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Solid-State Microwave High-Power Amplifiers

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Preface

To a large extent, this book originates from our shared experience at Microwave Power Inc. (MPI), a company dedicated to the design, development, and manufacturing of high power solid-state microwave amplifiers. We cofounded the company in 1986 and have managed it jointly for over twenty years. Working in a small company environment is certainly a good antidote against specialization—we developed a perception that many topics relevant to microwave amplifiers are of interdisciplinary nature and we have tried to convey this broad point of view in this book. While we cover all traditional power amplifier design topics, from large signal device characterization to power combining and all main design procedures, we have also given more space than usual to device physics, phase noise, bias circuits, and thermal design.

Throughout the book we have tried to emphasize fundamental concepts. We think it is the only way to avoid quick obsolescence when writing on a topic that is in continuous evolution. When we show the logic and principles behind the various design techniques, we mean to encourage the reader to apply the same ideas to future designs; or when we point to the fundamental laws behind present day devices, we offer a key to understand newer ones.

We hope that our emphasis on fundamental concepts and our wide range of subjects may appeal to a broad audience. For instance, while we are not specifically addressing the field of wireless communications, many of the topics covered in this book are of interest to designers of power amplifiers for base stations: in particular we are thinking of large signal device characterization, phase noise, design techniques, special amplifiers, and thermal design. We also hope that the book will be of interest as a reference or textbook in advanced microwave courses.

Since we started off mentioning Microwave Power, let us take this opportunity to thank all MPI employees who have worked with us through the years and have contributed in so many different ways. We also wish to thank Tim Heyboer, the present manager of MPI, and Dr. Tibby Mazilu, Ed McAvoy, Jacob Inbar, and Glenn Nakao of AML Communications for their encouragement during the writing of this book, especially in connection with the phase noise measurements and several of the figures. Finally, we wish to acknowledge the constructive criticism and suggestions of the Artech House reviewers.

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Introduction

1.1 Scope of This Book

Amplifiers are key components of most microwave systems, and their characteristics often determine a system's architecture. In the early days of microwave engineering, all amplifiers were based on vacuum tubes, such as klystrons, magnetrons, or traveling-wave tubes (TWT) but the tremendous progress of solid-state technology has been progressively eroding this dominant position. The advantages of solidstate devices in terms of reliability, ruggedness, characteristics of operation, size, and cost are such that, whenever a solid-state alternative becomes available, it is quickly adopted by the system designer. In a plot of power versus frequency, as shown in Figure 1.1 for narrow-band amplifiers, the progress of solid-state technology through the years can be visualized as a moving boundary that encloses an increasingly wide region, while the vacuum tubes' domain is progressively pushed toward higher and higher frequencies and powers. The gray areas marked 1989 and 2009 represent our uncertainty in the position of this moving boundary in these two years. Also shown in the figure is the region of powers and frequencies characteristic of handheld cell phones. Any plot of this type can be only approximate and general, at best. There are always going to be special cases related to cost, specifications, or legacy that will move a tube into solid-state space and vice-versa.

This book covers only solid-state power amplifiers (SSPA) and focuses on the highest powers reachable with solid-state technology. This may mean a few watts for multioctave bandwidths or hundreds of watts for narrow bands. As shown by the area marked in Figure 1.1, we might define our focus as "whatever power levels were beyond reach 20 years ago." Naturally, this is not to say that design principles and techniques discussed in this book would not apply to lower powers, but rather that topics such as power combining and heat management will receive more than the usual share of attention. The choice of examples will also reflect our area of interest.

The applications we have in mind are mostly in radars, electronic warfare, telecommunication equipment, and special test systems. A large body of literature is already available on amplifiers for cell phones and similar wireless applications [1–6], so we will not dwell on them; however, this book certainly applies to the high-power amplifiers used in base stations. We have also made the choice of concentrating on compound semiconductor devices. We feel some excellent books, reviews, and product literature [7–9] already cover the relatively low-frequency, high-power Si MOS transistors that have made such impressive progress in recent

