# FRONTIERS IN ELECTROMAGNETICS

IEEE Press
445 Hoes Lane, P.O. Box 1331
Piscataway, NJ 08855-1331



**Books of Related Interest from the IEEE Press . . .**

*PLANE-WAVE THEORY OF TIME-DOMAIN FIELDS: Near-Field Scanning Applications*
Thorkild B. Hansen and Arthur D. Yaghjian
1999 Hardcover 400 pp IEEE Order No. PC5702 ISBN 0-7803-3428-0

*COMPUTATIONAL METHODS FOR ELECTROMAGNETICS*
Andrew F. Peterson, Scott L. Ray, and Raj Mittra
1998 Hardcover 592 pp IEEE Order No. PC5581 ISBN 0-7803-1122-1

*FINITE ELEMENT METHOD FOR ELECTROMAGNETICS: Antennas, Microwave Circuits, and Scattering Applications*
John L. Volakis, Arindam Chatterjee, and Leo Kempel
1998 Hardcover 368 pp IEEE Order No. PC5698 ISBN 0-7803-3425-6

# FRONTIERS IN ELECTROMAGNETICS

Edited by

**Douglas H. Werner**
*Department of Electrical Engineering and*
*Applied Research Laboratory*
*The Pennsylvania State University*

**Raj Mittra**
*Department of Electrical Engineering*
*The Pennsylvania State University*

IEEE Antennas & Propagation Society, *Sponsor*

IEEE Microwave Theory and Techniques Society, *Sponsor*

MTTS ®

IEEE
PRESS

IEEE Press Series on Microwave Technology and RF
Richard Booton and Roger Pollard, *Series Editors*

The Institute of Electrical and Electronics Engineers, Inc., New York

This book and other books may be purchased at a discount
from the publisher when ordered in bulk quantities. Contact:

IEEE Press Marketing
Attn: Special Sales
Piscataway, NJ 08855-1331
Fax: (732) 981-9334

For more information about IEEE Press products,
visit the IEEE Press Home Page: http://www.ieee.org/press



Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

**ISBN 0-7803-4701-3**

**IEEE Order No. PC5754**

**Library of Congress Cataloging-in-Publication Data**
Frontiers in electromagnetics / edited by Douglas H. Werner, Raj Mittra.
p. cm. -- (IEEE Press series on Microwave Technology and RF)
"IEEE Microwave Theory and Techniques Society, sponsor. IEEE Antennas and Propagation Society, sponsor."
Includes bibliographical references and index.
ISBN 0-7803-4701-3
1. Electromagnetism. I. Werner, Douglas H., 1960– II. Mittra, Raj.
QC760.25.F76 1999
537—dc21 99-34950
CIP

We dedicate this book to our friend and colleague,
Professor Anthony J. Ferraro of The Pennsylvania State University,
who has served as a mentor and an inspiration to many undergraduate as well as
graduate students during his long and distinguished career in academia.

# CONTENTS

## PART II OPTIMIZATION AND ESTIMATION

## CHAPTER 8 BIOLOGICAL BEAMFORMING 329

*Randy L. Haupt, Hugh L. Southall, and Teresa H. O'Donnell*



## CHAPTER 9 MODEL-ORDER REDUCTION IN ELECTROMAGNETICS USING MODEL-BASED PARAMETER ESTIMATION 371

*Edmund K. Miller and Tapan K. Sarkar*

# PREFACE

The topics covered in this book are all relatively new and emerging areas of research in the field of electromagnetics. These topics were carefully selected not only because of their innovative nature, but also because they have the potential to make a significant impact on future directions in electromagnetics research. The chapters are designed to be as self-contained as possible with ample references provided for the benefit of interested readers. Many chapters also contain a brief tutorial intended to acquaint the unfamiliar reader with the mathematical foundations and fundamental concepts which form the basis for the more advanced material that follows.

The book contains 18 chapters that are organized into four sections. The first section (Chapters 1–7) addresses recent progress toward combining electromagnetic theory with concepts originating from several branches of mathematics including geometry, topology, and groups. State-of-the-art techniques in electromagnetic optimization and estimation are discussed in the second section of the book (Chapters 8–10). A variety of new developments in analytical and numerical methods for solving electromagnetics problems are considered in sections three (Chapters 11–13) and four (Chapters 14–18), respectively.

