

The background of the cover is a close-up photograph of a blue microcircuit board. It features numerous circular vias and intricate copper traces. The lighting is dramatic, with some areas appearing in deep shadow while others are highlighted with a bright, almost neon blue glow, creating a sense of depth and technological complexity.

L. F. Chen | C. K. Ong | C. P. Neo | V. V. Varadan | V. K. Varadan

microwave electronics

measurement and materials characterisation

 WILEY

Microwave Electronics

Measurement and Materials Characterization

L. F. Chen, C. K. Ong and C. P. Neo
National University of Singapore

V. V. Varadan and V. K. Varadan
Pennsylvania State University, USA



John Wiley & Sons, Ltd

Microwave Electronics

Microwave Electronics

Measurement and Materials Characterization

L. F. Chen, C. K. Ong and C. P. Neo
National University of Singapore

V. V. Varadan and V. K. Varadan
Pennsylvania State University, USA



John Wiley & Sons, Ltd

Copyright © 2004

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester,
West Sussex PO19 8SQ, England

Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk
Visit our Home Page on www.wileyeurope.com or www.wiley.com

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except under the terms of the Copyright, Designs and Patents Act 1988 or under the terms of a licence issued by the Copyright Licensing Agency Ltd, 90 Tottenham Court Road, London W1T 4LP, UK, without the permission in writing of the Publisher. Requests to the Publisher should be addressed to the Permissions Department, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England, or emailed to permreq@wiley.co.uk, or faxed to (+44) 1243 770620.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the Publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Other Wiley Editorial Offices

John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 33 Park Road, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 22 Worcester Road, Etobicoke, Ontario, Canada M9W 1L1

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 0-470-84492-2

Typeset in 10/12pt Times by Laserwords Private Limited, Chennai, India
Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire
This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

Contents

<i>Preface</i>		xi
1	Electromagnetic Properties of Materials	1
1.1	Materials Research and Engineering at Microwave Frequencies	1
1.2	Physics for Electromagnetic Materials	2
1.2.1	Microscopic scale	2
1.2.2	Macroscopic scale	6
1.3	General Properties of Electromagnetic Materials	11
1.3.1	Dielectric materials	11
1.3.2	Semiconductors	16
1.3.3	Conductors	17
1.3.4	Magnetic materials	19
1.3.5	Metamaterials	24
1.3.6	Other descriptions of electromagnetic materials	28
1.4	Intrinsic Properties and Extrinsic Performances of Materials	32
1.4.1	Intrinsic properties	32
1.4.2	Extrinsic performances	32
	References	34
2	Microwave Theory and Techniques for Materials Characterization	37
2.1	Overview of the Microwave Methods for the Characterization of Electromagnetic Materials	37
2.1.1	Nonresonant methods	38
2.1.2	Resonant methods	40
2.2	Microwave Propagation	42
2.2.1	Transmission-line theory	42
2.2.2	Transmission Smith charts	51
2.2.3	Guided transmission lines	56
2.2.4	Surface-wave transmission lines	73
2.2.5	Free space	83
2.3	Microwave Resonance	87
2.3.1	Introduction	87
2.3.2	Coaxial resonators	93
2.3.3	Planar-circuit resonators	95
2.3.4	Waveguide resonators	97
2.3.5	Dielectric resonators	103
2.3.6	Open resonators	115
2.4	Microwave Network	119
2.4.1	Concept of microwave network	119
2.4.2	Impedance matrix and admittance matrix	119

