Tutorials in
Complex Photonic Media

Library of Congress Cataloging-in-Publication Data

Tutorials in complex photonic media / editors, Mikhail A. Noginov ... [et al.].
p. cm. -- (Press monograph ; 194)
ISBN 978-0-8194-7773-6
1. Photonics. 2. Photonic crystals. 3. Metamaterials. I. Noginov, Mikhail A.
TA1520.T88 2009
621.36--dc22
2009035663

Published by

SPIE
P.O. Box 10
Bellingham, Washington 98227-0010 USA
Phone: +1 360.676.3290
Fax: +1 360.647.1445
Email: Books@spie.org
Web: http://spie.org

The content of this book reflects the work and thought of the author(s). Every effort has been made to publish reliable and accurate information herein, but the publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

Cover art from figures in Chapter 7, courtesy of authors K. O'Holleran, M. R. Dennis, and M. J. Padgett.

Printed in the United States of America.

Tutorials in Complex Photonic Media

Editors:
Mikhail A. Noginov
Graeme Dewar
Martin W. McCall
Nikolay I. Zheludev

SPIE PRESS
Bellingham, Washington USA

Contents

Foreword

Classical optics has been with us for some considerable time, yet the past decade has produced a cornucopia of new research, often revealing unsuspected phenomena hidden like nuggets of gold in the rich lode of optical materials. The key has often been complexity. The range of optical properties available in natural materials is limited, but by adding manmade structure to nature's offerings we can extend our reach, sometimes to achieve properties not seen before. I pick one example from the many included in this volume: negative refraction. Years ago it had been realised that a material with negative magnetic and electric responses would also have a negative refractive index. There, the idea languished for nearly half a century, lacking the naturally occurring materials to realise the effect. However by internally structuring a medium on a scale less than the relevant wavelength, it was proved possible to make a new form of material, a 'metamaterial,' which had the required negatively refracting properties. This concept alone has given rise to thousands of papers. There are other examples I could cite from the chapters in this book: exploitation of near-field properties of nanoparticle arrays, photonic band gap waveguides, metallic nanostructures for sensing proteins, and so on. All of these examples have in common that man adds complexity to the offerings of nature.

In the face of these myriad advances, how are students or other new entrants to the field to educate themselves in the new technology? This book provides the answer, collecting together a definitive series of tutorials, each provided by an expert in the field. It is published at a time when there are many such new entrants and will be of great value.

J. B. Pendry
Imperial College London

Preface

An increasingly large number of high- and low-tech technologies and devices benefit from employing optics and photonics phenomena, the latter originally being termed photon-based electronics. Progress in the research fields of optics and photonics, which have both experienced continuously strong growth over the last few decades, critically depends on the understanding and utilization of the physical, chemical and structural properties of optical materials. The optical materials used in traditional optics technology were macroscopically homogeneous in that their scale of inhomogeneity was much less than the wavelength. In more recent years, multiple breakthroughs have involved inhomogeneous, composite, and multiphase materials, whose structures are either photoinduced or determined by synthesis or fabrication. Examples include holography, optics of scattering media, and metamaterials. These breakthroughs make photonic materials inherently complex. The broad range of physical phenomena underlying complex photonic media makes it difficult for scientists, engineers, and students entering the field to navigate through the range of topics and to understand clearly how they relate to each other.

The purpose of this book is to provide the necessary coverage and inspire the reader's curiosity about the fascinating subject of complex photonic media. All of the tutorial chapters are designed to start with the basics and gradually move toward discussion of more advanced topics. We thus envisage that students and scholars with diverse backgrounds and levels of expertise will find this text interesting and useful. The book can be used as a supplemental text in courses on nanotechnology or optical materials, or a variety of other courses. It can also be used as the main text in a more focused course aimed at fundamental properties of scattering media and metamaterials. The anticipated level of preparation is equivalent to advanced senior undergraduate level, beginning graduate level, or higher. The book covers the topics in the following (rather loose) categorization:

Negative index materials (NIMs). One of the most exciting developments in complex photonic media in recent years is the realization that the basic parameters describing the electromagnetics of simple, isotropic media can take simultaneously negative values. This leads to all kinds of interesting phenomena, from a revised understanding of Snell's law, to lenses that defeat the conventional diffraction resolution limit. In "Negative Refraction" (Chapter 1), Martin W. McCall and Graeme Dewar describe the basic theory and impetus for negative refraction research. In "Optical Hyperspace: Negative Refractive Index and Subwavelength Imaging" (Chapter 2), Leonid V. Alekseyev, Zubin Jacob, and Evgenii Narimanov explore nonmagnetic routes that exploit materials with hyperbolic dispersion relations.

