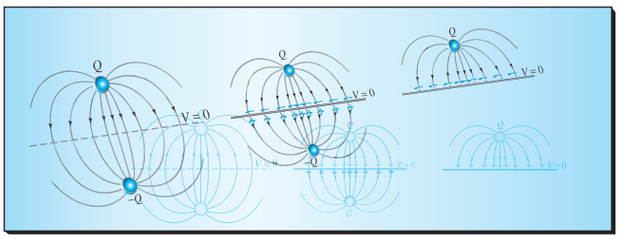
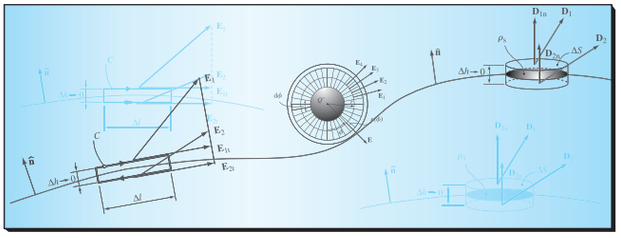


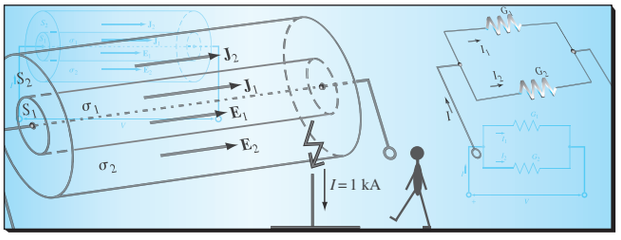
1 Electrostatic Field in Free Space

Page 1



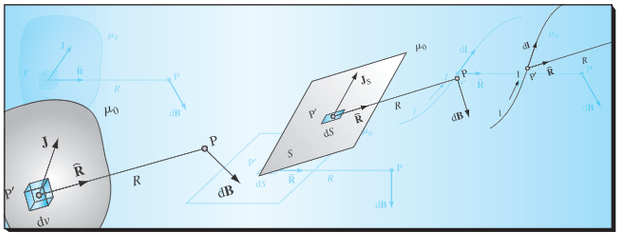
2 Dielectrics, Capacitance, and Electric Energy

Page 61



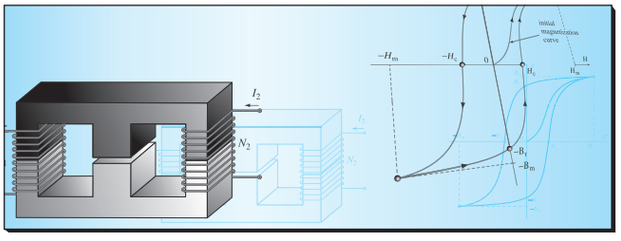
3 Steady Electric Currents

Page 124



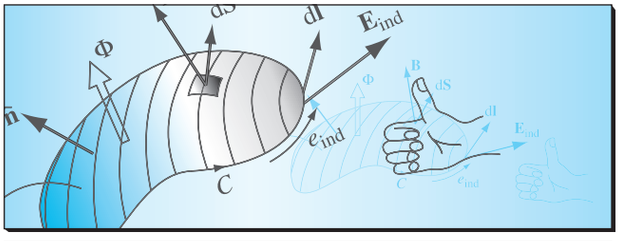
4 Magnetostatic Field in Free Space

Page 173



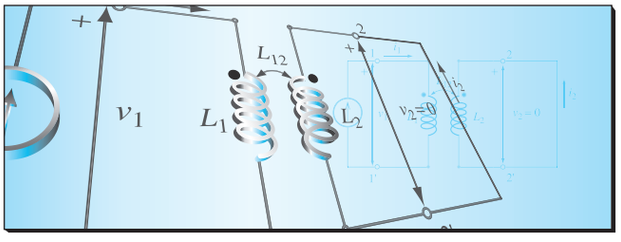
5 Magnetostatic Field in Material Media

Page 221



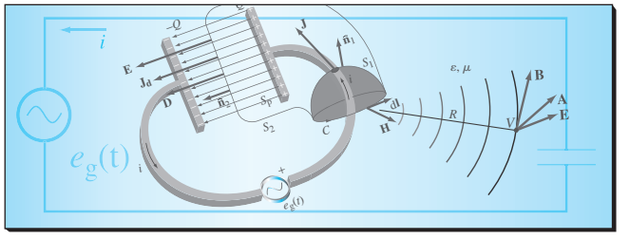
6 Slowly Time-Varying Electromagnetic Field

Page 263



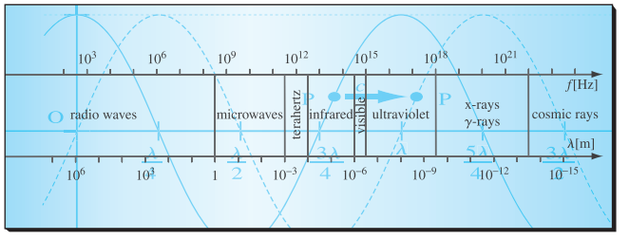
7 Inductance and Magnetic Energy

Page 311



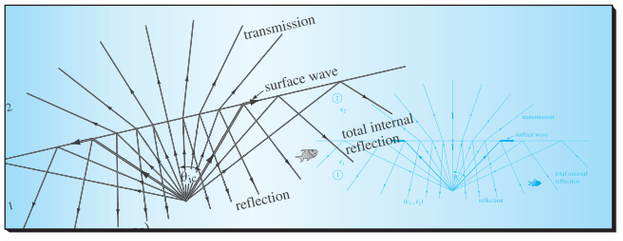
8 Rapidly Time-Varying Electromagnetic Field

