MICROWAVES

An introduction to microwave theory and techniques

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PERGAMON PRESS
OXFORD · NEW YORK · TORONTO · SYDNEY · PARIS · FRANKFURT

U.K.	Pergamon Press Ltd., Headington Hill Hall, Oxford OX3 0BW, England
U.S.A.	Pergamon Press Inc., Maxwell House, Fairview Park, Elmsford, New York 10523, U.S.A.
CANADA	Pergamon of Canada, Suite 104, 150 Consumers Road, Willowdale, Ontario M2J 1P9, Canada
AUSTRALIA	Pergamon Press (Aust.) Pty. Ltd., P.O. Box 544, Potts Point, N.S.W. 2011, Australia
FRANCE	Pergamon Press SARL, 24 rue des Ecoles, 75240 Paris, Cedex 05, France
FEDERAL REPUBLIC OF GERMANY	Pergamon Press GmbH, 6242 Kronberg-Taunus, Pferdstrasse 1, Federal Republic of Germany

First edition 1969

Reprinted 1978

Second edition 1979

British Library Cataloguing in Publication Data

Baden Fuller, Arthur John
Microwaves,—2nd ed.—(Applied electricity and electronics).—(Pergamon international library).
1. Microwave devices
I. Title II. Series
621.381'3 TK7876 79-40450

ISBN 0-08-024228-6 (Hard cover)
ISBN 0-08-024227-8 (Flexi cover)

Printed and bound in Great Britain by
William Clowes (Beccles) Limited, Beccles and London

PREFACE TO THE SECOND EDITION

EVEN though microwaves has become a mature part of the electronics industry, many changes have occurred in the ten years since I wrote the first edition of this book. The most fundamental change has been the widespread use of semiconductor oscillators and amplifiers to replace electron tube devices and the associated use of stripline or microstrip circuits instead of waveguide in low-power applications. As a consequence, the part of the chapter on Oscillators and Amplifiers dealing with semiconductor devices has been largely rewritten and a completely new Chapter 12 on stripline devices has been added. Consequently the chapter on Measurements has been renumbered as Chapter 13 and the descriptive part of the book now consists of Chapters 9 to 13. The theory of waveguide propagation does not change but some other improvements have been made to the text. The most important are an altered approach to the derivation of the wave impedance in waveguide and the derivation of the formulae for the attenuation in rectangular and circular waveguide which it is hoped will be found to be helpful. All the circuit diagrams have been redrawn to the latest international standards given by IEC 117 and BS 3939. However, the main aims and structure of the book as outlined in the original preface remain unchanged.

PREFACE TO THE FIRST EDITION

TWENTY years ago the science of microwave propagation was just emerging from the secrecy of war-time research and use in radar systems. Twenty years has seen the growth of a sizeable microwave industry. Today the general use of radar systems for navigation, together with the extension of radio communication links and satellite communications into the microwave frequency range, has meant a wider need for engineers and physicists with a knowledge of those aspects of electromagnetic theory that are applicable at microwave frequencies. Most electrical engineering degree courses include the study of microwave theory. This book seeks to provide an introduction to this subject, suitable for use as a textbook by undergraduate or senior technical college students. The contents fall into two main parts.

Initially, there is an introduction followed by one chapter on general transmission line equations. The first main part, Chapters 2 to 8, consists of a theoretical development of electromagnetic propagation of guided waves starting from Maxwell's equations and the material properties. Attention has been focused on those properties of wave propagation which are dependent on microwave scale: i.e. the wavelength is of the same order as the dimensions of the body handling the electromagnetic wave. No attempt has been made to discuss those topics where the scale of operation is such that the principles of optics are applicable or conversely using microcircuits, high-frequency circuit techniques are applicable. The treatment has been confined to those topics where the application of field theory is appropriate.

The second main part, Chapters 9 to 12, consists of a descriptive treatment of microwave components and measurements. A student, faced with tne need to operate microwave equipment in advance of learning the theory, may well dip into these final chapters before studying the earlier part of the book, and he will find that they are largely self-supporting. Alternatively, for the student following a course in microwave theory, these final chapters provide a useful background to the theory.

The book assumes a knowledge of vector analysis and differential equations. Where appropriate, i.e. vector analysis and Bessel functions, the mathematical terms are defined and all the necessary properties are quoted but not derived. Each chapter concludes with a summary and problems are given at the end of the first eight chapters. No worked examples are given in the main text of the book because electromagnetic theory does not lend itself to such treatment, but some worked solutions to selected problems are given at the end.

It is difficult to thank all the many people from whom I have learned and I hope that lack of acknowledgement will not be taken to imply lack of gratitude. I should like to thank Professor P. Hammond for his encouragement which inspired me to write this book and to Dr. A. G. Bailey for reading the manuscript and making helpful suggestions. My thanks are due to Professor G. D. S. MacLellan, Head of the Engineering Department at the University of Leicester, for making the facilities of the department available to me in the preparation of the manuscript.

