Microwave Engineering and Systems Applications

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Preface

This book had its beginnings when Richard A. Wainwright, Cir-Q-Tel President, asked Washington area microwave engineers to create a course to interest students in microwave engineering and prepare them for positions industry was unable to fill. Five of these microwave engineers, H. Warren Cooper, Albert W. Friend, Robert V. Garver, Roger Kaul, and Edward A. Wolff, responded to the request. These engineers formed the Washington Microwave Education Committee, which designed and developed the microwave course. Financial support to defray course expenses was provided by Bruno Weinschel, President of Weinschel Engineering.

The course was given for several years to seniors at the Capitol Institute of Technology in Laurel, Maryland. It was also given to seniors at the University of Maryland in College Park, Maryland and was given as a continuing education course to practicing engineers on several successive weekends at the University of Maryland Adult Education Center. The students had studied electromagnetic theory, so the emphasis of the course was placed on engineering and the types of problems encountered by practicing engineers. Lengthy proofs were only referenced so that the application of microwave techniques could be emphasized.

Once the course was designed and available textbooks were examined, it appeared to the Committee that it would need its own textbook to give a balanced, systems oriented presentation of modern microwave engineering. The course made extensive use of expert guest lecturers, and the notes used by the course lecturers provide the basis for this book. The course lasted two semesters or three quarters. The students were given extensive opportunity to use the SUPER-COMPACT computer program for the design of their own microwave circuits. This text should provide the basics for a beginning microwave engineer, a reference book to the fundamentals of microwave engineering for practicing engineers, and a text for short-course classes.

This textbook is divided into four parts. Part I (Chapters 2–4) provides the motivation for studying microwaves and describes the three major systems that use microwaves: communications, radar, and electronic warfare. These chapters show the importance of system parameters, such as noise temperature, bandwidth, and circuit losses which the microwave engineer must consider in circuit design.

Part II (Chapters 5–17) provides information on the design of various microwave components used for microwave generation, transmission, control, and detection. The components discussed include transmission lines, transmission line components, filters, ferrites, antennas, diodes, amplifiers, oscillators, vacuum tubes, and monolithic microwave integrated circuits.

Part III (Chapters 18–20) presents the measurement techniques needed to verify the performance of the components fabricated for a microwave subsystem. If a laboratory accompanies this course, Part III can be studied after Chapter 6 and can be taught simultaneously with Part II.

Part IV (Chapters 21 and 22) describes the design procedures for interconnecting microwave components into receiver and transmitter subsystems. These subsystems are the major microwave parts of communications, radar, or electronic warfare systems. The subsystem performance dictates the system performance presented in Part I and depends on the capabilities of the components described in Part II.

The creation of a comprehensive text— including applications and requirements, components, circuits, measurements, and subsystems—within the bounds of a single book has made it necessary to present engineering relations and equations without always including their often lengthy derivations. When derivations are omitted, references are given to sources in the literature.

Numerous periodicals and books provide a source of additional material on microwaves. After World War II and the development of radar, the MIT Radiation Laboratory Series of books became the "Bible" and main source of educational material. Soon to follow was the IEEE (formerly IRE) Transactions on Microwave Theory and Techniques, which began in 1953. (A cumulative index was published in June 1981.) In 1958, Theodore S. Saad began publication of *The Microwave Journal*. This was followed in 1962 by Hayden's regular publication of *Microwaves* (in a square format) and in 1971 by Weber Publications' *Microwave System News*. Add to this the digests from the International Solid State Circuits Conferences, the International Microwave Symposium, the *IEEE Journal of Solid State Circuits*, selected issues of the *IEEE Transactions on Electron Devices*, and *Proceedings of the IEEE*, and you can fill more than 6 meters of bookshelf. In more recent years, there have also been European and Japanese publications that should be included in any comprehensive microwave library. In 1963, A. F. Harvey attempted to condense all of the useful microwave information into one encyclopedic book.* It served as a good starting point for any new research endeavors because the researcher was not forced to scan all the old journals. The *Advances in Microwaves* series, edited by Dr. Leo Young (published from 1966 to 1971), presents in-depth articles on numerous microwave subjects, and the two-volume *Microwave Engineers' Handbook*, edited by Theodore Saad (published in 1971), provides excellent reference material for practicing engineers. *Introduction to Microwave Theory and Measurement*, written by Algie L. Lance in 1964, has been the most popular course text. Because all these books are at least ten years old, they do not include modern developments (such as monolithic integrated circuits) and generally do not emphasize the systems aspects found in this textbook.

We acknowledge the contributions Melvin Zisserson made to many of the chapters. Patricia Campbell meticulously typed the manuscript.

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* A. F. Harvey, *Microwave Engineering*, Academic Press, London, 1963.

