Wenshan Cai
Vladimir Shalaev

Optical Metamaterials

Fundamentals and Applications

Springer

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ISBN 978-1-4419-1150-6 e-ISBN 978-1-4419-1151-3
DOI 10.1007/978-1-4419-1151-3
Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2009936791

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Printed on acid-free paper

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To my son Sheling, my wife Yun Tai, and to the memory of my mother, Shuxin Wang (1943–2008).

– Wenshan Cai

To my family and close friends, who keep supporting me through my life and career.

– Vladimir M. Shalaev

Preface

This book deals with optical metamaterials – artificially structured materials with nanoscale inclusions and strikingly unconventional properties at optical frequencies. These materials can be treated as macroscopically homogeneous media and can exhibit a variety of unusual and exciting responses to light. Man-made materials with subwavelength inclusions have been purposely utilized by artists and craftsmen for centuries, as indicated by a number of glass vessels ranging from the late Roman era to the Renaissance period. However, optical metamaterials have flourished only in the present century thanks to combined advances in nanofabrication, numerical modeling, and characterization tools. In only a few years, the field of optical metamaterials has emerged as one of the most exciting topics in the science of light, with stunning and unexpected outcomes that have repeatedly fascinated researchers, scientists, and even the general public.

The philosophy behind the area of optical metamaterials is distinct from most other branches of optical studies in that it does not emphasize the explanation, implementation, or utilization of known phenomena, but rather it focuses on the creation of entirely new stories and new events that no one has even considered. This philosophy is best illustrated by a simple quotation from *Back to Methuselah* by George Bernard Shaw, one of the finest playwrights of the twentieth century. The quote became widespread after its adoption by Robert Kennedy during his presidential campaign:

> "Some men see things as they are and say 'Why?' I dream things that never were and say, 'Why not?'"

Indeed, the persistence of asking "why" has been fascinating scientists throughout the history of optics. From ancient scholars like Euclid, Ptolemy and Alhazen to the modern giants who shaped today's knowledge of optics, the pursuit of answers to observed phenomena has led to major discoveries that have made it possible for us to understand the realities of optics. By combing the knowledge derived from asking "why" and the implementation of available materials, numerous optical components, devices and systems have been developed that have radically altered both the everyday life of people around the globe and the scope of modern science.

With all the advances in optics throughout the ages, now is perhaps the time to focus more on the theme of "why not." It is time to rethink the limits of optics, and reconsider the long-established guidelines within which optical scientists often work. With this in mind, we choose to be bold and adventurous, rethinking the answers to questions such as, “Why not refract light the other way?” Or maybe we should ask, “Why not build a microscope to see a DNA strand with the naked eye?” We can even ponder more mysterious and mythical questions, including, “Why not create a cloak that makes an object invisible?” These concepts are not strictly prohibited by any fundamental physical laws, nor are many other equally fascinating possibilities. Perhaps, then, it is indeed time to explore many truly amazing ideas that may be temporarily beyond our vision, but not inherently beyond our reach.

All the questions above, now open for reconsideration by asking “why not,” are the pursuits of optical metamaterials. In this research field, the control of light is not limited by the properties of optical materials that are readily available. Instead, we choose to create materials that never were, by tailoring the elements of artificial structures down to the deeply subwavelength scale. This aspect of optical metamaterials is bound to revolutionarily alter the design strategies and implementation philosophies that people use in building optical devices and systems. The new research field of optical metamaterials opens a whole new world of fundamental studies and practical applications that were quite undreamt of in the realm of conventional optics. Still in its infancy, the optical metamaterials have already offered hope to the seemingly crazy dreams mentioned above, and they have demonstrated potential benefits in various applications including optical sensing, novel waveguides and antennas, sub-diffraction-limited imaging, nanoscale photolithography, photonic nanocircuits, and many more.

The intense development in the evolving field of optical metamaterials has started attracting an increasing number of students and researchers. Although a large and drastically growing number of publications are constantly added to the literature of this field, we feel there remains a lack of a reader-friendly book that helps to make optical metamaterials accessible to a wider audience. In particular, new participants in a highly interdisciplinary field of study like optical metamaterials can easily get lost if they have to wade through many textbooks of different subjects simultaneously. To describe optical metamaterials in a simple, easy-to-understand way was our primary motivation for embarking on this book.

In writing the book, we sought to provide an accessible entrance into the fascinating world of optical metamaterials. In a relatively slim volume, we are trying to provide students and researchers with the basic knowledge that is required to enter this research area, as well as providing the broad perspective that is now needed to understand the latest breakthroughs. It should be stressed that this book is not intended as a thorough treatise and up-to-date review of all research work available in this field. Instead, the book provides a comprehensive, self-contained but digestible introduction to the basic ideas and major topics in optical metamaterials. We hope that it will be useful to the interested reader as a stepping stone towards more advanced research currently underway in the field. We have tried to produce a balanced text from which the reader will be able to gain a perspective of optical metamaterials as a whole as well as a flavor for where the subject is going.

