

Tutorials in
Complex
Photonic
Media

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Contents

<i>Foreword</i>	xv
<i>Preface</i>	xvii
<i>List of Contributors</i>	xxi
<i>List of Abbreviations</i>	xxiii
1 Negative Refraction	1
<i>Martin W. McCall and Graeme Dewar</i>	
1.1 Introduction	1
1.2 Background	2
1.3 Beyond Natural Media: Waves That Run Backward	6
1.4 Wires and Rings	10
1.5 Experimental Confirmation	14
1.6 The “Perfect” Lens	14
1.7 The Formal Criterion for Achieving Negative Phase Velocity Propagation	18
1.8 Fermat’s Principle and Negative Space	20
1.9 Cloaking	21
1.10 Conclusion	23
1.11 Appendices	25
Appendix I: The $\epsilon(\omega)$ of a square wire array	25
Appendix II: Physics of the wire array’s plasma frequency and damping rate	26
References	29
2 Optical Hyperspace: Negative Refractive Index and Subwavelength Imaging	33
<i>Leonid V. Alekseyev, Zubin Jacob, and Evgenii Narimanov</i>	
2.1 Introduction	33
2.2 Nonmagnetic Negative Refraction	36
2.3 Hyperbolic Dispersion: Materials	39
2.4 Applications	40
2.4.1 Waveguides	40
2.4.2 The hyperlens	43
2.4.2.1 Theoretical description	43
2.4.2.2 Imaging simulations	46
2.4.2.3 Semiclassical treatment	47
2.5 Conclusion	51
References	52

3	Magneto-optics and the Kerr Effect with Ferromagnetic Materials	57
	<i>Allan D. Boardman and Neil King</i>	
3.1	Introduction to Magneto-optical Materials and Concepts	57
3.2	Reflection of Light from a Plane Ferromagnetic Surface	58
	3.2.1 Single-surface polar orientation	59
	3.2.2 Kerr rotation	64
3.3	Enhancing the Kerr Effect with Attenuated Total Reflection	66
3.4	Numerical Investigations of Attenuated Total Reflection	74
3.5	Conclusions	78
	References	78
4	Symmetry Properties of Nonlinear Magneto-optical Effects	81
	<i>Yutaka Kawabe</i>	
4.1	Introduction	81
4.2	Nonlinear Optics in Magnetic Materials	83
4.3	Magnetic-Field-Induced Second-Harmonic Generation	88
4.4	Effects Due to an Optical Magnetic Field or Magnetic Dipole Moment Transition	96
4.5	Experiments	99
	References	102
5	Optical Magnetism in Plasmonic Metamaterials	107
	<i>Gennady Shvets and Yaroslav A. Urzhumov</i>	
5.1	Introduction	107
5.2	Why Is Optical Magnetism Difficult to Achieve?	110
5.3	Effective Quasistatic Dielectric Permittivity of a Plasmonic Metamaterial	115
	5.3.1 The capacitor model	116
	5.3.2 Effective medium description through electrostatic homogenization	118
	5.3.3 The eigenvalue expansion approach	119
5.4	Summary	122
5.5	Appendix: Electromagnetic Red Shifts of Plasmonic Resonances	123
	References	125
6	Chiral Photonic Media	131
	<i>Ian Hodgkinson and Levi Bourke</i>	
6.1	Introduction	132
6.2	Stratified Anisotropic Media	133
	6.2.1 Biaxial material	133
	6.2.2 Propagation and basis fields	134
	6.2.3 Field transfer matrices	137
	6.2.4 Reflectance and transmittance	138
6.3	Chiral Architectures and Characteristic Matrices	139
	6.3.1 Five chiral architectures	139
	6.3.2 Matrix for a continuous chiral film	141
	6.3.3 Matrix for a biaxial film	141
	6.3.4 Matrix for an isotropic film	142
	6.3.5 Matrix for a stack of films	142

