Optical Metamaterials

This book introduces fundamental principles as well as applications of metasurfaces, i.e. electromagnetically thin structures manipulating EM wave propagation. The authors describe the precursors and history of metasurfaces before moving on to explore the physical insights that can be gained from the material parameters of the metasurface. They also present how to compute the fields scattered by a metasurface, with known material parameters, being illuminated by an arbitrary incident field, as well as how to realize a practical metasurface and relate it to its material parameters to physical structures. The book finishes with a discussion of the future of the field.

Active Metamaterials

This book offers a unified presentation of metamaterials building from fundamental nanophotonic principles.

Metamaterials

To meet the demands of students, scientists, and engineers for a systematic reference source, this book introduces, comprehensively and in a single voice, research and development progress in emerging metamaterials and derived functional metadevices. Coverage includes electromagnetic, optical, acoustic, thermal, and mechanical metamaterials and related metadevices. Metamaterials are artificially engineered composites with designed properties beyond those attainable in nature and with applications in all aspects of materials science. From spatially tailored dielectrics to tunable, dynamic materials properties and unique nonlinear behavior, metamaterial systems have demonstrated tremendous flexibility and functionality in electromagnetic, optical, acoustic, thermal, and mechanical engineering. Furthermore, the field of metamaterials has been extended from the mere pursuit of various exotic properties towards the realization of practical devices, leading to the concepts of dynamically-reconfigurable metadevices and functional metasurfaces. The book explores the fundamental physics, design, and engineering aspects, as well as the full array of state-of-the-art applications to electronics, telecommunications, antennas, and energy harvesting. Future challenges and potential in regard to design, modeling and fabrication are also addressed.

Mechanics of Metamaterials with Negative Parameters

"The field of metamaterials arose from a deeper understanding of how electromagnetic waves interact with materials and subwavelength-scaled scattering structures. This opened up the field of metamaterials or engineered materials through advances in understanding how material properties not found in nature could be designed along with advances in fabrication capabilities. Metamaterials advance the electromagnetic spectrum, with existing materials being more common at lower frequencies (e.g., microwaves). The microwave or x-band regime has proven to be a good testbed for the first generation of metamaterials, but recently we have seen optical and IR metamaterials emerging as well. The exploitation of these more complex material-wave interactions, based on arrangements of subwavelength scale components, has generated a lot of global activity. We can, in principle, engineer material properties to greatly extend those currently available. This tutorial text presents both the usual and unusual electromagnetic properties of materials, focusing especially man-made or engineered metamaterials. After a review of Maxwell's equations and material properties, the idea of resonant meta-atoms and composite media are introduced. The fabrication of metamaterials and the properties of negative index materials are explained. The difficulties associated with reducing the size of meta-atoms for use at optical frequencies are described, and the use of metamaterials for superresolution imaging is presented in some detail."--

Time-Domain Finite Element Methods for Maxwell's Equations in Metamaterials

Plasmonics gives researchers in universities and industries and designers an overview of phenomena enabled by artificially designed metamaterials and their application for plasmonic devices. The purpose of this book is to provide a detailed introduction to the basic modeling approaches and an overview of enabled innovative phenomena. The main research agenda of this book is aimed at the
M etamaterials

M etamaterials: Beyond Crystals, Noncrystals, and Quasicrystals is a comprehensive and updated research monograph that focuses on recent advances in metamaterials based on the effective medium theory in microwave frequencies. Most of these procedures were conducted in the State Key Laboratory of Millimeter Waves, Southeast University, China. The book conveys the essential concept of metamaterials from the microcosmic structure to the macroscopic electromagnetic properties and helps readers quickly obtain needed skills in creating new devices at microwave frequencies using metamaterials. The authors present the latest progress on metamaterials and transformation optics and provide abundant examples of metamaterial-based devices accompanied with detailed procedures to simulate, fabricate, and measure them. Comprised of ten chapters, the book comprehensively covers both the fundamentals and the applications of metamaterials. Along with an introduction to the subject, the first three chapters discuss effective medium theory and artificial particles. The next three chapters cover homogeneous metamaterials (super crystals), random metamaterials (super noncrystals), and inhomogeneous metamaterials (super quasicrystals). The final four chapters examine gradient-index inhomogeneous metamaterials, nearly isotropic inhomogeneous metamaterials, and anisotropic inhomogeneous metamaterials, after which the authors provide their conclusions and closing remarks. The book is completely self-contained, making it easy to follow.

