ELSEVIER

EMIL WOLF

EDITOR

PROGRESS IN OPTICS

VOLUME 51

CONTRIBUTORS

G. Björk, J.J.M. Braat, E. Brambilla, S. Cattaneo, P. Dirksen, I.R. Gabitov, A. Gatti, A.J.E.M. Janssen, M. Kauranen, A.B. Klimov, A. Lakhtakia, N.M. Litchinitser, L. Lugiato, T.G. Mackay, A.I. Maimistov, C.R. Pollock, L.L. Sánchez-Soto, V.M. Shalaev, S. Van Haver

PROGRESS IN OPTICS

VOLUME 51

EDITED BY

E. Wolf

University of Rochester, N.Y., U.S.A.

Contributors

G. Björk, J.J.M. Braat, E. Brambilla, S. Cattaneo, P. Dirksen, I.R. Gabitov, A. Gatti, A.J.E.M. Janssen, M. Kauranen, A.B. Klimov, A. Lakhtakia, N.M. Litchinitser, L. Lugiato, T.G. Mackay, A.I. Maimistov, C.R. Pollock, L.L. Sánchez-Soto, V.M. Shalaev, S. van Haver

ELSEVIER

Amsterdam · Boston · Heidelberg · London · New York · Oxford · Paris
San Diego · San Francisco · Singapore · Sydney · Tokyo

Elsevier
Radarweg 29, PO Box 211, 1000 AE Amsterdam, The Netherlands
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK

First edition 2008

Library of Congress Catalog Card number: 61-19297

ISBN: 978-0-444-53211-4
ISSN: 0079-6638

Transferred to Digital Printing in 2008

PROGRESS IN OPTICS

VOLUME 51

Preface

This volume presents seven review articles that cover a broad range of topics of current research interest in optics.

The first article by N.M. Litchinitser, I.R. Gabitov, A.I. Maimistov and V.M. Shalaev presents a review of theoretical as well as experimental research on metamaterials. Such materials have negative refractive index, making it possible to produce unusual effects that cannot be produced with ordinary materials. They include inverse geometrical optics effects, new types of modes in pulse propagation and new kinds of nonlinear interactions, for example.

The second article by M. Kauranen and S. Cattaneo reviews recent research on the use of polarization techniques in surface nonlinear optics. The techniques which are described in this article make it possible to determine, with great accuracy, various parameters and also to obtain qualitative information about the sample. The techniques can also be used to separate part of the multi-polar bulk background signal from surface contributions, which has been a longstanding problem in nonlinear surface optics.

The third article by T.G. Mackay and A. Lakhtakia is concerned with electromagnetic fields in linear bianisotropic media. In such media the fields $\boldsymbol{D}$ and $\boldsymbol{H}$ are coupled anisotropically to both the fields $\boldsymbol{E}$ and $\boldsymbol{B}$. The article discusses the properties of the electromagnetic fields in media of this kind, including constitutive relations, plane-wave propagation, Green's function and the realizations of bianisotropic media by the process of homogenization.

The next article by C.R. Polock presents a review in the field of ultrafast optical pulses. There has been great progress made on this area; the generation and applications of ultrafast pulses has grown from nanosecond pulses in the 1960s to attosecond pulses today. In this chapter the general principles behind the generation of ultrashort pulses are reviewed and some of their applications are discussed.

The fifth article by A. Gatti, E. Brambilla and L. Lugiato gives an overview of the relatively new field of quantum imagery. The quantum aspects of optical spatial pattern is first explained, followed by discussion of spatial intensity correlations. The so-called ghost imaging is also treated, followed by an account of image amplification by parametric down conversion. The article also included discussion of quantum laser pointers, which allow detection of displacement of a laser beam with a precision beyond the standard quantum limit.

The article which follows, by J.J.M. Braat, S. van Haver, A.J.E.M. Janssen and P. Dirksen, deals with the analysis and efficient computational techniques for determining point-spread functions of optical systems in the presence of aberrations. The article describes an extension of the Nijboer–Zernike diffraction theory of aberrations, including strong defocusing and vector diffraction effects. The extension makes it possible to determine intensity distribution in the focal region in focusing systems of high numerical aperture. It is shown that analytical expressions for the three-dimensional intensity distribution may be used to solve some inverse imaging problems. Both numerical and experimental examples of the inverse procedure are presented.

The concluding article by G. Björk, A.B. Klimov and L.L. Sánchez-Soto is concerned with the discrete Wigner function and with some of its uses. The continuous Wigner function has found numerous applications in many branches of physics. Its discrete counterpart is of more recent origin. It has a rich mathematical structure and has useful applications, for example, in quantum computing, in quantum cryptography and in connection with entanglement.

From the above remarks it is clear that this volume presents results of both basic and applied current research in broad areas of optics.