2.4.3	Scattering parameters	120
2.4.4	Conversions between different network parameters	121
2.4.5	Basics of network analyzer	121
2.4.6	Measurement of reflection and transmission properties	126
2.4.7	Measurement of resonant properties	134
	References	139
3	Reflection Methods	142
3.1	Introduction	142
3.1.1	Open-circuited reflection	142
3.1.2	Short-circuited reflection	143
3.2	Coaxial-line Reflection Method	144
3.2.1	Open-ended apertures	145
3.2.2	Coaxial probes terminated into layered materials	151
3.2.3	Coaxial-line-excited monopole probes	154
3.2.4	Coaxial lines open into circular waveguides	157
3.2.5	Shielded coaxial lines	158
3.2.6	Dielectric-filled cavity adapted to the end of a coaxial line	160
3.3	Free-space Reflection Method	161
3.3.1	Requirements for free-space measurements	161
3.3.2	Short-circuited reflection method	162
3.3.3	Movable metal-backing method	162
3.3.4	Bistatic reflection method	164
3.4	Measurement of Both Permittivity and Permeability Using Reflection Methods	164
3.4.1	Two-thickness method	164
3.4.2	Different-position method	165
3.4.3	Combination method	166
3.4.4	Different backing method	167
3.4.5	Frequency-variation method	167
3.4.6	Time-domain method	168
3.5	Surface Impedance Measurement	168
3.6	Near-field Scanning Probe	170
	References	172
4	Transmission/Reflection Methods	175
4.1	Theory for Transmission/reflection Methods	175
4.1.1	Working principle for transmission/reflection methods	175
4.1.2	Nicolson–Ross–Weir (NRW) algorithm	177
4.1.3	Precision model for permittivity determination	178
4.1.4	Effective parameter method	179
4.1.5	Nonlinear least-squares solution	180
4.2	Coaxial Air-line Method	182
4.2.1	Coaxial air lines with different diameters	182
4.2.2	Measurement uncertainties	183
4.2.3	Enlarged coaxial line	185
4.3	Hollow Metallic Waveguide Method	187
4.3.1	Waveguides with different working bands	187
4.3.2	Uncertainty analysis	187
4.3.3	Cylindrical rod in rectangular waveguide	189
4.4	Surface Waveguide Method	190

4.4.1	Circular dielectric waveguide	190
4.4.2	Rectangular dielectric waveguide	192
4.5	Free-space Method	195
4.5.1	Calculation algorithm	195
4.5.2	Free-space TRL calibration	197
4.5.3	Uncertainty analysis	198
4.5.4	High-temperature measurement	199
4.6	Modifications on Transmission/reflection Methods	200
4.6.1	Coaxial discontinuity	200
4.6.2	Cylindrical cavity between transmission lines	200
4.6.3	Dual-probe method	201
4.6.4	Dual-line probe method	201
4.6.5	Antenna probe method	202
4.7	Transmission/reflection Methods for Complex Conductivity Measurement	203
	References	205
5	Resonator Methods	208
5.1	Introduction	208
5.2	Dielectric Resonator Methods	208
5.2.1	Courtney resonators	209
5.2.2	Cohn resonators	214
5.2.3	Circular-radial resonators	216
5.2.4	Sheet resonators	219
5.2.5	Dielectric resonators in closed metal shields	222
5.3	Coaxial Surface-wave Resonator Methods	227
5.3.1	Coaxial surface-wave resonators	228
5.3.2	Open coaxial surface-wave resonator	228
5.3.3	Closed coaxial surface-wave resonator	229
5.4	Split-resonator Method	231
5.4.1	Split-cylinder-cavity method	231
5.4.2	Split-coaxial-resonator method	233
5.4.3	Split-dielectric-resonator method	236
5.4.4	Open resonator method	238
5.5	Dielectric Resonator Methods for Surface-impedance Measurement	242
5.5.1	Measurement of surface resistance	242
5.5.2	Measurement of surface impedance	243
	References	247
6	Resonant-perturbation Methods	250
6.1	Resonant Perturbation	250
6.1.1	Basic theory	250
6.1.2	Cavity-shape perturbation	252
6.1.3	Material perturbation	253
6.1.4	Wall-impedance perturbation	255
6.2	Cavity-perturbation Method	256
6.2.1	Measurement of permittivity and permeability	256
6.2.2	Resonant properties of sample-loaded cavities	258
6.2.3	Modification of cavity-perturbation method	261
6.2.4	Extracavity-perturbation method	265
6.3	Dielectric Resonator Perturbation Method	267
6.4	Measurement of Surface Impedance	268

