

# High Efficiency RF and Microwave Solid State Power Amplifiers

**Paolo Colantonio, Franco Giannini, and Ernesto Limiti**

*Department of Electronic Engineering, University of Roma,  
Tor Vergata, Italy*



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# Preface

Research on microwave power amplifiers has gained a growing importance demanded by the many continuously developing applications which require such subsystem performance. A broad set of commercial and strategic systems in fact have their overall performance boosted by the power amplifier, the latter becoming an enabling component wherever its efficiency and output power actually allows functionalities and operating modes previously not possible. This is the case for the many wireless systems and battery-operated systems that form the substrate of everyday life, but also of high-performance satellite and dual-use systems.

Clearly, the major role of the power amplifier (PA) resides not only in the generation of an adequate output power to be transmitted, but above all in how efficiently the conversion of battery-stored power into such output is performed. The role of amplifier efficient power generation therefore becomes central, thus attracting the efforts of researchers and practitioners towards design methodologies that do not optimize challenging parameters, at the expense of the transmitted signal quality (i.e. preserving the amplifier's linearity).

The authors started their adventure in power amplifier high efficiency design methodologies at the beginning of the '90s, driven by the growing interest of the academic and industrial community in such challenging component. This book is the result of many years experience in the field of micro and millimetre PA design, and it aims to present a unified overview of high efficiency microwave solid state power amplifier (SSPA) design approaches and methodologies. Many valuable contributions have already been presented on the general topic of power amplifiers, but, at least in the authors' opinion, a gap still exists in high efficiency design techniques, above all if microwave and millimetre-wave applications are considered.

The main concepts involved in PA design are presented in this book, clarifying some classical misunderstandings or confusing topics (such as bias classes, or PA nomenclatures) as well as suggesting optimum design approaches, combining theoretical (or analytical) results and computer-aided design solutions. Thus, starting from the theoretical basis of SSPA design, examples are provided to clarify each discussed topic. Both hybrid and monolithic microwave integrated circuit (MMIC) approaches are addressed, highlighting design guidelines and criteria.

The techniques for high efficiency microwave power amplifier design, developed by the authors and published in world-wide diffused scientific journals, are presented and detailed, stressing the *pros* and *cons* as compared to different approaches, with practical examples. As a result, the book is meant to represent a reference text for designers as well as a textbook for researchers and scientists operating in this field. The topics treated in the book are introduced starting from simple considerations, useful from the practical viewpoint, extending to advanced topics for people already working in the field of SSPA

design. Consequently, the book is composed of many sections that may be regarded as introductory, but also includes advanced material.

It is, however, self-consistent for post-doctorate researchers and wide portions may be used for senior undergraduate courses. Practitioners in the field with Masters degrees should not encounter any problems in picking up the relevant section dealing with their specific queries, together with the running examples provided.

The book is organised into three main parts.

The aim of the first one is to introduce the fundamental concepts related to PA design. Starting from the definition of the main figures of merit characterizing a PA in Chapter 1, in Chapter 2 a simplified approach is discussed to easily infer the power capabilities of a given active device. In this chapter, a step-by-step PA design example is discussed. Then, in Chapter 3 the non linear analysis issues intrinsically related with the design of a PA are outlined. This first portion of the book is finally completed by Chapter 4, focused on experimental methodologies adopted for PA design, i.e. load pull techniques.

The second part is the core of the entire book, and it is devoted to the description and detailed discussion of high efficiency design techniques for PAs. Moving from a general theory, discussed in Chapter 5, two main approaches are categorized, namely the switched-mode and the current-mode PA design approaches. In Chapter 6 the former design solution is described, mainly focused on Class E amplifiers. Starting from the low frequency theory, several topologies are discussed and the extension of the methodology to high RF and micro-millimetre wave frequency ranges is outlined. The chapter concludes with several design examples where theoretical concepts are applied and demonstrated. Then, in the following two chapters (7 and 8) the current mode harmonic tuned design approaches are detailed. In particular, Chapter 7 is devoted to Class F PA design solutions, while Chapter 8 covers the more general harmonic tuning strategies, based on both input and output network harmonic loading behaviour and design.