Page 351



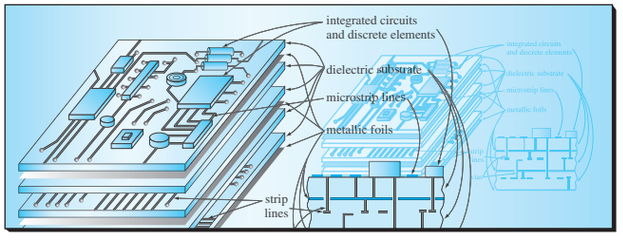
9 Uniform Plane Electromagnetic Waves

Page 408



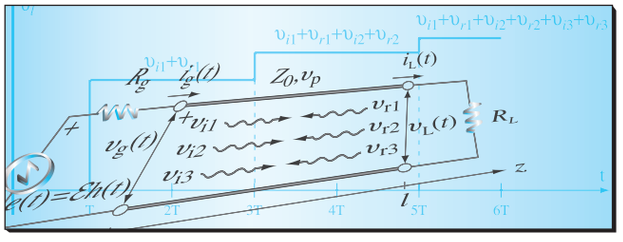
10 Reflection and Transmission of Plane Waves

Page 471



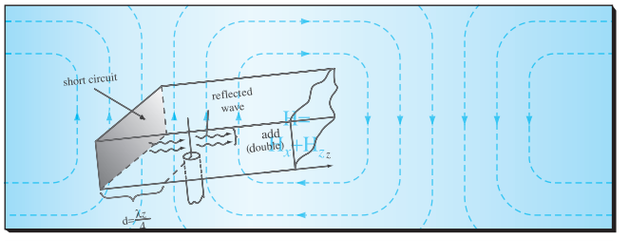
11 Field Analysis of Transmission Lines

Page 533



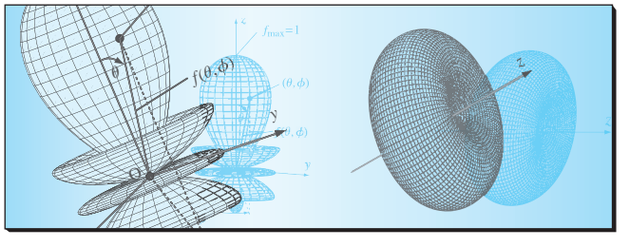
12 Circuit Analysis of Transmission Lines

Page 576



13 Waveguides and Cavity Resonators

Page 662



14 Antennas and Wireless Communication Systems

Page 713

Electromagnetics

Electromagnetics

Branislav M. Notaroš

Department of Electrical and Computer Engineering
Colorado State University

Prentice Hall

Upper Saddle River Boston Columbus San Francisco New York
Indianapolis London Toronto Sydney Singapore Tokyo Montreal
Dubai Madrid Hong Kong Mexico City Munich Paris Amsterdam Cape Town

Vice President and Editorial Director, Engineering and Computer Science: *Marcia J. Horton*
Senior Editor: *Andrew Gilfillan*
Editorial Assistant: *William Opaluch*
Vice President, Production: *Vince O'Brien*
Senior Managing Editor: *Scott Disanno*
Production Editor: *Pavithra Jayapaul, TexTech International*
Senior Operations Supervisor: *Alan Fischer*
Operations Specialist: *Lisa McDowell*
Executive Marketing Manager: *Tim Galligan*
Art Director: *Kenny Beck*
Cover Designer: *LCI Designs*
Art Editor: *Greg Dulles*
Media Editor: *Dan Sandin*
Composition/Full-Service Project Management: *TexTech International*

Copyright © 2011 by Pearson Education, Inc., Upper Saddle River, New Jersey 07458. All rights reserved. Manufactured in the United States of America. This publication is protected by Copyright and permissions should be obtained from the publisher prior to any prohibited reproduction, storage in a retrieval system, or transmission in any form or by any means, electronic, mechanical, photocopying, recording, or likewise. To obtain permission(s) to use materials from this work, please submit a written request to Pearson Education, Inc., Permissions Department, 1 Lake Street, Upper Saddle River, NJ 07458.

The author and publisher of this book have used their best efforts in preparing this book. These efforts include the development, research, and testing of the theories and programs to determine their effectiveness. The author and publisher make no warranty of any kind, expressed or implied, with regard to these programs or the documentation contained in this book. The author and publisher shall not be liable in any event for incidental or consequential damages in connection with, or arising out of, the furnishing, performance, or use of these programs.

Library of Congress Cataloging-in-Publication Data

Notaros, Branislav M.
Electromagnetics / Branislav M. Notaros.
p. cm.
ISBN 0-13-243384-2
1. Electromagnetism — Textbooks. I. Title.
QC760.N68 2010
537–dc22 2010002214

Prentice Hall
is an imprint of

www.pearsonhighered.com

10 9 8 7 6 5 4 3 2 1

ISBN-13: 978-0-13-243384-6
ISBN-10: 0-13-243384-2

To the pioneering giants of electromagnetics
Michael Faraday, James Clerk Maxwell, and others (please see the inside back cover)
for providing the foundation of this book.

To my professors and colleagues
Branko Popović (late), Antonije Djordjević, and others
for making me nearly understand and fully love this stuff.

To all my students in all my classes over all these years
for teaching me to teach.

To Olivera, Jelena, and Milica
for everything else.

