

Springer Series in
MATERIALS SCIENCE

Editors: R. Hull R. M. Osgood, Jr. J. Parisi H. Warlimont

The Springer Series in Materials Science covers the complete spectrum of materials physics, including fundamental principles, physical properties, materials theory and design. Recognizing the increasing importance of materials science in future device technologies, the book titles in this series reflect the state-of-the-art in understanding and controlling the structure and properties of all important classes of materials.

- | | | | |
|----|--|-----|---|
| 88 | Introduction to Wave Scattering, Localization and Mesoscopic Phenomena
By P. Sheng | 96 | GaN Electronics
By R. Quay |
| 89 | Magneto-Science
Magnetic Field Effects on Materials:
Fundamentals and Applications
Editors: M. Yamaguchi and Y. Tanimoto | 97 | Multifunctional Barriers for Flexible Structure
Textile, Leather and Paper
Editors: S. Duquesne, C. Magniez,
and G. Camino |
| 90 | Internal Friction in Metallic Materials
A Reference Book
By M.S. Blanter, I.S. Golovin,
H. Neuhäuser, and H.-R. Sinning | 98 | Physics of Negative Refraction and Negative Index Materials
Optical and Electronic Aspects
and Diversified Approaches
Editors: C.M. Krowne and Y. Zhang |
| 91 | Time-dependent Mechanical Properties of Solid Bodies
By W. Gräfe | 99 | Self-Organized Morphology in Nanostructured Materials
Editors: K. Al-Shamery and J. Parisi |
| 92 | Solder Joint Technology
Materials, Properties, and Reliability
By K.-N. Tu | 100 | Self Healing Materials
An Alternative Approach
to 20 Centuries of Materials Science
Editor: S. van der Zwaag |
| 93 | Materials for Tomorrow
Theory, Experiments and Modelling
Editors: S. Gemming, M. Schreiber
and J.-B. Suck | 101 | New Organic Nanostructures for Next Generation Devices
Editors: K. Al-Shamery, H.-G. Rubahn,
and H. Sitter |
| 94 | Magnetic Nanostructures
Editors: B. Aktas, L. Tagirov,
and F. Mikailov | 102 | Photonic Crystal Fibers
Properties and Applications
By F. Poli, A. Cucinotta,
and S. Selleri |
| 95 | Nanocrystals and Their Mesoscopic Organization
By C.N.R. Rao, P.J. Thomas
and G.U. Kulkarni | 103 | Polarons in Advanced Materials
Editor: A.S. Alexandrov |

Volumes 40–87 are listed at the end of the book.

C.M. Krowne Y. Zhang (Eds.)

Physics of Negative Refraction and Negative Index Materials

Optical and Electronic Aspects
and Diversified Approaches

With 228 Figures

 Springer

Dr. Clifford M. Krowne

Code 6851, Microwave Technology Branch
Electronics Science and Technology Division, Naval Research Laboratory
Washington, DC 20375-5347, USA
E-mail: krowne@webbsight.nrl.navy.mil

Dr. Yong Zhang

Materials Science Center, National Renewable Energy Laboratory (NREL)
1617 Cole Blvd., Golden, CO 80401, USA
E-mail: Yong_Zhang@nrel.gov

Series Editors:

Professor Robert Hull

University of Virginia
Dept. of Materials Science and Engineering
Thornton Hall
Charlottesville, VA 22903-2442, USA

Professor Jürgen Parisi

Universität Oldenburg, Fachbereich Physik
Abt. Energie- und Halbleiterforschung
Carl-von-Ossietzky-Strasse 9-11
26129 Oldenburg, Germany

Professor R. M. Osgood, Jr.

Microelectronics Science Laboratory
Department of Electrical Engineering
Columbia University
Seeley W. Mudd Building
New York, NY 10027, USA

Professor Hans Warlimont

Institut für Festkörper-
und Werkstofforschung,
Helmholtzstrasse 20
01069 Dresden, Germany

ISSN 0933-033X

ISBN 978-3-540-72131-4 Springer Berlin Heidelberg New York

Library of Congress Control Number: 2007925169

All rights reserved.