6.3.6	Matrices for discontinuous and structurally perturbed films	142
6.3.7	Herpin effective birefringent media	142
6.4	Reflectance Spectra and Polarization Response Maps	144
6.4.1	Film parameters	144
6.4.2	Standard-chiral media	144
6.4.3	Remittance at the Bragg wavelength	146
6.4.4	Modulated-chiral media	148
6.4.5	Chiral-isotropic media	149
6.4.6	Chiral-birefringent media	149
6.4.7	Chiral-chiral media	151
6.5	Summary	153
	References	154
7	Optical Vortices	157
	<i>Kevin O'Holleran, Mark R. Dennis, and Miles J. Padgett</i>	'
7.1	Introduction	157
7.2	Locating Vortex Lines	161
7.3	Making Beams Containing Optical Vortices	162
7.4	Topology of Vortex Lines	164
7.5	Computer Simulation of Vortex Structures	167
7.6	Vortex Structures in Random Fields	169
7.7	Experiments for Visualizing Vortex Structures	172
7.8	Conclusions	173
	References	174
8	Photonic Crystals: From Fundamentals to Functional Photonic Opals	179
	<i>Durga P. Aryal, Kosmas L. Tsakmakidis, and Ortwin Hess</i>	
8.1	Introduction	180
8.2	Principles of Photonic Crystals	182
8.2.1	Electromagnetism of periodic dielectrics	182
8.2.2	Maxwell's equations	182
8.2.3	Bloch's theorem	185
8.2.4	Photonic band structure	187
8.3	One-Dimensional Photonic Crystals	189
8.3.1	Bragg's law	189
8.3.2	One-dimensional photonic band structure	193
8.4	Generalization to Two- and Three-Dimensional Photonic Crystals	196
8.4.1	Two-dimensional photonic crystals	196
8.4.2	Three-dimensional photonic crystals	199
8.5	Physics of Inverse-Opal Photonic Crystals	201
8.5.1	Introduction	201
8.5.2	Inverse opals with moderate-refractive-index contrast	203
8.5.3	Toward a higher-refractive-index contrast	210
8.6	Double-Inverse-Opal Photonic Crystals (DIOPCs)	214
8.6.1	Introduction	214
8.6.2	Photonic band gap switching via symmetry breaking	215
8.6.3	Tuning of the partial photonic band gap	216
8.6.4	Switching of the complete photonic band gap	218

8.7	Conclusion	221
8.8	Appendix: Plane Wave Expansion (PWE) Method	222
	References	224
9	Wave Interference and Modes in Random Media	229
	<i>Azriel Z. Genack and Sheng Zhang</i>	
9.1	Introduction	229
9.2	Wave Interference	231
	9.2.1 Weak localization	231
	9.2.2 Coherent backscattering	234
9.3	Modes	237
	9.3.1 Quasimodes	238
	9.3.2 Localized and extended modes	239
	9.3.3 Statistical characterization of localization	244
	9.3.4 Time domain	252
	9.3.5 Speckle	256
9.4	Conclusions	264
	References	265
10	Chaotic Behavior of Random Lasers	277
	<i>Diederik S. Wiersma, Sushil Mujumdar, Stefano Cavaleri, Renato Torre, Gian-Luca Oppo, Stefano Lepri</i>	
10.1	Introduction	278
	10.1.1 Multiple scattering and random lasing	278
	10.1.2 Mode coupling	279
10.2	Experiments on Emission Spectra	280
	10.2.1 Sample preparation and setup	280
	10.2.2 Emission spectra	281
10.3	Experiments on Speckle Patterns	283
10.4	Modeling	285
	10.4.1 Monte Carlo simulations	285
	10.4.2 Results and interpretation	287
10.5	Lévy Statistics in Random Laser Emission	291
10.6	Discussion	294
	References	295
11	Lasing in Random Media	301
	<i>Hui Cao</i>	
11.1	Introduction	302
	11.1.1 "LASER" versus "LOSER"	302
	11.1.2 Random lasers	302
	11.1.3 Characteristic length scales for the random laser	303
	11.1.4 Light localization	304
11.2	Random Lasers with Incoherent Feedback	305
	11.2.1 Lasers with a scattering reflector	305
	11.2.2 The photonic bomb	306
	11.2.3 The powder laser	308
	11.2.4 Laser paint	311
	11.2.5 Further developments	313

11.3	Random Lasers with Coherent Feedback	316
11.3.1	“Classical” versus “quantum” random lasers	316
11.3.2	Classical random lasers with coherent feedback	317
11.3.3	Quantum random lasers with coherent feedback	320
11.3.3.1	Lasing oscillation in semiconductor nanostructures	320
11.3.3.2	Random microlasers	324
11.3.3.3	Collective modes of resonant scatterers	325
11.3.3.4	Time-dependent theory of the random laser	327
11.3.3.5	Lasing modes in diffusive samples	329
11.3.3.6	Spatial confinement of lasing modes by absorption	330
11.3.3.7	Effect of local gain on random lasing modes	332
11.3.3.8	The 1D photon localization laser	334
11.3.4	Amplified spontaneous emission (ASE) spikes versus lasing peaks	335
11.3.5	Recent developments	340
11.4	Potential Applications of Random Lasers	342
	References	344

