

Compendium on
Electromagnetic Analysis

From Electrostatics to Photonics: Fundamentals and
Applications for Physicists and Engineers

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Volume
1

Electrostatic
and Magnetic
Phenomena

Compendium on
Electromagnetic Analysis

From Electrostatics to Photonics: Fundamentals and
Applications for Physicists and Engineers

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Foreword

Electromagnetic technology touches our lives in ways too numerous to mention here, and if history is a model, it will only have a larger effect in the future. Think of some of the devices you use on a daily basis such as radio and television, cell phones, microwave ovens, computers, satellite navigation, lasers, and electric cars. The enabling technology for these and others is the abundant and reliable electric power grid, which we have taken for granted for well over a century. These devices and the electric grid which powers them are all based on electromagnetic technology.

While the laws of electromagnetics were known in the mid-19th century, the application of electromagnetic principles to daily life began to make an impact in the early 20th century and this impact has been increasing at an accelerating rate into the 21st century. This rate of increase shows no signs of slowing down. The 21st century will undoubtedly include advances in space travel, virtual reality, quantum computing, renewable energy, electrification of transportation, vastly improved medical diagnostics and treatment, as well as other applications that have not yet been imagined and which will be based on the application of electromagnetic principles.

Given the great importance of electromagnetics and the great strides that have been made recently in applications, materials, analytical and experimental techniques, and computer-aided design and optimization, there is, of course, an enormous body of literature on the subject. This work is scattered over hundreds of journals and thousands of conference proceedings. The task of keeping up with current developments and in coming up to speed on a subject is quite formidable. Looking for clear, up-to-date, and detailed comprehensive coverage of these subjects can be frustrating.

This five-volume compendium on Electromagnetics fills a void and bridges this gap. It brings together the various branches of electromagnetic theory and current practice. It is, to my knowledge, the most complete and current

reference set on the subject. The editors have selected some of the world's leading researchers and practitioners to write on their specialized subject.

The subjects include low frequency electromagnetic theory, applications, and practice in Volumes 1 and 2. Volumes 3, 4, and 5 deal with waves, antennas, and optics. This set should be an excellent introduction to the various subjects as well as a *vade mecum* for professionals working in electromagnetics. The editor-in-chief, Professor Igor Tsukerman, an expert in the field of applied and computational electromagnetics and photonics, has involved a highly talented and accomplished set of editors for each volume. Yilmaz Sozer has, for a number of years, worked in the area of low frequency electromagnetics with many applications including electric machines and drives. Michael Donahue is a well-known and accomplished mathematician and physicist with the US National Institute of Standards and Technology (NIST), with an impressive publication record. Professor Thomas Bauernfeind is from the Institute of Fundamentals and Theory in Electrical Engineering (IGTE), Graz University of Technology, Austria. While still early in his career, he has already made important contributions in the area of modeling and optimization of antennas and communication systems. Professor Vadim Markel is a theoretical physicist at the University of Pennsylvania and an expert with vast experience in optics, imaging, tomography, and inverse problems.

I congratulate the editors and authors of this compendium. It is a very welcome and timely addition to the literature.

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Emeritus Professor of Electrical, Computer,
and Systems Engineering
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Preface from the Editor-in-Chief

In our everyday life, electromagnetic phenomena are often taken for granted or go unnoticed. Yet, electromagnetism underlies everything we do and the whole world around us — from electric power generation and transmission to electronics, from radio waves to optics, and from biomolecular processes to magnetic materials.

It is the theoretical and practical significance of electromagnetism that served as our motivation for publishing this five-volume compendium. Our work was guided by several organizing principles.

First, we wanted the five volumes to serve as a comprehensive reference, covering methods and applications at all frequencies: from static to power to microwave to optical. Second, our intention was to make the technical content accessible to graduate students, engineers, and interdisciplinary researchers. Third, we did our best to combine in each volume pedagogical/tutorial material with state-of-the-art developments.

The synopsis of the volumes is as follows.

1. **Electrostatic and magnetic phenomena.** Colloidal systems; quantitative magnetic resonance imaging (MRI); magnetic logic and memory devices; nanostructured magnetic field sensors; detection of magnetic nanoparticles and microbeads; physics of spin transfer torque and its application to high-speed, non-volatile magnetic random access memory (MRAM); antiferromagnetic (AFM) materials; nanopatterned magnetic elements; micro- and nanomagnetic modeling and simulation.
2. **The new generation of electric machines.** Electric machine fundamentals. Renewable energy, hybrid vehicles, low-noise motors, topology optimization, core losses; modern machines for automotive applications, axial flux machines, superconducting machines, and magnetic gears.
3. **Antennas, antenna arrays, and microwave devices.** Antenna theory and simulation; waveguides; electromagnetic scattering; inverse problems and optimization; the finite element method (FEM) for wave

problems across all frequency ranges; special volume integral equation techniques; metamaterials, metasurfaces, and their applications; electrically small directional antennas; ultra-wideband antennas; high-density antenna arrays; rectifying antennas; radio frequency identification (RFID) and near-field communication (NFC); topology optimization of antenna structures.

4. **Optics and Photonics I.** A differential-geometric treatment of Maxwell's equations and constitutive relations; Green's functions; photonic crystals and their topological properties; amplifying media; transport through complex random media.
5. **Optics and Photonics II.** Raman scattering; fiber lasers and communication; surface plasmons in metal-dielectric structures; toroidal multipoles and associated optical resonances; optical beams.