Finally, the third and last part of the book discusses advanced concepts in the design of solid state PAs. In chapter 9 the linearity issue of a power stage is focused on in more detail. In particular, the synthesis methodologies adopted to design PA stages with high linearity performance are described, simultaneously optimizing power conversion efficiency. Then, in Chapter 10 an overview of power combining techniques is provided. Finally, to account for new and challenging requirements of solid state PA, in Chapter 11 the Doherty amplifier is discussed. Starting from the theoretical analysis, the design relationships inferred are explained through several design examples for classical or harmonic tuned (Class F) Doherty stage. The chapter is completed with a discussion about multi-way and multi-stage Doherty architectures.

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# About the Authors

**Paolo Colantonio** was born in Rome on March 1969 and he received Electronic Engineering and Ph.D degrees in Microelectronics and Telecommunications from the University of Roma ‘Tor Vergata’ in 1994 and 2000 respectively, working on design criteria for high efficiency power amplifiers. In 1999 he became a research assistant at the Electronic Engineering Department of the University of Roma ‘Tor Vergata’ and since 2002 he has been a professor of microwave electronics at the same university.

His research activities are mainly focused on the field of microwave and millimetre-wave electronics, and in particular on design criteria for nonlinear microwave subsystems. This activity resulted in the development of innovative design criteria for high efficiency and high linear power amplifiers, oriented to the optimization of power performance making use of harmonic tuning classes of operation. The results of such activities have been presented in major conferences and published in international journals.

Paolo Colantonio has been responsible for the work package activity on ‘power amplifier design overview’ in the VI-FP European Network of Excellence TARGET (January 2004–June 2005) and general chairman of the international event ‘First TARGET NoE Workshop on RF Power Amplifiers’, held in Orvieto, Italy 2005.

He is author or co-author of more than 120 papers on PA design published in refereed journals or international conference proceedings and he has been awarded Best Poster Paper at GAAS 2000 (*IMD performances of harmonically tuned microwave power amplifiers*) and Best Paper at EuMIC 2007 (*A 6W Uneven Doherty Power Amplifier in GaN Technology*).

**Franco Giannini** was born in Galatina (LE), on November 9, 1944, and graduated in Electronics Engineering, *summa cum laude* in 1968, before getting the chair of Full Professor of Applied Electronics in 1980. In 2008 he was awarded the *Laurea Honoris Causa Scientiarum Technicarum* degree by the Warsaw University of Technology (WUT), Poland

Since 1981 he has been at the University of Roma ‘Tor Vergata’, where he has been serving as Head of Department, Vice President for International Affairs, Pro-Rector, and Dean of the Faculty of Electronics Engineering. He presently chairs the Microwave Engineering Centre for Space Applications (MECSA).

He has been working on modelling, characterization and design methodologies of active and passive microwave components and circuits, including MICs and MMICs for telecommunication and space applications, authoring or co-authoring more than 400 scientific contributions.

He chaired the theme MMICs of the national project MADESS I of the CNR and was a member of the Management Board of MADESS II, chairman of the theme MMICs of the National Project MICROELECTRONICS, and member of the Board of Directors of the Italian Space Agency (ASI).

He has also been active in many European Projects, and was the Italian representative in the ‘European Working Group for GaAs Microelectronics’. He has been acting as consultant for various national and international organizations, including the ITU for the United Nations Development Program (UNDP), and the European Union for ESPRIT, LTR, ISTC projects. He has been chairman of various International Symposia on Microwave & Millimetre Wave Techniques and is a member of many committees of international scientific conferences.

In 1996 Professor Giannini was awarded the ‘Irena Galewska Kielbasinski Prize’ by the Technical University of Darmstadt, Germany, and an Honorary Professorship by WUT, Poland, in 2001.

**Ernesto Limiti** has been Full Professor of Electronics at the University of Roma ‘Tor Vergata’ since 2002, after being associate professor and researcher at the same university since 1991.

He teaches undergraduate courses in microwave electronics, namely Microwave Electronics (basic) and Microwave Instrumentation and Measurements, all of them at the *Laurea Magistrale* in the Electronic Engineering degree course (i.e. towards students with at least three years experience at the university). He also teaches MSc and PhD courses, both at the University of Roma ‘Tor Vergata’ and at other Italian universities.