Color Plate Section

12	Feedback in Random Lasers	359
	<i>Mikhail A. Noginov</i>	
12.1	Introduction	360
12.2	The Concept of a Laser	360
12.3	Lasers with Nonresonant Feedback and Random Lasers	363
12.4	Photon Migration and Localization in Scattering Media and Their Applications to Random Lasers	364
12.4.1	Diffusion	364
12.4.2	Prediction of stimulated emission in a random laser operating in the diffusion regime	365
12.4.3	Modeling of stimulated emission dynamics in neodymium random lasers	366
12.4.4	Stimulated emission in a one-dimensional array of coupled lasing volumes	368
12.4.5	Random laser feedback in a weakly scattering regime: space masers and stellar lasers	370
12.4.6	Localization of light and random lasers	371
12.5	Neodymium Random Lasers with Nonresonant Feedback	374
12.5.1	First experimental observation of random lasers	374
12.5.2	Emission kinetics in neodymium random lasers	375
12.5.3	Analysis of speckle pattern and coherence in neodymium random lasers	377
12.6	ZnO Random Lasers with Resonant Feedback	377
12.6.1	Narrow modes in emission spectra	377
12.6.2	Photon statistics in a ZnO random laser	380
12.6.3	Modeling of a ZnO random laser	381

12.7	Stimulated Emission Feedback: From Nonresonant to Resonant and Back to Nonresonant	383
12.7.1	Mode density and character of stimulated emission feedback	383
12.7.2	Transition from the nonresonant to the resonant regime of operation	384
12.7.3	Nonresonant feedback in the regime of ultrastrong scattering: electron-beam-pumped random lasers	387
12.8	Summary of Various Random Laser Operation Regimes	389
12.8.1	Amplification in open paths: the regime of amplified stimulated emission without feedback	389
12.8.2	Extremely weak feedback	390
12.8.3	Medium-strength feedback: diffusion	390
12.8.4	The regime of strong scattering	390
	References	391
13	Optical Metamaterials with Zero Loss and Plasmonic Nanolasers	397
	<i>Andrey K. Sarychev</i>	
13.1	Introduction	397
13.2	Magnetic Plasmon Resonance	400
13.3	Electrodynamics of a Nanowire Resonator	406
13.4	Capacitance and Inductance of Two Parallel Wires	414
13.5	Lumped Model of a Resonator Filled with an Active Medium	418
13.6	Interaction of Nanotennas with an Active Host Medium	422
13.7	Plasmonic Nanolasers and Optical Magnetism	426
13.8	Conclusions	429
	References	430
14	Resonance Energy Transfer: Theoretical Foundations and Developing Applications	439
	<i>David L. Andrews</i>	
14.1	Introduction	440
14.1.1	The nature of condensed phase energy transfer	441
14.1.2	The Förster equation	442
14.1.3	Established areas of application	445
14.2	Electromagnetic Origins	446
14.2.1	Coupling of transition dipoles	446
14.2.2	Quantum electrodynamics	448
14.2.3	Near- and far-field behavior	452
14.2.4	Refractive and dissipative effects	453
14.3	Features of the Pair Transfer Rate	453
14.3.1	Distance dependence	455
14.3.2	Orientation of the transition dipoles	456
14.3.3	Spectral overlap	458
14.4	Energy Transfer in Heterogeneous Solids	459
14.4.1	Doped solids	459
14.4.2	Quantum dots	462
14.4.3	Multichromophore complexes	463
14.5	Directed Energy Transfer	464

14.5.1 Spectroscopic gradient	465
14.5.2 Influence of a static electric field	467
14.5.3 Optically controlled energy transfer	467
14.6 Developing Applications	469
14.7 Conclusion	470
References	470
15 Optics of Nanostructured Materials from First Principles	479
<i>Vladimir I. Gavrilenko</i>	
15.1 Introduction	480
15.2 Optical Response from First Principles	482
15.3 Effect of the Local Field in Optics	485
15.3.1 Local field effect in classical optics	486
15.3.2 Optical local field effects in solids from first principles	486
15.4 Electrons in Quantum Confined Systems	489
15.4.1 Electron energy structure in quantum confined systems	489
15.4.2 Optical functions of nanocrystals	491
15.5 Cavity Quantum Electrodynamics	493
15.5.1 Interaction of a quantized optical field with a two-level atomic system	494
15.5.2 Interaction of a quantized optical field with quantum dots	497
15.6 Optical Raman Spectroscopy of Nanostructures	499
15.6.1 Effect of quantum confinement	500
15.6.2 Surface-enhanced Raman scattering: electromagnetic mechanism	502
15.6.3 Surface-enhanced Raman scattering: chemical mechanism	504
15.7 Concluding Remarks	506
15.8 Appendices	507
15.8.1 Appendix I: Electron energy structure and standard density functional theory	507
15.8.2 Appendix II: Optical functions within perturbation theory	511
15.8.3 Appendix III: Evaluation of the polarization function including the local field effect	516
15.8.4 Appendix IV: Optical field Hamiltonian in second quantization representation	518
References	519
16 Organic Photonic Materials	525
<i>Larry R. Dalton, Philip A. Sullivan, Denise H. Bale, Scott R. Hammond, Benjamin C. Olbricht, Harrison Rommel, Bruce Eichinger, and Bruce H. Robinson</i>	
16.1 Preface	525
16.2 Introduction	527
16.3 Effects of Dielectric Permittivity and Dispersion	532
16.4 Complex Dendrimer Materials: Effects of Covalent Bonds	535
16.5 Binary Chromophore Organic Glasses (BCOGs)	538
16.5.1 Optimizing EO activity and optical transparency	538
16.5.2 Laser-assisted poling (LAP)	542