CONTENTS

INTRODUCTION

MICROWAVES is the name given to the electromagnetic waves arising as radiation from electrical disturbances at high frequencies. At low frequencies, the radiation aspects of electromagnetic power distribution are negligible and it is only necessary to consider electric charges, stored or flowing as currents, and potential difference. As the frequency of operation increases, however, radiation becomes of more importance. The relative importance of radiation depends on the size of the circuit or system under consideration. Any system of electric charges gives rise to electric and magnetic fields in the surrounding space. At low frequencies with circuit theory, the effects of these fields are generally ignored. At higher frequencies, however, the effect of these fields becomes more pronounced. This is seen initially by the introduction of "stray" capacitance into circuit theory. At high frequencies, even a short length of wire acts as a radiation element, dissipating its electrical signals into surrounding space. The electromagnetic fields become the dominant factor in a study of electrical theory at high frequencies.

As will be shown, the characteristic wavelength of electromagnetic radiation is related to the frequency of the electrical signals by $\lambda = c/f$, where f is the frequency and c is the speed of light. It is only necessary to consider the radiation contribution to the understanding of an electrical system if the dimensions of the system are of the same order or larger than the characteristic wavelength of the electrical signals handled by the system. This means that for medium wave radio broadcasting with a wavelength of a few hundred metres, where the electrical signal goes from the transmitter to the receiver in the form of electromagnetic radiation, the radio receiver can be designed entirely by consideration of electrical currents flowing in wires and ignoring any electromagnetic radiation which is generated by the circuits.

Microwave techniques may be considered to cover those applications of electrical technology where the characteristic wavelength is smaller than the dimensions of the system or circuit and yet where it is not so small that only ray optical techniques need be considered. Microwaves are normally considered to embrace the frequency range 10^9 to 10^{12} Hz or a characteristic wavelength range of 30 cm to 0·3 mm. At these wavelengths, the components of conventional electronic circuits tend to behave like individual antenna, dissipating their electrical signals as radiation. New techniques are necessary to handle electrical signals in the microwave frequency range, leading to new techniques of analysis. Although the microwave frequency range given above is accepted by common usage as the region where these specialized techniques are used most frequently, the relationship of size to characteristic wavelength is the true guideline determining when microwave techniques or analysis are applicable to any particular system. For example, the power system designer has a radiation problem with a.c. transmission lines a few thousand miles long: conversely, microcircuits can be designed using conventional circuit techniques to operate at microwave frequencies.

The study of electromagnetic radiation is an exact science because it can be represented exactly by mathematical expressions. The ease with which the mathematical analysis can be performed depends on the complexity of the electromagnetic fields which in turn is determined by the shape of the constraining boundary. The elementary mathematical theory contained in this book is confined to a study of the fields due to simple boundary shapes. Although these simple shapes may not always arise in practice, many practical situations approximate to simple shapes and the simple theory gives good results for many applications.

The elementary mathematical theory is given in Chapters 1 to 8. The behaviour of electromagnetic radiation under various conditions is determined by mathematical analysis. To complement the theory of the first eight chapters, Chapters 9 to 13 contain a brief non-mathematical outline of practical microwaves. They contain a descriptive explanation of microwave components and measurements.

The frequency bands in the microwave region have been given letter codes. The band designations for both radio and microwave frequencies are given in the table.

STANDARD FREQUENCY BAND DESIGNATIONS

Band	Frequency GHz	Characteristic wavelength
h.f.	0·003–0·03	10–100 m
v.h.f.	0·03–0·3	1–10 m
u.h.f.	0·3–1	0·3–1 m
L	1–2	150–300 mm
S	2–4	75–150 mm
C	4–8	37·5–75 mm
X	8–12	25–37·5 mm
Ku	12–18	17·5–25 mm
K	18–27	11–17·5 mm
Ka	27–40	7·5–11 mm
Millimeter	40–300	1–7·5 mm

Microwaves possess certain useful characteristics, one of the most important being that microwave wavelengths are the same size as any structure used to guide or enclose them. Microwave pulses can be very short so that they can be used for distance or time measurement and which also makes them compatible with high speed computers. The high frequency of microwaves means that very large bandwidths are available for communication links. Microwave radiation penetrates fog and clouds, travels in straight lines and gives distinct shadows and reflections enabling it to be used for distance and direction measurement and in radar systems. Microwaves are necessary for communication with satellites because they can pass through the ionosphere which reflects lower frequency radio waves. Microwave power is absorbed by water or any material containing water so that microwaves can be used for heating and drying. Many atomic and molecular resonances occur at microwave frequencies so that they are a necessary part of some scientific measurements. Certain resonances can be used to make stable atomic clocks. All these properties mean that microwaves are becoming more and more widely used. Some applications are given in the following paragraphs.