No part of this book may be reproduced in any form, by photostat, microfilm, retrieval system, or any other means, without the written permission of Kodansha Ltd. (except in the case of brief quotation for criticism or review.)

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

Springer is a part of Springer Science+Business Media.

© Springer-Verlag Berlin Heidelberg 2007

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Typesetting: Data prepared by SPI Kolam using a Springer TeX macro package

Cover: eStudio Calamar Steinen

Printed on acid-free paper SPIN: 11810377 57/3180/SPI 5 4 3 2 1 0

Preface

There are many potentially interesting phenomena that can be obtained with wave refraction in the “wrong” direction, what is commonly now referred to as negative refraction. All sorts of physically new operations and devices come to mind, such as new beam controlling components, reflectionless interfaces, flat lenses, higher quality lens or “super lenses,” reversal of lenses action, new imaging components, redistribution of energy density in guided wave components, to name only a few of the possibilities. Negative index materials are generally, but not always associated with negative refracting materials, and have the added property of having the projection of the power flow or Poynting vector opposite to that of the propagation vector. This attribute enables the localized wave behavior on a subwavelength scale, not only inside lenses and in the near field outside of them, but also in principle in the far field of them, to have field reconstruction and localized enhancement, something not readily found in ordinary matter, referred to as positive index materials.

Often investigators have had to create, even when using positive index materials, interfaces based upon macroscopic or microscopic layers, or even heterostructure layers of materials, to obtain the field behavior they are seeking. For obtaining negative indices of refraction, microscopic inclusions in a host matrix material have been used anywhere from the photonic crystal regime all the way into the metamaterial regime. These regimes take one from the wavelength size on the order of the separation between inclusions to that where many inclusions are sampled by a wavelength of the electromagnetic field. Generally in photonic crystals and metamaterials, a Brillouin zone in reciprocal space exists due to the regular repetitive pattern of unit cells of inclusions, where each unit cell contains an arrangement of inclusions, in analogy to that seen in natural materials made up of atoms. Only here, the arrangements consist of artificial “atoms” constituting an artificial lattice.

The first two chapters of this book (Chaps. 1 and 2) address the use of uniform media to generate the negative refraction, and examine what happens

to optical waves in crystals, electron waves in heterostructures, and guided waves in bicrystals. The first chapter also contrasts the underlying physics in various approaches adopted or proposed for achieving negative refraction and examines the effects of anisotropy, as does the second chapter for negative index materials (left-handed materials). Obtaining left-handed material behavior by utilizing a permeability tensor modification employing magnetic material inclusions is investigated in Chap. 3. Effects of spatial dispersion in the permittivity tensor can be important to understanding excitonic–electromagnetic interactions (exciton–polaritons) and their ability to generate negative indices and negative refraction. This and other polariton issues are discussed in Chap. 4.

The next group of chapters, Chaps. 5 and 6, in the book looks at negative refraction in photonic crystals. This includes studying the effects in the microwave frequency regime on such lattices constructed as flat lenses or prisms, in two dimensional arrangements of inclusions, which may be of dielectric or metallic nature, immersed in a dielectric host medium, which could be air or vacuum. Even slight perturbations or crystalline disorder effects can be studied, as is done in Chap. 7 on quasi-crystals. Analogs to photonic fields do exist in mechanical systems, and Chap. 8 examines this area for acoustic fields which in the macroscopic sense are phonon fields on the large scale.

Finally, the last group of chapters investigates split ring resonator and wire unit cells to make metamaterials for creation of negative index materials. Chapter 9 does this as well as treating some of the range between metamaterials and photonic crystals by modeling and measuring split ring resonators and metallic disks. Chapter 10 looks at the effects of the split ring resonator and wire unit cells on left-handed guided wave propagation, finding very low loss frequency bands. Designing and fabricating split ring resonator and wire unit cells for lens applications is the topic of Chap. 11. This chapter has extensive modeling studies of various configurations of the elements and arrangements of their rectangular symmetry system lattice. The last chapter in this group and of the book, Chap. 12, delves into the area of nonlinear effects, expected with enhanced field densities in specific areas of the inclusions. For example, field densities may be orders of magnitude higher in the vicinity of the gaps in the split rings, than elsewhere, and it is here that a material could be pushed into its nonlinear regime.