16.5.3	Conductivity issues	546
16.6	Thermal and Photochemical Stability: Lattice Hardening	549
16.7	Thermal and Photochemical Stability: Measurement	551
16.8	Devices and Applications	555
16.9	Summary and Conclusions	558
16.10	Appendix: Linear and Nonlinear Polarization	559
	References	564
17	Charge Transport and Optical Effects in Disordered Organic Semiconductors	575
	<i>Harry H. L. Kwok, You-Lin Wu, and Tai-Ping Sun</i>	
17.1	Introduction	575
17.2	Charge Transport	576
17.2.1	Energy bands	576
17.2.2	Dispersive charge transport	577
17.2.3	Hopping mobility	577
17.2.4	Density of states	579
17.3	Impedance Spectroscopy: Bias and Temperature Dependence	580
17.4	Transient Spectroscopy	590
17.5	Thermoelectric Effect	595
17.6	Exciton Formation	597
17.7	Space-Charge Effect	604
17.8	Charge Transport in the Field-Effect Structure	612
	References	621
18	Holography and Its Applications	625
	<i>H. John Caulfield and Chandra S. Vikram</i>	
18.1	Introduction	625
18.2	Basic Information on Holograms	627
18.2.1	Hologram types	629
18.3	Recording Materials for Holographic Metamaterials	633
18.4	Computer-Generated Holograms	634
18.5	Simple Functionalities of Holographic Materials	635
18.6	Phase Conjugation and Holographic Optical Elements	636
18.7	Related Applications and Procedures	639
18.7.1	Holographic photolithography	639
18.7.2	Copying of holograms	639
18.7.3	Holograms in nature and general products	641
	References	641
	In Memoriam: Chandra S. Vikram	645
19	Slow and Fast Light	647
	<i>Joseph E. Vornehm, Jr. and Robert W. Boyd</i>	
19.1	Introduction	648
19.1.1	Phase velocity	648
19.1.2	Group velocity	650
19.1.3	Slow light, fast light, backward light, stopped light	652
19.2	Slow Light Based on Material Resonances	654
19.2.1	Susceptibility and the Kramers–Kronig relations	654

19.2.2	Resonance features in materials	655
19.2.3	Spatial compression	657
19.2.4	Two-level and three-level models	657
19.2.5	Electromagnetically induced transparency (EIT)	658
19.2.6	Coherent population oscillation (CPO)	659
19.2.7	Stimulated Brillouin and Raman scattering	660
19.2.8	Other resonance-based phenomena	661
19.3	Slow Light Based on Material Structure	661
19.3.1	Waveguide dispersion	661
19.3.2	Coupled-resonator structures	661
19.3.3	Band-edge dispersion	663
19.4	Additional Considerations	663
19.4.1	Distortion mitigation	663
19.4.2	Figures of merit	664
19.4.3	Theoretical limits of slow and fast light	664
19.4.4	Causality and the many velocities of light	665
19.5	Potential Applications	668
19.5.1	Optical delay lines	669
19.5.1.1	Optical network buffer for all-optical routing	669
19.5.1.2	Network resynchronization and jitter correction	669
19.5.1.3	Tapped delay lines and equalization filters	671
19.5.1.4	Optical memory and stopped light for coherent control	671
19.5.1.5	Optical image buffering	672
19.5.1.6	True time delay for radar and lidar	672
19.5.2	Enhancement of optical nonlinearities	672
19.5.2.1	Wavelength converter	673
19.5.2.2	Single-bit optical switching, optical logic, and other applications	673
19.5.3	Slow- and fast-light interferometry	674
19.5.3.1	Spectral sensitivity enhancement	674
19.5.3.2	White-light cavities	675
	References	675
	<i>About the Editors</i>	687
	<i>Index</i>	689

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 2003–2006¹. 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.

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List of Abbreviations

AFM	atomic force microscopy
APC	amorphous polycarbonate
APTE	<i>addition de photons par transferts d'énergie</i>
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 multiplexing
XC	exchange and correlation