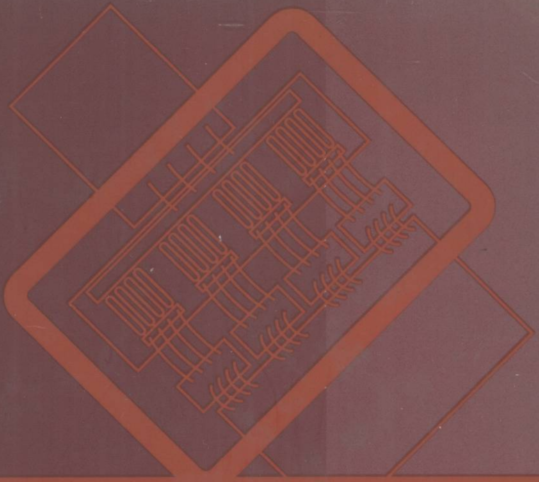

STEVE C. CRIPPS

RF Power Amplifiers for Wireless Communications

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Steve C. Cripps

Artech House
Boston • London

Library of Congress Cataloging-in-Publication Data
Cripps, Steve C.
RF power amplifiers for wireless communications / Steve C. Cripps.
p. cm. — (Artech House microwave library)
Includes bibliographical references and index.
ISBN 0-89006-989-1
1. Power amplifiers. 2. Amplifiers, Radio frequency. I. Title.
II. Series.
TK7871.58.P6C75 1999
621.384'12—dc21 99-17792
CIP

British Library Cataloguing in Publication Data
Cripps, Steve C.
RF power amplifiers for wireless communications. – (Artech House microwave library)
1. Amplifiers, Radio frequency 2. Power amplifiers
I. Title
621.3'81'535

ISBN 0-89006-989-1

Cover design by Lynda Fishbourne

685 Canton Street
Norwood, MA 02062

International Standard Book Number: 0-89006-989-1
Library of Congress Catalog Card Number: 99-17792

10 9 8 7 6 5 4 3

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Preface

Wherever there are wireless communications, there are transmitters, and wherever there are transmitters, there are RF power amplifiers. Whether it's a cellular phone transmitting a few hundred milliwatts, a base station transmitting tens of watts, a 100W microwave link, or a TV transmitter radiating hundreds of watts, the underlying principles in the power amplifier (PA) design are much the same. The PA specification and design will, in each and every case, have been the subject of close scrutiny. The PA is usually the "long pole in the tent" as far as cost, power consumption, reliability, and system performance are concerned. It is surprising, therefore, that few books have focused on the subject, and that even fewer have been published in recent years.

One reason, perhaps, is that RF power amplifier design could be considered a very old subject, one in which little remains to be said. The timeless ABC classification of amplifiers dates from the 1930s and still forms part of any introductory electronics course. Yet even the transition from tubes to transistors seems to be less well covered in available literature, and the much more recent revolution in personal communications is redefining many of the older concepts, with different and complex tradeoffs caused by the use of digital modulation systems. One of the primary objectives of this book is to bring a distinguished and traditional subject up to date, and in doing so, I probably will amuse (but, I hope, not irritate) some older practitioners by reinventing—or redescribing—the wheel; so be it.

Electronic design has, of course, gone through its own revolution over the last two decades with the widespread availability of affordable simulation software and personal computers. As a result, it seems to be almost statutory for RF authors to make an opening statement to the effect that the old black magic or hack-and-tweak approach to the design of RF components is now a thing of the past, and their books will show you how to design circuits that always work the first time, thanks to the use of modern CAD techniques. In fact, I adopt an intermediate position on that issue. Notwithstanding the pronouncements of the merchant electronics CAD community, most RF designers still do use some empirical techniques to optimize their designs while still at the development stage, and I am one of them. PA designs must run the active device to its full limits to make it cost effective; one works in a hostile environment where even tenths of decibels of power can make a significant difference to the overall system budget. A $200 transistor rated to deliver 100W is not paying its way if it makes a decibel less. But neither a CAD analysis program nor a green-fingered technician can come up with the correct matching topology in the first place, which is what this book tries to emphasize. Knowledge of the basic underlying principles of operation of the many older and newer PA modes enables better circuit topologies to be designed, *a priori,* no matter how they are finally optimized.