6.4.1	Surface resistance and surface reactance	268
6.4.2	Measurement of surface resistance	269
6.4.3	Measurement of surface reactance	275
6.5	Near-field Microwave Microscope	278
6.5.1	Basic working principle	278
6.5.2	Tip-coaxial resonator	279
6.5.3	Open-ended coaxial resonator	280
6.5.4	Metallic waveguide cavity	284
6.5.5	Dielectric resonator	284
	References	286
7	Planar-circuit Methods	288
7.1	Introduction	288
7.1.1	Nonresonant methods	288
7.1.2	Resonant methods	290
7.2	Stripline Methods	291
7.2.1	Nonresonant methods	291
7.2.2	Resonant methods	292
7.3	Microstrip Methods	297
7.3.1	Nonresonant methods	298
7.3.2	Resonant methods	300
7.4	Coplanar-line Methods	309
7.4.1	Nonresonant methods	309
7.4.2	Resonant methods	311
7.5	Permeance Meters for Magnetic Thin Films	311
7.5.1	Working principle	312
7.5.2	Two-coil method	312
7.5.3	Single-coil method	314
7.5.4	Electrical impedance method	315
7.6	Planar Near-field Microwave Microscopes	317
7.6.1	Working principle	317
7.6.2	Electric and magnetic dipole probes	318
7.6.3	Probes made from different types of planar transmission lines	319
	References	320
8	Measurement of Permittivity and Permeability Tensors	323
8.1	Introduction	323
8.1.1	Anisotropic dielectric materials	323
8.1.2	Anisotropic magnetic materials	325
8.2	Measurement of Permittivity Tensors	326
8.2.1	Nonresonant methods	327
8.2.2	Resonator methods	333
8.2.3	Resonant-perturbation method	336
8.3	Measurement of Permeability Tensors	340
8.3.1	Nonresonant methods	340
8.3.2	Faraday rotation methods	345
8.3.3	Resonator methods	351
8.3.4	Resonant-perturbation methods	355
8.4	Measurement of Ferromagnetic Resonance	370
8.4.1	Origin of ferromagnetic resonance	370
8.4.2	Measurement principle	371

8.4.3	Cavity methods	373
8.4.4	Waveguide methods	374
8.4.5	Planar-circuit methods	376
	References	379
9	Measurement of Ferroelectric Materials	382
9.1	Introduction	382
9.1.1	Perovskite structure	383
9.1.2	Hysteresis curve	383
9.1.3	Temperature dependence	383
9.1.4	Electric field dependence	385
9.2	Nonresonant Methods	385
9.2.1	Reflection methods	385
9.2.2	Transmission/reflection method	386
9.3	Resonant Methods	386
9.3.1	Dielectric resonator method	386
9.3.2	Cavity-perturbation method	389
9.3.3	Near-field microwave microscope method	390
9.4	Planar-circuit Methods	390
9.4.1	Coplanar waveguide method	390
9.4.2	Coplanar resonator method	394
9.4.3	Capacitor method	394
9.4.4	Influence of biasing schemes	404
9.5	Responding Time of Ferroelectric Thin Films	405
9.6	Nonlinear Behavior and Power-Handling Capability of Ferroelectric Films	407
9.6.1	Pulsed signal method	407
9.6.2	Intermodulation method	409
	References	412
10	Microwave Measurement of Chiral Materials	414
10.1	Introduction	414
10.2	Free-space Method	415
10.2.1	Sample preparation	416
10.2.2	Experimental procedure	416
10.2.3	Calibration	417
10.2.4	Time-domain measurement	430
10.2.5	Computation of ϵ , μ , and β of the chiral composite samples	434
10.2.6	Experimental results for chiral composites	440
10.3	Waveguide Method	452
10.3.1	Sample preparation	452
10.3.2	Experimental procedure	452
10.3.3	Computation of ϵ , μ , and ξ of the chiral composite samples	453
10.3.4	Experimental results for chiral composites	454
10.4	Concluding Remarks	458
	References	458
11	Measurement of Microwave Electrical Transport Properties	460
11.1	Hall Effect and Electrical Transport Properties of Materials	460
11.1.1	Direct current Hall effect	461
11.1.2	Alternate current Hall effect	461
11.1.3	Microwave Hall effect	461