Magneto-optics. The term magneto-optics is used when the direction and polarization state of light are controlled by the application of external magnetic fields, offering opportunities for optical storage and isolation in optical systems. In "Magneto-optics and the Kerr Effect with Ferromagnetic Materials" (Chapter 3), Allan D. Boardman and Neil King introduce the magneto-optics derived from air-ferroelectric interfaces and glass/ferromagnetic film/air multilayer systems. "Nonlinear Magneto-Optics" (Chapter 4) by Yutaka Kawabe gives emphasis to the relationship between the tensors describing the nonlinearity and the underlying crystal point group symmetry. In "Optical Magnetism in Plasmonic Metamaterials" (Chapter 5), Gennady Shvets and Yaroslav A. Urzhumov describe some of the difficult challenges that lie ahead for achieving magnetic activity at optical frequencies.

Chiral media and vortices. Light, being composed of unit spin photons, is inherently chiral. However, chirality in optical systems can also be engaged at structural and macroscopic electromagnetic levels. Structural chirality is covered by Ian Hodgkinson and Levi Bourke in "Chiral Photonic Media" (Chapter 6), which describes the multilayer matrix formalism for novel elliptically polarized filters. When optical beams interfere, phase singularities occur; in "Optical Vortices" (Chapter 7) Kevin O'Holleran, Mark R. Dennis, and Miles J. Padgett describe some of the remarkable topological knots and 3D twists that result.

Scattering in periodic and random media. Scattering of light is fundamental to complex photonic media. Structures that are periodic are generally referred to as photonic crystals. In "Photonic Crystals: From Fundamentals to Functional Photonic Materials" (Chapter 8), Durga P. Aryal, Kosmas L. Tsakmakidis, and Ortwin Hess describe how photonic bandstructure emerges in both 1- and 2D structures, and how optical switching is achievable in inverse-opal structures. When the material inhomogeneity is random, different methods must be employed. In "Wave Interference and Modes in Random Media" (Chapter 9), Azriel Z. Genack and Sheng Zhang describe photon transport in a medium in terms of the interference of multiply scattered partial waves as well as by considering the different spatial, spectral, and temporal characters of the electromagnetic modes.

Photonic media with gain and lasing phenomena. Photonic media with gain and lasing phenomena represents the generic class of active photonic media. "Chaotic Behavior of Random Lasers" (Chapter 10) by Diederik Wiersma, Sushil Mujumdar, Stefano Cavalieri, Renato Torre, Gian-Luca Oppo, and Stefano Lepri examines the irreproducibility of experimental emission spectra and the change of statistics at near threshold. "Lasing in Random Media" (Chapter 11) by Hui Cao provides a detailed review of the concepts and advances in the field of random lasers. "Feedback in Random Lasers" (Chapter 12) by Mikhail A.

Noginov emphasizes the significance of the strength of scattering and/or feedback in determining the properties of random lasers. In “Optical Metamaterials with Zero Loss and Plasmonic Nanolasers” (Chapter 13), Andrey Sarychev discusses how nano-horseshoe inclusion in an active host medium results in a plasmonic nanolaser.

Fundamentals. In “Resonance Energy Transfer: Theoretical Foundations and Developing Applications” (Chapter 14), David L. Andrews explores how the intricate interplay between quantum mechanical and electromagnetic medium properties leads to schemes for energy transfer and all-optical switching. In “Optics of Nanostructured Materials from First Principle Theories” (Chapter 15) Vladimir I. Gavrilenko provides a tutorial on the microscopic modelling of optical response functions using density functional theory and related approaches.

Organic photonic materials. Materials whose nonlinear coefficients often exceed their inorganic counterparts both in magnitude and response rate are examined in “Organic Photonic Materials” (Chapter 16) by Larry R. Dalton, Philip A. Sullivan, Denise H. Bale, Scott R. Hammond, Benjamin C. Olbricht, Harrison Rommel, Bruce Eichinger, and Bruce H. Robinson. These authors explore organic optical material design in terms of critical structure/function relationships. “Charge Transport and Optical Effects in Disordered Organic Semiconductors” (Chapter 17) by Harry H. L. Kwok, You-Lin Wu, and Tai-Ping Sun highlights how, as with regular semiconductors, charge transport can be modified by doping in organic materials, which possess enhanced carrier mobilities.