Contents

Preface xi

1 Electrostatic Field in Free Space 1

1.1 Coulomb's Law 2
1.2 Definition of the Electric Field Intensity Vector 7
1.3 Continuous Charge Distributions 8
1.4 On the Volume and Surface Integration 9
1.5 Electric Field Intensity Vector due to Given Charge Distributions 10
1.6 Definition of the Electric Scalar Potential 16
1.7 Electric Potential due to Given Charge Distributions 18
1.8 Voltage 21
1.9 Differential Relationship between the Field and Potential in Electrostatics 22
1.10 Gradient 23
1.11 3-D and 2-D Electric Dipoles 26
1.12 Formulation and Proof of Gauss' Law 28
1.13 Applications of Gauss' Law 31
1.14 Differential Form of Gauss' Law 35
1.15 Divergence 36
1.16 Conductors in the Electrostatic Field 39
1.17 Evaluation of the Electric Field and Potential due to Charged Conductors 43
1.18 Electrostatic Shielding 46
1.19 Charge Distribution on Metallic Bodies of Arbitrary Shapes 48
1.20 Method of Moments for Numerical Analysis of Charged Metallic Bodies 49
1.21 Image Theory 51

2 Dielectrics, Capacitance, and Electric Energy 61

2.1 Polarization of Dielectrics 62
2.2 Polarization Vector 63
2.3 Bound Volume and Surface Charge Densities 64
2.4 Evaluation of the Electric Field and Potential due to Polarized Dielectrics 68
2.5 Generalized Gauss' Law 70
2.6 Characterization of Dielectric Materials 71
2.7 Maxwell's Equations for the Electrostatic Field 75
2.8 Electrostatic Field in Linear, Isotropic, and Homogeneous Media 75
2.9 Dielectric-Dielectric Boundary Conditions 79
2.10 Poisson's and Laplace's Equations 82
2.11 Finite-Difference Method for Numerical Solution of Laplace's Equation 84
2.12 Definition of the Capacitance of a Capacitor 86
2.13 Analysis of Capacitors with Homogeneous Dielectrics 88
2.14 Analysis of Capacitors with Inhomogeneous Dielectrics 95
2.15 Energy of an Electrostatic System 102
2.16 Electric Energy Density 104
2.17 Dielectric Breakdown in Electrostatic Systems 108

3 Steady Electric Currents 124

3.1 Current Density Vector and Current Intensity 125
3.2 Conductivity and Ohm's Law in Local Form 128
3.3 Losses in Conductors and Joule's Law in Local Form 132
3.4 Continuity Equation 133
3.5 Boundary Conditions for Steady Currents 137

3.6 Distribution of Charge in a Steady Current Field 138
3.7 Relaxation Time 139
3.8 Resistance, Ohm's Law, and Joule's Law 140
3.9 Duality between Conductance and Capacitance 146
3.10 External Electric Energy Volume Sources and Generators 149
3.11 Analysis of Capacitors with Imperfect Inhomogeneous Dielectrics 152
3.12 Analysis of Lossy Transmission Lines with Steady Currents 156
3.13 Grounding Electrodes 162

4
Magnetostatic Field in Free Space 173

4.1 Magnetic Force and Magnetic Flux Density Vector 174
4.2 Biot-Savart Law 177
4.3 Magnetic Flux Density Vector due to Given Current Distributions 179
4.4 Formulation of Ampère's Law 185
4.5 Applications of Ampère's Law 187
4.6 Differential Form of Ampère's Law 193
4.7 Curl 195
4.8 Law of Conservation of Magnetic Flux 198
4.9 Magnetic Vector Potential 201
4.10 Proof of Ampère's Law 204
4.11 Magnetic Dipole 206
4.12 The Lorentz Force and Hall Effect 209
4.13 Evaluation of Magnetic Forces 211

5
Magnetostatic Field in Material Media 221

5.1 Magnetization Vector 222
5.2 Behavior and Classification of Magnetic Materials 223
5.3 Magnetization Volume and Surface Current Densities 227
5.4 Generalized Ampère's Law 234
5.5 Permeability of Magnetic Materials 236
5.6 Maxwell's Equations and Boundary Conditions for the Magnetostatic Field 239
5.7 Image Theory for the Magnetic Field 241
5.8 Magnetization Curves and Hysteresis 243
5.9 Magnetic Circuits – Basic Assumptions for the Analysis 247
5.10 Kirchhoff's Laws for Magnetic Circuits 250
5.11 Maxwell's Equations for the Time-Invariant Electromagnetic Field 258

6
Slowly Time-Varying Electromagnetic Field 263

6.1 Induced Electric Field Intensity Vector 264
6.2 Slowly Time-Varying Electric and Magnetic Fields 269
6.3 Faraday's Law of Electromagnetic Induction 271
6.4 Maxwell's Equations for the Slowly Time-Varying Electromagnetic Field 276
6.5 Computation of Transformer Induction 277
6.6 Electromagnetic Induction due to Motion 283
6.7 Total Electromagnetic Induction 289
6.8 Eddy Currents 294

7
Inductance and Magnetic Energy 311

7.1 Self-Inductance 312
7.2 Mutual Inductance 318
7.3 Analysis of Magnetically Coupled Circuits 324
7.4 Magnetic Energy of Current-Carrying Conductors 331
7.5 Magnetic Energy Density 334
7.6 Internal and External Inductance in Terms of Magnetic Energy 342

8
Rapidly Time-Varying Electromagnetic Field 351

8.1 Displacement Current 352
8.2 Maxwell's Equations for the Rapidly Time-Varying Electromagnetic Field 357
8.3 Electromagnetic Waves 361
8.4 Boundary Conditions for the Rapidly Time-Varying Electromagnetic Field 363
8.5 Different Forms of the Continuity Equation for Rapidly Time-Varying Currents 364
8.6 Time-Harmonic Electromagnetics 366
8.7 Complex Representatives of Time-Harmonic Field and Circuit Quantities 369

8.8 Maxwell's Equations in Complex Domain 373
8.9 Lorenz Electromagnetic Potentials 376
8.10 Computation of High-Frequency Potentials and Fields in Complex Domain 381
8.11 Poynting's Theorem 389
8.12 Complex Poynting Vector 397