Indeed, if I were to take a negative stand on the CAD "debate," it would not be to point the traditionalist's finger at the inability of CAD simulators to predict experimental results with great accuracy, since that discrepancy undoubtedly will diminish as the years slip by and the models improve. My own concern is the decline of *a priori* design methods; too often a CAD optimizer is used to force an inadequate circuit topology into doing a job it is fundamentally incapable of doing. In some ways, I feel that as the CAD simulator continues to play a bigger role in the design cycle of new RF products, the utility of the simplified, possibly idealized, set of analytical design equations should increase. A simple set of equations, based on idealized models for an active device and its associated circuit elements can put the designer in a much better starting position to begin a rigorous CAD simulation and a more objective optimization exercise.

It was in this spirit that in 1983 I published a theory for predicting the elliptical shape of load-pull contours plotted on a Smith chart (reproduced here in Chapter 2). The key thing about that theory was its simplicity. Surely, some asked (and some still do!), could nonlinear behavior ever be this simple? In reality, of course, it is not, but the value of having a simple theory on which to base a design, to establish the right approximate network topology, including initial element values, was warmly received and is still widely used. Time and again, I see that the element values do not actually change all that much, even after much CAD number crunching; the "un-idealization" takes its toll mainly on the final performance parameters. Powers, gains, and efficiencies are lower in the final design, but the Ls, Cs Zos, and θs often seem to end up remarkably close to the initial idealized analysis.

I have written this book almost entirely from my own notes and recollections from 25 years' experience in the microwave amplifier business and have used few secondary sources. Every chart, graph, and table started its existence as a blank page in a notebook; the underlying algebraic derivation was performed from scratch and a Q-Basic interpreter used to plot out the curves. This approach inevitably means that here and there I may stray a little from conventional wisdom and terminology. I may even occasionally reach a point where priority could be claimed for a particular set of results. That may apply, for example, to some analysis in Chapter 4 that shows quantitatively that the perennial issue of harmonic terminations in class B and AB amplifiers may sometimes be adequately resolved by the output capacitance of the device itself, with no real need for extra stubs or resonators. Also, the analysis of clipping effects on class B amplifiers in Chapter 5, resulting in a wider set of design tradeoffs in the conventional class F to class D zone, may at least represent a different viewpoint on previously published accounts. In general, however, I have found we are operating in a field so well trodden by others over several decades that the likelihood is that someone sometime previously has visited the place in question. Indeed, to those who think they have done so, I offer a pre-emptive apology if they feel their work, unknown to me, should rightly have been referenced.

Those who have encountered me on my professional globetrotting career will no doubt recall that I have always had an eye for the controversial subject and rarely resist the temptation to weigh in with my personal views. Perhaps it is only fair to warn those not so initiated to treat sentences or paragraphs that start "It would appear that . . ." with due circumspection. It is difficult to write a technical book that is also a readable book, and I hope my efforts to that end do not intrude too much on the technical material itself.

Acknowledgments

Most of what appears in this book represents knowledge and experience I acquired during my 15-year tour of duty in the gallium arsenide division of Silicon Valley. During that time, I had the good fortune to work with some seasoned experts in the microwave business, all of whom have contributed in an indirect sense to much of the technical content in this book. So many times, a new or vital insight into a technical problem comes out of a chance meeting with a local guru at the office coffee machine or at the admirable and well-attended meetings of the Santa Clara Valley Microwave Theory and Techniques (MTT) chapter.

The key thing is that some gurus seem more willing to have such discussions than others, and it is to those individuals that I wish to express a more personal gratitude for their willingness and enthusiasm to share their thoughts and ideas: Jim Crescenzi, whose open-doored office I quickly recognized as a place where new results could be discussed with enthusiasm and encouragement during my early times in California; Ross Anderson, whose semiconductor expertise and wider perspectives on microwave circuit design helped me break out of my own personal tunnel vision on both subjects; Allen Podell, whose innovative talent and intuitive understanding of just about anything to do with electronic devices were always a great inspiration; John Eisenberg, George Vendelin, Alfy Riddle, Steve Kenney, and Larry Burns for many discussions on many different subjects that all had the common denominator of persuading me to use CAD techniques just a *little* bit more than I otherwise would have done.