Holographic media. “Holography and Its Applications” (Chapter 18) by H. John Caulfield and Chandra S. Vikram discusses holograms used as parts of complex light-controlled or light-defined systems that manipulate the direction, spectrum, polarization, or speed of pulse propagation of light in a medium.

Slow and fast light. Slow and fast light is an intriguing topic demystified by Joseph E. Vornehm, Jr. and Robert W. Boyd in the final chapter “Slow and Fast Light” (Chapter 19). The authors show how manipulation of the material dispersion can lead to very slow, halted, or even backward propagating optical pulses.

The conception of *Tutorials in Complex Photonic Media* lies in an effort to consolidate the conference series, Complex Mediums: Light and Complexity, a subconference of the annual SPIE Optics and Photonics meeting held over the years 2003–2006[1]. Incentive for this book was also largely compelled by

---

[1] In 2003 the conference was titled Complex Mediums IV: Beyond Linear Isotropic Dielectrics; in 2006 it was titled Complex Photonic Media.

Introduction to Complex Mediums for Optics and Electromagnetics, edited by Werner S. Weiglhofer and Akhlesh Lakhtakia, SPIE Press (2003), which is a consolidation of the Complex Mediums conferences from 1999 to 2002. We have taken special emphasis in this book to avoid the somewhat disjointed presentation that often accompanies books based on conferences. To this end, all of the chapters underwent round-robin reviews by several editors and coauthors who were frequently not directly involved in the research area. Much "back and forth" has hopefully ironed out the specialist's tendency to dive headlong into details that can only be appreciated once sufficient underpinning motivational material has been presented. Another issue is notation. Eventually, we decided that keeping a consistent notation throughout the book would be self-defeating, as anyone entering a new area must, to a certain extent, be flexible to individual authors' preferences. Nevertheless, we went to some lengths to ensure that the notation within each chapter is consistent.

The four editors who undertook this project have had a unique opportunity to work with some of the leading specialists in the field. Of course, there have been frustrations, but in the end, we hope that that this book presents a broad and balanced summary that will lead many others to take up the exciting challenges of working in complex photonic media. In the introduction to the predecessor volume noted above, Akhlesh Lakhtakia wrote 'I shall be delighted if a companion volume were published after another two or three editions of this conference.' Well, here it is.

Mikhail A. Noginov
Graeme Dewar
Martin W. McCall
Nikolay I. Zheludev
September 2009

List of Contributors

Leonid V. Alekseyev
Princeton University, USA and
Purdue University, USA

David L. Andrews
University of East Anglia
Norwich, UK

Durga P. Aryal
University of Surrey, UK

Denise H. Bale
University of Washington, USA

Allan D. Boardman
University of Salford, UK

Levi Bourke
University of Otago, New Zealand

Robert W. Boyd
The Institute of Optics,
University of Rochester, USA

Hui Cao
Yale University, USA

H. John Caulfield
Fisk University, USA

Stefano Cavalieri
University of Florence, Italy

Larry R. Dalton
University of Washington, USA

Mark R. Dennis
University of Bristol, UK

Graeme Dewar
University of North Dakota, USA

Bruce Eichinger
University of Washington, USA

Vladimir I. Gavrilenko
Norfolk State University, USA

Azriel Z. Genack
Queens College, City University
of New York, USA

Scott R. Hammond
University of Washington, USA

Ortwin Hess
University of Surrey, UK

Ian Hodgkinson
University of Otago, New Zealand

Zubin Jacob
Purdue University, USA

Yutaka Kawabe
Chitose Institute of Science and
Technology, Japan

Neil King
University of Salford, UK

Harry H. L. Kwok
University of Victoria, Canada

Stefano Lepri
Institute of Complex Systems,
CNR, Italy

Martin W. McCall
Imperial College London, UK

Sushil Mujumdar
Tata Institute of Fundamental
Research, India

Evgenii Narimanov
Purdue University, USA

Mikhail A. Noginov
Norfolk State University, USA

Kevin O'Holleran
University of Glasgow, UK

Benjamin C. Olbricht
University of Washington, USA

Gian-Luca Oppo
University of Strathclyde, UK

Miles J. Padgett
University of Glasgow, UK

Bruce H. Robinson
University of Washington, USA

Harrison Rommel
University of Washington, USA

Andrey K. Sarychev
Institute of Theoretical and Applied
Electrodynamics, Russia

Gennady Shvets
University of Texas at Austin, USA

Philip A. Sullivan
University of Washington, USA

Tai-Ping Sun
National Chi-Nan University,
Taiwan

Renato Torre
University of Florence, Italy

Kosmas L. Tsakmakidis
University of Surrey, UK

Yaroslav A. Urzhumov
COMSOL, Inc. USA

Chandra S. Vikram (deceased)
Fisk University, USA

Joseph E. Vornehm, Jr.
The Institute of Optics,
University of Rochester, USA

Diederik S. Wiersma
LENS—European Laboratory for
Non-Linear Spectroscopy, BEC-INFM,
Italy