9
Uniform Plane Electromagnetic Waves 408

9.1 Wave Equations 409
9.2 Uniform-Plane-Wave Approximation 411
9.3 Time-Domain Analysis of Uniform Plane Waves 412
9.4 Time-Harmonic Uniform Plane Waves and Complex-Domain Analysis 416
9.5 The Electromagnetic Spectrum 425
9.6 Arbitrarily Directed Uniform TEM Waves 427
9.7 Theory of Time-Harmonic Waves in Lossy Media 429
9.8 Explicit Expressions for Basic Propagation Parameters 433
9.9 Wave Propagation in Good Dielectrics 436
9.10 Wave Propagation in Good Conductors 439
9.11 Skin Effect 441
9.12 Wave Propagation in Plasmas 447
9.13 Dispersion and Group Velocity 452
9.14 Polarization of Electromagnetic Waves 458

10
Reflection and Transmission of Plane Waves 471

10.1 Normal Incidence on a Perfectly Conducting Plane 472
10.2 Normal Incidence on a Penetrable Planar Interface 483
10.3 Surface Resistance of Good Conductors 492
10.4 Perturbation Method for Evaluation of Small Losses 497
10.5 Oblique Incidence on a Perfect Conductor 499
10.6 Concept of a Rectangular Waveguide 505
10.7 Oblique Incidence on a Dielectric Boundary 507
10.8 Total Internal Reflection and Brewster Angle 513
10.9 Wave Propagation in Multilayer Media 520

11
Field Analysis of Transmission Lines 533

11.1 TEM Waves in Lossless Transmission Lines with Homogeneous Dielectrics 534
11.2 Electrostatic and Magnetostatic Field Distributions in Transversal Planes 538
11.3 Currents and Charges of Line Conductors 539
11.4 Analysis of Two-Conductor Transmission Lines 540
11.5 Transmission Lines with Small Losses 547
11.6 Attenuation Coefficients for Line Conductors and Dielectric 550
11.7 High-Frequency Internal Inductance of Transmission Lines 556
11.8 Evaluation of Primary and Secondary Circuit Parameters of Transmission Lines 557
11.9 Transmission Lines with Inhomogeneous Dielectrics 563
11.10 Multilayer Printed Circuit Board 567

12
Circuit Analysis of Transmission Lines 576

12.1 Telegrapher's Equations and Their Solution in Complex Domain 577
12.2 Circuit Analysis of Lossless Transmission Lines 581
12.3 Circuit Analysis of Low-Loss Transmission Lines 581
12.4 Reflection Coefficient for Transmission Lines 583
12.5 Power Computations of Transmission Lines 589
12.6 Transmission-Line Impedance 592
12.7 Complete Solution for Line Voltage and Current 597
12.8 Short-Circuited, Open-Circuited, and Matched Transmission Lines 601
12.9 Transmission-Line Resonators 608
12.10 Quality Factor of Resonators with Small Losses 610
12.11 The Smith Chart – Construction and Basic Properties 614
12.12 Circuit Analysis of Transmission Lines Using the Smith Chart 618

12.13 Transient Analysis of Transmission Lines 628
12.14 Thévenin Equivalent Generator Pair and Reflection Coefficients for Line Transients 630
12.15 Step Response of Transmission Lines with Purely Resistive Terminations 634
12.16 Analysis of Transmission Lines with Pulse Excitations 640
12.17 Bounce Diagrams 646
12.18 Transient Response for Reactive or Nonlinear Terminations 649

13
Waveguides and Cavity Resonators 662

13.1 Analysis of Rectangular Waveguides Based on Multiple Reflections of Plane Waves 663
13.2 Propagating and Evanescent Waves 666
13.3 Dominant Waveguide Mode 668
13.4 General TE Modal Analysis of Rectangular Waveguides 671
13.5 TM Modes in a Rectangular Waveguide 676
13.6 Cutoff Frequencies of Arbitrary Waveguide Modes 677
13.7 Wave Impedances of TE and TM Waves 680
13.8 Power Flow along a Waveguide 681
13.9 Waveguides with Small Losses 684
13.10 Waveguide Dispersion and Wave Velocities 688
13.11 Waveguide Couplers 692
13.12 Rectangular Cavity Resonators 696
13.13 Electromagnetic Energy Stored in a Cavity Resonator 700
13.14 Quality Factor of Rectangular Cavities with Small Losses 703

14
Antennas and Wireless Communication Systems 713

14.1 Electromagnetic Potentials and Field Vectors of a Hertzian Dipole 715
14.2 Far Field and Near Field 720
14.3 Steps in Far-Field Evaluation of an Arbitrary Antenna 722
14.4 Radiated Power, Radiation Resistance, Antenna Losses, and Input Impedance 730
14.5 Antenna Characteristic Radiation Function and Radiation Patterns 736
14.6 Antenna Directivity and Gain 740
14.7 Antenna Polarization 745
14.8 Wire Dipole Antennas 745
14.9 Image Theory for Antennas above a Perfectly Conducting Ground Plane 751
14.10 Monopole Antennas 754
14.11 Magnetic Dipole (Small Loop) Antenna 758
14.12 Theory of Receiving Antennas 760
14.13 Antenna Effective Aperture 766
14.14 Friis Transmission Formula for a Wireless Link 768
14.15 Antenna Arrays 772

APPENDICES

1
Quantities, Symbols, Units, and Constants 791

2
Mathematical Facts and Identities 796

3
Vector Algebra and Calculus Index 801

4
Answers to Selected Problems 802

Bibliography 806

Index 809

Preface

Electromagnetic theory is a fundamental underpinning of technical education, but, at the same time, one of the most difficult subjects for students to master. In order to help address this difficulty and contribute to overcoming it, here is another textbook on electromagnetic fields and waves for undergraduates, entitled, simply, *Electromagnetics*. This text provides engineering and physics students and other users with a comprehensive knowledge and firm grasp of electromagnetic fundamentals by emphasizing both mathematical rigor and physical understanding of electromagnetic theory, aimed toward practical engineering applications.