This Compendium is a collective effort of 114 chapter authors from 16 countries,¹ four volume editors, the editor-in-chief, and several editors and managers from World Scientific. I am really grateful to all my colleagues for providing high-quality material and for the editorial work.

The idea of this Compendium was conceived by Zvi Ruder, and the production process was managed by Amanda Yun and Sree Meenakshi Sajani.

Special thanks go to the volume editors, who devoted a massive amount of time to this book project: Michael Donahue, Yilmaz Sozer, Thomas Bauernfeind, and Vadim Markel.

I gratefully acknowledge financial support from the National Science Foundation (award 1620112). My work on the compendium was also facilitated by my professional development leave in 2017–2018. I thank the university administration as well as my colleagues in the Department of Electrical & Computer Engineering for their support and cooperation. I am also extremely grateful to all my national and international hosts for sharing their knowledge and for their hospitality, patience, and financial support through various funding agencies in their respective countries and institutions: Boris Gralak, Sebastien Guenneau, Olav Breinbjerg,

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August 2019

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Preface to Volume 1

This volume of the Compendium is devoted to electrostatic and magnetic phenomena, which play an important role in many areas of science, technology, and in biological processes. Our intention has been to make the material accessible to graduate students, engineers, and interdisciplinary researchers and to combine pedagogical/tutorial material with state-of-the-art developments.

The first chapter of this volume deals with electrostatic interactions between colloidal particles; similar electrostatic effects are critical in many biomolecular processes. The second chapter looks at probing materials with electromagnetic waves to extract key material parameters. This can be used to characterize bulk samples and metamaterials.

In medicine, magnetic resonance imaging (MRI) is widely used for diagnoses, but historically, the results have required qualitative interpretation by human specialists. This is beginning to change, as accurate models and sophisticated phantoms are bringing about quantitative MRI (Chapter 3).

The next three chapters are devoted to magnetic devices. Chapter 4 looks at the pinning of magnetic domain walls pertinent for magnetic logic and memory devices. Chapter 5 provides an overview of nanostructured magnetic field sensors used in automotive, aerospace, communication, and medical fields. A special focus of the chapter is on the detection of magnetic nanoparticles and microbeads in biomedical and biochemical applications. Chapter 6 details the physics of spin transfer torque and its application to high-speed, non-volatile magnetic random access memory (MRAM).

The THz frequency electromagnetic response and properties of canted antiferromagnetic (AFM) materials are studied in Chapter 7. AFM materials are currently of great interest due to potential applications in a wide range of spintronic devices. In Chapter 8, modeling helps interpret Brillouin light scattering (BLS) experiments for the investigation of magnetic eigenmodes of nanopatterned magnetic elements. This analysis relies in part on

micromagnetic modeling, which is the direct modeling of material magnetization at the nanometer scale. Micromagnetic modeling is also the focus of the final two chapters of this volume. Chapter 9 details the development of a suite of test problems, the μ MAG standard problems, used by the global micromagnetic community to verify and improve micromagnetic modeling programs. The final chapter is devoted to the modeling of hard magnetic materials, such as Nd-Fe-B, widely used in powerful permanent magnets for applications such as computer hard disks, audio speakers, headphones, electric motors, and wind turbines. High-resolution nanoanalytic material characterization combined with detailed finite-element micromagnetic modeling may lead the way toward development of strong, economical, rare-earth-free magnets.

I would like to thank the National Institute of Standards and Technology for allowing me the time to work on this endeavor. Also, special thanks are due to the chapter authors for their fine work on the material contained within.

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August 2019

About the Editor-in-Chief



Igor Tsukerman is Professor of Electrical and Computer Engineering at the University of Akron, Ohio, where he has been a faculty member since 1995. His research is focused on the simulation of nanoscale systems, applied electromagnetics and photonics, plasmonics, computational methods, and homogenization of materials. He teaches a variety of undergraduate and graduate courses (Basic Electrical Engineering, Signals & Systems, Circuits, Electromagnetic Fields, Digital Signal Processing, Random Signal Analysis, Simulation of Nanoscale Systems, and others). Tsukerman has approximately 200 refereed publications, has authored a monograph (Computational Methods for Nanoscale Applications: Particles, Plasmons and Waves, Springer 2008) and co-edited a book (Plasmonics and Plasmonic Metamaterials: Analysis and Applications, World Scientific, 2011).

Before joining the University of Akron, Tsukerman worked at the Department of Electrical & Computer Engineering, the University of Toronto (1990–1995). A joint project with GE Canada involved electromagnetic field analysis and noise reduction in large electric motors.

Tsukerman's academic degrees are from St. Petersburg Polytechnic in Russia: a combined BSc/MSc degree (with honors) in Control Systems (1982) and a PhD in Electrical Engineering (1988).

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About the Editor



Michael Donahue is a mathematician and leader of the Mathematical Software Group at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland, USA. The Mathematical Software Group performs original research and develops software for scientific computing, including finite element packages for simulation of material behavior (OOF: Finite Element Analysis of Microstructures, PHAML: Parallel Hierarchical Adaptive MultiLevel) as well as producing the NIST Digital Library of

Mathematical Functions (DLMF), which is an online update to the well-regarded 1964 *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables*, edited by Milton Abramowitz and Irene A. Stegun. Dr Donahue's personal research centers on micromagnetics and he heads development of the OOMMF public domain micromagnetics package. Prior to joining NIST, he was an industrial postdoctoral research associate at the University of Minnesota, working in conjunction with Siemens Corporate Research on artificial neural networks and computer vision. Dr Donahue holds PhDs in mathematics and engineering from The Ohio State University and has authored over 50 journal publications.

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