Fractal electrodynamics is the area of research that combines fractal geometric concepts with Maxwell's theory of electromagnetism in order to study a new class of radiation, scattering, and propagation problems. Recent advancements in fractal electrodynamics research are presented in Chapters 1–3. Chapter 1 starts out with an introduction to the properties of fractals, followed by an overview of research into the fundamental nature of electromagnetic wave interactions with fractal surfaces and superlattices. Applications of fractals to the design of antenna elements and arrays are discussed in Chapters 2 and 3, respectively. Chapters 4 and 5 deal with applications of group theory to the solution of electromagnetic problems that possess certain geometrical symmetries. The impact of reciprocity and geometrical symmetry of a target on the associated scattering dyadic is considered in Chapter 4. Chapter 5 introduces a generalized theory of self-complementary structures that is based on conformal and stereographic projections. The application of some topological results from knot theory to electromagnetics is addressed in Chapters 6 and 7. In Chapter 6, particular emphasis is placed on investigating the topological features of twisted or knotted field line configurations. The electromagnetic radiation and scattering properties of thin, knotted wires are discussed in Chapter 7.

Genetic algorithms are a group of powerful optimization methods that are based on the processes of procreation and natural evolution. Chapter 8 describes some novel approaches to antenna array beamforming based on genetic algorithms and neural networks. An approach for model-order reduction, known as *model-based* *parameter estimation*, has been successfully applied to expedite the solution of a wide variety of computational electromagnetics problems. Chapter 9 includes a brief background discussion of model-based parameter estimation techniques followed by several examples illustrating its many practical uses in computational electromagnetics. Wavelets have received a considerable amount of recent attention for the potential advantages they offer in the solution of many electromagnetics problems. A newly developed wavelet-based method for the adaptive decomposition of electromagnetic signals into a wide range of physically meaningful mechanisms is presented in Chapter 10.

A technique for finding analytical solutions to a special class of electromagnetics problems which relies on Lommel expansions is outlined in Chapter 11. Several examples are presented in Chapter 11 including the derivation of an exact representation for the cylindrical wire kernel, and of useful near-field expansions for the circular loop antenna. Fractional calculus is the branch of mathematics that deals with a generalization of the well-known operations of differentiation and integration to non-integer orders. Chapter 12 explores applications as well as physical interpretation of non-integer order differential and integral operators in electromagnetics. A vector spherical-multipole analysis technique is presented in Chapter 13 that may be used for deriving analytical solutions to a wide range of interesting scattering and diffraction problems.

The recently introduced concept of perfectly matched layers and their application to the general problem of mesh truncation in finite methods for computational electromagnetics analysis are discussed in Chapter 14. A new method for the rapid calculation of interconnect capacitances is introduced in Chapter 15 which combines an electrostatic finite differencing scheme with a perfectly matched layer approach for mesh truncation. Chapter 16 examines the most recent and popular advances in finite-difference time-domain algorithm development for analysis of wave propagation in complex media. A new discrete mechanics approach to computational electromagnetics is introduced in Chapter 17. This new computational method offers several advantages over conventional approaches for the simulation of the interaction between electromagnetic fields and physically realistic media. Chapter 18 begins with a background discussion on the classification of bianisotropic composites, which are formed by embedding miniature complex-shaped inclusions, such as helices or omegas, in a host medium. This is followed by a more in-depth coverage of both analytical and numerical methods for modeling the electromagnetic properties of individual bianisotropic inclusions as well as composites.