The book is designed primarily (but by no means exclusively) for junior-level undergraduate university and college students in electrical and computer engineering, physics, and similar departments, for both two-semester (or two-quarter) course sequences and one-semester (one-quarter) courses. It includes 14 chapters on electrostatic fields, steady electric currents, magnetostatic fields, slowly time-varying (low-frequency) electromagnetic fields, rapidly time-varying (high-frequency) electromagnetic fields, uniform plane electromagnetic waves, transmission lines, waveguides and cavity resonators, and antennas and wireless communication systems.

Apparently, there are an extremely large number of quite different books for undergraduate electromagnetics available (perhaps more than for any other discipline in science and engineering), which are all very good and important. This book, however, aims to combine the best features and advantages of all of them. It also introduces many new pedagogical features not present in any of the existing texts.

This text provides many nonstandard theoretically and practically important sections and chapters, new style and approaches to presenting challenging topics and abstract electromagnetic phenomena, innovative strategies and pedagogical guides for electromagnetic field and wave computation and problem solving, and, most importantly, outstanding (by the judgment of students so far) worked-out examples, homework problems, conceptual questions, and MATLAB exercises. The goal is to significantly improve students' understanding of electromagnetics and their attitude toward it. Overall, the book is meant as an ***"ultimate resource" for undergraduate electromagnetics***.

The distinguishing features of the book are:

- *371 realistic examples with very detailed and instructive solutions, tightly coupled to the theory, including strategies for problem solving*
- *650 realistic end-of-chapter problems, strongly and fully supported by solved examples (there is a demo example for every homework problem)*
- *Clear, rigorous, complete, and logical presentation of material, balance of breadth and depth, balance of static (one third) and dynamic (two thirds) fields, with no missing steps*
- *Flexibility for different options in coverage, emphasis, and ordering the material in a course or courses, including the transmission-lines-first approach*
- *Many nonstandard topics and subtopics and new derivations, explanations, proofs, interpretations, examples, pedagogical style, and visualizations*
- *500 multiple-choice conceptual questions (on the Companion Website), checking conceptual understanding of the book material*
- *400 MATLAB computer exercises and projects (on the Companion Website), many with detailed solutions (tutorials) and MATLAB codes (m files)*

www.pearsonhighered.com/notaros

The following sections explain these and other features in more detail.

WORKED EXAMPLES AND HOMEWORK PROBLEMS

The most important feature of the book is an extremely large number of realistic examples, with detailed and pedagogically instructive solutions, and end-of-chapter (homework) problems, strongly and fully supported by solved examples. There are a total of 371 worked examples, all tightly coupled to the theory, strongly reinforcing theoretical concepts and smoothly and systematically developing the problem-solving skills of students, and a total of 650 end-of-chapter problems, which are essentially offered and meant as end-of-section problems (indications appear at the ends of sections as to which problems correspond to that section).

Most importantly, for each homework problem or set of problems, there is always an example or set of examples in the text whose detailed solution provides the students and other readers with all necessary instruction and guidance to be able to solve the problem on their own, and to complete all homework assignments and practice for tests and exams. The abundance and quality of examples and problems are enormously important for the success of the course and class: students always ask for more and more solved examples, which must be relevant for the many problems that follow (for homework and exam preparation) – and this is exactly what this book attempts to offer.

Examples and problems in the book emphasize physical conceptual reasoning and mathematical synthesis of solutions, and not pure formulaic (plug-and-chug) solving. They also do not carry dry and too complicated pure mathematical formalisms. The primary goal is to teach the readers to reason through different (more or less challenging) situations and to help them gain confidence and really understand and like the material. Many examples and problems have a strong practical engineering context.

Solutions to examples show and explain every step, with ample discussions of approaches, strategies, and alternatives. Very often, solutions are presented in more than one way to aid understanding and development of true electromagnetic problem-solving skills. By acquiring such skills, which are definitely not limited to a skillful browsing through the book pages in a quest for a suitable "black-box" formula or set of formulas nor a skillful use of pocket calculators to plug-and-chug, the reader also acquires true confidence and pride in electromagnetics, and a strong appreciation for both its theoretical fundamentals and its practical applications.

"Physical" nontrivial examples are good also for instructors – for lectures and recitations – as they are much more interesting and suitable for logical presentation and discussion in the class than the "plug-and-chug" or purely "mathematical" examples.

CLARITY, RIGOR, AND COMPLETENESS

Along with the number and type of examples and problems (and questions and exercises), the most characteristic feature of the book is its consistent attention to clarity, completeness, and pedagogical soundness of presentation of the material throughout the entire text, aiming for an optimal balance of breadth and depth. Electromagnetics, as a fundamental science and engineering discipline, provides complete physical explanations for (almost) everything within its scope and rigorous mathematical models for everything it covers. Thus, besides a couple of experimental fundamental laws (like Coulomb's law) that have to be taken for granted for the model to build on, all other steps in building the most impressive and exciting structure called the electromagnetic theory can be readily presented to the reader in a consistent and meaningful manner and with enough detail to be understandable and appreciable. This is exactly what this book attempts to do.

Simply speaking, literally everything is derived, proved, and explained (except for a couple of experimental facts), with many new derivations, explanations, proofs, interpretations, and visualizations. Difficult and important concepts and derivations are regularly presented in more than one way to help students understand and master the subject at hand. Maximum effort has been devoted to a continuous logical flow of topics, concepts, equations, and ideas, with practically no "intentionally skipped" steps and parts. This, however, is done in a structural and modular manner, so that the reader who feels that some steps, derivations, and proofs can be bypassed at the time (with an opportunity of redoing it later) can do so, but this is left to the reader's discretion (or to the discretion and advice of the course instructor), not the author's.