Broadband M etamaterials in Electromagnetics

From science fiction to science laboratories Discover the State of the Art in Photonic M etamaterials M etamaterials—composite media with unusual optical properties—have revolutionized the landscape of optical science and engineering over the past decades. M etamaterials have transformed science-fiction-like concepts of superresolution imaging and optical cloaking to the realm of science laboratories, and further promise to transform these into the realm of our everyday life. This new era of optical metamaterials calls for the development of experimental and theoretical methods capable of analyzing optical behavior on the multitude of scales—from the nanoscale level of individual inhomogeneity, to the micrometer level and the larger scale of metamaterials-based devices. Tutorials in M etamaterials offers a collection of chapters that were designed as self-contained tutorials describing photonic metamaterials and the state of the art in metamaterials research. Chapters cover: Linear and nonlinear properties of photonic metamaterials and their potential applications Fabrication techniques for optical metamaterials, ranging from electron-beam lithography, focused ion beam milling, and nanoimprint lithography to direct laser writing Recent achievements in metamaterial research at visible, IR, and microwave frequencies Novel applications of metamaterials for light guiding, steering, and refraction Efforts to compensate and eliminate optical loss by introducing optical gain into the metamaterial matrix A comprehensive overview of metamaterial photonics, this reference is suitable for graduate students as well as physicists and engineers interested in entering this dynamic new field.

M etamaterials and M etasurfaces

Complex-mediums electromagnetics (CME) describes the study of electromagnetic fields in materials with complicated response properties. This truly multidisciplinary field commands the attentions of scientists from physics and optics to electrical and electronic engineering, from chemistry to materials science, to applied mathematics, biophysics, and nanotechnology. This book is a collection of essays to explain complex mediums for optical and electromagnetic applications. All contributors were requested to write with two aims: first, to educate; second, to provide a state-of-the-art review of a particular subtopic. The vast scope of CME exemplified by the multitude of scales—from the nanometer scale of individual inhomogeneity, to the micrometer level and the larger scale of metamaterials—requires a study of modeling techniques and novel functionalities such as plasmonic enhancement of solar cell efficiency, plasmonics in sensing, etc. The topics addressed in this book cover the major strands: theory, modeling and design, applications in practical devices, fabrication, characterization, and measurement. It is worthwhile mentioning that the strategic objectives of developing new artificial functional materials require close cooperation of the research in each subarea.

Electromagnetic M etamaterials

Hyperbolic metamaterials were originally introduced to overcome the diffraction limit of optical imaging. Soon thereafter it was realized that hyperbolic metamaterials demonstrate a number of novel phenomena resulting from the broadband singular behavior of their density of photonic states. These novel phenomena and applications include super resolution imaging, new stealth technologies, enhanced quantum-electrodynamic effects, thermal hyperconductivity, superconductivity, and interesting gravitation theory analogs. Here I review typical material systems, which exhibit hyperbolic behavior and outline important new applications of hyperbolic metamaterials, such as imaging experiments with plasmonic hyperbolic metamaterials and novel VCSEL geometries, in
which the Bragg mirrors may be engineered in such a way that they exhibit hyperbolic properties in the long wavelength infrared range, so that they may be used to efficiently remove excess heat from the laser cavity. I will also discuss potential applications of self-assembled photonic hypercrystals. This system bypasses 3D nanofabrication issues, which typically limit hyperbolic metamaterial applications. Photonic hypercrystals combine the most interesting features of hyperbolic metamaterials and photonic crystals.

Electromagnetic Metamaterials

This book provides a comprehensive overview of the theory and practical development of metamaterial-based perfect absorbers (MMPAs). It begins with a brief history of MMPAs which reviews the various theoretical and experimental milestones in their development. The theoretical background and fundamental working principles of MMPAs are then discussed, providing the necessary background on how MMPAs work and are constructed. There then follows a section describing how different MMPAs are designed and built according to the operating frequency of the electromagnetic wave, and how their behavior is changed. Methods of fabricating and characterizing MMPAs are then presented. The book elaborates on the performance and characteristics of MMPAs, including electromagnetically-induced transparency (EIT). It also covers recent advances in MMPAs and their applications, including multi-band, broadband, tunability, polarization independence and incidence independence. Suitable for graduate students in optical sciences and electronic engineering, it will also serve as a valuable reference for active researchers in these fields.