His scientific interests encompass a broad range of topics, including microwave active device characterization and modelling, regarding both linear (small-signal and noise) and nonlinear regimes and microwave subsystems design methodologies. Regarding the latter, high efficiency power amplifier design methodologies have been his focus since 1992, oriented towards power performance optimization making use of harmonic tuning operating classes. This research topic has been investigated also in the frame of European research projects, e.g. Manpower, Edge, and others. The results on the work in high efficiency power amplifier design approaches have been presented in major conferences and published in international journals.

Ernesto Limiti is author or co-author of more than 200 papers appearing in refereed journals or international conference proceedings. He is a member of the Editorial Board of the International Journal of Microwave and Millimetre-Wave CAE (Wiley Interscience), serving also as a reviewer for various IEEE Transactions and IET Journals.

He has been general chairman and organizer of the 2004 international workshop on Integrated Nonlinear Microwave and Millimetre-wave Circuits (INMMiC 2004) as well as the 11<sup>th</sup> International Symposium on Microwave and Optical Technology (ISMOT 2007).

**The authors** are experienced PA designers and gained such experience in over 16 years of research activities in this specific field. They developed new design criteria based on harmonic tuning for high efficiency and linear power amplifiers. Their experience has matured through the implementation of design criteria in both hybrid and monolithic solutions. The results of their research activities on high efficiency PA design strategies have been published in more than 50 refereed journal contributions and chapters of the Wiley Encyclopedia on Microwave Electronics entitled *Microwave Power Amplifier and Load-Pull Techniques* (with other co-authors).

In addition to their institutional duties, the authors also teach in postgraduate and PhD schools, including the International Travelling Summer School (<http://itss.elka.pw.edu.pl/>), International course for PhD students at Warsaw University of Technology (MiTraPAs) and the Short Course on ‘Fundamentals of Microwave Power Amplifier Design’ organized and held within the framework of the European Microwave Week.

# Acknowledgments

This book contains the results of more than a decade of research activities performed in this frame by the authors.

In this context, the long interaction and discussion with colleagues and researchers working on the same or related topics has been very helpful to determine the most suitable organization and focus of the book. Many people deserve therefore our thanks for their direct help in useful discussion and a long list should be provided. Nevertheless, some of them have to be acknowledged for their effort, without which this work would not have been possible.

Among them, we acknowledge the support of all the members of the High Frequency Electronic group of University of Roma Tor Vergata, and in particular our young engineers and PhD students (R. Giofrè, L. Piazzon, E. Cipriani and M. Jankowski) whose work has been extremely useful in developing several PA designs and relative characterizations.

We would also like to thank our colleagues from Politecnico di Torino, Italy (G. Ghione, M. Pirola, V. Camarchia, A. Ferrero and V. Teppati), for their support and long cooperation in performing both active device load pull and PA characterizations.

A grateful appreciation goes to people from Selex-SI (A. Cetronio, C. Lanzieri and M. Peroni) for their support in providing state-of-the-art active devices at the beginning of our research efforts and results.

Finally, a special thanks to G. Magerl (Technology University of Vienna) for his encouragement, support and useful “general discussions”.

Since writing a book typically implies a decrease in human interactions and duties, we hope that the latter effect has not been so dramatic in our case, apologizing to all those, including our families, who suffered from it: the promise is to jump back to normality as soon as possible!

As a final acknowledgement, the authors would like to express their sincere appreciation to all the Wiley staff involved in this project, for their cheerful professionalism and outstanding efforts.



# 1

# Power Amplifier Fundamentals

## 1.1 Introduction

A power amplifier (PA) is an essential component, playing a key role in the realization of many microwave and millimetre-wave systems. PA applications span a broad range of areas [1], among which telecommunications, radar [2–4], electronic warfare, heating [5, 6], and medical microwave imaging [7–12] represent just a few examples. Given such extremely diversified fields, PA specifications may greatly differ in operating, technological and design requirements. As a consequence, a wide variety of PA realizations results, from travelling-wave tube amplifiers in satellite payloads to solid-state amplifiers for personal wireless communication handsets, from microwave heating tubes to amplifiers composing hyperthermia apparatus.

Regardless of its physical realization, the task of a PA is to increase the power level of the signal at its input in a given frequency band, up to a predefined level at its output. As contrasted therefore to low-level (i.e. linear) amplifiers, often specified in term of small-signal gain, the absolute output power level, as well as the power gain, become the PA's primary performance.