Overall, my approach is to provide all possible (or all necessary) explanations, guidance, and detail

in the theoretical parts and examples in the text, whereas students' actual understanding of the material, their thinking "on their own feet," and ability to do independent work are tested and challenged through numerous and relevant end-of-chapter problems and conceptual questions, and not through filling the missing gaps in the text.

On the other hand, I am fully aware that brevity may seem attractive to students at first glance because it typically means fewer pages for reading assignments. However, most students will readily acknowledge that it is indeed much easier and faster to read, grasp, and use several pages of thoroughly explained and presented material as opposed to a single page of condensed material with too many missing parts. During my dealings with students over so many years, I have been constantly told that they in fact prefer having everything derived and explained, and host of sample problems solved, to a lower page count and too many important parts, steps, and explanations missing, and too few detailed solutions, and this was the principal motivation for my writing this book.

This approach, in my opinion, is also good for instructors, as they have a self-contained, ready-to-use continuous "story" for each of their lectures, instead of a set of discrete formulas and sample facts with little or no explanations and detail. On the other hand, the instructor may choose to present only main facts for a given topic in class and rely on students for the rest, as they will be able to quickly and readily understand all reading assignments from the book. Indeed, I expect that every instructor using this text will have different "favorite" topics presented in class with all details and in great depth, including a number of examples, while "giving away" some other topics to students to cover on their own, with more or less depth, including worked examples.

OPTIONS IN COVERAGE OF THE MATERIAL

This book promotes and implements the direct or chronological and not inverse order of topics in teaching/learning electromagnetics, which can briefly be characterized as: first static and then dynamic topics, or first fields (static, quasistatic, and rapidly time-varying) and then waves (uniform plane waves, transmission lines, waveguides, and antennas). In addition, the book features a favorable balance of static (one third) and dynamic (two thirds) fields. Ideally, a course or a sequence of courses using this text would completely cover the book material, with a likelihood that some portions would be given to students as a reading assignment only. However, the book allows a lot of flexibility and many different options in actually covering the material, or parts of it, and ordering the topics in a course (or courses).

One scenario is to quickly go through Chapters 1–7, do just basic concepts and equations, and a couple of examples in each chapter, quickly reach Chapter 8 (general Maxwell's equations, etc.), and then do everything else as applications of general Maxwell's equations, including selected topics from Chapters 1–7 and more or less complete coverage of all other chapters. This scenario would essentially reflect the inverse (nonchronological) order of topics in teaching/learning electromagnetics. In fact, there may be many different scenarios suitable for different areas of emphasis and specialized outcomes of the course and the available time, all of them advancing in chronological order, through Chapters 1–14 of the book, just with different speeds and different levels of coverage of individual chapters.

To help the instructors create a plan for using the book material in their courses and students and other readers prioritize the book contents in accordance with their learning objectives and needs, Tables 1 and 2 provide classifications of all book chapters and sections, respectively, in two levels, indicating which chapters and sections within chapters are suggested as more likely candidates to be skipped or skimmed (covered lightly). This is just a guideline, and I expect that there will be numerous extremely creative, effective, and diverse combinations of book topics and subtopics constituting course outlines and learning/training plans, customized to best meet the preferences, interests, and needs of instructors, students, and other book users.

Most importantly, if chapters and sections are skipped or skimmed in the class, they are not skipped nor skimmed in the book, and the student will always be able to quickly find and apprehend additional information and fill any missing gaps using pieces of the book material from chapters and sections that are not planned to be covered in detail.

Table 1. **Classification of book chapters in two groups**, where "mandatory" chapters are those that would likely be covered in most courses, while some of the "elective" chapters could be skipped (or skimmed) based on specific areas of emphasis and desired outcomes of the course or sequence of courses and the available time. In selecting the material for the course(s), this classification at the chapter level could be combined with the classification at the section level given in Table 2.

"Mandatory" Chapters: 1, 3, 4, 6, 8, 9, 12	"Elective" Chapters: 2, 5, 7, 10, 11, 13, 14
1. Electrostatic Field in Free Space	2. Dielectrics, Capacitance, and Electric Energy
3. Steady Electric Currents	5. Magnetostatic Field in Material Media
4. Magnetostatic Field in Free Space	7. Inductance and Magnetic Energy
6. Slowly Time-Varying Electromagnetic Field	10. Reflection and Transmission of Plane Waves
8. Rapidly Time-Varying Electromagnetic Field	11. Field Analysis of Transmission Lines
9. Uniform Plane Electromagnetic Waves	13. Waveguides and Cavity Resonators
12. Circuit Analysis of Transmission Lines	14. Antennas and Wireless Communication Systems

Table 2. **Classification of book sections in two "tiers"** in terms of the suggested priority for coverage; if one or more sections in any of the chapters are to be skipped (or skimmed) given the areas of emphasis and specialized outcomes of the course or courses and the available time, then it is suggested that they be selected from the "tier two" sections, which certainly does not rule out possible omission (or lighter coverage) of some of the "tier one" sections as well.