Broadcasting. At the moment radio broadcasting and television use frequencies below the microwave range. However, increasing congestion of the radio spectrum is making reception difficult for some listeners. There are no frequencies available for any large increase in broadcasting at radio frequencies, so that any further increase must occur at higher frequencies, which will be in the microwave region. A number of countries are investigating the use of 12 GHz either for local television stations or for satellite television broadcasting. The domestic consumer will have a microwave receiver on the roof as part of a small aerial and a radio frequency signal will be transmitted along the aerial cable to the television set.

Communication. Increased bandwidth for communication channels requires higher carrier frequencies. Line of sight radio relay systems have been operating for a number of years. The microwave system consists of tower mounted directional aerials which receive signals, amplify them and transmit them on to the next tower in the chain. Post Office towers have enabled such microwave relay systems to enter into the centre of many big cities. In many developed countries, all the frequencies available for such links have been fully utilized. However, such a system is ideal for underdeveloped areas or difficult terrain since the relay towers and equipment can be positioned by helicopter and powered by small generators or batteries. Laying landline communications is difficult across mountainous or similarly inhospitable country and it is simpler to set up a microwave relay system. Where the microwave relay frequencies are already fully occupied, microwaves enclosed in metal waveguide pipe can be used for long distance communication. The circular waveguide operates at about 80 GHz and gives an enormous available channel capacity to replace a very large number of underground cables. Because the ionosphere is opaque to lower frequencies, microwave frequencies have to be used for satellite communications and for communications with satellites. The microwave communication channel has a very large bandwidth and will accommodate thousands of telephone conversations or dozens of television channels at once.

Radar is the traditional use of microwaves. It started at about the beginning of the second world war. The name is derived from the initial letters of RAdio Detection And Ranging. The simplest form of radar is the pulse radar giving a plan position indication (p.p.i.); it measures the time for an echo to return, operates by echo sounding with a narrow beam like a searchlight, and is used for navigation. The CW (carrier wave) or doppler radar gives a velocity indication; it is used in military applications because it is more difficult for an enemy to jam. The doppler radar also has many industrial and consumer uses; it is used in industrial controls for flow or velocity measurement. It can also be used for motion detection. As an intruder alarm, it is difficult to eliminate false alarms, such as those from a cat or from curtains moving in a breeze, but it is very suitable for other applications such as controlling a door opener. It is already in use for the police speed radar and it is hoped to develop it into an anticollision device for vehicles. A form of radar can be used to detect hidden objects; it is much more sophisticated in application than the simple metal detector since it can locate non-metallic objects such as water pipes. Microwave radiometry, which uses microwave radiation in the same way that photography uses light, can give useful information about the object being observed such as the moisture content of soils and vegetation.

Microwave heating. The rate of microwave power absorption in most materials is proportional to its water content. This property can be used to provide microwave heating. Because the microwave signal penetrates most non-conductors, microwave power provides a most efficient means of applying heat uniformly throughout a body. Because the heat does not have to be conducted through but is generated inside the body, microwave heating reduces the time needed for heating a body to a uniform temperature. The rate of heating usually depends on the water content. Microwave ovens are in use in many homes and catering establishments and microwave heating is used in many process industries for heating, drying, curing or sterilizing.

Moisture measurement. Microwave absorption by water also means that moisture content measurement by microwaves is possible. The attenuation of a microwave signal in passing through the specimen is measured.

Microwave power transmission has been advocated for electric power distribution since it can be used directly for heating and for exciting fluorescent lights. The possibility is being actively investigated of satellite power generation with microwave transmission to earth.

The satellite is powered with solar cells and the microwave power generating valves will operate in high vacuum without any glass envelope. The microwave power will be beamed to earth where it will be collected and rectified. The system will be expensive in capital cost but uses a free non-expendable energy supply.

Computers. As computers work at faster rates, high frequency circuits are required so as not to degrade the pulse shape. Application of transmission-line and microwave techniques in the design of computer modules will become necessary.

Clocks. Microwave clocks measure the frequency of some particular atomic transitions and have an accuracy of about one second in a million years. The second is defined as: the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom. This corresponds to a frequency of 9192·63177 MHz—right in the middle of the microwave range.

Biological hazards. Microwaves are potentially hazardous because of their heating effect. The effect may not be felt until damage has already been done because the heating may be internal whereas our body is designed to warn us about externally applied heat. Such heating is especially dangerous where the excess heat is not dissipated easily as in the case of the cornea of the eye, and there the most likely effect of excessive microwave exposure is the formation of cataracts. From heat balance considerations of standard man in standard conditions, 100 W/m^2 (10 mW/cm^2) is considered to be the safe upper limit even during infinite exposure because thermoregulatory systems compensate for any power absorption. A power level of 10 W/m^2 can be considered to give no heating effect even under adverse conditions of ambient temperature and humidity. However there is also some evidence of a non-thermal effect through the nervous system, although the effect is harder to prove and controversy still surrounds it. It is claimed that exposure over a period of years to power levels greater than 2 W/m^2 can lead to nervous system disturbances, although occupational exposure of healthy adults to this power level seems to have no adverse effects. However the probable safe level for continuous exposure of the general population ought to be even lower. In the U.S.A. and many western countries, the only recommended limit is