An Introduction to Metamaterials and Waves in Composites

About the book: This book is the first comprehensive review on acoustic metamaterials; novel materials which can manipulate sound waves in surprising ways, which include collimation, focusing, cloaking, sonic screening and extraordinary transmission. It covers both experimental and theoretical aspects of acoustic and elastic waves propagating in structured composites, with a focus on effective properties associated with negative refraction, lensing and cloaking. Most related books in the field address electromagnetic metamaterials and focus on numerical methods, and little (or no) experimental section. Each chapter will be authored by an acknowledged expert, amongst the topics covered will be experimental results on non-destructive imaging, cloaking by surface water waves, flexural waves in thin plates. Applications in medical ultrasound imaging and modeling of metamaterials will be emphasized too. The book can serve as a reference for researchers who wish to build a solid foundation of wave propagation in this class of novel materials.

An Introduction to Metamaterials and Waves in Composites

Ever since the first experimental demonstration was reported in 2000, the interest in metamaterials and left-handed media that exhibit a negative refractive index has increased exponentially. Surveying this explosive growth, Physics and Applications of Negative Refractive Index Materials covers the fundamental physical principles and emerging engineering applications of structured electromagnetic metamaterials that yield a negative refraction as well as other unexpected physical properties. It provides detailed explanations on the history, development, and main achievements of metamaterials. Making it easy to access relevant, up-to-date information on the field, the authors bring together the most important and influential papers related to metamaterials. They present the principles of negative refraction and compare the uniqueness of novel metamaterials with other media that exhibit similar properties. The book discusses the design, optimization, and testing of structured metamaterials as well as applications of metamaterials at frequencies ranging from radio wave to optical. It also explores novel concepts and phenomena, such as the perfect lens for super-resolution imaging, hyper lenses that couple the near-field to radiative modes, electromagnetic cloaking and invisibility, and near-field optical imaging. Connecting theoretical ideas to recent experimental techniques and results, this state-of-the-art book enables an understanding of the basic principles of and research contributions to metamaterials with negative refractive index and their electromagnetic properties.

Composites and Metamaterials

This book provides an overview of the use of toroidal moments. This includes methods of excitation, numerical analysis, and experimental measurements of associating structures. Special emphasis is placed on understanding the fundamental physics, characteristics, and real-world applications of toroidal multipoles. This book also covers a variety of both planar and 3D meta-atom
Read Online An Introduction To Metamaterials And Waves In Composites

and metamolecule schemes capable of sustaining toroidal moments across a wide range of spectrum. It discusses the implementation of innovative approaches, for exploring the spectral features and excitation methodologies, predicting the properties of the correlating metasystems in their excited states. A valuable text for undergraduate, graduate, and postgraduate students, this book is also of interest to researchers, theorists, and experimentalists working in optical physics, photonics, and nanotechnology.

An Introduction to Metamaterials and Nanophotonics

Requiring no advanced knowledge of wave propagation, An Introduction to Metamaterials and Waves in Composites focuses on theoretical aspects of metamaterials, periodic composites, and layered composites. The book gives novices a platform from which they can start exploring the subject in more detail. After introducing concepts related to elasticity, acoustics, and electrodynamics in media, the text presents plane wave solutions to the equations that describe elastic, acoustic, and electromagnetic waves. It examines the plane wave expansion of sources as well as scattering from curved interfaces, specifically spheres and cylinders. The author then covers electrodynamics, acoustic, and elastodynamics from metamaterials. He also describes examples of transformations, aspects of acoustic cloaking, and applications of metamaterials to acoustic cloaking. With a focus on periodic composites, the text uses the Bloch-Floquet theorem to find the effective behavior of composites in the quasistatic limit, presents the quasistatic equations of elastodynamic and electromagnetic waves, and investigates Brillouin zones and band gaps in periodic structures. The final chapter discusses wave propagation in smoothly varying layered media, anistropic density of a periodic layered medium, and quasistatic homogenization of laminates. This book provides a launch pad for research into elastic and acoustic metamaterials. Metamaterials will find this book extremely useful. The book will also serve as a good reference for developing artificial materials and materials that may one day form the basis of many new materials for a variety of applications. Key Features Provides background for design and development of metamaterial structures using novel unit cells Gives in-depth performance study of miniaturization of microstrip antennas Discusses design and development of both transmission and reflection types, surfacematerials and their practical applications. Verifies a variety of M metamaterial structures and Metasurfaces experimentally. The target audience of this book is postgraduate students and researchers. Leading experts explore the exotic properties and exciting applications of electromagnetic metamaterials Metamaterials: Physics and Metamaterials for Antenna Applications