You-Lin Wu
National Chi-Nan University,
Taiwan

Sheng Zhang
Queens College, City University
of New York, USA

List of Abbreviations

AFM	atomic force microscopy
APC	amorphous polycarbonate
APTE	*addition de photons par transfers d'énergie*
ASE	amplified spontaneous emission
ATR	attenuated total reflection
BCOG	binary chromophore organic glass
BEC	Bose-Einstein condensate
BER	bit-error rate
BZ	Brillouin zone
CCD	charge-coupled device
CCW	coupled-cavity waveguide
CDM	correlated disorder model
CGH	computer-generated hologram
CGS	centimeter-gram-second
CP	circularly polarized
CPO	coherent population oscillation
CQED	cavity QED
CROW	coupled-resonator optical waveguide
CT	charge transfer
CVD	chemical vapor deposition
DBP	delay–bandwidth product
DFB	distributed feedback
DFT	density functional theory
DIOPC	double-inverse-opal PC
DOS	density of states
DPCM	double phase-conjugate mirror
DSC	differential scanning calorimetry
ECP	effective core potential
EE	electrostatic eigenvalue
EET	electronic energy transfer
EFISH	electric-field-induced second harmonic
EIT	electromagnetically induced transparency
EM	electromagnetic
EO	electro-optic
fcc	face-center cubic
FEFD	finite element frequency domain

FRET	fluorescence RET
FWHM	full width at half maximum
FWM	four-wave mixing
GDM	Gaussian disorder model
GEDE	generalized eigenvalue differential equation
GLC	geometric LC
GMR	gap-to-midgap ratio
GVD	group velocity dispersion
hcp	hexagonal close-packed
HOE	holographic optical element
HOMO	highest occupied molecular orbit
HRS	hyper-Raleigh scattering
IR	infrared
IVR	intramolecular vibrational redistribution
JCM	Jaynes-Cummings model
LAP	laser-assisted poling
LCP	left-circular polarization
LDA	local density approximation
LED	light-emitting diode
LF	local field
LHM	left-handed material
LO	longitudinal optical
LUMO	lowest unoccupied molecular orbit
ME	magneto-electric
MO	magneto-optic
MOCVD	metalorganic CVD
MPR	magnetic plasmon resonance
MSHG	magnetization-induced SHG
MTHG	magnetization-induced THG
NA	numerical aperture
NIM	negative index material
NLO	nonlinear optical
NPV	negative phase velocity
OCRET	optically controlled RET
OCT	optical coherence tomography
OEO	optical-electrical-optical
OLED	organic light-emitting diode
OPD	optical path length distance
OPO	optical parameter oscillator
PC (PhC)	photonic crystal
PEC	perfect electric conductor
PFT	power Fourier transform
PGB	photonic band gap
PMT	photomultiplier tubes
PWE	plane wave expansion

QED	quantum electrodynamics
QD	quantum dot
QP	quasi-particle
QW	quantum well
RCP	right-circular polarization
RET	resonance energy transfer
RF	radiofrequency
RIE	reaction ion etching
rms	root mean square
RPA	random-phase approximation
SBS	stimulated Brillouin scattering
SE	stimulated emission
SEIRA	surface-enhanced IR absorption
SEM	scanning electron microscope
SFG	sum frequency generation
SERS	surface-enhanced Raman scattering
SHG	second-harmonic generation
SLM	spatial light modulator
SOA	semiconductor optical amplifier
SP	surface plasmon
SPD	square of the polarizability derivative
SPOF	strip pair-one film
SPP	spiral phase plate
SPR	surface plasmon resonance
SR	slit ring
SRS	stimulated Raman scattering
SRR	split-ring resonator
TD-DFT	time-dependent DFT
TE	transverse electric
TF	Thomas-Fermi
THG	third-harmonic generation
TLS	two-level amplifying system
TM	transverse magnetic
UV	ultraviolet
VCSEL	vertical-cavity surface-emitting laser
WDM	wavelength division multipling
XC	exchange and correlation