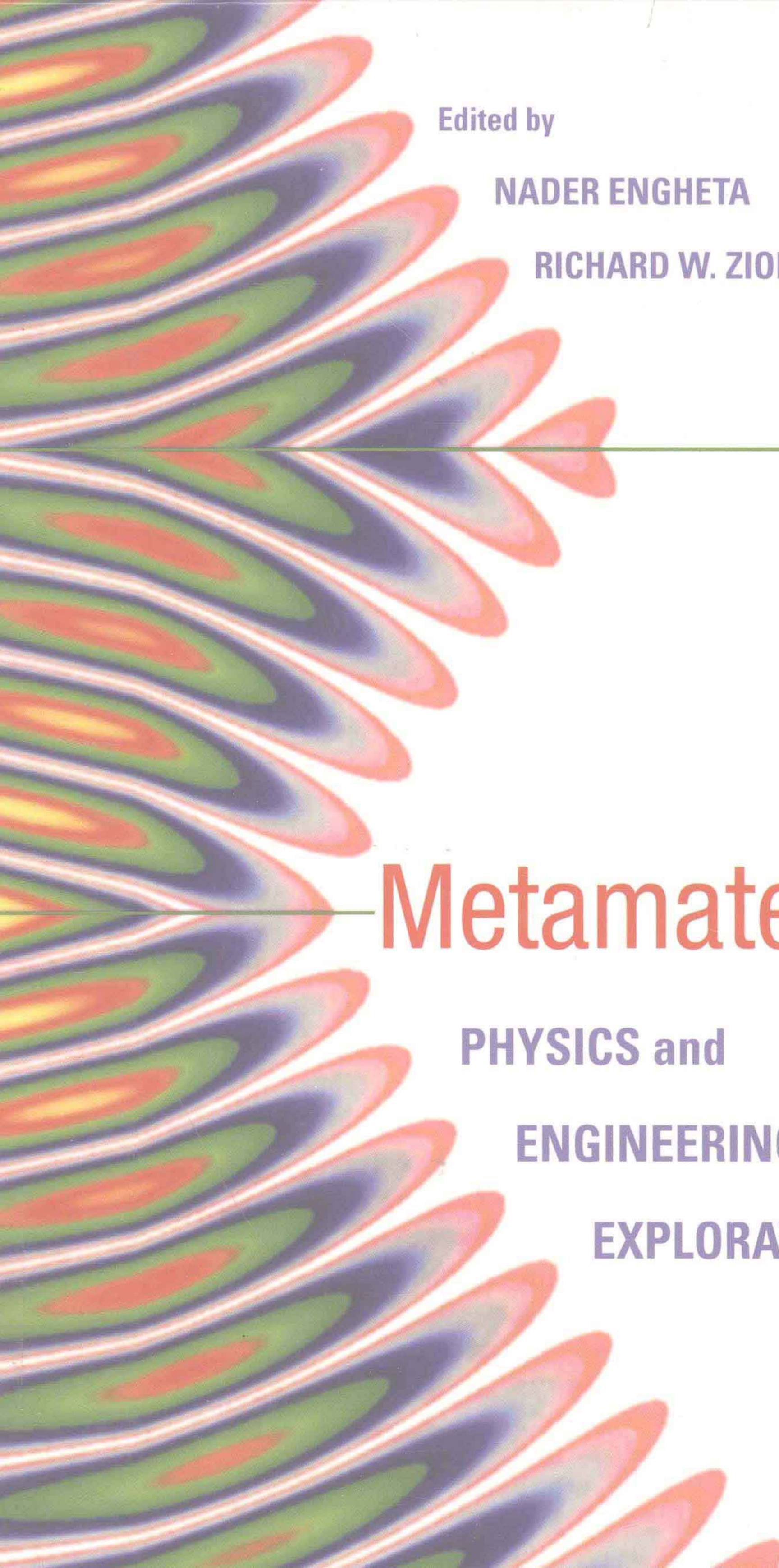

Edited by

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Metamaterials

PHYSICS and ENGINEERING EXPLORATIONS

METAMATERIALS
Physics and Engineering Explorations

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PREFACE

While we were organizing, coordinating, and guest editing the October 2003 special issue of the *IEEE Transactions on Antennas and Propagation* on the topic of metamaterials, we began toying with the idea of editing a book on this topic with contributions from experts who are active in this area of research. The senior acquisitions editor of the IEEE Press, Cathy Faduska, was also interested in a book project on this timely topic, and during the 2002 IEEE Antennas and Propagation Society International Symposium in San Antonio, Texas, she suggested to us, and encouraged us, to begin this project. And finally, with a longer time dilation than expected, we have completed this book.

The amount of research in this metamaterials area has grown extremely quickly in this time frame. We have tried to capture, through the selected authors, both some interesting physics and engineering explorations in this area. Why this two-pronged approach? We note that physics asks how nature works, and engineering asks how the works of nature can be used. Thus, we wanted to include some of the metamaterial fundamentals and how they are already being applied.

What is a "metamaterial"? In recent years, there has been a growing interest in the fabricated structures and composite materials that either mimic known material responses or qualitatively have new, physically realizable response functions that do not occur or may not be readily available in nature. The unconventional response functions of these *metamaterials* are often generated by artificially fabricated inclusions or inhomogeneities embedded in a host medium or connected to or embedded on a host surface. Exotic properties for such metamaterials have been predicted; many experiments have confirmed our basic understanding of many of them. The underlying interest in metamaterials is the potential to have the ability to engineer the electromagnetic and optical properties of materials for a variety of applications. The impact of metamaterials may be enormous: If one can tailor and manipulate the wave properties, significant decreases in the size and weight of components, devices, and systems along with enhancements in their performance appear to be realizable.