Chapter	"Tier One" Sections	"Tier Two" Sections
1. Electrostatic Field in Free Space	1.1–1.4, 1.6, 1.8–1.10, 1.13–1.16	1.5, 1.7, 1.11, 1.12, 1.17–1.21
2. Dielectrics, Capacitance, and Electric Energy	2.1, 2.6, 2.7, 2.9, 2.10, 2.12, 2.13, 2.15, 2.16	2.2–2.5, 2.8, 2.11, 2.14, 2.17
3. Steady Electric Currents	3.1–3.4, 3.8, 3.10, 3.12	3.5–3.7, 3.9, 3.11, 3.13
4. Magnetostatic Field in Free Space	4.1, 4.2, 4.4–4.7, 4.9	4.3, 4.8, 4.10–4.13
5. Magnetostatic Field in Material Media	5.1, 5.5, 5.6, 5.8, 5.11	5.2–5.4, 5.7, 5.9, 5.10
6. Slowly Time-Varying Electromagnetic Field	6.2–6.5	6.1, 6.6–6.8
7. Inductance and Magnetic Energy	7.1, 7.4, 7.5	7.2, 7.3, 7.6
8. Rapidly Time-Varying Electromagnetic Field	8.2, 8.4, 8.6–8.8, 8.11, 8.12	8.1, 8.3, 8.5, 8.9, 8.10
9. Uniform Plane Electromagnetic Waves	9.3–9.7, 9.11, 9.14	9.1, 9.2, 9.8–9.10, 9.12, 9.13
10. Reflection and Transmission of Plane Waves	10.1, 10.2, 10.4–10.7	10.3, 10.8, 10.9
11. Field Analysis of Transmission Lines	11.4–11.6, 11.8	11.1–11.3, 11.7, 11.9, 11.10
12. Circuit Analysis of Transmission Lines	12.1–12.6, 12.11, 12.12, 12.15	12.7–12.10, 12.13, 12.14, 12.16–12.18
13. Waveguides and Cavity Resonators	13.1–13.3, 13.6, 13.8, 13.9, 13.12	13.4, 13.5, 13.7, 13.10, 13.11, 13.13, 13.14
14. Antennas and Wireless Communication Systems	14.1, 14.2, 14.4–14.6, 14.8, 14.14, 14.15	14.3, 14.7, 14.9–14.13

Table 3. **Ordering the book material for the transmission-lines-first approach**; Chapter 12 (Circuit Analysis of Transmission Lines) is written using only pure circuit-theory concepts (all field-theory aspects of transmission lines are placed in Chapter 11 – Field Analysis of Transmission Lines), so it can be taken at the very beginning of the course (or at any other time in the course). Note that two sections introducing (or reviewing) complex representatives of time-harmonic voltages and currents (Sections 8.6 and 8.7) must be done before Chapter 12.

Section 8.6: Time-Harmonic Electromagnetics
Section 8.7: Complex Representatives of Time-Harmonic Field and Circuit Quantities
Chapter 12: Circuit Analysis of Transmission Lines (or a selection of sections from Chapter 12 – see Table 2)
Chapters 1-11, 13, 14 or a selection of chapters (see Table 1) and sections (see Table 2)

TRANSMISSION-LINES-FIRST APPROACH

One possible exception from the chronological sequence of chapters (topics) in using this text implies a different placement of Chapter 12 (Circuit Analysis of Transmission Lines), which is written in such a manner that it can be taken at any time, even at the very beginning of the course, hence constituting the transmission-lines-first approach to teaching the course and learning the material. Namely, the field and circuit analyses of transmission lines are completely decoupled in the book, so that any field-theory aspects are placed in Chapter 11 (Field Analysis of Transmission Lines) and only pure circuit-theory concepts are used in Chapter 12 with per-unit-length characteristics (distributed parameters) of the lines being taken for granted (are assumed to be known) from the field analysis if the circuit analysis is done first. Table 3 shows the transmission-lines-first scenario using this book.

MULTIPLE-CHOICE CONCEPTUAL QUESTIONS

The book provides, on the *Companion Website*, a total of 500 conceptual questions. These are multiple-choice questions that focus on the core concepts of the material, requiring conceptual reasoning and understanding rather than calculations. They serve as checkpoints for readers following the theoretical parts and worked examples (like homework problems, conceptual questions are referred to at the ends of sections). Generally, conceptual questions may appear simple, but students often find them harder than the standard problems. Pedagogically, they are an invaluable resource. They are also ideal for in-class questions and discussions (so-called active teaching and learning) to be combined with traditional lecturing – if so desired.

In addition, conceptual questions are perfectly suited for class assessments, namely, to assess students' performance and evaluate the effectiveness of instruction, usually as the "gain" between the course "pretest" and "posttest" scores, and especially in light of ABET and similar accreditation criteria (the key word in these criteria is "assessment"). Selected conceptual questions from the large collection provided in the book can readily be used by instructors as partial and final assessment instruments for individual topics at different points in the course and for the entire class.

MATLAB EXERCISES, TUTORIALS, AND PROJECTS

The book provides, on the *Companion Website*, a very large and comprehensive collection of MATLAB computer exercises, strongly coupled to the book material, both the theory and the worked examples, and designed to help students develop a stronger intuition and a deeper understanding of electromagnetics, and find it more attractive and likable. MATLAB is chosen principally because it is a generally accepted standard in science and engineering education worldwide.

There are a total of 400 MATLAB exercises, which are referred to regularly within all book chapters, at the ends of sections, to supplement problems and conceptual questions. Each section of this collection starts with a comparatively very large number of tutorial exercises with detailed completely

worked out solutions, as well as MATLAB codes (m files). This resource provides abundant opportunities for instructors for assigning in-class and homework projects – if so desired.

VECTOR ALGEBRA AND CALCULUS

Elements of vector algebra and vector calculus are presented and used gradually across the book sections with an emphasis on physical insight and immediate links to electromagnetic field theory concepts, instead of having a purely mathematical review in a separate chapter. They are fully integrated with the development of the electromagnetic theory, where they actually belong and really come to life.

The mathematical concepts of gradient, divergence, curl, and Laplacian, as well as line (circulation), surface (flux), and volume integrals, are literally derived from physics (electromagnetics), where they naturally emanate as integral parts of electromagnetic equations and laws and where their physical meaning is almost obvious and can readily be made very visual. Furthermore, the text is written in such a way that even a reader with little background in vector algebra and vector calculus will indeed be able to learn or refresh vector analysis concepts directly through the first several chapters (please see Appendix 3 – Vector Algebra and Calculus Index).