The chapters here all report on recent research within the last few years, and it is expected that the many interesting fundamental scientific discoveries that have occurred and the applications which have resulted from them on negative index of refraction and negative index materials, will have a profound effect on the technology of the future. The contributors to this book prepared their chapters coming from very diversified backgrounds, and as such, provide the reader with unique perspectives toward the subject matter. Although the chapters are presented in the context of negative refraction and related

phenomena, the contributions should be found relevant to broad areas in fundamental physics and material science beyond the original context of the research. We expect this area to continue to yield new discoveries, applications, and insertion into devices and components as time progresses.

Washington and Golden, June 2007

Clifford M. Krowne
Yong Zhang

Contents

1 Negative Refraction of Electromagnetic and Electronic Waves in Uniform Media	
<i>Y. Zhang and A. Mascarenhas</i>	1
1.1 Introduction	1
1.1.1 Negative Refraction	1
1.1.2 Negative Refraction with Spatial Dispersion	3
1.1.3 Negative Refraction with Double Negativity	4
1.1.4 Negative Refraction Without Left-Handed Behavior	5
1.1.5 Negative Refraction Using Photonic Crystals	6
1.1.6 From Negative Refraction to Perfect Lens	6
1.2 Conditions for Realizing Negative Refraction and Zero Reflection	8
1.3 Conclusion	15
References	16
2 Anisotropic Field Distributions in Left-Handed Guided Wave Electronic Structures and Negative Refractive Bicrystal Heterostructures	
<i>C.M. Krowne</i>	19
2.1 Anisotropic Field Distributions in Left-Handed Guided Wave Electronic Structures	19
2.1.1 Introduction	19
2.1.2 Anisotropic Green's Function Based Upon LHM or DNM Properties	21
2.1.3 Determination of the Eigenvalues and Eigenvectors for LHM or DNM	32
2.1.4 Numerical Calculations of the Electromagnetic Field for LHM or DNM	42
2.1.5 Conclusion	65
2.2 Negative Refractive Bicrystal Heterostructures	66
2.2.1 Introduction	66
2.2.2 Theoretical Crystal Tensor Rotations	67

2.2.3	Guided Stripline Structure	67
2.2.4	Beam Steering and Control Component Action	67
2.2.5	Electromagnetic Fields	69
2.2.6	Surface Current Distributions	70
2.2.7	Conclusion	72
	References	72

3 “Left-Handed” Magnetic Granular Composites

	<i>S.T. Chui, L.B. Hu, Z. Lin and L. Zhou</i>	75
3.1	Introduction	75
3.2	Description of “Left-Handed” Electromagnetic Waves: The Effect of the Imaginary Wave Vector	76
3.3	Electromagnetic Wave Propagations in Homogeneous Magnetic Materials	78
3.4	Some Characteristics of Electromagnetic Wave Propagation in Anisotropic “Left-Handed” Materials	80
3.4.1	“Left-Handed” Characteristic of Electromagnetic Wave Propagation in Uniaxial Anisotropic “Left-Handed” Media	80
3.4.2	Characteristics of Refraction of Electromagnetic Waves at the Interfaces of Isotropic Regular Media and Anisotropic “Left-Handed” Media	85
3.5	Multilayer Structures Left-Handed Material: An Exact Example	88
	References	93

4 Spatial Dispersion, Polaritons, and Negative Refraction

	<i>V.M. Agranovich and Yu.N. Gartstein</i>	95
4.1	Introduction	95
4.2	Nature of Negative Refraction: Historical Remarks	97
4.2.1	Mandelstam and Negative Refraction	97
4.2.2	Cherenkov Radiation	100
4.3	Maxwell Equations and Spatial Dispersion	102
4.3.1	Dielectric Tensor	102
4.3.2	Isotropic Systems with Spatial Inversion	105
4.3.3	Connection to Microscopics	106
4.3.4	Isotropic Systems Without Spatial Inversion	110
4.4	Polaritons with Negative Group Velocity	111
4.4.1	Excitons with Negative Effective Mass in Nonchiral Media	111
4.4.2	Chiral Systems in the Vicinity of Excitonic Transitions	114
4.4.3	Chiral Systems in the Vicinity of the Longitudinal Frequency	116
4.4.4	Surface Polaritons	118
4.5	Magnetic Permeability at Optical Frequencies	121
4.5.1	Magnetic Moment of a Macroscopic Body	122