The need for high output power levels is the main driver in the selection of the active devices composing the PA, on the basis of their output power capabilities. Moreover, to limit the power consumption, active devices are typically operated under large-signal regimes, so fully swinging their nonlinear characteristics. Otherwise, a sufficiently large active device could be adopted, resulting in an almost linear behaviour, while dissipating a large amount of DC power for voltage and current biasing.

A PA is therefore to be considered as a nonlinear system component, whose large-signal operating conditions often lead to detrimental effects on the output signal, resulting in a distorted replica of the input. On the other hand, the linear approximation underlying small-signal amplifier design techniques is no longer strictly valid, hence not allowing their direct application to PA design. Dedicated methodologies have to be exploited and adopted, even if preliminary and first guess approaches can be employed.

PA design is typically the result of a trade-off, trying to fulfil several conflicting requirements such as linearity *vs.* efficiency or high output power level *vs.* low distortion. The design approach to be selected depends on operating frequency and bandwidth, available device technology, application (fixed, mobile or satellite communications, modulated CW or pulsed signal, etc.) and many other factors [13].

## 1.2 Definition of Power Amplifier Parameters

In a PA, the **output power**  $P_{out}$  is the power delivered to the external load (usually 50 ohm) at a specified frequency  $f$  or in a frequency band  $B = [f_{Low}, f_{High}]$ , expressed as:

$$P_{out} = P_{out}(f) = \frac{1}{2} \operatorname{Re} \left\{ V_{out} \cdot I_{out}^* \right\} \quad f \in [f_{Low}, f_{High}] \quad (1.1)$$

while the **input power**  $P_{in}$  is the available input power at the same frequency, i.e.

$$P_{in} = P_{in,av}(f) = \frac{1}{2} \operatorname{Re} \left\{ V_{in} \cdot I_{in}^* \right\} \quad f \in [f_{Low}, f_{High}] \quad (1.2)$$

The PA **power gain**  $G$  is defined as the ratio between output and input power:

$$G(f) = \frac{P_{out}(f)}{P_{in}(f)} \quad f \in [f_{Low}, f_{High}] \quad (1.3)$$

The power gain, due to the nonlinear behaviour of the devices used in the PA, clearly depends on the input signal level. However, for very small drive levels, the amplifier behaves almost linearly, and it is usually possible to refer to this linear gain  $G_L$ , defined as:

$$G_L(f) = \lim_{P_{in} \rightarrow 0} [G(f)] \quad f \in [f_{Low}, f_{High}] \quad (1.4)$$

On the contrary, when the input drive is increased, output current and voltage swings allowed by the active device tend to be limited by its nonlinearities. Thus output power tends to saturate to the value

$$P_{sat}(f) = \lim_{P_{in} \rightarrow \infty} [P_{out}(f)] \quad f \in [f_{Low}, f_{High}] \quad (1.5)$$

with the corresponding power gain approaching zero

$$\lim_{P_{in} \rightarrow \infty} [G(f)] = 0 \quad f \in [f_{Low}, f_{High}] \quad (1.6)$$

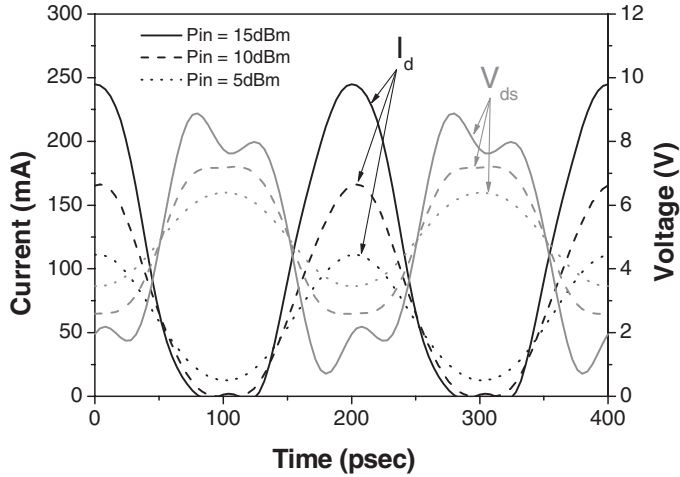
A typical plot of the active device output current and voltage waveforms, for an increasing input power level  $P_{in}$ , is reported in Fig. 1.1.

