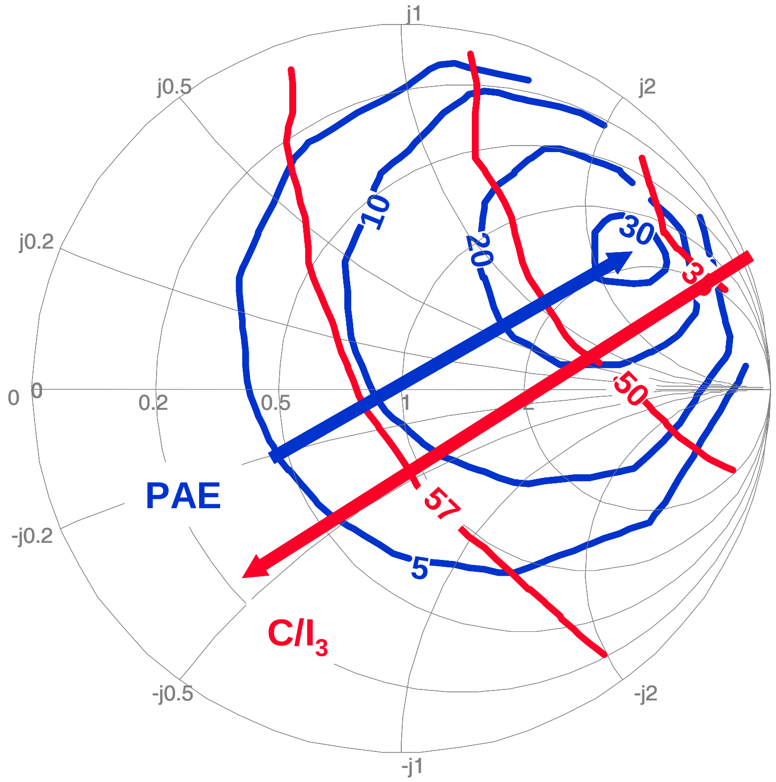


Fig. 6: Example of load pull for PAE (blue lines) and C/I_3 (red lines) on the fundamental output load.

As described in the previous section, if P_{out} and η performance are concerned, an established solution consists in making use of suitable harmonic tuning strategies, exploiting device non linear behavior [16]. When linearity performance becomes critical, a possible design technique is based on the identification (and related PA networks design) of the so-called large-signal IMD sweet-spots [23,24], e.g. circuit condition giving rise to a null for the third order intermodulation product (IMD_3). Such peculiar nonlinear effects can be qualitatively explained as opposite phase interactions of small- and large-signal IMD components, typically arising from the mild nonlinearities of device output current. Even if IMD sweet spots seems to be related to some design parameters, as device bias voltage (especially input voltage), input power level, temperature and load impedances [25], actually a well-established design approach to maximize C/I_3 through IMD sweet spots control has not been identified yet, and a fundamental role is played by designer experience and active device non linear model consistency.

Mechanisms generating *IMD* asymmetries in active devices have been in focus in recent years, typically adopting Volterra series analysis [26,27]. With this approach, assuming a two-tone drive (at frequencies f_1 and f_2, with $f_2 = f_1 + \Delta f$), the effects of active device terminations at fundamental and harmonic frequencies were deeply analysed. In particular, the condition to null *IMD* asymmetry (ΔIM_3) was inferred, resulting in a purely resistive load condition at the intrinsic device output (drain) port at base-band frequency (Δf) [26,27,28]. For instance, in Fig. 7 ΔIM_3 variation, as a function of active device base-band terminating conditions, is reported.