11.2	Nonresonant Methods for the Measurement of Microwave Hall Effect	464
11.2.1	Faraday rotation	464
11.2.2	Transmission method	465
11.2.3	Reflection method	469
11.2.4	Turnstile-junction method	473
11.3	Resonant Methods for the Measurement of the Microwave Hall Effect	475
11.3.1	Coupling between two orthogonal resonant modes	475
11.3.2	Hall effect of materials in MHE cavity	476
11.3.3	Hall effect of endplate of MHE cavity	482
11.3.4	Dielectric MHE resonator	484
11.3.5	Planar MHE resonator	486
11.4	Microwave Electrical Transport Properties of Magnetic Materials	486
11.4.1	Ordinary and extraordinary Hall effect	486
11.4.2	Bimodal cavity method	487
11.4.3	Bimodal dielectric probe method	489
	References	489
12	Measurement of Dielectric Properties of Materials at High Temperatures	492
12.1	Introduction	492
12.1.1	Dielectric properties of materials at high temperatures	492
12.1.2	Problems in measurements at high temperatures	494
12.1.3	Overviews of the methods for measurements at high temperatures	496
12.2	Coaxial-line Methods	497
12.2.1	Measurement of permittivity using open-ended coaxial probe	498
12.2.2	Problems related to high-temperature measurements	498
12.2.3	Correction of phase shift	500
12.2.4	Spring-loaded coaxial probe	502
12.2.5	Metallized ceramic coaxial probe	502
12.3	Waveguide Methods	503
12.3.1	Open-ended waveguide method	503
12.3.2	Dual-waveguide method	504
12.4	Free-space Methods	506
12.4.1	Computation of ϵ_r^*	507
12.5	Cavity-Perturbation Methods	510
12.5.1	Cavity-perturbation methods for high-temperature measurements	510
12.5.2	TE _{10n} mode rectangular cavity	512
12.5.3	TM mode cylindrical cavity	514
12.6	Dielectric-loaded Cavity Method	520
12.6.1	Coaxial reentrant cavity	520
12.6.2	Open-resonator method	523
12.6.3	Oscillation method	524
	References	528
	<i>Index</i>	531

Preface

Microwave materials have been widely used in a variety of applications ranging from communication devices to military satellite services, and the study of materials properties at microwave frequencies and the development of functional microwave materials have always been among the most active areas in solid-state physics, materials science, and electrical and electronic engineering. In recent years, the increasing requirements for the development of high-speed, high-frequency circuits and systems require complete understanding of the properties of materials functioning at microwave frequencies. All these aspects make the characterization of materials properties an important field in microwave electronics.

Characterization of materials properties at microwave frequencies has a long history, dating from the early 1950s. In past decades, dramatic advances have been made in this field, and a great deal of new measurement methods and techniques have been developed and applied. There is a clear need to have a practical reference text to assist practicing professionals in research and industry. However, we realize the lack of good reference books dealing with this field. Though some chapters, reviews, and books have been published in the past, these materials usually deal with only one or several topics in this field, and a book containing a comprehensive coverage of up-to-date measurement methodologies is not available. Therefore, most of the research and development activities in this field are based primarily on the information scattered throughout numerous reports and journals, and it always takes a great deal of time and effort to collect the information related to on-going projects from the voluminous literature. Furthermore, because of the paucity of comprehensive textbooks, the training in this field is usually not systematic, and this is undesirable for further progress and development in this field.

This book deals with the microwave methods applied to materials property characterization, and it provides an in-depth coverage of both established and emerging techniques in materials characterization. It also represents the most comprehensive treatment of microwave methods for materials property characterization that has appeared in book form to date. Although this book is expected to be most useful to those engineers actively engaged in designing materials property–characterization methods, it should also be of considerable value to engineers in other disciplines, such as industrial engineers, bioengineers, and materials scientists, who wish to understand the capabilities and limitations of microwave measurement methods that they use. Meanwhile, this book also satisfies the requirement for up-to-date texts at graduate and senior undergraduate levels on the subjects in materials characterization.

Among this book's most outstanding features is its comprehensive coverage. This book discusses almost all aspects of the microwave theory and techniques for the characterization of the electromagnetic properties of materials at microwave frequencies. In this book, the materials under characterization may be dielectrics, semiconductors, conductors, magnetic materials, and artificial materials; the electromagnetic properties to be characterized mainly include permittivity, permeability, chirality, mobility, and surface impedance.

The two introductory chapters, Chapter 1 and Chapter 2, are intended to acquaint the readers with the basis for the research and engineering of electromagnetic materials from the materials and microwave fundamentals respectively. As general knowledge of electromagnetic properties of materials is helpful for understanding measurement results and correcting possible errors, Chapter 1 introduces the general

properties of various electromagnetic materials and their underlying physics. After making a brief review on the methods for materials properties characterization, Chapter 2 provides a summary of the basic microwave theory and techniques, based on which the methods for materials characterization are developed. This summary is mainly intended for reference rather than for tutorial purposes, although some of the important aspects of microwave theory are treated at a greater length. References are cited to permit readers to further study the topics they are interested in.

