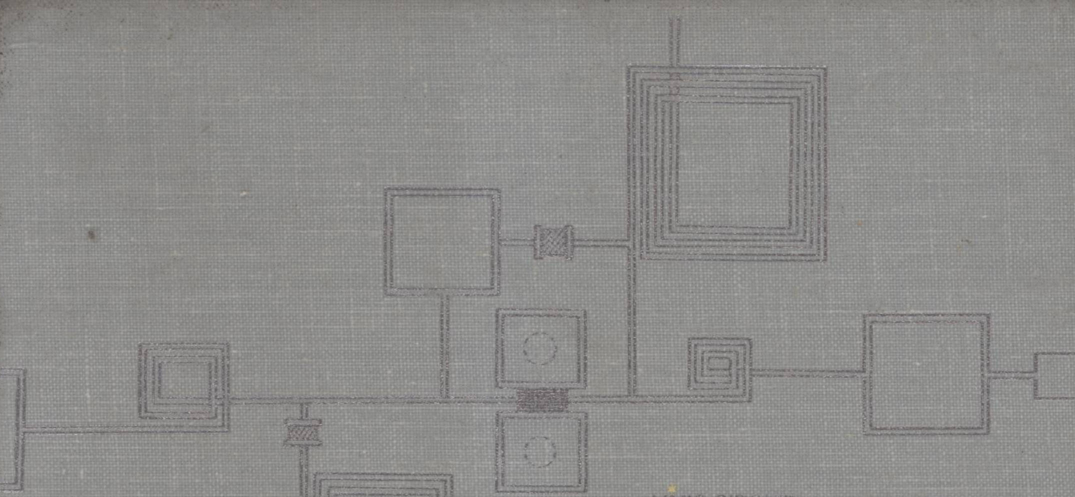


# MIC & MMIC AMPLIFIER and OSCILLATOR CIRCUIT DESIGN

**Allen Sweet**

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Allen A. Sweet



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# *Preface*

The microwave electronics field, since its inception at the MIT Radiation Laboratory during WWII, has been in a continual state of evolution. No area of the field has seen greater changes than that of microwave amplifiers and oscillators. The active devices used in amplifiers and oscillators have evolved from vacuum tubes (klystrons and magnetrons) to two terminal solid state devices (Gunn, IMPATT, tunnel, and varactor diodes) and finally to three terminal solid state devices (GaAs FETs, and silicon bipolar transistors). At the same time, the transmission line media has changed from waveguides, to coaxial cable, and finally to microstrip lines. The analytic design tools available to the microwave circuits designer have gone through similar changes. Analytic calculations based on the application of Maxwell's equation to particular situations have given way to numerical solutions calculated by mainframe computers, which have largely been replaced by general transmission line optimizing software (Touchstone and SuperCompact) that runs on PC computers and workstations.

These three parallel paths have now evolved to such a point that, in most cases, all of the active, passive, and transmission line elements of an amplifier or oscillator are located on one or two semiconductor chips plus a ceramic circuit board, all of which are interconnected by hybrid assembly techniques (i.e., microwave integrated circuits, or MICs); or all the circuit elements are located on a single chip of semiconductor material (i.e., monolithic microwave integrated circuits, or MMICs). This is not to say that vacuum tubes and waveguide transmission lines are no longer important. They are very important in high power applications and at millimeter wavelengths, but most low and medium power microwave components and subsystems are constructed now with solid state devices and microstrip transmission lines. The improvements in size, weight, electrical performance, and cost of the new technologies compared to the early vacuum tube/ waveguide amplifiers and oscillators is truly fantastic. In fact, the present generation of airborne radar, communications, and EW systems simply would not be possible without the newer technologies. These rapidly developing technologies have placed a heavy burden on the circuits designer, who must stay current with all of these new trends.