Emil Wolf

Department of Physics and Astronomy,
University of Rochester,
Rochester, NY 14627, USA

September 2007

Contents

E. Wolf, Progress in Optics 51

Chapter 1

Negative refractive index metamaterials in optics

by

Natalia M. Litchinitser

Department of Electrical Engineering and Computer Science, University of Michigan, 2200 Bonisteel Boulevard, 3113 ERB1, Ann Arbor, Michigan 48109, USA
e-mail: natashan@eecs.umich.edu

Ildar R. Gabitov

Department of Mathematics, University of Arizona, 617 North Santa Rita Avenue, Tucson, Arizona 85721, USA

Andrei I. Maimistov

Department of Solid State Physics, Moscow Engineering Physics Institute, Kashirskoe sh. 31, Moscow 115409, Russian Federation

Vladimir M. Shalaev

School of Electrical and Computer Engineering and Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA

ISSN: 0079-6638 DOI: 10.1016/S0079-6638(07)51001-2

Contents

§ 1. Introduction

Recent advances in nanofabrication have led to the demonstration of a novel class of optical materials – metamaterials – that are artificially engineered structures with electromagnetic properties unattainable in nature. One of the most fascinating examples of such structures is negative-index metamaterials (NIMs). The emergence of optical metamaterials opens up fundamentally new regimes of light–matter interaction and prompts unique opportunities for manipulating light.

Over the last seven years there has been enormous progress in the field of NIMs from both theoretical and experimental viewpoints (Ramakrishna [2005], Veselago, Braginsky, Shklover and Hafner [2006]). The latest developments in the field of negative refraction and microwave/terahertz NIMs have been reviewed by Pendry [2004], Smith, Pendry and Wiltshire [2004], Boardman, King and Velasco [2005] and others. Recent advancements in the studies of highly unusual linear properties of optical NIMs have been discussed by Veselago and Narimanov [2006], Agranovich and Gartstein [2006], and Klar, Kildishev, Drachev and Shalaev [2006]. Some remarkable nonlinear properties of NIMs have been highlighted in the recent *Nature Photonics* article by Shalaev [2007]. In this review we intend to present a comprehensive overview of the state of the art in the design and fabrication of NIMs at optical frequencies, their linear and nonlinear properties, and potential applications of optical NIMs and a more general class of optical metamaterials.

1.1. Ambidextrous light in a left-handed world

The propagation of electromagnetic waves in optical media is determined by two material parameters: dielectric permittivity ε and magnetic permeability μ, related to the refractive index n through $n = \sqrt{\varepsilon\mu}$. Figure 1a shows a diagram of all possible combinations of ε and μ. The majority of conventional materials belongs to region I where $\varepsilon > 0$ and $\mu > 0$ corresponding to $n > 0$, where propagating waves are allowed. It is noteworthy that the magnetic susceptibility of most natural materials is very small in comparison with their dielectric sus-

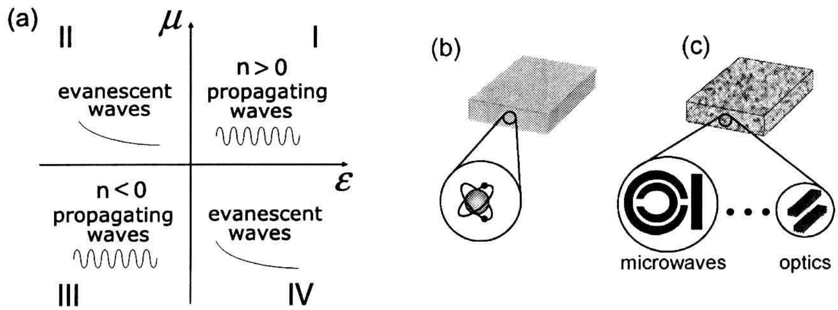

Fig. 1. (a) A diagram of all possible combinations of dielectric permittivity ε and magnetic permeability μ. (b) A conventional material built of regular atoms. (c) A metamaterial built of "meta-atoms".

ceptibility, thus limiting the interaction of atoms to the electric component of the electromagnetic wave, leaving the magnetic component largely unexploited. Indeed, μ is close to unity for many naturally existing materials. The reason for this difference in the strength of electric and magnetic field coupling to atoms is that the magnetization of any (non-ferromagnetic) material is a relativistic effect, of the order $\sim v^2/c^2 \sim \alpha^2 \ll 1$, where v is the velocity of the electrons in the atoms, and $\alpha \cong 1/137$ is the fine-structure constant (Landau, Lifshitz and Pitaevskii [1984]). Magnetism is particularly weak at optical frequencies because the relaxation times of paramagnetic and ferromagnetic processes are significantly longer than the optical period, leaving the electron movement in atoms as the only mechanism for the magnetic response. As a result, the magnetic field component is usually not involved in light–matter interactions. Only at very high intensities of $\sim 10^{18}$ W/cm^2 do the effects of the magnetic and electric fields on the electron motion become comparable, giving rise to a number of new effects such as the photon-drag effect (Wegener [2005]) and nonlinear Thomson scattering or Larmor radiation (Wegener [2005], Chen, Maksimchuk and Umstadter [1998]).

The second ($\varepsilon < 0$ and $\mu > 0$) and fourth ($\varepsilon > 0$ and $\mu < 0$) quarters of the diagram in fig. 1 correspond to opaque materials that cannot support any propagating waves. However, materials with parameters corresponding to the third quarter of the diagram ($\varepsilon < 0$ and $\mu < 0$) are transparent and allow wave propagation. While the dielectric permittivity of some naturally occurring materials is negative in certain frequency ranges (e.g. metals including gold, silver and aluminum possess negative ε at the visible and near-ultraviolet frequencies), no isotropic materials with negative μ are readily available. Some antiferromagnets and insulating ferromagnets have been shown to provide negative effective magnetic permeability (Campley and Mills [1982], Hartstein, Burstein, Maradudin, Brewer