Leading experts explore the exotic properties and exciting applications of electromagnetic metamaterials. Physics and Engineering Explorations gives readers a clearly written, richly illustrated introduction to the most recent research developments in the area of electromagnetic metamaterials. It explores the fundamental physics, the designs, and the engineering aspects, and points to a myriad of exciting potential applications. The editors, acknowledged leaders in the field of metamaterials, have invited a group of leading researchers to present both their own findings and the full array of state-of-the-art applications for antennas, waveguides, devices, and components. Following a brief overview of the history of artificial materials, the publication divides its coverage into two major classes of metamaterials. The first half of the publication examines effective media with single (SNG) and double negative (DNG) properties; the second half examines electromagnetic band gap (EBG) structures. The book further divides each of these classes into their three-dimensional (3D volumetric) and two-dimensional (2D planar or surface) realizations. Examples of each type of metamaterial are presented, and their known and anticipated properties are reviewed. Collectively, Metamaterials: Physics and Engineering Explorations presents a review of recent research advances associated with a highly diverse set of electromagnetic metamaterials. Its multifaceted approach offers readers a combination of theoretical, numerical, and experimental perspectives for a better understanding of their behaviors and their potential applications in components, devices, and systems. Extensive reference lists provide opportunities to explore individual topics and classes of metamaterials in greater depth. With full-color illustrations throughout to clarify concepts and help visualize actual results, this book provides a dynamic, user-friendly resource for students, engineers, physicists, and other researchers in the areas of electromagnetic materials, microwaves, millimeter waves, and optics. It equips newcomers with the basic understanding of metamaterials and their potential applications.
researchers will benefit from thought-provoking perspectives that will deepen their knowledge and lead them to new areas of investigation.

**Tutorials in Metamaterials**

This book discusses bulk solids that derive their mechanical properties not from those of their base materials, but from their designed microstructures. Focusing on the negative mechanical properties, it addresses topics that reveal the counter-intuitive nature of solids, specifically the negativity of properties that are commonly positive, such as negative bulk modulus, negative compressibility, negative hygroexpansion, negative thermal expansion, negative stiffness phase, and negative Poisson’s ratio. These topics are significant not only due to the curiosity they have sparked, but also because of the possibility of designing materials and structures that can behave in ways that are not normally expected in conventional solids, and as such, of materials that can outperform solids and structures made from conventional materials. The book includes illustrations to facilitate learning, and, where appropriate, reference tables. The presentation is didactic, starting with simple cases, followed by increasingly complex ones. It provides a solid foundation for graduate students, and a valuable resource for practicing materials engineers seeking to develop novel materials through the judicious design of microstructures and their corresponding mechanisms.

**Metamaterials**

Metamaterials have been in research limelight for the last few years owing to the exotic electromagnetic features these exhibit. With certain combinational forms of the design, these can be of prudent applications in developing antennas, filters, absorbers, sensors, energy harvesters, and many others. As such, the role of engineered mediums remains greatly important as the frequency region of operation determines the structure (of the medium(s)) to be developed - the fact that is exploited in the on-demand kind of tailoring the electromagnetic response of metamaterials. The relevant R&D investigators show keen interest in the fabrication of varieties of novel miniaturized devices that can be of great potentials in many micro- as well as nanotechnology-oriented applications. With this view point in mind, the book provides the glimpse of phenomenal growth of research in this direction through covering the topics pivoted to fundamental descriptions, and theoretical and experimental results reported by pioneering scientists. It is expected that the book will be of benefit to novice researchers (such as graduate students) and expert scientists in universities and research laboratories. Some of the contents in the book are centered on industrial applications of metamaterials, thereby making the volume useful to the R&D scientists in certain industries. In summary, the book

**Metamaterials for Perfect Absorption**

This book presents novel and fundamental aspects of metamaterials, which have been overlooked in most previous publications, including chirality, non-reciprocity, and the Dirac-cone formation. It also describes the cutting-edge achievements of experimental studies in the last several years: the development of high-regularity metasurfaces in optical frequencies, high-performance components in the terahertz range, and active, chiral, nonlinear and non-reciprocal metamaterials in the microwave range. Presented here are unique features such as tunable metamaterials based on the discharge plasma, selective thermal emission from plasmonic metasurfaces, and the classical analogue of the electromagnetically induced transparency. These most advanced research achievements are explained in understandable terms by experts in each topic. The descriptions with many practical examples facilitate learning, and not only researchers and experts in this field but also graduate students can read the book without difficulty. The reader finds how these new concepts and new developments are being utilized for practical applications.

