High Frequency Techniques

An Introduction to RF and Microwave Design and Computer Simulation

JOSEPH F. WHITE

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HIGH FREQUENCY TECHNIQUES

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Joseph F. White
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PREFACE

Since the initial publication of this book, it has occurred to me that both its content and style may not have been apparent. I intended that the undergraduate electrical engineering student could use the book as an introductory text. However, the book contains much more content and analytical depth than what reasonably can be presented in an introductory course. In fact, the book also can serve as a text and reference for the graduate student or the practicing electronics engineer.

Despite this, all one needs to understand its content are introductory courses in calculus and physics, as would usually be given in the freshman year of an engineering curriculum. A review of the *Table of Contents* or the *Index* will reveal to the reader the thoroughness with which the electrical engineering topics are treated. The book is self-contained, not requiring recourse to other texts, and, therefore, is a completely explanatory text and reference for the interested reader.

Initially, it can be used in a first course to introduce alternating circuit (AC) analysis at the sophomore level. For example, complex number math (Appendix B) and the basis of steady-state AC analysis using complex numbers (Chapters 1 and 2) are treated at the introductory level. The usefulness of AC analysis is illustrated by the *Q matching method* (Section 3.5), a convenient design technique derived from the formulas for series-to-parallel impedance transformations. Other topics include the definition and use of matrix algebra (Chapter 6) to describe two-port networks. This gives details for *y*, *z*, *abcd*, and *s* matrices (the latter also known as *s parameters*).

The *impedance transformation equation* is derived (Section 4.14), which gives the input impedance to a transmission line of arbitrary length when terminated in an arbitrary load impedance. While useful, this equation requires complex calculations to apply, yet it does not provide insight into the locus of impedances to which the load may be transformed. An epic solution to this limitation was the *Smith Chart*.

The Smith Chart is developed in detail. It begins with how the chart was derived from the variation of the reflection coefficient on uniform transmission lines and, then, how it evolved mathematically to the graphical aid we now know. This is followed by illustrative examples of impedance matching using the chart.

The book also can be used at the junior and senior levels, as for example, for the introduction of field analysis using vector calculus (Chapter 7). *Maxwell's equations* are presented and their usefulness demonstrated by the proof that *radio waves propagate through a vacuum and at the speed of light* (see Section 7.20), an astounding discovery credited to James Clerk Maxwell, circa 1863.

Finally, the book can be used as text for a graduate-level course. Advanced topics such as *electromagnetic (EM) circuit simulation, vector potential, retarded potentials*,

Green's functions, and *higher order modes*, advanced filter techniques (*elliptic filters*, *the Richards transformation*, and *Kuroda's identities*); *statistical design and yield analysis;* and advanced amplifier design (including *noise figure*, nonlinearity, broadbanding, and cascading sections) may be covered.

The use of circuit simulator software is employed throughout the book, and this leads into the design of transistor amplifiers. This analysis, based on *S* parameters, can be readily covered provided the student has access to microwave circuit simulator software, a practical requirement for today's electrical engineering student. Amplifier design criteria are presented, which include gain, impedance matching, and stability (resistance to oscillation). Some firms may make these simulator software available free to engineering schools that apply for it.

Antennas are presented, including wire, aperture, and phased array types. The coverage of antennas, path loss, and propagation (Section 7.3) provides an insightful introduction to the design of wireless (radio) systems.

The presentation of EM simulation (Section 7.34) is illustrative of how EM-based software can provide a more accurate prediction of actual circuit behavior. This is illustrated by a comparison of the performance of a practical transmission line stub as revealed by EM simulation with the predicted performance of an ideal (zero line width) stub.

This book treats many topics that I encountered as a practicing microwave engineer, in a period during which computer aids were evolving.

For example, I found the behavior of backward wave couplers fascinating, and sought to understand them. Questions arose: How could the quarter wave coupler (Chapter 8) be matched at all frequencies, and how could its direct and coupled arm outputs always be 90° out of phase, even for broad bandwidths over which the coupling region departs widely from its 90°, center frequency value? The *even- and odd-mode analysis* for this coupler is complex, a credit to the original researchers who formulated it. But it is presented in its entirety in this book (and in few other texts). Through these equations, one can find and prove the answers.

