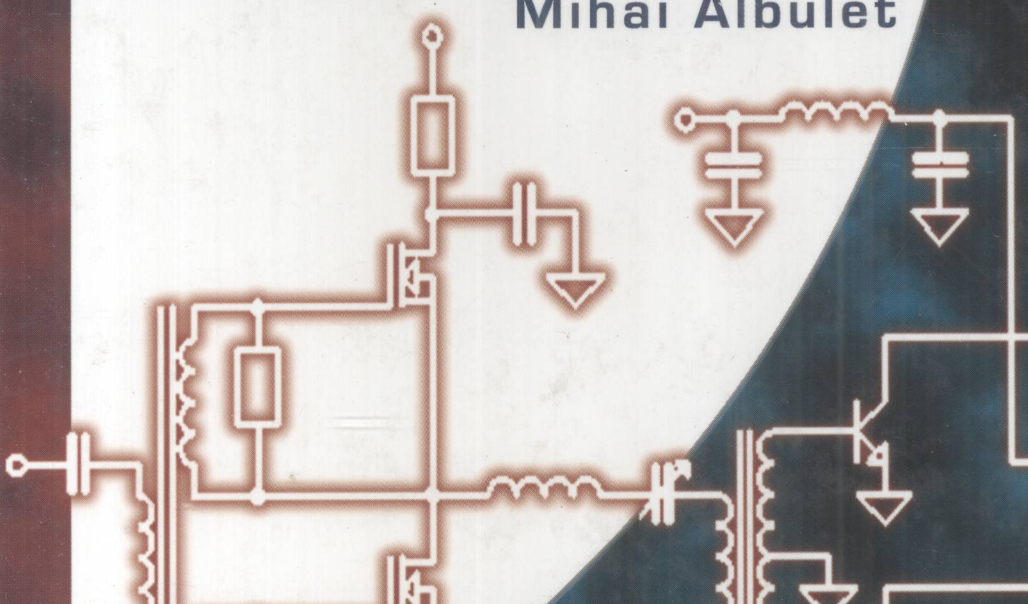
RF POWER AMPLIFIERS

Mihai Albulet



RF Power Amplifiers

Mihai Albulet

NOBLE
PUBLISHING
Noble Publishing Corporation
Atlanta, GA

Library of Congress Cataloging-in-Publication Data

Albulet, Mihai, 1962-
RF power amplifiers / Mihai Albulet.
p.cm.
Includes bibliographical references and index.
ISBN 1-884932-12-6
1. Power amplifiers. 2. Amplifiers, Radio frequency. I. Title.

TK7871.58.P6 A43 2001
621.348'12--dc21

2001030069

NOBLE
PUBLISHING

Printed in the Unites States of America

ISBN 1-884932-12-6

RF Power Amplifiers

Preface

Many practicing engineers view RF, especially large-signal RF circuits, as a somewhat mysterious, "black magic" subject. This book attempts to show that there is nothing unusual or inexplicable about RF power amplifiers — understanding them is simply a matter of understanding several basic principles and their applications. Although accurate CAD modeling and/or optimization can become almost impossible, since mathematical modeling of RF power amplifiers is often too difficult or complex to provide useful practical results, yield design equations, or predict a circuit's performance, the main purpose of a theoretical approach is to provide a starting point for computer simulations or experimental tweaking, or simply a physical understanding of the circuit.

Given this relative obscurity of the subject, this book is certainly not as practical as some readers would undoubtedly prefer it to be. No "miraculous recipe" is given for the design of the perfectly suited RF power amplifier for a particular application. In some cases, readers may even decide that my book does not indicate a practical enough design method for a particular circuit nor suggest a way to approach the design. This book does not describe either because I did not intend to write a practical handbook on RF power amplifiers — I believe that this is not an appropriate area for cookbook solutions.

The primary purpose of this book is to present the basic concepts used in the analysis and design of RF power amplifiers. Detailed mathematical derivations reveal the assumptions and limitations of the presented results, allowing the reader to estimate their usefulness in practical applications. Theory is the best practice and a good theoretical understanding is the quickest way toward achieving practical results. A designer must know a priori the circuit topologies and the basic operation principles as well as limitations of the various amplification classes. Selecting the appropriate circuit topology and operating mode, knowing their pros and cons, and setting realistic goals for the expected performance are imperative for beginning a practical design. Then CAD simulators and/or experimental tweaking will be successful in optimizing the design.

This book covers the basics of the RF power amplifiers, such as amplification classes, basic circuit topologies, bias circuits and matching networks. An exhaustive coverage of the power amplifier area is beyond the scope of the book; therefore, applications, system architecture concepts, and linearization techniques are not discussed here.