**Optical Metamaterials: Qualitative Models**

Metamaterials have provided applications in spectral ranges covering radio frequencies and ultraviolet. However, most applications have been extrapolated to the visible or near-infrared after being developed at the GHz level. This is due to technological reasons since fabrication of microwave antennas is not as demanding as THz resonators or plasmonic nanostructures. Accordingly, this book has been divided into three parts. In the first part, fundamentals of metamaterials and metadevices are discussed, while describing recent advances in the field. In the second part, the discussion is extended to the different spectral ranges focusing on the strategies for enabling the reconfigurability of metadevices. Given the increasing interest in THz applications, these can be found in the third part.

**Engineered Materials and Metamaterials**

Electromagnetic metamaterials-from fundamental physics to advanced engineering applications. This book presents an original generalized transmission line approach associated with non-resonant structures that exhibit larger bandwidths, lower loss, and higher design flexibility. It is based on the novel concept of composite right/left-handed (CRLH) transmission line metamaterials (MMs), which has led to the development of novel guided-wave, radiated-wave, and refracted-wave devices and structures. The authors introduced this powerful new concept and are therefore able to offer readers deep insight into the fundamental physics needed to fully grasp the technology. Moreover, they provide a host of practical engineering applications. The book begins with an introductory chapter that places resonant type and transmission line metamaterials in historical perspective. The next six chapters give readers a solid foundation in the fundamentals and practical applications. Fundamentals of LH MMs describes the fundamental physics and exotic properties of left-handed metamaterials TL. Theory of MMs establishes the foundations of CRLH structures in three progressive steps: ideal transmission line, LC network, and real distributed structure Two-Dimensional MMs develops both a transmission matrix method and a transmission line method to address the problem of finite-size 2D metamaterials excited by arbitrary sources Guided-Wave Applications and Radiated-Wave Applications present a number of groundbreaking
applications developed by the authors. The Future of Metamaterials sets forth an expert view on future challenges and prospects. This engineering approach to metamaterials paves the way for a new generation of microwave and photonic devices and structures. It is recommended for electrical engineers, as well as physicists and optical engineers, with an interest in practical negative refractive index structures and materials.

**Introduction to Complex Mediums for Optics and Electromagnetics**

Metamaterials—artificially structured materials with engineered electromagnetic properties—have enabled unprecedented flexibility in manipulating electromagnetic waves and producing new functionalities. This book details recent advances in the study of optical metamaterials, ranging from fundamental aspects to up-to-date implementations, in one unified treatment. Important recent developments and applications such as superlenses and cloaking devices are also treated in detail and made understandable. The planned monograph can serve as a very timely book for both newcomers and advanced researchers in this extremely rapid evolving field.

**Plasmonics**

The interest towards photonic crystals and metamaterials and their strategic importance are evident in the steadily growing rate of topical publications. This title addresses that ranges topics, including aspects pertaining to modeling, phenomenologies, experiments, technologies and applications.

**Metamaterials and Negative Refraction**

This book presents the most recent theoretical developments and numerical/experimental validations of new metamaterials and phononic crystals for the broadband absorption of elastic waves and vibrations in structures. These nine chapters explore many aspects of phononic crystals and acoustic/elastic metamaterials, including sound attenuation/absorption, extraordinary transmission, wave broadband mitigation, wave steering, cloaking via the transformation method, optimization of phononic crystals, and active acoustic metamaterials.

**Selected Topics in Photonic Crystals and Metamaterials**

Metamaterials have become one of the most important emerging technologies in the scientific community due to its unusual electromagnetic properties. Consequently, during the last years, a huge deal of efforts has been concentrated in order to design functional components and devices based on metamaterials for many potential applications. The main objective of this book is to present in-depth analysis of the theory, properties, and realizations of novel devices that could be integrated within modern and future communication systems. The book contains 11 chapters written by acknowledged experts, researchers, academics, and microwave engineers, providing comprehensive information and covering a wide range of topics on several aspects of microwaves and optics, including polarization conversion, asymmetric transmission, transmission lines, filters, plasmonic lenses, tunable metamaterials, light manipulation, absorbers, and antennas, among others. This book is suitable for scholars from large scientific domain and therefore given to engineers, scientists, graduates, and other interested professionals as a reference on these artificial materials of tomorrow.