Chapters 3 to 8 deal with the measurements of the permittivity and permeability of low-conductivity materials and the surface impedance of high-conductivity materials. Two types of nonresonant methods, reflection method and transmission/reflection method, are discussed in Chapters 3 and 4 respectively; two types of resonant methods, resonator method and resonant-perturbation method, are discussed in Chapters 5 and 6 respectively. In the methods discussed in Chapters 3 to 6, the transmission lines used are mainly coaxial-line, waveguide, and free-space, while Chapter 7 is concerned with the measurement methods developed from planar transmission lines, including stripline, microstrip-, and coplanar line. The methods discussed in Chapters 3 to 7 are suitable for isotropic materials, which have scalar or complex permittivity and permeability. The permittivity of anisotropic dielectric materials is a tensor parameter, and magnetic materials usually have tensor permeability under an external dc magnetic field. Chapter 8 deals with the measurement of permittivity and permeability tensors.

Ferroelectric materials are a special category of dielectric materials often used in microwave electronics for developing electrically tunable devices. Chapter 9 discusses the characterization of ferroelectric materials, and the topics covered include the techniques for studying the temperature dependence and electric field dependence of dielectric properties.

In recent years, the research on artificial materials has been active. Chapter 10 deals with a special type of artificial materials: chiral materials. After introducing the concept and basic characteristics of chiral materials, the methods for chirality measurements and the possible applications of chiral materials are discussed.

The electrical transport properties at microwave frequencies are important for the development of high-speed electronic circuits. Chapter 11 discusses the microwave Hall effect techniques for the measurement of the electrical transport properties of low-conductivity, high-conductivity, and magnetic materials.

The measurement of materials properties at high temperatures is often required in industry, scientific research, and biological and medical applications. In principle, most of the methods discussed in this book can be extended to high-temperature measurements. Chapter 12 concentrates on the measurement of the dielectric properties of materials at high temperatures, and the techniques for solving the problems in high-temperature measurements can also be applied for the measurement of other materials property parameters at high temperatures.

In this book, each chapter is written as a self-contained unit, so that readers can quickly get comprehensive information related to their research interests or on-going projects. To provide a broad treatment of various topics, we condensed mountains of literature into readable accounts within a text of reasonable size. Many references have been included for the benefit of the readers who wish to pursue a given topic in greater depth or refer to the original papers.

It is clear that the principle of a method for materials characterization is more important than the techniques required for implementing this method. If we understand the fundamental principle underlying a measurement method, we can always find a suitable way to realize this method. Although the advances in technology may significantly change the techniques for implementing a measurement method, they cannot greatly influence the measurement principle. In writing this book, we tried to present the fundamental principles behind various designs so that readers can understand the process of applying fundamental concepts to arrive at actual designs using different techniques and approaches. We believe that an engineer with a sound knowledge of the basic concepts and fundamental principles for materials property characterization and the ability apply to his knowledge toward design objectives, is

the engineer who is most likely to make full use of the existing methods, and develop original methods to fulfill ever-rising measurement requirements.

We would like to indicate that this text is a compilation of the work of many people. We cannot be held responsible for the designs described that are still under patent. It is also difficult to always give proper credits to those who are the originators of new concepts and the inventors of new methods. The names we give to some measurement methods may not fit the intentions of the inventors or may not accurately reflect the most characteristic features of these methods. We hope that there are not too many such errors and will appreciate it if the readers could bring the errors they discover to our attention.

There are many people to whom we owe many thanks for helping us prepare this book. However, space dictates that only a few of them can receive formal acknowledgements. But this should not be taken as a disparagement of those whose contributions remain anonymous. Our foremost appreciation goes to Mr. Quek Gim Pew, Deputy Chief Executive (Technology), Singapore Defence Science & Technology Agency, Mr. Quek Tong Boon, Chief Executive Officer, Singapore DSO National Laboratories, and Professor Lim Hock, Director, Temasek Laboratories, National University of Singapore, for their encouragement and support along the way. We are grateful to Pennsylvania State University and HVS Technologies for giving us permission to include the HVS Free Space Unit and the data in this book. We really appreciate the valuable help and cooperation from Dr. Li Zheng-Wen, Dr. Rao Xuesong, and Mr. Tan Chin Yaw. We are very grateful to the staff of John Wiley & Sons for their helpful efforts and cheerful professionalism during this project.

L. F. Chen
C. K. Ong
C. P. Neo
V. V. Varadan
V. K. Varadan