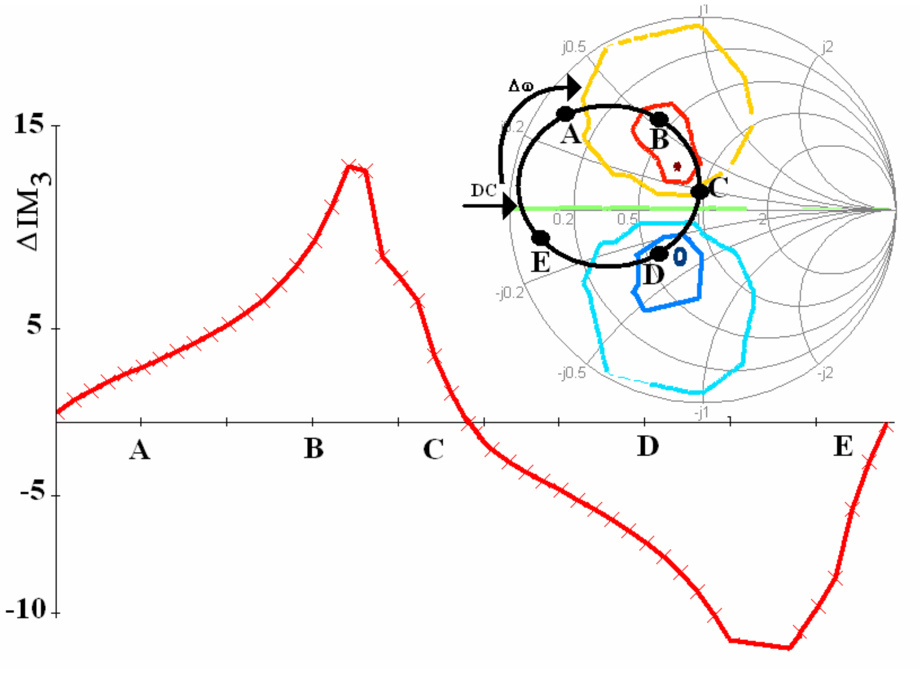


Fig. 7: Example of ΔIM_3 behavior varying the base-band output device termination.

Thus, following an analytical approach, several solutions involving base-band schemes [29] or “ad hoc” drain bias networks [28] minimising *IMD* asymmetry have been successfully proposed. Nevertheless, such schemes increase *PA* design complexity and its resulting physical dimensions, without ensuring any minimization on the absolute IM_3 output level.

Recently, another condition to null ΔIM_3 has been outlined, based on a suitable selection of fundamental and second harmonic device output terminations [30, 26, 27]. The proposed approach is also effective in the minimisation of IM_3 absolute values. In particular, the inferred condition suggest the synthesis of a purely resistive termination at fundamental and second harmonic frequencies, at the device output intrinsic current source, in spite of controlling the network base-band behavior.

As a test vehicle for the proposed design guidelines, a C-Band 2nd HT GaN amplifier has been designed, and compared to the previously described one (Fig. 5), demonstrating 32.5dBm output power with 60% efficiency at 1dB compression, and simultaneously optimising intermodulation performance, both in terms of AM-PM conversion and ΔIM_3, with a 400MHz tone spacing. Measured performance of the PA already discussed (Fig. 5) and the new version designed to minimise IMD behaviour are reported in Fig. 8, thus showing a modest AM/PM variation.

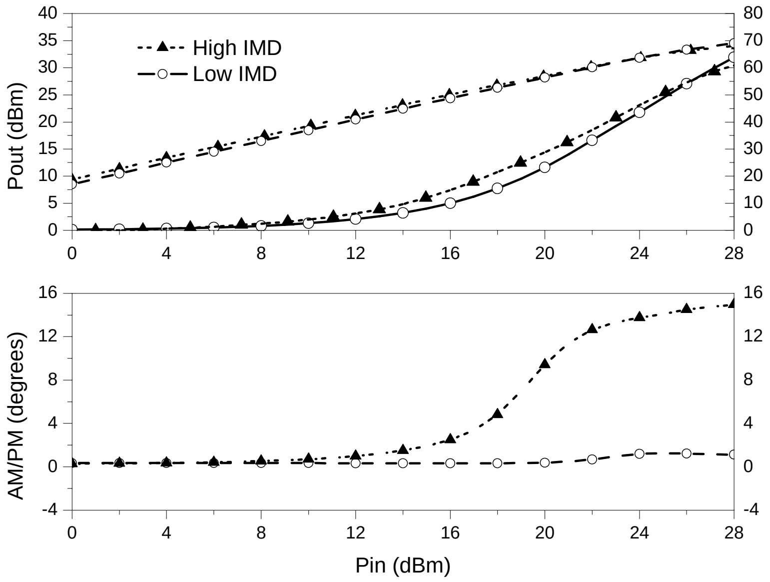


Fig. 8: Comparisons between Class C PA designed to fulfill HT criteria (dashed lines, PA in Fig. 5) or low IMD behavior (continuous lines).