**Metamaterials**

Metamaterials have established themselves as one of the most important topics in physics and engineering, and have found practical application across a wide variety of fields including photonics, condensed matter physics, materials science, and biological and medical physics. This modern and self-contained text delivers a pedagogical treatment of the topic, rooted within the fundamental principles of nanophotonics. A detailed and unified description of metamaterials and metasurfaces is developed, beginning with photonic crystals and their underlying electromagnetic properties before introducing plasmonic effects and key metamaterial configurations. Recent developments in research are also presented along with cutting-edge applications in the field. This advanced textbook will be invaluable to students and researchers working in the fields of optics and nanophotonics.

**Information Metamaterials**

This book is an excellent primer for students to learn about physical properties, particularly mechanical properties of heterogeneous and multiphase materials and the cultivation of physical insight. Written by a prominent author who pioneered many of the concepts, this book provides a comprehensive coverage of current topics in new heterogenous materials. Topics covered include: Principles of the mechanics of solid multiphase systems. Role of heterogeneity and anisotropy in determining physical properties including elastic, dielectric, and piezoelectric properties. Coupled fields; smart materials including piezoelectric materials and thermal actuators. Applications in lightweight structures, ultra-strong materials, materials for protection of the body, and materials for the replacement of human tissues. Materials with fibrous, lamellar, particulate, and cellular structures. Lattice metamaterials. Extreme and unusual physical properties. Heterogeneous materials of biological origin. Metamaterials and biomimetic and bio-inspired materials.

**Acoustic Metamaterials**

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Read Online An Introduction To Metamaterials And Waves In Composites

This book uses the first volume’s exploration of theory, basic properties, and modeling topics to develop readers’ understanding of applications and devices that are based on artificial materials. It explores a wide range of applications in fields including electronics, telecommunications, sensing, medical instrumentation, and data storage. The text also includes a practical user’s guide and explores key areas in which artificial materials have developed. It includes experts’ perspectives on current and future applications of metamaterials, to present a well-rounded view on state-of-the-art technologies.

An Introduction to Metamaterials and Nanophotonics

In the last few decades, metamaterials have revolutionized the ways in which waves are controlled, and applied in physics and practical situations. The extraordinary properties of metamaterials, such as their locally resonant structure with deep subwavelength band gaps and their ranges of frequency where propagation is impossible, have opened the way to a host of applications that were previously unavailable. Aoustic metamaterials have been able to replace traditional treatments in several sectors, due to their better performance in targeted and tunable frequency ranges with strongly reduced dimensions. This is a training book composed of nine chapters written by experts in the field, giving a broad overview of acoustic metamaterials and their uses. The book is divided into three parts, covering the state-of-the-art, the fundamentals and the real-life applications of acoustic metamaterials.

A Convincing and Controversial Alternative Explanation of Metamaterials with a Negative Index of Refraction

In a book that will generate both support and controversy, one of the world’s foremost authorities on periodic structures addresses several of the current fashions in antenna design—most specifically, the popular subject of double negative metamaterials. Professor Munk provides a comprehensive theoretical electromagnetic investigation of the issues and concludes that many of the phenomena claimed by researchers may be impossible. While denying the existence of negative refraction, the author provides convincing alternative explanations for some of the experimental examples in the literature. Although the debate on this subject is just beginning, Professor Munk has received support by various numerical simulations, winning him the encouragement of numerous experts in the field. The issues that are raised here have not been addressed thoroughly by the metamaterials community, and this book will serve as a catalyst for much healthy debate and discussion. Metamaterials: Critique and Alternatives is destined to become a classic resource for graduate students and researchers in electromagnetics, antenna theory, materials research, and chemistry.

Toroidal Metamaterials

The rapid development of technology based on metamaterials coupled with the recent introduction of the transformation optics technique provides an unprecedented ability for device designers to manipulate and control the behavior of electromagnetic wave phenomena. Many of the early metamaterial designs, such as negative index materials and electromagnetic bandgap surfaces, were limited to operation only over a very narrow bandwidth. However, recent groundbreaking work reported by several international research groups on the development of broadband metamaterials has opened up the doors to an exciting frontier in the creation of new devices for applications ranging from radio frequencies to visible wavelengths. This book contains a collection of eight chapters that cover recent cutting-edge contributions to the theoretical, numerical, and experimental aspects of broadband metamaterials.