4.6	Related Interesting Effects	127
4.6.1	Generation of Harmonics from a Nonlinear Material with Negative Refraction	127
4.6.2	Ultra-Short Pulse Propagation in Negative Refraction Materials	128
4.7	Concluding Remarks	129
	References	130
5 Negative Refraction in Photonic Crystals		
	<i>W.T. Lu, P. Vodo, and S. Sridhar</i>	133
5.1	Introduction	133
5.2	Materials with Negative Refraction	134
5.3	Negative Refraction in Microwave Metallic Photonic Crystals	135
5.3.1	Metallic PC in Parallel-Plate Waveguide	135
5.3.2	Numerical Simulation of TM Wave Scattering	140
5.3.3	Metallic PC in Free Space	141
5.3.4	High-Order Bragg Waves at the Surface of Metallic Photonic Crystals	144
5.4	Conclusion and Perspective	145
	References	146
6 Negative Refraction and Subwavelength Focusing in Two-Dimensional Photonic Crystals		
	<i>E. Ozbay and G. Ozkan</i>	149
6.1	Introduction	149
6.2	Negative Refraction and Subwavelength Imaging of TM Polarized Electromagnetic Waves	150
6.3	Negative Refraction and Point Focusing of TE Polarized Electromagnetic Waves	154
6.4	Negative Refraction and Focusing Analysis for a Metallodielectric Photonic Crystal	157
6.5	Conclusion	162
	References	163
7 Negative Refraction and Imaging with Quasicrystals		
	<i>X. Zhang, Z. Feng, Y. Wang, Z.-Y. Li, B. Cheng and D.-Z. Zhang</i>	167
7.1	Introduction	167
7.2	Negative Refraction by High-Symmetric Quasicrystal	168
7.3	Focus and Image by High-Symmetric Quasicrystal Slab	172
7.4	Negative Refraction and Focusing of Acoustic Wave by High-Symmetric Quasiperiodic Phononic Crystal	179
7.5	Summary	180
	References	181

8 Generalizing the Concept of Negative Medium to Acoustic Waves

J. Li, K.H. Fung, Z.Y. Liu, P. Sheng and C.T. Chan 183

8.1 Introduction 183

8.2 A Simple Model 186

8.3 An Example of Negative Mass 190

8.4 Acoustic Double-Negative Material 193

 8.4.1 Construction of Double-Negative Material
 by Mie Resonances 197

8.5 Focusing Effect Using Double-Negative
 Acoustic Material 205

8.6 Focusing by Uniaxial Effective Medium Slab 205

References 215

9 Experiments and Simulations of Microwave Negative Refraction in Split Ring and Wire Array Negative Index Materials, 2D Split-Ring Resonator and 2D Metallic Disk Photonic Crystals