LINKS TO CIRCUIT THEORY

The book provides detailed discussions of the links between electromagnetic theory and circuit theory throughout all of its chapters. It contains physical explanations for all elements of circuit theory, for both dc and ac regimes. All basic circuit-theory equations (circuit laws, element laws, etc.) are derived from electromagnetic theory. The goal is for the reader to develop both an appreciation of electromagnetic theory as a foundation of circuit theory and electrical engineering as a whole, as well as an understanding of limitations of circuit theory as an approximation of field theory.

HISTORICAL ASIDES

Throughout almost all chapters of the book, dozens of Historical Asides appear with quite detailed and fascinating biographies of famous scientists and pioneers in the field of electricity and magnetism. There are a total of 40 biographies, which are, in my view, not only very interesting historically and informative in terms of providing the factual chronological review of the development of one of the most impressive, consistent, and complete theories of the entire scientific and technological world – the electromagnetic theory – but they also often provide additional technical facts and explanations that complement the material in the text. I also feel that some basic knowledge about the discoverers – who made such epochal scientific achievements and far-reaching contributions to humanity – like Faraday, Maxwell, Henry, Hertz, Coulomb, Tesla, Heaviside, Oersted, Ampère, Ohm, Weber, and others should be made an irreplaceable part of a sort of "general education" of our engineering and physics students.

SUPPLEMENTS

The book is accompanied by the Solutions Manual (for instructors) with detailed solutions to all end-of-chapter problems (written in the same manner as the solutions in the examples in the book), answers to all conceptual questions, and MATLAB codes (m files) for all MATLAB computer exercises and projects, as well as by PowerPoint slides with all illustrations from the text and by other supplements. *Pearson eText* of the book is also available.

www.pearsonhighered.com/notaros

ACKNOWLEDGMENTS

This text is based on my electromagnetics teaching and research over more than 20 years at the University of Belgrade, Yugoslavia (Serbia), University of Colorado at Boulder, University of Massachusetts Dartmouth, and Colorado State University, in Fort Collins, U.S.A. I gratefully acknowledge my colleagues and/or former Ph.D. students at these institutions whose discussions, advice, ideas, enthusiasm, initiatives, co-teaching, and co-authorships have shaped my knowledge, teaching style, pedagogy, and writing in electromagnetics, including: Prof. Branko Popović (late), Prof. Milan Ilić, Prof. Miroslav Djordjević, Prof. Antonije Djordjević, Prof. Zoya Popović, Gradimir Božilović, Prof. Momčilo Dragović (late), Prof.

Branko Kolundžija, Prof. Vladimir Petrović, and Prof. Jovan Surutka (late). All I know in electromagnetics and about its teaching I learned from them or with them or because of them, and I am enormously thankful for that.

I am grateful to all my students in all my classes over all these years for all the joy I have had in teaching them electromagnetics and for teaching me to teach better.

I especially thank my current Ph.D. students Nada Šekeljić, Ana Manić, and Sanja Manić for their invaluable help in writing MATLAB computer exercises, tutorials, and codes, checking the derivations and examples in the book, and solving selected end-of-chapter problems. I owe a particular debt of gratitude to my colleague and former Ph.D. student Prof. Milan Ilić, for his outstanding work and help with the initial electronic artwork in the book. My colleagues and former students Andjelija Ilić and Prof. Miroslav Djordjević, as well as Olivera Notaroš, also contributed very significantly to the artwork, for which I am sincerely indebted.

I would like to express my gratitude to the reviewers of the manuscript for their extremely detailed, useful, positive, and competent comments that I feel helped me to significantly improve the quality of the book, including: Professors Indira Chatterjee, Robert J. Coleman, Cindy Harnett, Jianming Jin, Leo Kempel, Edward F. Kuester, Yifei Li, Krzysztof A. Michalski, Michael A. Parker, Andrew F. Peterson, Costas D. Sarris, and Fernando L. Teixeira.

Special thanks to all members of the Pearson Prentice Hall team, who all have been excellent, and particularly to my editor Andrew Gilfillan, who has been extremely helpful and supportive, and whose input was essential at many stages in the development of the manuscript and book, my production manager Scott Disanno, for expertly leading the book production, Marcia Horton, Vice President and Editorial Director with Prentice Hall, for great conversations and support in the initial phases of the project, and Tom Robbins, former Publisher at Prentice Hall, for the first encouragements. I hope they enjoyed our dealings and discussions as extensively as I did.

I thank my wife Olivera Notaroš, who also teaches in the ECE Department at Colorado State University, not only for her great and constant support and understanding but also for her direct involvement and absolutely phenomenal ideas, advice, and help in all phases of writing the manuscript and production of the book. Without her, this book would not be possible or would, at least, be very different. I also acknowledge extraordinary support by my wonderful daughters Jelena and Milica, and I hope that I will be able to keep my promise to them that I will now take a long break from writing. I am very sad that the writing of this book took me so long that my beloved parents Smilja and Mile did not live to receive the first dedicated copy of the book from me, as had been the case with my previous books.

Finally, on a very personal note as well, I really love electromagnetics and teaching it, and I hope that this book will convey at least a portion of my admiration and enthusiasm to the readers and help more and more students start liking and appreciating this fascinating discipline with endless impacts. I am proud of being able to do that in my classes, and am now excited and eager to try to spread that message to a much larger audience using this text. Please send me your comments, suggestions, questions, and corrections (I hope there will not be many of these) regarding the book to notaros@colostate.edu.

Branislav M. Notaroš
Fort Collins, Colorado

"I believe but cannot explain that the author's confidence is somehow transferred to the student as a trust that the text they are reading and learning from is worth their time."
—Anonymous reviewer of the book manuscript