THE DESIGN OF CHIRAL METAMATERIALS AND METASURFACES

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YAOLIANG SONG
Nanjing University of Science and Technology, Nanjing, China

IGOR SEMCHENKO
Francisk Skorina Gomel State University, Gomel, Belarus
National Academy of Sciences, Minsk, Belarus

SERGEI KHAKHOMOV
Francisk Skorina Gomel State University, Gomel, Belarus

LEI WANG
Nanjing University of Science and Technology, Nanjing, China

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About the authors

Y.L. Song is a professor at Nanjing University of Science and Technology. He received his BEng, MSc, and PhD in electrical engineering from Nanjing University of Science and Technology, China, in 1983, 1986, and 2000, respectively. He was a research fellow in the Department of Engineering Science at the University of Oxford from September 2004 to 2005. His major research interests include UWB communications, UWB radar imaging, and advanced signal processing and metamaterials and their applications in radar, medical imaging, and communication systems. He is currently heading the UWB Radar Imaging Group. He is a senior member of the IEEE Communications Society and Signal Processing Society, a senior member of the Chinese Electronics Society, and serves on the editorial board of the Journal of Radar, Circuits and Systems, Journal of Electrical & Electronic Engineering, etc. He presided over a number of National Natural Science Fund, international cooperation projects, provincial-level research funds, and other projects, and has participated in major national and key special projects. He has received several National Ministerial Science and Technology Awards and Provincial Science and Technology Progress Awards.

I.V. Semchenko is a professor in the Department of General Physics at Francisk Skorina Gomel State University, Gomel, Belarus. He is also the deputy director for scientific activities at State Scientific and Production Association of Optics, Optoelectronics, and Laser Technology, National Academy of Sciences of Belarus, Minsk. In 2021, he was elected a corresponding member of the National Academy of Sciences of Belarus. He graduated from Gomel State University in 1981 with a degree in physics. Since 1984, he has worked at the University as a senior lecturer, associate professor, head of the department, dean, and vice-rector. He earned his PhD in physics and mathematics in 1984 from the Institute of Physics of the National Academy of Sciences of Belarus in Minsk. He was awarded doctor of physics and mathematics at the Institute of Physics of the National Academy of Sciences of Belarus in 1997. He became a full professor at the Higher Attestation Commission of the Republic of Belarus in Minsk in 1999. His research interests focus on electrodynamics of artificial anisotropic structures and metamaterials. He was a scientific supervisor of six PhD students and one doctor of science candidate. He was a supervisor of more than 25 international scientific projects. He is a coauthor of more than 400 scientific papers. His works include 5 monographs, 14 chapters in collective monographs, more than 140 articles in journals, more than 130 articles in conference proceedings, 9 patents, 5 preprints, and 60 abstracts.

S.A. Khakhomov is a professor in the Department of Optics and the rector of Francisk Skorina Gomel State University. He graduated from Francisk Skorina Gomel State University in 1991 with a degree in physics. He earned his PhD in physics and mathematics from the Belarusian State University in 1997. He was awarded the degree of doctor of physics and mathematics at the Institute of Physics of the National Academy of Sciences of Belarus in 2018. After completing postgraduate studies, he has worked at Gomel State University as a senior lecturer in 1997, and as an associate professor in 1998. He served as head of the Department of Optics from 2003 to 2009, the dean of the Faculty of Physics from 2009 to 2010, the vice-rector for academic affairs from 2010 to 2014, and first vice-rector from September 2014 to June 2016. He has been rector of Francisk Skorina Gomel State University since June 2016 and professor of the Department of Optics since May 2018. He has been an executive and supervisor of more than 20 international projects. Professor Sergei Khakhomov is the scientific supervisor of one PhD student and the author of more than 390 scientific and scientific-methodical works, including 4 monographs, 18 chapters in books, 26 educational-methodical and reference books, over 90 scientific articles in journals, more than 80 scientific and methodical articles in conference proceedings, and 8 patents.

L. Wang is an associate professor at Nanjing University of Science and Technology. He graduated from the Department of Physics at Dalian University of Technology in 1985 and received his PhD in 2000 from Saint Petersburg National Research University of Information Technologies, Mechanics, and Optics. His research focuses on millimetre-wave technology, radar theory and system design, signal information processing technology, and other work at Nanjing University of Science and Technology. He has led and participated in multiple preresearch projects, National Natural Science Foundation projects, and scientific and technological cooperation projects, and holds several national invention and utility model patents.