F.J. Rachford, D.L. Smith and P.F. Loschialpo 217

9.1 Introduction 217

9.2 Theory 219

9.3 FDTD Simulations in an Ideal Negative Index Medium 220

9.4 Simulations and Experiments with Split-Ring Resonators
 and Wire Arrays 223

9.5 Split-Ring Resonator Arrays as a 2D Photonic Crystal 226

9.6 Hexagonal Disk Array 2D Photonic Crystal Simulations:
 Focusing 231

9.7 Modeling Refraction Through the Disk Medium 236

9.8 Hexagonal Disk Array Measurements – Transmission
 and Focusing 240

9.9 Hexagonal Disk Array Measurements – Refraction 242

9.10 Conclusions 248

References 248

10 Super Low Loss Guided Wave Bands Using Split Ring Resonator-Rod Assemblies as Left-Handed Materials

C.M. Krowne 251

10.1 Introduction 251

10.2 Metamaterial Representation 252

10.3 Guiding Structure 255

10.4 Numerical Results 257

10.5 Conclusions 258

References 259

11 Development of Negative Index of Refraction Metamaterials with Split Ring Resonators and Wires for RF Lens Applications	
<i>C.G. Parazzoli, R.B. Gregor and M.H. Tanielian</i>	261
11.1 Electromagnetic Negative Index Materials	261
11.1.1 The Physics of NIMs	262
11.1.2 Design of the NIM Unit Cell	264
11.1.3 Origin of Losses in Left-Handed Materials	266
11.1.4 Reduction in Transmission Due to Polarization Coupling	270
11.1.5 The Effective Medium Limit	272
11.1.6 NIM Indefinite Media and Negative Refraction	272
11.2 Demonstration of the NIM Existence Using Snell's Law	277
11.3 Retrieval of ϵ_{eff} and μ_{eff} from the Scattering Parameters	281
11.3.1 Homogeneous Effective Medium	282
11.3.2 Lifting the Ambiguities	283
11.3.3 Inversion for Lossless Materials	286
11.3.4 Periodic Effective Medium	287
11.3.5 Continuum Formulation	288
11.4 Characterization of NIMs	289
11.4.1 Measurement of NIM Losses	289
11.4.2 Experimental Confirmation of Negative Phase Shift in NIM Slabs	290
11.5 NIM Optics	295
11.5.1 NIM Lenses and Their Properties	295
11.5.2 Aberration Analysis of Negative Index Lenses	296
11.6 Design and Characterization of Cylindrical NIM Lenses	299
11.6.1 Cylindrical NIM Lens in a Waveguide	300
11.7 Design and Characterization of Spherical NIM Lenses	305
11.7.1 Characterization of the Empty Aperture	305
11.7.2 Design and Characterization of the PIM lens	307
11.7.3 Design and Characterization of the NIM Lens	308
11.7.4 Design and Characterization of the GRIN Lens	311
11.7.5 Comparison of Experimental Data for Empty Aperture, PIM, NIM, and GRIN Lenses	314
11.7.6 Comparison of Simulated and Experimental Aberrations for the PIM, NIM, and GRIN Lenses	317
11.7.7 Weight Comparison Between the PIM, NIM, and GRIN Lenses	327
11.8 Conclusion	327
References	328
12 Nonlinear Effects in Left-Handed Metamaterials	
<i>I.V. Shadrivov and Y.S. Kivshar</i>	331
12.1 Introduction	331

XIV Contents

12.2	Nonlinear Response of Metamaterials	333
12.2.1	Nonlinear Magnetic Permeability	334
12.2.2	Nonlinear Dielectric Permittivity	336
12.2.3	FDTD Simulations of Nonlinear Metamaterial	337
12.2.4	Electromagnetic Spatial Solitons	340
12.3	Kerr-Type Nonlinear Metamaterials	343
12.3.1	Nonlinear Surface Waves	343
12.3.2	Nonlinear Pulse Propagation and Surface-Wave Solitons . .	349
12.3.3	Nonlinear Guided Waves in Left-Handed Slab Waveguide . .	351
12.4	Second-Order Nonlinear Effects in Metamaterials	355
12.4.1	Second-Harmonics Generation	355
12.4.2	Enhanced SHG in Double-Resonant Metamaterials	363
12.4.3	Nonlinear Quadratic Flat Lens	367
12.5	Conclusions	369
	References	370
	Index	373

List of Contributors

Vladimir M. Agranovich

The University of Texas at Dallas
NanoTech Institute
Richardson, TX 75083-0688 USA

and

Institute of Spectroscopy
Russian Academy of Sciences
Troitsk, Moscow obl. 142190, Russia
vladimir.agranovich@utdallas.edu

Che Ting Chan

Physics Department
Hong Kong University of Science
and Technology
Clear Water Bay, Hong Kong, China
phchan@ust.hk