I also would like to acknowledge some of my own indentured personal assistants who experienced my marginally successful years as an engineering manager. These faithful types tested, tweaked, and redesigned my circuits and managed ludicrously overcommitted engineering programs while I was sitting in meetings and committing them to even more. They usually did not get the credit when things worked out but caught plenty of static when they did not (which was only occasionally). I am pleased to note that they all have moved on to bigger and better things, so I hope they will not be too offended in making this list, which refers to some valued and competent times from their past: Dave Olsen, Craig Christmas, Jeff Smith, Bob Buss, and Leonard Carr.

Finally, I should add that the physical origins of this book are to be found in the course material for a series of technical training classes that I have given for some years for Besser Associates. My personal thanks are due to Les Besser for giving me the opportunity to organize my thoughts and material in such a manner as to make this project even remotely feasible and also to the many course participants, whose intelligent and perceptive comments and questions have helped me correct and improve the material over the years.

Steve C. Cripps
Somerset, England
March 1999

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Introduction

This book is about radio frequency (RF) power amplifiers (PAs), and a logical starting point would be to recall some of the classical results of linear RF amplifier theory, because many PA designs are simple extensions or modifications of linear designs.

PAs usually operate with the active device displaying some (maybe even gross) nonlinear behavior. Straightaway, we are faced with the issue of nonlinear modeling. This is a big subject and has been the focus of hundreds of papers and several books in recent years. (Section 1.4 serves as an introduction to the subject.) For the purposes of developing useful, practical *a priori* design methods, however, we can manage quite adequately with some very simple and basic models. Sections 1.2 and 1.3 introduce these models and discuss the important distinction between strong and weak nonlinearities. Those simple models are used and referred to throughout this book.

One of the principal differences between linear RF amplifier design and PA design is that, for optimum power, the output of the device is not presented with the impedance required for a linear conjugate match. That causes much consternation and has been the subject of extensive controversy about the meaning and nature of conjugate matching. It is necessary, therefore, to swallow that apparently unpalatable result as early as possible (Section 1.5), before going on to give it more extended interpretation and analysis (Chapter 2).

1.1 Linear RF Amplifier Theory

Mason [1] and Rollett [2] originally derived the basic results of two-port matched linear RF amplifiers, although most microwave engineers first encounter these results in a famous application note (AN-95) written by Bodway and available from the Hewlett Packard Company [3]. Many books on basic RF design techniques cover this material in greater detail [4].

The key results can be illustrated by examining the schematic shown in Figure 1.1, in which a transistor is represented as a two-port *s*-parameter matrix. The input and output impedance, or reflection coefficient presented to the transistor, can be adjusted with conceptual tuning devices. Because the tuners are realized using passive circuitry (e.g., transmission lines and shunt capacitive slugs or stubs), the reflection coefficients Γ_S and Γ_L at the input and output device reference planes are restricted to the range of $0 < |\Gamma_{S,L}| < 1$ in magnitude.

Much of the complexity of the behavior of this system is characterized by the relative magnitude of the reverse transmission parameter s_{12}; however, a more concise parameter emerges after some extensive analysis, called *k*, or Rollett's stability factor. The key equations are straightforward and represent the change in the input reflection s_{11}, to s_{11}', due to the output plane being presented with the output load reflection Γ_L.

The input match is

$$s_{11}' = s_{11} + \frac{s_{21}s_{12}\Gamma_L}{1 - s_{22}\Gamma_L} \tag{1.1}$$

The output match is

$$s_{22}' = s_{22} + \frac{s_{21}s_{12}\Gamma_s}{1 - s_{11} - \Gamma_s} \tag{1.2}$$

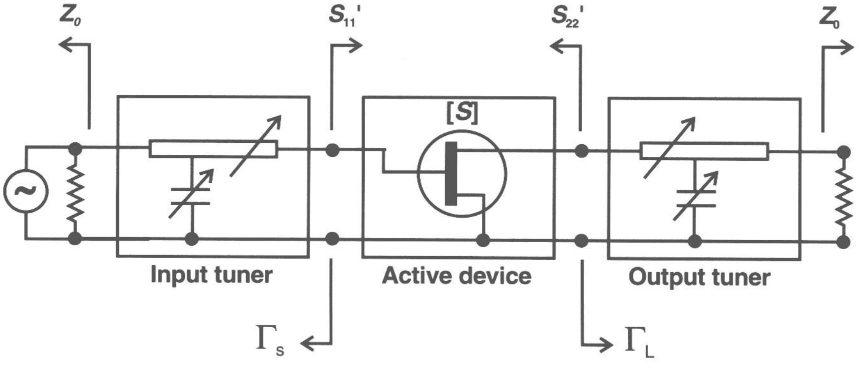

Figure 1.1 Schematic for 2-port gain and stability analysis.