We now would like to take a moment to guide you through the contents of this book. The material in the book is presented in an order that aims to progressively increase the reader's comprehension of the subject. The book starts with a discussion of the definition, emergence, motivation and scope of the research field of optical metamaterials. Then in Chap. 2 we discuss the optical properties of metals, dielectrics and their composites. The delicate arrangement of these materials forms the constituent building blocks for the metamaterials we are truly interested in studying. Chapter 3 covers the fabrication techniques, characterization schemes and data treatment methods for optical metamaterials. Once the basics have been established, from Chap. 4–6 we present three major categories of optical metamaterials, namely electric metamaterials, magnetic metamaterials, and negative-index metamaterials. The principles, advances, and examples for each category will be analyzed in detail. The last three chapters deal with exciting novel opportunities made possible by optical metamaterials. In Chap. 7 we discuss nonlinear effects in optical metamaterials, including the necessary mathematical descriptions. Chapter 8 describes metamaterial-based imaging systems with subwavelength resolution. Most notably, several milestone experiments related to super-resolution in both the near- and far-field regimes are discussed. Finally, in Chap. 9 we provide the principles and applications of transformation optics, which molds the flow of light in an unprecedented manner by specifying the spatial distributions of anisotropic material parameters. In particular, this chapter gives a detailed discussion of the most intriguing outcome of transformation optics – an electromagnetic cloak of invisibility.

We have attempted to introduce most of the major subjects involved in optical metamaterials while at the same time keeping the book within a relatively small compass. Although the frontier in the study of optical metamaterials is developing rapidly, the basic knowledge and ways of thinking presented in this book are expected to be widely adopted in many of the new topics of optical metamaterials that are either ongoing or about to breach the horizon. The book can be used as a reference text by people working in metamaterials, plasmonics, nanophotonics, and other related fields. It can also be used as a course textbook or a book for self-instruction at the senior undergraduate or graduate level, as well as for a short course offered by a professional society. As such, the book presumes that the reader has a general knowledge of basic electrodynamics at the undergraduate level.

This book would not have been completed without the help of many people. In particular, we are deeply grateful to Mark Thoreson for his painstaking review and critical proofreading of the entire manuscript. We are also thankful for the support and helpful suggestions from Professor Mark Brongersma at Stanford University.

In addition, it is a pleasure to acknowledge our debt and gratitude to many colleagues whose expertise, discussions, and collaboration have benefited us over the years. These include Drs. A. V. Kildishev, A. K. Sarychev, V. P. Drachev, A. K. Popov, U. K. Chettiar, H.-K. Yuan, I. R. Gabitov, S. A. Myslivets, N. M. Litchinitser, E. E. Narimanov, A. E. Boltasseva, T. A. Klar, Sir J. B. Pendry, V. G. Veselago,

X. Zhang, D. R. Smith, M. Wegener, N. Engheta, N. I. Zheludev, U. Leonhardt, M. A. Noginov, V. A. Podolskiy, G. W. Milton, D. H. Werner, I. C. Khoo, A. I. Maimistov, R. Z. Sagdeev, D. A. Genov, A. Boardman, and I. I. Smolyaninov. We are also grateful to our families and close friends for their support.

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Metamaterials—artificially structured materials with engineered electromagnetic properties—have enabled unprecedented flexibility in manipulating electromagnetic waves and producing new functionalities. In just a few years, the field of optical metamaterials has emerged as one of the most exciting topics in the science of light, with stunning and unexpected outcomes that have fascinated scientists and the general public alike.

This volume 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. *Optical Metamaterials* will serve as a very timely book for both newcomers and advanced researchers in this rapidly evolving field.

Early praise for *Optical Metamaterials:*

"...this book is timely bringing to students and other new entrants to the field the most up to date concepts. The authors are amongst the leaders in the field and ideally positioned to write such a comprehensive volume: their enthusiasm shines through every chapter of the text. This book will I am sure play an important part in taking the subject of metamaterials to new heights of invention and application. We should all have a copy on our shelves."

— *Professor Sir John Pendry, Imperial College London*

"This book provides an understandable introduction to the field of optical metamaterials, including all the necessary background and a comprehensive review of this new paradigm in the science of light. Professor Shalaev, a world-leading expert in optics and metamaterials, and his former student, Dr. Cai, a rising star in his own right, have skillfully developed a volume that will prove important for both experts and students just entering the exciting field of photonic metamaterials and transformation optics. This book will certainly find a place within easy reach on my shelf."

— *Professor Victor G. Veselago, A.M.Prokhorov Institute of General Physics, Moscow*

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ISBN 978-1-4419-1150-6

EAN

9 781441 911506 >

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