Contents

1 Introduction

This book is an introduction to microwave engineering. Microwave engineering is the branch of electrical engineering that deals with the transmission, control, detection, and generation of radio waves whose wavelength is short compared to the physical dimensions of the system. Wavelengths less than 30 cm (corresponding to frequencies in excess of 10^9 Hz), but greater than 0.03 mm (10^{13} Hz) are considered microwaves. Millimeter waves are a subset of microwaves in the 10–0.03 mm range. Microwaves are bounded on the long wavelength side by radio waves and on the short wavelength side by infrared waves. The relationship between wavelength and frequency is

$$f\lambda = c = 3 \times 10^8 \text{ m/s} \tag{1.1}$$

where frequency f is in units of Hertz, wavelength λ is in meters, and c is the speed of light. This relation applies in a vacuum (free space); in a dielectric medium, the wavelength λ is shortened. Unless specified otherwise, the relation between frequency and wavelength assumes a free space condition.

1.1 EARLY HISTORY OF MICROWAVES (1)

The history of microwaves is embodied in the evolution of electromagnetic waves. One of the earliest talks on this subject was Michael Faraday's (1791–1867) impromptu presentation to the Friday Night Lectures of the Royal Society of London in 1846 entitled "Thoughts on Ray Vibrations." [Faraday's talk was given because Charles Wheatstone (1802–1875) was afraid to give his scheduled presentation entitled "Electromagnetic Chronoscope" before this prestigious audience.] Faraday's idea included the propagation of magnetic disturbances by means of transverse vibrations. Later James Clerk Maxwell (1831–1879) credited this idea for helping him determine the electromagnetic theory of light.

Maxwell was primarily a theoretician and began to translate Faraday's experimentally generated ideas into mathematical relations (1864). The resulting four relations express the fundamental laws for the electromagnetic spectrum. These relations along with Newton's laws, the three laws of thermodynamics, the quantum theory, and the theories of relativity form the basis for our current understanding of the physical universe. The Maxwell relations appear to be quite fundamental in that they are not modified by relativity as Newton's relations are when particle velocities approach the speed of light.

Heinrich Rudolf Hertz (1857–1894) confirmed Maxwell's predictions via experiments conducted between 1886 and 1888. Hertz used an oscillating electric spark near 10 cm wavelength to induce similar oscillations in a distant wire loop. Although this was the first microwave-like experiment, the first developments in the microwave region of the spectrum were carried out by Guglielmo Marconi (1874–1937) in the 20th century. Marconi built parabolic antennas to demonstrate wireless telegraphic communications via Hertzian waves up to 550 MHz (5.5×10^8 Hz). Marconi is considered the first "microwave engineer" because of these trendsetting experiments demonstrating the use of ever higher frequencies.

More detailed development of the microwave technology involving waveguides (hollow conductors for propagation of microwave frequencies above cutoff frequencies determined by dimensions and dielectric properties) was done by George C. Southworth in 1930. In preliminary experiments he also observed standing waves (1920) that proved to be functions of the dimensions of the experimental apparatus. In 1933 Southworth and his colleagues at AT&T sent and received telegraph messages over 6 m of enclosed transmission line (waveguide).

The next major advance in microwave technology was the development of a continuous wave source called the klystron in 1937. This microwave vacuum tube was invented at Stanford by Russell and Sigurd Varian and William Hansen. This invention was helped by the financial support from the Sperry Gyroscope Company and its desire to develop an instrument landing system for aircraft during poor weather conditions. Concurrently, companies (AT&T, ITT, Marconi) were supporting microwave developments primarily for use in communications.

Based on these developments before World War II, radio detection and ranging (radar) motivated an immense increase in microwave developments. Most of the microwave devices used today had their early development during WWII in the British and U.S. war laboratories. These developments are well documented in a 28 volume set written by members of the MIT Radiation Laboratory.

1.2 ADVANTAGES OF MICROWAVES

The advantages of microwaves over other regions of the electromagnetic spectrum arise from the short wavelength monochromatic radiation and from the width of the spectrum available for use. The short wavelength monochromatic radiation results in high directivity and resolving power of microwave antennas. At longer wavelengths, much larger physical structures would be required for the same directivity and resolving power. Here resolving power is defined as the ability of the antenna to resolve two objects with different reflectivities. By contrast, the infrared spectrum would be expected to be even more directive and possess higher resolving power, but some infrared sources are not monochromatic (emit only one coherent frequency) and suffer from significant attenuation when propagating through the atmosphere except in certain narrow "windows" or regions of low attenuation. Thus, for some applications microwaves give the best overall system performance, having properties of high directivity and resolving power and low atmospheric attenuation.

The second major advantage of microwaves is the wide frequency spectrum available for communications. For example, the frequency range between a 10 and 1 cm radiator is 27,000 MHz (27 GHz), or more than 50 times the combined frequency bandwidth of the AM radio, FM radio, and television allocations. In addition modern microwave sources and systems are readily modulated (modified to carry information) at large bandwidths so that all modulation formats and high data rates are possible.

1.3 APPLICATIONS OF MICROWAVES

The most important applications of microwaves are in communications and radar. In the communications application, radio relay systems for telephone and television are the largest markets, with Earth–space (satellite) communications growing rapidly. Numerous special communications applications such as point-to-point communications have replaced the use of telephone lines in metropolitan regions where the lines are very expensive to install. Within a few years, direct broadcast satellites will open an immensely competitive microwave market unknown heretofor.