Chapter 1 discusses several basic concepts, terminology and definitions. Chapter 2 is dedicated to classic RF power amplifiers. Included are the oldest and best-known classes of amplification: A, B, AB, and C. This classification is based on the conduction angle of the active device and also includes the so-called mixed-mode Class C. Separate sections treat bias circuits, narrowband and broadband matching networks, gain leveling and VSWR correction, amplitude modulation, stability, thermal calculations, and Class C frequency multipliers.

Chapter 3 focuses on switching-mode Class D amplifiers. Described are the idealized operation of these amplifiers as well as practical considerations (parasitics and non-ideal components, mistuning or frequency variation, drive considerations). Other sections in this chapter cover Class D circuits operating in intermediate classes (BD and DE) or as frequency multiplies. The last section focuses on computer simulation of Class D circuits.

Chapter 4 presents switching-mode Class E power amplifiers. The chapter begins with an outline of the idealized operation, followed by a discussion of the practical considerations. Additional sections describe amplitude modulation, Class E frequency multipliers, and computer simulation of this circuit.

Chapter 5 is dedicated to Class F amplifiers. This includes established techniques to improve efficiency using harmonic injection in Class B or C circuits, the so-called Class F1 amplifier (also known as "high-efficiency Class C" "Class C using harmonic injection," or "biharmonic or polyharmonic Class C"), but also more recent switching-mode circuits, such as Classes F2 and F3.

Chapter 6 comments on switching-mode Class S amplifiers and modulators. Although these circuits are audio- or low-frequency amplifiers, they are important subsystems in many high-efficiency transmitters. Finally, Chapter 7 presents several considerations regarding bipolar and MOS RF power transistors.

Acknowledgments

I would like to express my deep appreciation to a number of people who contributed to this book in many ways. My thanks to Mr. Nathan O. Sokal (president, Design Automation, Inc.), and to Dr. Frederick H. Raab (Green Mountain Radio Research Company) for taking the time to review several parts of this manuscript and making useful comments and suggestions. I owe much to Mr. Sokal for providing the HB-PLUS and HEPA-PLUS programs developed by Design Automation.

I am grateful to the Department of Telecommunications at the Technical University of Iasi, Romania, where I first became involved in the RF power amplifier field. A large part of this book comes from knowledge acquired and research conducted during my tenure at this university.

Last, and certainly not least, I am indebted to my wife, Lucretia, and my daughter, Ioana, for their support and understanding during the writing of this book.

Contents

1

Introduction

The understanding of RF power amplifiers is greatly helped by a background knowledge of the most important theoretical features of small-signal high-frequency amplifiers. A summary of the subject is well beyond the scope of this book; instead, a short overview is offered. For a full discussion of small-signal amplifiers, please refer to references [1–5].

"Small signal" implies that the signal amplitude is small enough such that a linear equivalent circuit (such as a hybrid-pi circuit or any linear two-port circuit with constant coefficients) can model the amplifier. RF power amplifiers function very differently from small-signal amplifiers. Power amplifiers operate with large signals, and the active devices display strong nonlinear behavior. The amplifier output may be modeled as an infinite power series consisting of nonlinear terms added to a linear term and a dc offset. The power series coefficients depend on the transistor operating point (dc bias point, or the average operating point) and are considered constant to changes in the input and output RF signal. A more realistic model could use the Volterra series, which allows for the inclusion of phase effects. However, all these models have a serious limitation in that they can only accurately model weak nonlinear circuits for which the power series coefficients are almost constant (a narrow operation zone around the dc-bias point). In a large-signal power amplifier, nonlinear effects are very strong because transistor parameters depend on many factors, including the input and output matching network configuration and the input and output signal amplitudes and waveforms. In addition, the active device may be driven into saturation or cut-off for a certain portion of the RF cycle. Modeling these strong nonlinear effects is a very difficult task, even if CAD models and tools are available.

Power amplifiers are identified by classes (named A, B, C...). The amplifier class of operation depends on circuit topology, operating principle, how the transistor is biased or driven, and the specific component values in the load network. Further, combinations of operating modes and intermediate classes are possible. In this book, the classification provided in Reference [6] is used.

1.1 Ideal Parallel-Tuned Circuit

An ideal parallel-tuned circuit is a paralleled LC circuit that provides zero conductance (that is, infinite impedance) at the tuning frequency, f_0, and infinite conductance (zero impedance) for any other frequency. When connected in parallel to a load resistor, R, the ideal parallel-tuned circuit only allows a sinusoidal current (with frequency f_0) to flow through the load. Therefore, the voltage across the RLC parallel group is sinusoidal, while the total current (that is, the sum of the current through load and the current through the LC circuit) may have any waveform.