Hyperbolic Metamaterials

This book covers the theoretical background, experimental methods and implementation details to engineer for communication and imaging application, terahertz devices using metamaterials, in mainstream semiconductor foundry processes. This book will provide engineers and physicists an authoritative reference to construct such devices with minimal background. The authors describe the design and construction of electromagnetic (EM) devices for terahertz frequencies (108-1010 cycles/sec) using artificial materials that are a fraction of the wavelength of the incident EM wave, resulting in an effective electric and magnetic properties (permittivity and permeability) that are unavailable in natural materials.

Waves in Gradient Metamaterials

The purpose of this book is to provide an up-to-date introduction to the time-domain finite element methods for Maxwell’s equations involving metamaterials. Since the first successful construction of a metamaterial with both negative permittivity and permeability in 2000, the study of metamaterials has attracted significant attention from researchers across many disciplines. Thanks to enormous efforts on the part of engineers and physicists, metamaterials present great potential applications in antenna and radar design, sub-wavelength imaging, and invisibility cloak design. Hence the efficient simulation of electromagnetic phenomena in metamaterials has become a very important issue and is the subject of this book, in which various metamaterial modeling equations are introduced and justified mathematically. The development and practical implementation of edge finite element methods for metamaterial Maxwell’s equations are the main focus of the book. The book finishes with some interesting simulations such as backward wave propagation and time-domain cloaking with metamaterials.

Physics and Applications of Negative Refractive Index Materials

Metamaterials: Theory, Design, and Applications goes beyond left-handed materials (LHM) or negative index materials (NIM) and focuses on recent research activity. Included here is an introduction to optical transformation theory, revealing invisible cloaks, EM concentrators, beam splitters, and new-type antennas, a presentation of general theory on artificial metamaterials composed of periodic structures, coverage of a new rapid design method for inhomogeneous metamaterials, which makes it easier to design a
cloak, and new developments including but not limited to experimental verification of invisible cloaks, FDTD simulations of invisible cloaks, the microwave and RF applications of metamaterials, sub-wavelength imaging using anisotropic metamaterials, dynamical metamaterial systems, photonic metamaterials, and magnetic plasmon effects of metamaterials.

**Theory and Design of Acoustic Metamaterials**

The discovery of artificial electromagnetic materials, called metamaterials, not only redefines the human perception of constitutive parameters in electromagnetic theory, but also brings forward new phenomena, such as negative refraction. We provide a comprehensive introduction to the unique characteristics of metamaterials, starting with Maxwell’s equations and the kDB coordinate system, and moving through to theoretical concepts and design principles of negative refraction in metamaterials. For each kind of media, including isotropic, anisotropic and bianisotropic metamaterials, we discuss the characteristic waves and their properties. We show examples of negative refraction both theoretically and experimentally.

**Metamaterials**

This book opens a new avenue to an engendering field of applied physics, located at the OC crossing of modern photonics, electromagnetics, acoustics and material science. It also highlights the concept of non-locality, which proves to be not a special feature of quantum phenomena, but is shown to have an important counterpart in classical physics and its engineering applications too. Furthermore, it visualizes the physical results by means of simple analytical presentations, reduced sometimes to the elementary functions.

**Functional Metamaterials and Metadevices**

Metamaterials have attracted enormous interests from both physics and engineering communities in the past 20 years, owing to their powerful ability in manipulating electromagnetic waves. However, the functionalities of traditional metamaterials are fixed at the time of fabrication. To control the EM waves dynamically, active components are introduced to the meta-atoms, yielding active metamaterials. Recently, a special kind of active metamaterials, digital coding and programmable metamaterials, are proposed, which can achieve dynamically controllable functionalities using field programmable gate array (FPGA). Most importantly, the digital coding representations of metamaterials set up a bridge between the digital world and physical world, and allow metamaterials to process digital information directly, leading to information metamaterials. In this Element, we review the evolution of information metamaterials, mainly focusing on their basic concepts, design principles, fabrication techniques, experimental measurement and potential applications. Future developments of information metamaterials are also envisioned.