Preface

Artificial composite materials are created in addition to existing natural materials in order to obtain their special properties, including special behavior in the electromagnetic field. Metamaterials and metasurfaces, which have emerged in the past decade, are artificial composite materials designed based on subwavelength structures and possess unconventional physical properties. These unusual properties, desirable for practical use, are primarily due to the shape, size, and location of the artificial elements of metamaterials used. In this case, the substance from which artificial inclusions, or metaatoms, are made plays a much less significant role. For metamaterials, as for natural substances, the behavior of the electromagnetic field is determined by the classical Maxwell equations and the equations of the coupling between the vectors of the fields, which are commonly called constitutive equations. The coupling equations for metamaterials, as well as for natural substances, in turn, correspond to generally accepted fundamental approaches that take into account the principle of causality, the law of conservation of energy, and the symmetry of the spatial structure of the metamaterial. The introduction of metamaterials breaks through the conventional design ideas of traditional materials, suggesting that one can directly obtain equivalent apparent performance through the structural design of subwavelength units at the material's physical scale. This opens up possibilities for developing new materials, predicting new phenomena, discovering new principles, and exploring new applications. Artificial chiral electromagnetic materials based on chiral unit structure design are a category of novel metamaterials with special properties. Compared to ordinary materials, chiral dielectric materials exhibit cross-coupling between electric and magnetic fields. By manipulating the chiral structure (chiral parameter), the propagation characteristics of electromagnetic waves in chiral dielectric materials can be altered. Therefore chiral dielectric materials provide more capabilities for controlling electromagnetic wave propagation and find extensive applications in fields such as communication, radar, and electronic warfare.

This book is a collaborative effort between the Ultra-Wideband Radar Research Laboratory at Nanjing University of Science and Technology and the Laboratory of Physics of Wave Processes at Francisk Skorina Gomel State University. The authors from China and Belarus have been engaged in research on electromagnetic metamaterials and metasurfaces, metamaterial optics, and electromagnetic wave propagation theory for many years. Since 2018, they have conducted cooperative research on metamaterial theory and design, focusing on the design and implementation of chiral metamaterials based on spiral structures, under the support of the National Natural Science Foundation of China, the Belarusian Republican Foundation for Fundamental Research, and the State Committee on Science and Technology of the Republic of Belarus. This book presents some of the recent achievements of both teams in their individual and collaborative research on chiral metamaterials and metasurfaces.

Chapter 1 introduces the basic concepts of metamaterials and chiral materials, reviews their development history and typical applications, and highlights prominent figures and major research trends in this field.

Chapter 2 discusses the molecular structure, characteristics, and typical examples of natural chiral materials. It covers the constitutive equations and characterization of chirality, calculation of chiral parameters, and obtaining electromagnetic invisibility by using absorbing coatings based on natural and artificial chiral metamaterials. The chapter also explores conventional fabrication techniques and typical processes for metamaterials.

Chapter 3 focuses on the electromagnetic wave polarization transformation mechanism, design, and parameter optimization methods of helical chiral metamaterials. It discusses the design method for electromagnetic invisibility using helical chiral materials, the interaction between electromagnetic waves at different incident angles on the helical metamaterials, and the microwave electrodynamics of Ω-shaped artificial composite materials.

Chapter 4 investigates the design and experimental verification methods for helical structure-based chiral metamaterials and metamaterials with compensated chirality in the terahertz frequency range. It analyzes the polarization rotation and circular dichroism of chiral materials and explores boundary value problems, impedance characteristics, and nonreflective propagation of electromagnetic wave issues in single- and double-layer helical chiral metamaterials.

In Chapter 5, helical molecular structures of biological objects such as deoxyribonucleic acid (DNA) and proteins are investigated based on the principle of electrodynamic similarity. It examines the model of electromagnetic radiation for the DNA double helix, the optimal pitch angles of the DNA double helix, the interaction of DNA-like helices with electromagnetic fields, and the selectivity of polarization of electromagnetic waves. Experimental results are presented for microwave absorption, reflection, and propagation by DNA-like double helices and single helices.

Chapter 6 starts with the design, characterization, and experimental fabrication methods for single-layer planar chiral structures. It then expands to the design and characterization of chiral materials, including circular dichroism and circularly polarized conversion, in double-layer or even multilayer stack configurations. The chapter also introduces several typical applications and experimental validations of planar chiral materials.

Chapter 7 introduces the design and fabrication methods of three-dimensional chiral materials based on double-layer and multilayer planar interconnected structures, such as metal vias. It analyzes the circular dichroism and circular polarization conversion dichroism of different structural chiral materials and provides typical applications and experimental verification results of multilayer interconnected chiral materials.

The preface and Chapter 1 of this book were jointly written by Professor Yaoliang Song, Professor I.V. Semchenko, Professor S.A. Khakhomov, and Lei Wang. Chapters 2–5 were written by Professor I.V. Semchenko and Professor S.A. Khakhomov, with translation assistance from Associate Researcher Lei Wang and Senior Lecturer Ms. Tatyana Lozovskaya. Professor Yaoliang Song made adjustments and additions to the relevant content. Chapters 6 and 7 were written by Professor Yaoliang Song, and all the chapters were proofread by Professor Yaoliang Song, Professor I.V. Semchenko, and Professor S.A. Khakhomov.

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