Rigor has been used throughout the book, with complete mathematical derivations given for all presented formulas (other than those empirically derived, such as Maxwell's equations). Is such thoroughness necessary? I believe so. This developmental rigor provides insight to the engineer on how he or she can develop equations for other circuits that may be encountered in practice. In essence, the basis of this book is the mathematics of electrical engineering, particularly high-frequency engineering. For this reason, I believe the book's content will remain ever applicable, no matter how the technology evolves in the future.

It was a pleasure to write this book. I will be happy to hear from you.

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The *Smith chart* symbolized on the cover and employed within this text is reproduced through the courtesy of Anita Smith, owner of Analog Instrument Company, Box 950, New Providence, New Jersey 07974. I am happy to acknowledge the late Phillip Smith for this remarkable tool, arguably the most profound insight of the microwave field. Numerous Smith chart matching solutions were performed using the software program *WinSmith* available from Noble Publishing Co., Norcross, Georgia 30071.

All of the circuit simulations have been performed using the Genesys software suite provided through the courtesy of Randall Rhea, founder of Eagleware Inc, Norcross, Georgia 30071. My thanks also go to the members of the Eagleware on-line support team, whose assistance improved the many simulation examples that appear in this text.

My gratitude to Dr. Les Besser who encouraged me to begin microwave teaching and shared with me many RF and microwave facts and design methods. I also thank Gerald DiPiazza for his patience and help in critical field theory development in this text.

I gratefully acknowledge Dr. Peter Rizzi, my colleague and friend, who patiently read the manuscript and made numerous suggestions to improve its readability, usefulness, and accuracy. He directly contributed the portions on noise and noise temperature. Dr. Rizzi is the author of *Microwave Engineering and Passive Circuits*, an important, widely used text that is referenced extensively in these notes. He is a professor of microwaves who is loved by his students. No one but I can appreciate the magnitude of his contributions.

Anyone who has written a book knows how much patience his spouse requires. My thanks and love to Eloise.

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Questions, corrections and comments about this book are welcome. Please e-mail them to the author at jfwhite@ieee.org.

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CHAPTER 1

Introduction

1.1 BEGINNING OF WIRELESS

> WIRELESS TELEGRAPHY—At a time when relations are strained between Spain and this country, nothing could be more welcome than a practical method of carrying on electrical communication between distant points on land, and between ships at sea, without any prearranged connection between the two points. During the last year Guglielmo Marconi, an Italian student, developed a system of wireless telegraphy able to transmit intelligible Morse signals to a distance of over ten miles. It has been left, however, for an American inventor to design an apparatus suitable to the requirements of wireless telegraphy in this country. After months of experimenting, Mr. W. J. Clarke, of the United States Electrical Supply Company, has designed a complete wireless telegraphy apparatus that will probably come rapidly into use.
>
> —Scientific American April, 1898

This announcement appeared near the beginning of radio technology. Webster's dictionary [1] lists over 150 definitions that begin with the word *radio*, the first being:

> 1a. ... the transmission and reception of electric impulses or signals by means of electromagnetic waves without a connecting wire (includes wireless, television and radar).

This remains today the real definition of *wireless* and, equivalently, *radio*. Today the uses of radio communication include not only the broadcast of sound through amplitude modulation (AM) and frequency modulation (FM) radio and video through television, but also a broad collection of radio applications, cordless telephones, cell phones, TV, and VCR remotes, automobile remote door locks, garage door openers, and so on.

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There is some question about who actually invented radio as a communicative method. Mahlon Loomis, a dentist, experimented with wireless telegraphy using wires supported by kites and a galvanometer to sense the changes in current flow in a second wire when the ground connection of the first was interrupted. He received a patent in 1873 for this system [2].

James Clerk Maxwell [3], more about Maxwell's equations later, predicted the propagation of electromagnetic waves through a vacuum in about 1862. Nathan Stubblefield, a Kentucky farmer and sometimes telephone repairman, demonstrated wireless telephony as early as 1892, but to only one man, and in 1902 to a group [2].

Alexander Popov is said to have "utilized his equipment to obtain information for a study of atmospheric electricity ... On 7 May 1895, in a lecture before the Russian Physicist Society of St. Petersburg, he stated he had transmitted and received signals at an intervening distance of 600 yards" [4]. In 1888 Heinrich Hertz conducted an experimental demonstration in a classroom at Karlsruhe Polytechnic in Berlin of the generation and detection of the propagating electromagnetic waves predicted by Maxwell [2].