So, for a conjugate match, we can set $s_{22}' = \Gamma_L^*$ and $s_{11}' = \Gamma_s^*$, giving two equations that, in principle, can be solved for Γ_S and Γ_L.

It should be noted that, in general, this solution always exists. There is an additional constraint, however, that the magnitudes of Γ_S and Γ_L must be less than unity for passive external circuitry. That is where the *k*-factor makes its appearance. After lengthy and admirable manipulations of complex algebra, Rollett (*et al.*) showed that the $0 < |\Gamma_{S,L}| < 1$ condition corresponds to the *k*-factor being greater than unity, where

$$k = \frac{1 - |s_{11}|^2 - |s_{22}|^2 + D^2}{2|s_{21}||s_{12}|},$$

and

$$D = s_{11}s_{22} - s_{12}s_{21}$$

In practical terms, if $k > 1$, the device will never display an input or output reflection coefficient that is greater than unity in magnitude, whatever passive matching may be placed at its input or output. That is clearly a strong statement about its stability. Unfortunately, formulating the problem as a two-port introduces some restrictions that are not general enough for some applications. A quest has been ongoing in the literature to find a "best and final" set of conditions for absolute stability under all conditions [5, 6], but the simple $k > 1$ condition is a good practical guideline to follow.

It should not, however, be stretched too far. In the world of PA design, we often struggle to obtain adequate signal gain, as well as extract optimum power from a device. That is an inevitable consequence of cost-driven designs; large periphery transistors have lower gain and designers usually are constrained to use the lowest cost technology. We will see later how, when the signal gain drops below 10 dB, the extra RF drive power required often cancels out any efficiency advantage that had been carefully designed. The upshot is that a designer often is looking for an optimum situation in which the *k*-factor is greater than unity—which is just good basic design practice—but not too much greater. Devices with high *k*-factors also tend to have low gain, and some extra gain can be retrieved by deliberately introducing positive feedback around the device, while keeping the *k*-factor above unity. That trick is often used, albeit sometimes inadvertently, by the microwave and millimeter-wave amplifier community and was a mainstay of the pre-World War II tube radio industry, "reaction" controls and all.

If $k > 1$, expressions can be found in the literature for the conjugate match and corresponding maximum available gain (MAG). Those expressions are well known and are not repeated here. But a few ramifications are worth noting.

- Any device that has a k-factor greater than, but not much greater, than unity displays a more aggressive gain/match characteristic than a theoretical unilateral device. In particular, the final MAG may be considerably higher, in a nearly matched condition, than a simple VSWR-mismatch calculation would indicate (e.g., such a device displaying a 10-dB return loss may show more than the calculated 0.5 dB increase in gain when finally matched to a return loss of –20 dB).
- Circuit losses can play havoc with the k-factor and especially the frequency where it crosses unity. In practice, devices can be safely used some way below the unity k-factor point, if the k-factor is based on fully de-embedded s-parameter measurements.
- The circuit environment in which a transistor is placed can significantly modify its effective s-parameters, especially the critical s_{12}. This is probably the main cause of unexpected or unsimulatable stability problems.
- k-factor analysis, as presented here in its classical form, is applicable only to a single-stage amplifier. In a multistage environment, the condition $0 < |\Gamma_{S,L}| < 1$ no longer applies, because the input and/or output planes of an intermediate stage are terminated with active networks. Thus, taking a multistage amplifier as a single two-port and analyzing its k-factor is a necessary, but by no means sufficient, condition for overall stability. That problem is often bypassed in multistage RF amplifier designs by the use of some form of isolation between stages, although multistage stability analysis and design strategies have been published [7].

1.2 Weakly Nonlinear Effects: Power and Volterra Series

The possibility—or the reality—of nonlinear effects in linear amplifiers usually are introduced in the form of a black-box power series expression, as shown in Figure 1.2.

The amplifier symbol in Figure 1.2 represents a transistor with its associated input and output matching circuitry, and the lower-case voltages are the small RF signal variations about the transistor operating point. The amplifier