The pursuit of artificial materials for electromagnetic applications is not new; this activity has a long history which dates back to Jadagis Chunder Bose in 1898 when he worked and experimented on the constructed twisted elements that exhibit properties nowadays known as chiral characteristics. In the early part of the twentieth century, Karl Ferdinand Lindman studied wave interaction with collections of metallic helices as artificial chiral media. Artificial dielectrics were explored, for example, in the 1950s and 1960s for lightweight microwave antenna lenses. Artificial chiral materials were investigated extensively in the 1980s and 1990s for microwave radar absorbers and other applications. The developments of electromagnetic bandgap (EBG) structured materials and single-negative (SNG) and double-negative (DNG) materials and their fascinating properties have driven the recent explosive interest in metamaterials.

We have divided this book into two major classes of metamaterials: the SNG and DNG metamaterials and the EBG structured metamaterials. The SNG and DNG metamaterials involve inclusions and interinclusion distances that are much smaller than a wavelength and, as a consequence, such media can be described by homogenization and effective media concepts. On the other hand, the EBG metamaterials involve distances that are on the order of half a wavelength or more and are described by the Bragg reflection and other periodic media concepts. We have furthered subdivided each of these classes into their three-dimensional (3D volumetric) and two-dimensional (2D planar or surface) realizations. Examples of these types of metamaterials are presented, and their known and anticipated properties are reviewed in this book.

This book begins with DNG metamaterial concepts, simulations, and experiments in Chapters 1 to 6. In Chapter 1 we present a brief recapitulation of the history of artificial materials and metamaterials and their exotic properties, including negative indices of refraction, negative angles of refraction, and focusing using planar slabs. This is followed in Chapter 2 with theoretical and numerical studies of SNG and DNG metamaterials and their particular applications to waveguiding environments and to antennas and is presented by us and our students, Andrea Alù and Aycan Erentok. Next in Chapter 3 Silvio Hrabar describes several waveguide experiments that have been used to characterize the properties of SNG and DNG metamaterials. Tomasz Grzegorczyk, Jin Au Kong, and Ran Lixin present in Chapter 4 their several experiments in waveguide environments to demonstrate the negative refraction properties of DNG metamaterials. In Chapter 5 George Eleftheriades discusses the realization of planar metamaterials and their demonstration of many of the exotic properties of DNG metamaterials, including evanescent wave growth and subwavelength focusing. The use of a planar metamaterial to realize resonance cone antennas is shown by Keith Balmain and Andrea Lüttgen in Chapter 6. Christophe Caloz and Tatsuo Itoh describe in Chapter 7 a variety of microwave coupler and resonator applications of negative-refractive-index planar structures. The book is then transitioned into a review of EBG metamaterial concepts, simulations, and experiments in Chapters 8 to 14. Maria Kafesaki and Costas Soukoulis provide a historical perspective and a review of the fundamental principles in modeling 3D periodic structures with an emphasis on volumetric EBGs in Chapter 8. Peter de Maagt and Peter Huggard describe in Chapter 9 the fabrication, experimentation, and applications of EBG structures. In Chapter 10 Boris Gralak, Stefan Enoch, Gérard Tayeb present their work on superprism effects and EBG antenna applications. Dan Sievenpiper provides in Chapter 11 a review of the theory, fabrication, and applications of high-impedance ground planes. In Chapter 12 Yahya Rahmat-Samii and Fan Yang discuss their development of complex artificial ground planes for antenna engineering. Stefano Maci and Alessio Cucini address frequency-selective EBG surfaces in Chapter 13. Finally, John McVay, Nader Engheta, and Ahmad Hoorfar describe in Chapter 14 their application of space-filling curves to realize high-impedance ground planes.

In all chapters, the authors have presented recent research advances associated with a diverse set of metamaterials. As noted, the chapters include a combination of theoretical, numerical, and experimental contributions to the understanding of the behavior of metamaterials and to their potential applications in components, devices, and systems. We sincerely hope that the work presented provide the newcomer to metamaterial research with the ability to come up to speed with a basic understanding of metamaterials and their potential for a variety of applications. For the advanced metamaterial researcher, the material reviews the state-of-the-art as viewed by many seasoned veterans in this area. In both cases, the extensive reference lists should provide ample additional reading materials for further considerations.

We would like to thank Cathy Faduska, Anne Reifsnyder, Developmental Editor, and Lisa Van Horn, Production Editor, at IEEE Press for their efforts in interfacing between us, IEEE Press, and John Wiley & Sons. When problems arose, they provided excellent support. Most of all, we would like to thank all the contributing authors for their time and wonderful efforts. We believe that the outcome is an impressive resource for future efforts.

We sincerely hope that the materials presented here will stimulate discussions and new avenues of research in this very exciting research area of metamaterials. We note

Science never solves a problem without creating ten more.
George Bernard Shaw (1856–1950)

Have fun reading!

NADER ENGHETA
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CONTENTS

CHAPTER 12 *DEVELOPMENT OF COMPLEX ARTIFICIAL GROUND PLANES IN ANTENNA ENGINEERING* 313

Yahya Rahmat-Samii and Fan Yang

CHAPTER 13 *FSS-BASED EBG SURFACES* 351

Stefano Maci and Alessio Cucini