A good approximation for the ideal parallel-tuned circuit is a circuit with a very high loaded Q (the higher the Q, the closer the approximation). Note that a high-Q parallel-tuned circuit uses small inductors and large capacitors, which may be a serious limitation in practical applications.

1.2 Ideal Series-Tuned Circuit

An ideal series-tuned circuit is a series LC circuit that provides zero impedance at the tuning frequency, f_0, and infinite impedance for any other frequency. When connected in series to a load resistor, R, the ideal series-tuned circuit only allows a sinusoidal current with frequency f_0 to flow through the load. Therefore, the current through the series RLC group is sinusoidal, while the voltage across the RLC group may have any waveform.

A good approximation for the ideal series-tuned circuit is a circuit with a very high loaded Q (the higher the Q, the closer the approximation). Note that a high-Q series-tuned circuit must use large inductors and small capacitors, which may be a serious limitation in practical applications.

1.3 Efficiency

Efficiency is a crucial parameter for RF power amplifiers. It is important when the available input power is limited, such as in battery-powered portable or mobile equipment. It is also important for high-power equipment where the cost of the electric power over the lifetime of the equipment and the cost of the cooling systems can be significant compared to the purchase price of the equipment.

Efficiency is output power versus input power. However, this definition is too broad, because "output power" and "input power" may have different meanings. Input power may include both the dc-input power (that is, the power supplied by the dc supply) and the RF input power (the drive power), or only the dc-input power. The most common definitions encountered are presented below [3–6].

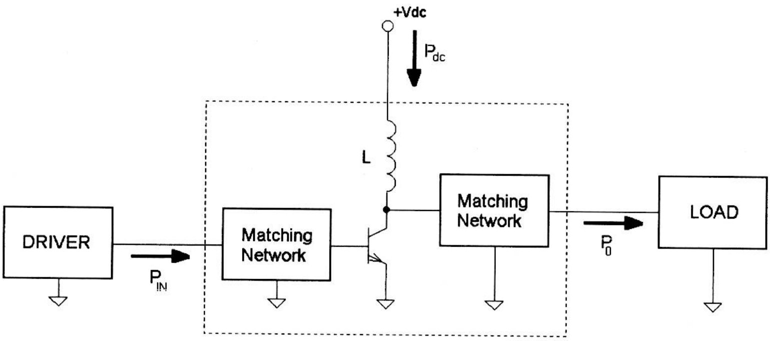


Figure 1-1 *Efficiency definitions in RF power amplifiers.*

1.4 Collector Efficiency

Collector efficiency is a term more appropriate for amplifiers using *bipolar transistors* (BJTs), although it is often used for any RF power amplifiers. Some authors prefer to use *plate efficiency* for amplifiers using vacuum tubes or *drain efficiency* for amplifiers using MOSFETs or, simply refer to it as *efficiency*. Collector efficiency is defined as (see Figure 1-1)

$$\eta = \frac{P_0}{P_{dc}} \tag{1.1}$$

where P_0 is the RF output power (dissipated into the load) and $P_{dc} = V_{dc} I_{dc}$ is the input power supplied by the dc supply to the collector (or drain / plate) circuit of the power amplifier. P_0 usually includes both the RF fundamental power and the harmonics power. In many applications, harmonic suppression filters are included in the output-matching network. Because the harmonic power is negligible, the RF fundamental power is a very good approximation for P_0. Unless stated otherwise, the definition above will be used in this book.

1.5 Overall Efficiency

Although it is a very convenient measure of a circuit's performance, collector efficiency does not account for the drive power required, which may be quite substantial in a power amplifier. Power gains (that is the ratio of output power to drive power) of 10 dB or less are common at high RF frequencies (and even at low frequencies in switching-mode amplifiers). In general, RF power amplifiers designed for high collector efficiency tend to achieve a low power gain, which is a disadvantage for the overall power budget.

From a practical standpoint, a designer's goal is to minimize the total dc power required to obtain a certain RF output power. The overall efficiency is defined as

$$\eta_{OVERALL} = \frac{P_0}{P_{dc} + P_{IN}} = \frac{P_0}{P_{dc} + \frac{P_0}{G_P}} \tag{1.2}$$

where

$$G_P = \frac{P_0}{P_{IN}} \tag{1.3}$$

is the power gain.

1.6 Power-Added Efficiency

Power-added efficiency is an alternative definition that includes the effect of the drive power used frequently at microwave frequencies and is defined as

$$\eta_{POWER-ADDED} = \frac{P_0 - P_{IN}}{P_{dc}} = \frac{P_0 - \frac{P_0}{G_P}}{P_{dc}} \tag{1.4}$$

The overall efficiency and the power-added efficiency, although related to each other, differ in their numerical values.