Assuming a non-zero quiescent bias current and increasing the input power, both output current and voltage waveforms change from a sinusoidal shape to a distorted one, as a result of the device nonlinearities.

Due to the broad dynamic range of the signals involved in a PA, power quantities are usually expressed in logarithmic units. In particular, assuming 1 mW as a reference, power levels are expressed in decibels over 1 mW, i.e. in dBm:

$$P_{dBm} = 10 \cdot \log_{10} \left( \frac{P}{1 \text{ mW}} \right) = 10 \cdot \log_{10}(P_{mW}) = 10 \cdot \log_{10}(P_W) + 30 \quad (1.7)$$

$$P_{mW} = 10^{\frac{P_{dBm}}{10}}$$



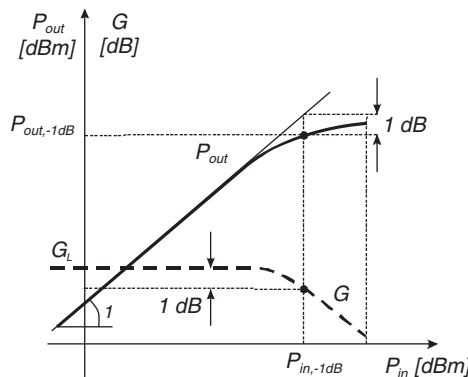
**Figure 1.1** Example of active device output current and voltage waveforms for three different input power levels  $P_{in}$ .

Similarly, for the power gain the logarithmic scale is adopted, defining

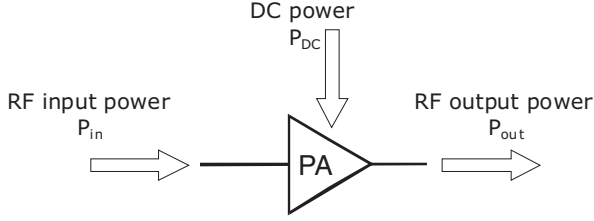
$$G_{dB} = 10 \cdot \log_{10}(G) = P_{out,dBm} - P_{in,dBm} \tag{1.8}$$

Output power and power gain are graphically represented as functions of the input power (while performing a *power sweep*) using logarithmic scales. In particular, with the input power expressed in dBm on the abscissa, output power in dBm or the power gain in dB is reported on the y-axis, as illustrated in Fig. 1.2.

The power sweep in Fig. 1.2 reveals that the power gain decreases from its linear value  $G_L$  (small signal regime) down to  $-\infty$  in dB scale (i.e. 0 in linear scale). Such behaviour, due to nonlinear



**Figure 1.2** Sample  $P_{in} - P_{out}$  power sweep (continuous line) and corresponding amplifier power gain  $G$  (dashed line). From both  $P_{-1dB}$  can be derived.



**Figure 1.3** Energetic schematic representation of PA operation.

phenomena in the large signal regime, is referred to as *gain compression*. In some cases, and in particular for some bias conditions, an eventual gain expansion from  $G_L$  can be observed before a gain compression is experienced. A widely used figure-of-merit for the compression behaviour, namely the *-1dB compression point*  $P_{out,-1dB}$ , is defined as the output power level corresponding to a 1 dB deviation from the ideal linear behaviour (see Fig. 1.2). The corresponding input power level,  $P_{in,-1dB}$ , is used to mark the border between ‘highly nonlinear’ and ‘almost linear’ drive level regions. Input  $P_{in,-1dB}$  and output  $P_{out,-1dB}$  powers are clearly related through the linear power gain  $G_L$  by:

$$P_{out,-1dB} = (G_{L,dB} - 1) \cdot P_{in,-1dB} \quad (1.9)$$

It is however possible to define (and determine) the power levels corresponding to any gain compression level, as required by the particular application (e.g. in pulsed radar or saturated power operations, where up to 2 or 3 dB gain compression is required).