Radar provided the major incentive for the development of microwave technology because only this region of the spectrum could provide the required resolution with antennas of reasonable size. More details of the communication and radar applications will be found in Chapters 2 and 3.

A relatively recent application of microwave technology has been electronic warfare. As the name implies, this is a military application of microwaves involving specialized broadband receivers and high-power jamming transmitters. The receivers are used to monitor the enemy's transmissions passively, primarily for intelligence purposes. The jammer transmitters are used to confuse and deceive the enemy's received signals thus making their systems less effective. More information on this application of microwaves is given in Chapter 4.

The most familiar consumer application of microwaves is the microwave oven. This application uses a minimum of sophisticated microwave circuitry but has revolutionized the technique for heating foods and other products without convectively heating their entire surroundings.

Microwaves have also flourished in basic research and science applications. Atomic clocks use microwave resonance interactions with either ammonia or cesium molecules to provide extremely stable oscillating frequencies. In a similar application, the fine structure of the hydrogen atom known as the Lamb shift was discovered with microwaves at 1420 MHz. This line has been observed in stellar radiation with masers (low-noise microwave amplifiers) by radio astronomers. Finally, microwave spectroscopy is used to study the structure of numerous molecules and crystals.

1.4 OVERVIEW OF MODERN MICROWAVE ENGINEERING

To compose a book of finite length, the material must be tailored to what the reader needs to know and already knows. Too many microwave books start out with Maxwell's equations, immediately immersing the reader in a highly complex and mathematical marathon. Microwaves is more exciting than that. The physical concepts are really the most important aspect of the art and certainly more interesting. The mathematics should follow after as required. We have chosen to begin with the more exciting system applications of microwaves.

Microwave theory and techniques of today permit circuits to be modeled on the computer in great detail. The circuit can be built up "on paper" (really in the computer memory) and exercised to ascertain its performance over wide frequency bands, temperature ranges, and variations in dielectric constants, mechanical dimensions, and components. The computer can account for nuisance problems like irregularities due to discontinuities, propagation velocities that may vary with frequency, and small attenuations that accumulate to have a large effect on overall design. Once the model on the computer is made to perform satisfactorily, a working model can be built up and tested. The computer comes to the rescue again. Now the measurements can be carried out automatically with great precision using a computer-controlled network analyzer. If any difference exists between the experimental model and the computer model, it can be reconciled by experimenting on the computer model. When the troublesome design parameter is isolated, a working model is modified and the modifications are noted for future designs. Before powerful computers and computer programs were available, the design cycle was much slower and more empirical. The mathematical concepts used today did not even exist in the 1950s. It was not possible to combine discrete components and transmission lines in the same formulation. Both types of elements are now easily handled by *ABCD* matrices, and all measurements are made in *S*-parameters (see Chapter 6). Mathematical manipulation of these two types of matrices provides all of the computational power required to solve most of the microwave analysis and design problems today using computers.

The computer has the added convenience that it can store for immediate recall a large collection of tables. Thus, when a large computer program such as SUPER-COMPACT® (see Chapter 7) is used, all of the lookup information is already on file and automatically called up by the program as needed.

What do microwave engineers need to know today in order to carry out their work? There can be no substitute for going back and learning all that the literature has to offer. It is most interesting to go back by seeking out the root of the design being pursued. Frequently the original authors gave a better overview of the design than do those who have built upon their work. This is accomplished by looking up references and references in the references, and so on. But as a beginning point, a book for new microwave engineers must dwell on the types of technology being used in the design of devices now. The microwave state-of-the-art today makes use of semiconductor devices for generating, controlling, amplifying, and detecting microwave signals. The more advanced systems are made using microwave integrated circuits (MIC) (see Chapter 8). The information processing at radio frequency (RF) is done on transmission line structures using a high dielectric substrate (to keep it small) and transverse electromagnetic (TEM) transmission lines (see Chapter 5), typically microstrip. The trend is toward higher frequencies (10 GHz and higher) in order to make the circuits their smallest (shorter wavelengths). The present art of MIC uses an alumina substrate, and the components are mounted on it as chips. Future art will make use of monolithic structures (see Chapter 16) in which the transmission lines and components are all made on gallium arsenide substrate much as other integrated circuits are made. In order to accomplish designs of this type, the computer models must be highly refined so that few remakes are required. Monolithic MIC must grow out of conventional MIC. Thus, learning the art of conventional MIC is a good first step in preparation for carrying out future microwave work.

1.5 MICROWAVE UNITS

Microwave engineering progressed rapidly during World War II. Because the early documentation used a mixture of English, CGS, and MKS units, this convention has continued into today's literature and practice. For example, the inside dimensions of a common-sized waveguide are 0.4 by 0.9 in., whereas two common 50-ohm coaxial air lines measure 3.5 and 7 mm for the inside dimension of the outer conductor. This book will use the International System (SI) of units and parenthetically reference the common usage units where appropriate.

REFERENCES

1. T. S. Saad, National Lecturer's Talk, IEEE Microwave Theory and Techniques Society, 1972.