Sir Oliver Lodge, a professor at Liverpool University was experimenting with wireless telegraphy in 1888, and he patented a system in 1897. Marconi purchased his patent in 1911 [2].

In the public mind Guglielmo Marconi enjoys the most credit for "inventing" radio. He was awarded patents for it; therefore, the Patent Office believed that he had made radio-related inventions. However, the U.S. Navy report [4] states

> Marconi can scarcely be called an inventor. His contribution was more in the fields of applied research and engineering development. He possessed a very practical business acumen, and he was not hampered by the same driving urge to do fundamental research, which had caused Lodge and Popoff to procrastinate in the development of a commercial radio system.

This is perhaps the most accurate description of Marconi's role in developing radio technology, a new communication medium. Nikola Tesla had earlier patents, although the focus of his work appears to have been directed to the transmission of power rather than to communication via radio waves. Tesla, well known for his *Tesla coil* that generated high voltages, actually detected signals consisting of noise bursts, resulting from the large atmospheric electrical discharges he originated, that had traveled completely around the earth. In 1943 the U.S. Supreme Court ruled that Marconi's patents were invalid due to Tesla's prior descriptions, but by that time both Marconi and Tesla were deceased [2].

From its beginnings around 1900, radio moved out to fill many communicative voids. In 1962 George Southworth, a well-known researcher in the field of microwaves, wrote a book about his 40 years of experience in the field [5, p. 1]. He begins:

One of the more spectacular technical developments of our age has been radio. Beginning about the turn of the century with ship-to-shore telegraphy, radio has been extended through the years to intercontinental telegraphy, to broadcasting, to radio astronomy and to satellite communications.

Today, after an additional 40 years, Southworth could make a much longer list of radio applications. It would include garage door openers, global positioning satellites, cellular telephones, wireless computer networks, and radar applications such as speed measurement, ship and aircraft guidance, military surveillance, weapon directing, air traffic control, and automobile anticollision systems. The frequency spectrum for practical wireless devices has expanded as well. Amplitude modulated radio begins at 535 kHz and television remote controls extend into the infrared.

The advance of wireless applications is not complete and probably never will be. Certainly the last decade has seen an explosive growth in applications. And the quantities of systems has been extraordinary, too. Witness the adoption of the cellular telephone, which today rivals the wired telephone in numbers of applications.

Sending signals over telegraph wires formed the basis for the early wireless technology to follow. Using the Current International Morse code characters for the early Morse code message transmitted over the first telegraph wires, the first message inaugurating service between Baltimore and Washington, D.C., in 1843, would have looked like

.-- .... .- -	.... .- -	--. --- -.. .-- .-. --- ..- --. .... -	..--..
W h a t	*h a t h*	*G o d w r o u g h t*	*?*

Most of the full code cipher is shown in Figure 1.1-1. Morse code remains useful, although fewer individuals can interpret it on the fly. A distress signal using the code in Figure 1.1-1 can be sent using a transmitting radio or even a flashlight. Marconi's early wireless transmissions used pulse code modulation,

A .-	*K* -.-	*U* ..-	*5*	,	*(COMMA)*	--..--
B -...	*L* .-..	*V* ...-	*6* -....	.	*(PERIOD)*	.-.-.-
C -.-.	*M* --	*W* .--	*7* --...	?		..--..
D -..	*N* -.	*X* -..-	*8* ---..	;		-.-.-.
E .	*O* ---	*Y* -.--	*9* ----.	:		---...
F ..-.	*P* .--.	*Z* --..	*0*-----	'	*(APOSTROPHE)*	.----.
G --.	*Q* --.-	*1* .----		-	*(HYPHEN)*	-....-
H	*R* .-.	*2* ..---		/	*(slash)*	-..-.
I ..	*S* ...	*3* ...--		(or)	*PARENTHESIS*	-.--.-
J .---	*T* -	*4* ....-		_____	*UNDERLINE*	..--.-

Figure 1.1-1 International Morse Code remains a standard for distress signals, S.O.S. is (... --- ...) *(English Characters, [1]). Derived from the work of Samuel Morse (1791–1872).*

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