From the energetic point of view, and regardless of the specific application, a PA may be ultimately regarded as a component converting DC power from supplies ( $P_{DC}$ ) into microwave power (i.e.  $P_{out}$ ). This process is schematically illustrated in Fig. 1.3, where, if a voltage supply is assumed,

$$P_{DC} = V_{bias} \cdot \frac{1}{T} \cdot \int_0^T I_{bias}(t) \cdot dt \quad (1.10)$$

The effectiveness of this conversion process is usually measured by means of the amplifier’s *efficiency*,  $\eta$ , defined as the ratio between output RF and supplied DC power:

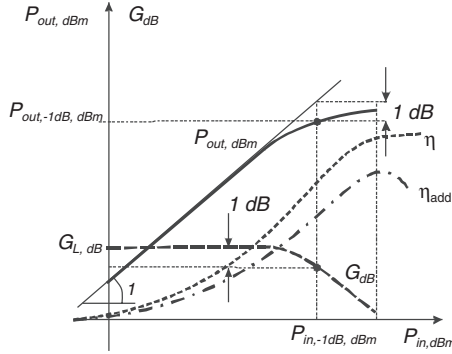
$$\eta \triangleq \frac{P_{out}}{P_{DC}} \quad (1.11)$$

Efficiency is often further specified as *drain* efficiency ( $\eta_d$ ) or *collector* efficiency ( $\eta_c$ ) in the case of a solid-state PA based on field-effect or bipolar transistors, respectively.

The amplifier’s efficiency is indeed one of the key parameters in specifying overall system performance: for a given output power requested to the PA, efficiency actually determines the DC power budget and hence the supply power. A reduced supply power resulting from high efficiency performance is a key goal of mobile apparatus, typically battery-operated, whose operating time strictly depends on the transmitting section power requests.

Since practical and physical constraints impose an actual efficiency lower than the 100% theoretical maximum,<sup>1</sup> high efficiency performance implies in turn a low power dissipated on the power-amplifying

<sup>1</sup> Assuming an ideal active device without leakage currents and paths.



**Figure 1.4** Typical performance in a PA as a function of input drive.

device, therefore reducing actual size and weight of the heat sinks eventually required. On the other hand, for a given available DC power, a high efficiency performance allows higher transmitted power with a corresponding increase in overall system capabilities.

The efficiency is usually expressed as a percentage, i.e.

$$\eta\% = 100 \cdot \eta \quad (1.12)$$

and it is usually reported on the same plot together with power and gain, as shown in Fig. 1.4. In such a plot the efficiency is exponentially dependent on the input power reported on the abscissa, since

$$\eta = \frac{P_{out}}{P_{DC}} = \frac{G \cdot P_{in}}{P_{DC}} = \frac{G}{1000 \cdot P_{DC}} \cdot 10^{\frac{P_{in, dBm}}{10}} \quad (1.13)$$

Therefore, at least in the linear region, where  $G$  remains constant and thus independent of  $P_{in}$ , efficiency increases exponentially while increasing the input drive. If  $P_{in}$  is further increased, due to the gain compression phenomena related to the nonlinear active device behaviour, both gain  $G$  and DC power  $P_{DC}$  start depending on  $P_{in}$ , and efficiency usually tends to saturate to a maximum value, as depicted in Fig. 1.4.

As frequency increases, however, the PA gain decreases, as a result of its active constituents gain roll-off behaviour. The contribution to the output power coming directly from the input drive cannot therefore be neglected, since it constitutes, at microwave frequencies and beyond, a significant portion of the total. As a consequence, the *added power*,  $P_{add}$ , i.e. the net increase in the signal power from the PA input to its output, is defined as:

$$P_{add} \triangleq P_{out} - P_{in} = P_{out} \cdot \left(1 - \frac{1}{G}\right) \quad (1.14)$$

A more meaningful parameter, the *Power-Added Efficiency* (PAE or  $\eta_{add}$  are the typically adopted symbols) is therefore defined as the ratio between the added power and the supplied DC power:

$$\eta_{add} \triangleq \frac{P_{add}}{P_{DC}} = \frac{P_{out} - P_{in}}{P_{DC}} = \frac{P_{out} \cdot \left(1 - \frac{1}{G}\right)}{P_{DC}} = \eta \cdot \left(1 - \frac{1}{G}\right) \quad (1.15)$$

An alternative definition of  $\eta_{add}$ , less frequently used in common practice, is [14]:

$$\eta_{add} \triangleq \frac{P_{out}}{P_{DC} + P_{in}} = \eta \cdot \frac{1}{1 + \frac{\eta}{G}} \quad (1.16)$$

expressing the ratio of output power to the total input power (*RF* plus *DC*, see Fig. 1.3) to the amplifier.