Bingying Cheng

Institute of Physics
Chinese Academy of Sciences
Beijing 100080

Siu-Tat Chui

Department of Physics
and Astronomy
University of Delaware
Newark, DE 19716, USA
chui@bartol.udel.edu

Zhifang Feng

Institute of Physics
Chinese Academy of Sciences
Beijing 100080

K.H. Fung

Physics Department
Hong Kong University of Science
and Technology
Clear Water Bay, Hong Kong, China

Yuri N. Gartstein

Department of Physics
The University of Texas at Dallas
Richardson, Texas 75083, USA

Robert B. Greegor

Boeing Phantom Works
Seattle, WA 98124
Robert.b.greegor@boeing.com

L.B. Hu

Bartol Research Institute
and Department of Physics
and Astronomy
University of Delaware
Newark, DE 19711, USA

Yuri S. Kivshar

Nonlinear Physics Centre and Center
for Ultra-High Bandwidth Devices
for Optical Systems (CUDOS)
Research School of Physical Sciences
and Engineering
Australian National University
Canberra, ACT 0200, Australia
ysk@internode.on.net

Clifford M. Krowne

Microwave Technology Branch
Electronics Science and Technology
Division
Naval Research Laboratory
Washington, DC 20375-5347
krowne@webbsight.nrl.navy.mil

Jensen Li

Physics Department
Hong Kong University of Science
and Technology
Clear Water Bay, Hong Kong, China

Zhi-Yuan Li

Institute of Physics
Chinese Academy of Sciences
Beijing 100080

Zifang Lin

Bartol Research Institute
and Department of Physics
and Astronomy
University of Delaware
Newark, DE 19711, USA

Z.Y. Liu

Physics Department
Wuhan University
Wuhan, China

Peter F. Loschialpo

Naval Research Laboratory
Washington, DC 20375

Wentao Lu

Department of Physics
and Electronic Materials
Research Institute
Northeastern University
Boston, MA 02115, USA
w.lu@neu.edu

Angelo Mascarenhas

Materials Science Center
National Renewable Energy
Laboratory (NREL)
1617 Cole Blvd.
Golden, CO 80401, USA

Ekmel Ozbay

Nanotechnology Research Center
Department of Physics
and Department of Electrical
and Electronics Engineering
Bilkent University
Bilkent, 06800 Ankara, Turkey
ozbay@bilkent.edu.tr

Gonca Ozkan

Nanotechnology Research Center
Bilkent University
Bilkent 06800, Ankara, Turkey

Claudio G. Parazzoli

Boeing Phantom Works
Seattle, WA 98124

Frederic Rachford

Material Science and Technology
Division
Naval Research Laboratory
Washington, DC 20375
rachford@anvil.nrl.navy.mil

Ilya V. Shadrivov

Nonlinear Physics Centre
Research School of Physical Sciences
and Engineering
Australian National University
Canberra ACT 0200, Australia

Ping Sheng

Physics Department
Hong Kong University of Science
and Technology
Clear Water Bay, Hong Kong, China

Douglas L. Smith

Naval Research Laboratory
Washington, DC 20375

Srinivas Sridhar

Vice Provost for Research
Director, Electronic Materials
Research Institute
Arts and Sciences Distinguished
Professor of Physics
Northeastern University
360 Huntington Avenue,
Boston, MA 02115, USA
ssridhar@neu.edu

Minas H. Tanielian

Boeing Phantom Works
Seattle, WA 98124

P. Vodo

Department of Physics
and Electronic Materials
Research Institute
Northeastern University
Boston, MA 02115, USA

Yiquan Wang

Institute of Physics
Chinese Academy of Sciences
Beijing 100080

Dao-Zhong Zhang

Institute of Physics
Chinese Academy of Sciences
Beijing 100080

Xiangdong Zhang

Beijing Normal University
Beijing 100875, China
zhangxd@bnu.edu.cn

Yong Zhang

Materials Science Center
National Renewable Energy
Laboratory (NREL)
1617 Cole Blvd.
Golden, CO 80401
Yong.Zhang@nrel.gov

Lei Zhou

Bartol Research Institute
and Department of Physics
and Astronomy
University of Delaware
Newark, DE 19711, USA