EXAMPLE 1.1

An RF power amplifier delivers $P_0 = 100$ W into the load resistance. The input power supplied by the dc power supply to the collector circuit is $P_{dc} = 150$ W and the power gain is $G_p = 10$ (that is 10 dB). Collector efficiency is 100/150 = 66.67%, overall efficiency is 100/(150 + 100/10) = 62.50%, and power-added efficiency is (100 – 100/10)/150 = 60%.

1.7 Power Output Capability

The power output capability, C_P, provides a means of comparing different types of power amplifiers or amplifier designs. The power output capability is defined as the output power produced when the device has a peak collector voltage of 1 volt and a peak collector current of 1 ampere. If the power amplifier uses two or more transistors (as in push-pull designs, or in circuits with transistors connected in parallel, or using combiners), then the number of devices is included in the denominator (thus allowing a fair comparison of various types of amplifiers, both single-ended or using several transistors).

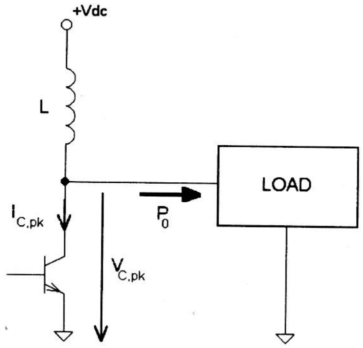


Figure 1-2 *Power output capability in RF power amplifiers.*

If P_0 is the RF output power, $I_{C,pk}$ is the peak collector current, $V_{C,pk}$ is the peak collector voltage, and N is the number of transistors in circuit, then the power output capability is given by

$$C_P = \frac{P_0}{N I_{C,pk} V_{C,pk}} \tag{1.5}$$

Power transistors are the most expensive components in power amplifiers. In cost-driven designs, designers are constrained to use the lowest cost transistors. This means the devices have to be used as close as possible to their maximum voltage and current ratings. Therefore, the larger the power output capability of the circuit, the cheaper its practical implementation.

EXAMPLE 1.2

An RF power amplifier must deliver $P_0 = 100$ W into the load resistance. A Class D circuit using two active devices can achieve a maximum theoretical power output capability $C_{P,\,Class\ D} = 0.1592$ (see Chapter 3). If the circuit is designed so that the peak collector voltage is $V_{C,pk} = 100$ V, then the peak collector current is

$$I_{C,pk} = \frac{P_0}{N\,C_{P,Class\,D}\,V_{C,pk}} = \frac{100}{2 \cdot 0.1592 \cdot 100} = 3.14\,\text{amps}$$

and the required device ratings for the two transistors used in the Class D circuit are 100 volts and 3.14 amps. A single-ended Class E circuit can achieve a maximum theoretical power output capability $C_{P,\,Class\ E} = 0.0981$ (see Chapter 4). If the circuit is designed so that the peak collector voltage is $V_{C,pk} = 100$ V, then the peak collector current is

$$I_{C,pk} = \frac{P_0}{N\,C_{P,Class\,E}\,V_{C,pk}} = \frac{100}{0.0981 \cdot 100} = 10.19\,\text{amps}$$

and the required device ratings for the transistor used in the Class E circuit are 100 volts and 10.19 amps. Another possible alternative is to use a push-pull Class E circuit ($C_{P,\,Class\ E,\ push\text{-}pull} = 0.0981$, see Chapter 4). In this case, the circuit could use two transistors with the required ratings of 100 volts and 5.1 amps. The Class D circuit is the best in terms of power output capability and could potentially be the lowest cost design. The Class E circuits have to use transistors with higher ratings, which are more expensive, in order to provide the same output power. However, in practical designs the tradeoffs are much more complicated because circuit complexity, gain, efficiency and overall cost are part of the equation.

1.8 References

1. Carson, R. S. *High-Frequency Amplifiers*. New York: John Wiley & Sons, 1982.
2. Vendelin, G., A. Pavio, and U. Rhode. *Microwave Circuit Design*. New York: John Wiley & Sons, 1982.
3. Terman, F. E. *Radio Engineering*. New York: McGraw-Hill, 1947.
4. Clarke, K. K. and D. T. Hess. *Communication Circuits: Analysis and Design*. Boston: Addison-Wesley, 1971.
5. Krauss, H. L., C. V. Bostian, and F. H. Raab. *Solid-State Radio Engineering*. New York: John Wiley & Sons, 1980.
6. Sokal, N. O., I. Novak, and J. Donohue. "Classes of RF Power Amplifiers A Through S, How They Operate, and When to Use Them." *Proceedings of RF Expo West 1995*, (San Diego, CA) (1995): 131–138.