Conclusions

In this contribution an overview of the main research activities performed in the field of RF and microwave power amplifiers design have been discussed. Starting from a review of PA design strategies, the results achieved by TARGET NoE activities have been presented, providing state-of-the-art amplifier performance. Measured data have been shown on amplifier realised both in GaAs and GaN technologies and making use of different design strategies.

Acknowledgment

Research reported here was performed in the context of the network TARGET- "Top Amplifier Research Groups in a European Team" and supported by the Information Society Technologies Programme of the EU under contract IST-1-507893-NOE, www.target-org.net.
The support of Selex – Sistemi Integrati (Roma, Italy), providing the active devices on which the presented amplifiers have been based, is gratefully acknowledged.

References

[1] F. H. Raab, P. Asbeck, S. Cripps, P. B. Kenington, Z. B. Popovic, N. Pothecary, J. F. Sevic, and N. O. Sokal, "*Power amplifiers and transmitters for RF and microwave*," IEEE Trans. on Microwave Theory and Tech., Vol. 3, N. 50, March 2002, pp. 814–826.

[2] P. Colantonio, F. Giannini, E. Limiti, "*Nonlinear Approaches to the Design of Microwave Power Amplifiers*," Int. Journal of RF and Microwave Computer-Aided Engineering, Vol. 14, N. 6, Nov. 2004, pp. 493-506.

[3] L.J. Kushner, "*Output performance of idealised microwave power amplifiers*," Microwave Journal 1989, pp. 103-116.

[4] H. L. Krauss, C.W. Bostian, and F. H. Raab, *Solid State Radio Engineering*, Wiley, New York, 1980.

[5] P. Colantonio, F. Giannini, G. Leuzzi, E. Limiti, "*Multi Harmonic Manipulation for Highly Efficient Microwave Power Amplifiers*," Int. Journal of RF and Microwave Computer-Aided Engineering, Vol. 11, N. 6, Nov. 2001, pp. 366-384.

[6] N. O. Sokal and A. D. Sokal, "*Class-E: A new class of high-efficiency tuned single-ended switching power amplifiers*," IEEE Journal of Solid-State Circuits, Vol. 10, N. 3, June 1975, pp. 168-176.

[7] N. O. Sokal, "*Class-E RF power amplifiers*," QEX (published by American Radio Relay League, 225 Main St., Newington, CT 06111-1494, USA), Jan./Feb. 2001, pp. 9–20.

[8] A.V. Grebennikov, "*RF and Microwave Power Amplifier Design*", McGraw-Hill

[9] A.V. Grebennikov, H. Jaeger, "*Class E with parallel circuit – a new challenge for high-efficiency RF and microwave power amplifiers*", 2002 IEEE MTT-S Int. Microwave Symp. Digest, Vol. 3, June 2002, pp. 1627-163.

[10] Q.S. Tan, C. Ciotti, H.J. Schmitt, "*Class-E high efficiency power amplifiers*," Proceedings of the 35th Midwest Symposium on Circuits and Systems, Aug. 1992, Vol. 1, pp. 118-120.

[11] T. B. Mader and Z. Popovic, "*The transmission-line high-efficiency Class-E amplifier*," IEEE Microwave Guided Wave Lett., Vol. 5, N. 9, Sep. 1995, pp. 290-292.

[12] P. Colantonio, F. Giannini, R. Giofrè, M. A. Yarleque Medina, D. Schreurs, and B. Nauwelaers, "*High frequency Class E design methodologies*," Proceedings of the Gallium Arsenide Applications Symposium, GAAS 2005, Paris, France, October 2005, pp. 329-331.

[13] N. Wang, X. Peng, V. Yousefzadeh, D. Maksimovic, S. Pajic, and Z. Popovic, "*Linearity of X-band class-E power amplifiers in EER operation*," IEEE Trans. on Microwave Theory & Tech., Vol. 53, N. 3, Mar. 2005, pp. 1092-1102.

[14] S. Gao, "*High efficiency class-F RF/microwave power amplifiers*," IEEE Microwave Magazine, Vol. 7, N. 1, Feb. 2006, pp. 40-48.