The two definitions practically converge for high-gain amplifiers, while giving substantially different results for low-gain amplifiers, especially when hardly driven into compression (note that the conventional definition of  $\eta_{add}$  may lead to negative values in hard compression).

Regardless of the adopted definition for  $\eta_{add}$ , its maximization is to be achieved at the nominal drive level for the PA, i.e. while the latter is delivering the desired output power. In such operating conditions, the amplifier is typically driven into compression, thus leaving its almost linear region and approaching the nonlinear active device physical limitations, as depicted in Fig. 1.4, where the typical swept power performance of a PA is reported.

The peak drain/collector or power-added efficiency usually occurs at high drive levels, corresponding to 2–4 dB gain compression: in this region the active device behaviour is therefore highly nonlinear and correspondingly design methodologies for high efficiency operation must cope with such an intrinsic deviation from linearity.

If non-constant envelope signals have to be handled by the PA, an *average efficiency* can be introduced [13–15], defined as in (1.11), where the quantities in the expression are replaced by input and output powers averaged over an envelope period and weighted by the envelope probability density function (PDF), i.e.

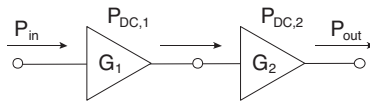
$$\eta_{AVG} = \frac{P_{out,AVG}}{P_{DC,AVG}} = \frac{\frac{1}{T} \int_0^T P_{out}(t) \cdot PDF(t) \cdot dt}{\frac{1}{T} \int_0^T P_{DC}(t) \cdot PDF(t) \cdot dt} \quad (1.17)$$

For cascaded amplifying stages, as depicted in Fig. 1.5, the overall efficiency  $\eta_{tot}$  is easily computed by:

$$\eta_{tot} = \frac{P_{out}}{P_{DC,1} + P_{DC,2}} = \frac{\eta_2}{1 + \frac{P_{DC,1}}{P_{DC,2}}} = \frac{\eta_2}{1 + \frac{\eta_2}{\eta_1 \cdot G_2}} \quad (1.18)$$

Since the *DC* supply power for final stages ( $P_{DC,2}$ ) is usually much larger than the driver supply ( $P_{DC,1}$ ), overall efficiency is dominated from the former amplifier. On the contrary, for a low-gain final amplifier, also the driver's effect becomes crucial for overall conversion efficiency.

The conversion from *DC* to *RF* power implies that a fraction of the supplied power is lost and actually dissipated on the active power device. The major part of such loss is located at the active device



**Figure 1.5** Cascade connection of two PAs.

output, and is given by:

$$P_{diss,out} \triangleq \frac{1}{T} \cdot \int_T v(t) \cdot i(t) \cdot dt \quad (1.19)$$

$v(t)$  and  $i(t)$  being the device output voltage and current, integrated over a period ( $T$ ) of the RF signal. To increase conversion efficiency, to be discussed later, a possible strategy consists in the minimization of such dissipated power, i.e. in the proper shaping of device output voltage and current waveforms.

It is possible to relate the power dissipated in the active device output to the power added efficiency. In fact, assuming that such dissipated power is the portion of the DC supplied power not contributing to the added power, then

$$P_{diss,out} = P_{DC} - P_{add} = P_{DC} - P_{out} + P_{in} \quad (1.20)$$

In the case of a reasonably high gain, it is easy to get

$$P_{diss,out} = P_{out} \cdot \frac{\left[ (1 - \eta_{add}) - \frac{(1 - \eta_{add})}{G} \right]}{\eta_{add}} \approx P_{out} \cdot \left( \frac{1}{\eta_{add}} - 1 \right) \quad (1.21)$$

Thus a higher power added efficiency implies a lower power dissipation in the active device, with major effects in reducing thermal issues and increasing device lifetime.

### 1.3 Distortion Parameters

As previously described, efficiency and output power of a PA are limited by compression and saturation, due to nonlinear phenomena. Such a nonlinear behaviour clearly introduces a distortion on the output voltage and current waveforms, thus degrading the signal quality and consequently the information content to be transmitted, often beyond acceptable levels. In particular, and especially in communication systems featured by non-constant envelope signals (as in the case of QAM or in digital cellular communications with GSM and NADC standards), the transmitter has to fulfil tight requirements not only in terms of efficiency but also regarding linearity and spectral purity.