Douglas H. Werner
*Department of Electrical Engineering and Applied Research Laboratory*
*The Pennsylvania State University*

Raj Mittra
*Department of Electrical Engineering*
*The Pennsylvania State University*

# LIST OF CONTRIBUTORS


Nicolaos G. Alexopoulos
U.C.I.—School of Engineering
305 Rockwell Engineering Center
Irvine, CA 92697-2700

Angel Cardama Aznar
Dept. Teoria del Senyal i Comunicacions
Universitat Politecnica de Catalunya (UPC)
Modul D3, Campus Nord, UPC
c/ Jordi Girona 1-3
08034, Barcelona, Spain

Carles Puente Baliarda
Dept. Teoria del Senyal i Comunicacions
Universitat Politecnica de Catalunya (UPC)
Modul D3, Campus Nord, UPC
c/ Jordi Girona 1-3
08034, Barcelona, Spain

Carl E. Baum
PL/WSQW
3550 Aberdeen Ave., SE
Kirtland AFB, NM 87117-5776

Siegfried Blume
Department of Electrical Engineering
Ruhr-Universität Bochum
Gebäude IC-FO 05/556
Universitätsstrasse 150
D-44780, Bochum, Germany

Joseph W. Burns
Research Engineer
Environmental Research Institute of Michigan
P.O. Box 134001
Ann Arbor, MI 48113-4001

Franco De Flaviis
U.C.I. — School of Engineering
305 Rockwell Engineering Center,
Irvine, CA 92697-2700

Rodolfo E. Diaz
Arizona State University
Mechanical and Aerospace Engineering
P.O. Box 876106
Tempe, AZ 85287-6106

Nader Engheta
Moore School of Electrical Engineering
University of Pennsylvania
200 South 33rd Street
Philadelphia, PA 19104-6390

Panyaiotis V. Frangos
National Technical University of Athens
Department of Electrical and Computer Engineering
Electroscience Division
9 Iroon Polytechniou Street
GR-157 73 Zografou
Athens, Greece

Randy L. Haupt
University of Nevada
Electrical Engineering Dept./260
College of Engineering
Reno, NV 89557-0153

Aaron D. Jaggard
Department of Mathematics
University of Pennsylvania,
Philadelphia, PA 19104-6395

Dwight L. Jaggard
113 Towne/6391
School of Engineering and Applied Science
University of Pennsylvania
Philadelphia, PA 19104-6391

Ludger Klinkenbusch
Computational Electromagnetics Group, University of Kiel,
Kaiserstrasse 2, D-24143 Kiel, Germany

Mustafa Kuzuoglu
Department of Electrical Engineering
Middle East Technical University
06531, Ankara, Turkey

Frédéric Mariotte
Laboratoire PIOM
ENSCPB
33402, Talence Cedex, France

Gerald E. Marsh
Argonne National Laboratory
9700 S. Cass Avenue, Building 900
Argonne, IL 60439

Edmund K. Miller
3225 Calle Celestial
Sante Fe, NM 87501-9613

Raj Mittra
The Pennsylvania State University
Department of Electrical Engineering
319 Electrical Engineering East
University Park, PA 16802

Massimo Noro
UCLA
Department of Chemistry
405 Hilgard Avenue
Los Angeles, CA 90095-1594

Teresa H. O'Donnell
Senior Scientist
ARCON Corporation
260 Bear Hill Rd
Waltham, MA 02451

Jordi Romeu Robert
Dept. Teoria del Senyal i Comunicacions
Universitat Politecnica de Catalunya (UPC)
Modul D3, Campus Nord, UPC
c/ Jordi Girona 1-3
08034, Barcelona, Spain

Tapan K. Sarkar
Department of Electrical Engineering and Computer Science
121 Link Hall
Syracuse University
Syracuse, NY 13244-1240

Bruno Sauviac
Laboratoire PIOM
ENSCPB
33402, Talence Cedex, France

Hugh L. Southall
RL/ERAA
31 Grenier Street
Hanscom AFB, MA 01824-3010

Nikola S. Subotic
Senior Scientist
Advanced Information Systems Group
Environmental Research Institute of Michigan
P.O. Box 134001
Ann Arbor, MI 48113-4001

Sergei Tretyakov
St. Petersburg State Technical University
Radiophysics Department
195251, St. Petersburg, Russia

Vladimir V. Veremey
The Pennsylvania State University
Department of Electrical Engineering
224 Electrical Engineering East
University Park, PA 16802

Douglas H. Werner
The Pennsylvania State University
Department of Electrical Engineering
211A Electrical Engineering East
University Park, PA 16802

Pingjuan L. Werner
The Pennsylvania State University
College of Engineering
DuBois, PA 15801

Jeffrey L. Young
Department of Electrical Engineering
University of Idaho
Moscow, ID 83844-1023