[15] P. Colantonio, F. Giannini, G. Leuzzi, E. Limiti, "*On the Class-F Power Amplifier Design*," Int. Journal of RF and Microwave Computer-Aided Engineering, Vol. 9, N. 2, March 1999, pp.129-149.

[16] P. Colantonio, F. Giannini, G. Leuzzi, E. Limiti, "*Theoretical Facet and Experimental Results of Harmonic Tuned PAs*," Int. Journal of RF and Microwave Computer-Aided Engineering, Vol.13, N.6, Nov. 2003, pp. 459-472.

[17] P. Colantonio, F. Giannini, E. Limiti, V. Teppati, "*An Approach to Harmonic Load– and Source–Pull Measurements for High-Efficiency PA Design*," IEEE Trans. on Microwave Theory and Tech., Vol. 52, N. 1, Jan. 2004, pp.191-198.

[18] P. Colantonio, F. Giannini, R. Giofrè, E. Limiti, C. Lanzieri, S. Lavanga, "*Class F High Power Amplifier for X-Band Applications*," Proceedings of the COMITE 2005, Prague, Czech Republic, September 2005, pp.123-126.

[19] P. Colantonio, F. Giannini, R. Giofrè, E. Limiti, C. Lanzieri, S. Lavanga, "*A two stage High Frequency Class F power amplifier*," Proceedings of the Integrated Nonlinear Microwave and Millimetre-wave Circuits (INMMiC 2006), Aveiro, Portugal, Jan. 2006, pp 165-168 (ISBN: 88-88748-34-2).

[20] P. Colantonio, F. Giannini, R. Giofrè, E. Limiti, "*Combined Class F Monolithic PA Design*," to be published on Microwave and Optical Technology Letters –Wiley.

[21] A. Costantini, G. Vannini, F. Filicori, A. Santarelli, "*Stability analysis of multi-transistor microwave power amplifiers*," in Proceedings Gallium Arsenide Applications Symposium GAAS 2000, Paris, October 2000, pp. 342-345.

[22] P. Colantonio, F. Giannini, R. Giofrè, E. Limiti, A. Serino M. Peroni, P. Romanini, C. Proietti "*A C-Band High Efficiency Second Harmonic Tuned Hybrid Power Amplifier in*

GaN technology", IEEE Transactions on Microwave Theory and Techniques, Vol.54, N.6, Part: 2, pp.2713-2722.

[23] N. B. Carvalho, J. C. Pedro, "*Large and Small Signal IMD Behaviour of Microwave Power Amplifiers*", IEEE Trans. on Microwave Theory and Tech., vol. MTT-47, Dec. 1999, pp. 2364-2374.

[24] J. C. Pedro, N. B. Carvalho, "*Intermodulation Distortion in Microwave and Wireless Circuits*," Artech House, 2003.

[25] S. R. Novis, L. Pelletier, "*IMD Parameters Describe LDMOS Device Performance*," Microwave RF, Vol. 37, N. 7, July 1998, pp. 69-74.

[26] J. Brinkhoff, and A. E. Parker, "*Effect of Baseband Impedence on FET Intermodulation*," IEEE Trans. on Microwave Theory and Techniques, Vol. 51, N. 3, March 2003, pp.1045-1051.

[27] P. Colantonio, F. Giannini, E. Limiti, A. Nanni, "*Investigation of IMD Asymmetry in Microwave FETs via Volterra Series*," Proc. of Gallium Arsenide Application Symposium, GAAS, Paris, France, October 2005, pp 53-56.

[28] B. De Carvalho, J. C. Pedro, "*Comprehensive explanation of distortion sideband asymmetries*," IEEE Trans. MTT, Vol. 50, N. 9, Sept. 2002, pp. 2090-2101.

[29] A. Richards, K. A. Morris, J. P. McGeehan, "Cancellation of Electrical Memory Effects in FET Power Amplifiers", Paris, France, Oct. 2005, pp 971-974.

[30] P. Colantonio, F. Giannini, R. Giofrè, E. Limiti, A. Nanni, "*Power Amplifier Design Strategy to null IMD asymmetry*," Proceedings of the 36th European Microwave Week, Manchester, UK, September 2006, pp. 1304-1307.