The purpose of this book is to help enable circuit designers to produce both cost effective and reliable amplifier and oscillator designs by using the latest device, circuit, and simulator technologies. Since the author strongly believes in learning through example, a dozen up-to-date design examples are presented which systematically "walk" the designer through the entire process from conception to completed art work and assembly drawings. A systematic design process emerges from these examples, and all of the necessary analytic tools are provided which enable the designer to use this process. A heavy emphasis is placed on the use of computer aided design tools. Similarly, a heavy emphasis is also placed on the importance of each designer cultivating his or her own creative design strategies.

Many good books are available which discuss the theory of operation of various microwave devices, and they are carefully referenced in this book. However, the intent of this book is to go beyond a theoretical discussion and present the strategies of design as a systematic process.

I am truly grateful for all the helpful suggestions and comments that have been offered over the past decade by colleagues and students, all of whom have helped to bring to light many of the issues addressed in this book. These individuals include students participating in courses I have taught for the University of California at Berkeley Extension Division and for Technology Services Corporation, many of whom repeatedly requested an "advanced design course." This book is the foundation of such a course.

I also wish to thank my many colleagues throughout the industry for their numerous helpful technical discussions in which I have been privileged to participate over the years. Of these, two are especially deserving of a special note of thanks. George Vendelin, friend, colleague, and associate, who for many years took on the lengthy task of reading the entire manuscript, offered many helpful suggestions. John Mezak, also a long time friend and colleague, read the YIG resonator section and offered many useful suggestions on this material.

Finally, I most gratefully acknowledge the long, countless hours devoted by my wife, Fran, to the word processing and editing of the entire manuscript. Her ability to arrange words properly in order to bring out the clarity of intended meaning, and her occasional use of the pointed question, "What are you really trying to say here?" at just the right time proved invaluable to the process of manuscript preparation. Without her tireless efforts and unyielding support, this book would not have been possible.

# Contents

# *Chapter 1*
# *Introduction*

Most texts and reference books in the microwave electronics field focus on a general theoretical approach to design. My belief is that most of us learn best by first studying specific examples and then proceeding to a general understanding. Such a philosophy is the basis for this book. The material is structured to provide a definite process of design and is illustrated by numerous specific examples that have been taken from the author's design experience acquired since the mid-1970s.

The book had its beginnings in the numerous courses on microwaves and microwave amplifiers and oscillators taught by the author since 1981. These include courses for Technology Service Corporation of Silver Spring, Maryland, and the University of California, Berkeley, Extension Division. The content of these courses emphasized either basic operational principles or computer-aided design techniques, depending on the particular course. Over the years, students have asked for an advanced design course that would address all of these ideas simultaneously. The book is partially motivated by these requests. The author hopes that the book will simultaneously provide a text for an advanced amplifier and oscillator design course and a reference handbook for the practicing design engineer.

Certain important modifications have been made to the previous course materials in preparing this book. These modifications fall into three general areas:

- *Computer-aided design* (CAD) techniques are emphasized throughout the book. Because of the complexity of modern microwave circuits, to design without making use of CAD techniques is now virtually impossible. Chapter 4 is devoted to this topic, and all of the examples make use of CAD techniques. "Hand calculations" are discussed, not as an end product, but merely as a "first guess" for a CAD analysis and optimization, which then follows.
- A *monolithic microwave integrated circuit* (MMIC) design process with examples is included, along with the more standard MIC hybrid techniques. MMIC circuits, which are totally functional amplifiers or oscillators fabricated on a single chip of GaAs, are a very important new class of circuit that

has grown swiftly in popularity in recent years. These circuits pose some unique design challenges in terms of economics, design precision, and manufacturing yield. Because of its uniqueness, MMIC design is treated as a separate area.

- Considerable detail on the fabrication techniques for both MIC and MMIC circuits is presented. This material is provided to familiarize the designer with how designs are fabricated so that he or she can become sensitive to the design issues affecting fabrication. Remember that *if a circuit cannot be economically fabricated, it is a failure, regardless of its performance.*

The paradox of microwave circuit design is that the basic topology of most microwave amplifiers and oscillators is very straightforward. Often the only components involved are an active device (GaAs FET or Si bipolar) plus four or five microstrip transmission line elements of various lengths and widths. Compared to a large analog IC chip or a digital microprocessor chip, such a microwave circuit seems very simple. However, strange as it may sound, the design of microwave amplifiers and oscillators poses one of the greatest technical challenges to circuit designers within the electronics industry today. In the past, there had been a heavy reliance on empirical techniques (tweaking, cut-and-try, scatter gunning) to make microwave circuits respond as expected. However, economic pressures and the advent of MMIC technology make the old empirical techniques very undesirable and sometimes impossible.