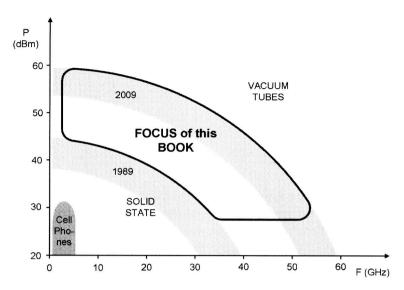


Figure 1.1 This book's area of interest is marked by a heavy line on top of a graph representing the progress of solid-state power amplifiers vs. vacuum tubes over 20 years. Also shown are typical frequencies and powers used in cell phones.

years, while there is not much new to add on Si bipolars [10–12]. They were the first transistors to reach microwave frequencies back in the 1960s. They are still quite popular because of their low cost and good phase-noise characteristics, but their use in amplifiers, especially at high-power levels, does not extend much beyond 4–5 GHz. The ability of a semiconductor to respond to higher frequencies is mostly related to electron velocity, and several semiconductor materials are known to have both higher mobility and higher peak velocities for electrons than Si. Among them, GaAs has been the most successful so far. This is due to a combination of factors. Certainly its well-developed technology, driven by the large market in the optical field (as an LED and laser material) was a major element in its early success. Another favorable factor is its relatively large bandgap leading to a fairly high intrinsic resistivity. This makes it suitable (though not optimum) as a substrate for microwave propagation, and it was therefore a key to the success of monolithic microwave integrated circuits (MMICs). However, new materials are now gaining ground, and we will review some of the most promising results.

Considering its title, this book covers an unusual amount of solid-state and device physics, possibly too much for some readers. To make life easier for them, we have concentrated most of this subject in Chapter 3, so that whoever is either not interested or already knowledgeable can easily skip it. Our emphasis reflects our experience that understanding solid-state physics is a major asset in the effective utilization of a power microwave device. A solid-state device used in a power amplifier often exploits to the limit all the characteristics of a given material and technology. Knowing these boundaries, and the physical reasons behind them, is essential for a sound and reliable design. Finally, we feel a microwave designer is faced with a continuous stream of new devices, technologies, and materials, but, actually, the basic principles behind them are not that numerous. A grasp of these fundamental ideas will help in finding logic and continuity behind the variety.

In terms of frequencies, we will address the whole range from 1 to 50 GHz, but will concentrate mostly on broadband applications and higher frequencies (as long as significant power is available). These seem to us the most challenging areas for future development. Although we have tried to justify some of our choices on a rational basis, there is no denying that they also reflect our professional interests. We feel that these are the topics where we can offer more original insight.

1.1.1 Future Developments

The demand for higher solid-state power is very strong in all fields of application, and the general trend is always toward higher powers at higher frequencies. For solid-state amplifiers, there are two main possibilities: improved combining techniques and higher power devices.

Most SSPAs, and certainly all the highest-power ones, use some kind of power combination. We believe new low-loss combining techniques are very promising. The main advantage of increasing power output this way is the ability to distribute power dissipation more effectively. As an example, we will see in Chapter 7 that power amplifiers based on planar radial combiners are built with power devices evenly distributed around the periphery of the combiners, and heat is very effectively distributed. Today, many low-loss, high-power combiners introduce limitations in the bandwidth, but we expect new and improved techniques will progressively lead to efficient broadband combining, while maintaining the important thermal advantage.

In terms of device power, the greatest hopes come from the new wide-gap semiconductors, especially GaN. When the active layers of GaN are grown on SiC, the device takes advantage of the excellent heat conductivity of the substrate, and power outputs five times as high as those of present-day GaAs devices may be within reach. The area is developing so fast that any reported result is quickly obsolete. We have tried to overcome this problem by stressing basic principles in the hope that the reader will be able to apply them also to devices and materials not yet available today.

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High-Power Amplifiers

2.1 Applications and Specifications

In designing a microwave system, the specification of the power amplifier is generally one of the most critical steps: the power amplifier is often the most expensive component, and its characteristics leave a clear footprint on the whole system. This is especially true when choosing between a traveling wave tube (TWT) and a solid-state power amplifier (SSPA), since the properties of the two types of amplifiers are extremely different. Even if we consider only the solid-state option, however, there is much more to a power amplifier than its output power and frequency of operation. Depending on the application and the type of system, many different properties can become important or desirable. Some of them may weigh substantially on the cost of the system and therefore represent a clear economic trade-off, but others may be available at very low cost by making the correct choices.