The nonlinear behaviour (i.e. the distortion) must therefore be properly classified and evaluated as a further PA figure of merit.

Several indicators of PA linearity or deviation from linearity are used, depending on the system specifications and modulation schemes that are to be adopted.

In order to introduce and define such indicators, a simple third-order approximation of the PA transfer characteristic is usually adopted, i.e.

$$y(t) = k_1 \cdot x(t) + k_2 \cdot x^2(t) + k_3 \cdot x^3(t) \quad (1.22)$$

where  $x(t)$  and  $y(t)$  are the input and output signal to the amplifier, respectively (normalized voltages or currents, measured in  $\sqrt{W}$ ),  $k_1$  is the small-signal voltage (or current) gain, and  $k_2$ ,  $k_3$  are the first two coefficients of a McLaurin series expansion of the PA transfer characteristic, truncated to third order.

Please note that the above approximation, relating the output signal to the instantaneous input value, actually describes a memoryless system, and therefore memory effects cannot be accounted for in this

description. Moreover, in this case the coefficient  $k_1$ ,  $k_2$  and  $k_3$  correspond to the first three orders of Volterra kernels, which will be discussed in chapter 3 [16, 17].

If a single-tone excitation is assumed for the input signal, with amplitude  $X$  and frequency  $f$ , i.e.

$$x(t) = X \cdot \cos(2\pi f \cdot t) = X \cdot \cos(\omega \cdot t) = \frac{X}{2}(e^{j\omega t} + e^{-j\omega t}) \quad (1.23)$$

The corresponding input power  $P_{in}$  (on a unitary normalizing resistor) is:

$$P_{in} = \frac{X^2}{2} \quad (1.24)$$

The output signal, according to (1.22), becomes:

$$y(t) = X \cdot \left( k_1 + \frac{3}{4}k_3 \cdot X^2 \right) \cdot \cos(\omega \cdot t) + k_2 \cdot \frac{X^2}{2} + k_2 \cdot \frac{X^2}{2} \cdot \cos(2\omega \cdot t) + k_3 \cdot \frac{X^3}{4} \cdot \cos(3\omega \cdot t) \quad (1.25)$$

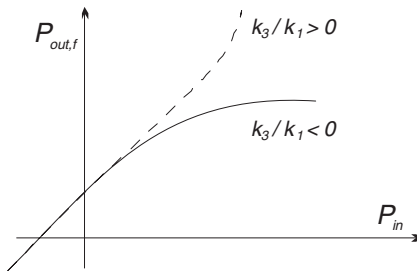
Thus the output power at frequency  $f$ ,  $P_{out,f}$ , and large-signal gain  $G$ , are obtained as

$$\begin{aligned} P_{out,f} &= \frac{1}{2} \cdot \left[ X \cdot \left( k_1 + \frac{3}{4}k_3 \cdot X^2 \right) \right]^2 = k_1^2 \cdot \left( 1 + \frac{3}{2} \cdot \frac{k_3}{k_1} \cdot P_{in} \right)^2 \cdot P_{in} \\ &= G_L \cdot \left( 1 + \frac{3}{2} \cdot \frac{k_3}{k_1} \cdot P_{in} \right)^2 \cdot P_{in} \end{aligned} \quad (1.26)$$

$$G = \frac{P_{out,f}}{P_{in}} = G_L \cdot \left( 1 + \frac{3}{2} \cdot \frac{k_3}{k_1} \cdot P_{in} \right)^2 \quad (1.27)$$

It can be noted from (1.26) that the term  $3k_3/2k_1$  represents a gain compression factor if negative, or an expansion factor if positive, as depicted in Fig. 1.6.

Since usually  $k_3/k_1$  is negative, the previous derivation accounts for large-signal gain compression, i.e. decrease from the ideal constant value ( $G_L$ ).



**Figure 1.6**  $P_{out,f}$  vs.  $P_{in}$  for  $k_3/k_1 < 0$  (gain compression, continuous line) or  $k_3/k_1 > 0$  (expansion, dashed).

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