Why does a simple microwave circuit require a very complicated design process? The answer is threefold: (a) many layout "parasitic" elements complicate the circuit's basic topology; (b) the active devices are not completely reproducible and vary with a degree of randomness from circuit to circuit; and (c) circuit elements at microwave frequencies are distributed by nature, and care must be taken to consider the "distributed" aspect of many so-called lumped elements. The predicted performance of a circuit is only as accurate as the model used to make the prediction. Furthermore, modeling in the world of microwave circuits is a very complicated process (and a fine art), which often involves exacting measurements as well as applying appropriate simplifying assumptions. Because the modeling of active devices quite often is left to designers, they must become expert modelers. The modeling process is explored in depth throughout the book.

All of the numerous examples are practical circuits that, if constructed, will yield good performance. Each example is worked through a series of design steps, culminating in a final layout appropriate for fabrication.

Enough background material is given on the basics of semiconductor devices (GaAs FETs, bipolar transistors, varactor, and PIN diodes) and microstrip transmission lines so that the designer will have all of the important basic relationships at his or her fingertips.

The chapters describing layout (MIC and MMIC) tie it closely to fabrication techniques. A layout strategy is developed that from the beginning includes modeling of parasitic elements. The layout process is seen as interactive in the sense that changes in the layout always must be checked for how they affect performance. Often several iterations will be required before the designer simultaneously achieves the desired performance and a realistic layout.

The two final chapters deal exclusively with GaAs MMIC circuits. Because MMIC circuits cannot be experimentally modified (except with great difficulty), their calculated performance must be extremely accurate and, at the same time, forgiving enough to deliver the specified performance despite process variations of certain key device parameters. MMIC design requires very special strategies that combine the best modeling and layout techniques with a statistically based yield analysis.

The author hopes that designers at all levels of experience will profit from this book. Although the core material was derived from classroom lecture notes, the book is not intended to function only as a text, but rather as a reference and guide for both students and practicing design engineers.

# Chapter 2
# Devices

## 2.1 GaAs FETs

### 2.1.1 GaAs FET Material Overview

The principal component of all GaAs FET devices is the gallium arsenide material itself. GaAs has been recognized as a very special microwave material since the 1960s. The technological evolution of GaAs has made great strides over the past two decades, and today it rivals silicon in terms of purity, precision, and manufacturability.

The significance of gallium arsenide as a microwave material was first recognized by J. B. Gunn[1] of IBM, who discovered periodic high-frequency oscillations in a biased "resistor" of N-type GaAs in 1965. These mysterious oscillations were soon traced to a phenomenon called *negative differential mobility,* which is caused by an even more obscure phenomenon called *intervalley scattering*[2], which occurs within the energy band structure of GaAs. Negative differential mobility is visible in the velocity field diagram of GaAs shown in Figure 2.1. Many workers joined the gallium arsenide field in the mid-1960s, to both understand more about its material properties, and to apply GaAs as a material to potential applications, which turned out to be largely in the microwave region of the EM spectrum. This was a time of experimentation with various "diode" structures, including transit time, hybrid, LSA, "modes"[3] to name a few; all of which used gallium arsenide as their basic material.

Not until the 1970s was gallium arsenide applied to the field-effect transistor (FET). Because of the significantly higher electron drift velocity in gallium arsenide relative to silicon, the transit time delay in a GaAs FET is much less than it is in an equivalent silicon FET, resulting in a considerably higher frequency of operation for GaAs FETs than for silicon FETs. Today, GaAs FETs that operate up to 50 GHz are commercially available.