Power output, gain, frequency of operation, bandwidth, and cost are almost always included even in the shortest specification list. Other characteristics are more significant in specific cases: for a high power amplifier (several watts and above), thermal management is typically a major issue; efficiency, weight, and size are most critical in an airborne application; and reliability (which is always important) becomes foremost in a space application. As we will see later in more detail, many modern communications systems require high linearity and low phase noise. Finally, the time required to develop an amplifier with specific characteristics is always an important cost component, but sometimes it may become a dominant parameter, for example, when the amplifier is timed in conjunction with a particular system.

This chapter will briefly touch upon the complex issue of the relationship between the power amplifier and the overall system. Occasionally, the relationship is so tight that the only practical possibility is designing them both at the same time, but more often a two-way relationship develops. Sometimes it is the amplifier manufacturer who responds to specific system requests by modifying some characteristics or adding new features, and other times it is a new amplifier development which makes a different or improved system feasible. By considering the effects of some of the amplifier properties on the system, we intend to stress the importance of an optimum match between specifications and application. At the same time, we hope to clarify our choice of topics for the following chapters and their relative emphases.

Let us then look at a few specific issues. One of the most important aspects of a system design drastically affected by the power amplifier is heat management. This is especially true when using solid-state devices. First, transistors are much less efficient than tubes. In addition, in an SSPA, the high power output is achieved by

combining several solid-state devices in parallel, and each level of combination contributes additional losses. On the other hand, both reliability and power output decrease substantially if the temperature of operation is increased. Consider the case of a typical 100W amplifier for a transmitter station in the popular 14-14.5-GHz radio link [1]. All but 100W of its DC power consumption, which may be close to 2 kW, has to be removed from the active devices, where most of the heat is generated. At the same time, the devices need to remain as cool as possible. Indeed, for every increase of only 10°C in device temperature, the RF power output typically decreases by as much as 5%, and the life expectancy by almost a factor of 2. Heat removal is generally accomplished by bulky forced-air heat sinks: this approach may be acceptable in a commercial ground station, but may be difficult to accommodate in other cases, such as in an airborne application. A careful thermal evaluation, as early as possible in the design cycle, is clearly a very important part of both the amplifier specification and the system design (as will be discussed in more detail in Chapter 13). But even using fairly sophisticated heat sinks, these may contribute well over one-half of both weight and volume to the overall amplifier. The problem of heat transfer is magnified by the need to maintain the temperature drop between heat source and heat sink as low as possible; introducing new devices capable of efficient operation at higher temperatures would considerably ease the problem. This is one of the main factors behind the development of semiconductors with larger energy gaps, such as GaN and SiC, which are already showing excellent results and will be reviewed in Chapter 3. Finally, this example also illustrates the significant role of losses, not only in the active devices, but also in all other elements, which are often treated as "ideal" in low power applications, but cannot be considered so at high power levels. Not only do losses in the various stages of combination contribute, of course, directly to the heat to be dissipated, but also, the higher the loss, the larger the number of devices required to achieve the desired power. In the particular amplifier mentioned above, an additional loss of only 0.8 dB in the output combiner is enough to require an increase in the required number of active devices from ten to twelve. All the other stages have to be scaled accordingly, and, in practice, the 20% increase in the devices directly translates into a similar increase in DC power consumption. As we will see in Sections 6.2 and 7.5, the remarkably low loss of waveguides (especially when compared to microstrips) has made them the favorite structure for high-power combiners. One drawback is their limited bandwidth, and this is indeed a major drawback for a number of very important applications, such as instrumentation and electronic warfare, where there seems to be no limit to the desired bandwidth.

Not all applications require a broad band but, for those that do, the trade-off between power and bandwidth often becomes the dominant issue. This is exemplified in Figure 2.1 by a selection of commercial products [2]. The figure is divided by shaded gaps in three regions, each corresponding to a different architecture. As sketched in Figure 2.2, a typical layout for an SSPA comprises a gain stage, which is essentially a low-power amplifier providing most of the gain, followed by the driver and output stages. Both of these are generally structured as combinations of simple amplifying modules, which may be either microwave monolithic integrated circuits (MMICs) or equivalent ceramic circuits. We will see in Section 8.6, when discussing design issues, that the product of power and bandwidth can be viewed