

Arti Agrawal · Trevor Benson
Richard M. De La Rue · Gregory A. Wurtz
Editors

Recent Trends in Computational Photonics

Contents

1	Finite Element Time Domain Method for Photonics	1
	S.M. Raiyan Kabir, B.M.A. Rahman and A. Agrawal	
1.1	Introduction	1
1.2	Derivation from Maxwell's Equations	3
1.2.1	Two Dimensional Formulation	4
1.2.2	Three Dimensional Formulation	5
1.2.3	Discretisation	5
1.2.4	Discretised Governing Equations	7
1.3	The Mesh	8
1.3.1	The Space Mesh System	9
1.3.2	The Time Mesh System	12
1.4	Simulation Results	13
1.4.1	Simulation in Two Dimensions	13
1.4.2	Simulation in Three Dimensions	14
1.5	Numerical Dispersion	17
1.5.1	Numerical Dispersion Relation for Two Dimensions	17
1.5.2	Numerical Dispersion Relation for Three Dimensions	19
1.5.3	Numerical Dispersion for Two Dimensions	20
1.5.4	Numerical Dispersion for Three Dimensions	23
1.5.5	Comparison with the FDTD Method	24
1.6	Calculating Resolution Reduction Factor	26
1.6.1	Resolution Reduction Factor for Two Dimensions	27
1.6.2	Resolution Reduction Factor for Three Dimensions	28
1.7	Theoretical CPU Performance	29
1.7.1	CPU Optimised Form	29
1.7.2	CPU Time/Latency of the Governing Equations	32
1.7.3	Performance Comparison of Proposed FETD and FDTD for Two Dimensions	33
1.7.4	Performance Comparison of Proposed FETD and FDTD for Three Dimensions	34

1.8	Concluding Remarks.	35
	References.	36
2	The Modelling of Fibre Lasers for Mid-Infrared Wavelengths	39
	L. Sojka, T.M. Benson, D. Furniss, Z. Tang, H. Sakr, A.B. Seddon and S. Sujecki	
2.1	Introduction to Mid-Infrared Fibre Lasers.	39
2.1.1	Mid-Infrared Lasers; Technology Drivers and Potential Applications	39
2.1.2	Overview of Mid-Infrared Fibre Lasers.	40
2.2	The Physics of Fibre Laser Systems.	41
2.2.1	Light-Matter Interactions in Gain Medium	41
2.2.2	Cross-Section.	43
2.2.3	Lifetime.	43
2.2.4	Nonradiative Lifetimes	44
2.2.5	Branching Ratio.	45
2.2.6	Gain in Active Media	45
2.2.7	Laser Systems	47
2.2.8	Laser Theory	47
2.2.9	Rare Earth Doping.	48
2.2.10	Fibre Lasers.	49
2.3	Materials and Dopants	49
2.3.1	Short Review of Mid-Infrared Optical Fibre Materials	49
2.3.2	Overview of Mid-Infrared Emission from Chalcogenide Glasses and Fibres Doped with Pr^{3+} , Dy^{3+} , Tb^{3+}	51
2.4	Obtaining Spectroscopic Parameters as Inputs to the Numerical Model	54
2.4.1	Absorption Cross-Section Measurements.	54
2.4.2	Emission Cross-Section Measurements	55
2.4.3	Lifetime Measurements	55
2.5	Models for Fibre Lasers	57
2.5.1	Laser Rate and Propagation Equations	59
2.5.2	Boundary Conditions.	61
2.5.3	Numerical Calculation Procedure.	62
2.5.4	Numerical Algorithm.	64
2.6	Numerical and Theoretical Studies of Mid-Infrared Laser Action in Chalcogenide Glasses Doped with Dy^{3+} , Pr^{3+} or Tb^{3+}	65
2.6.1	Parameters Used in Modelling.	66
2.6.2	Modelling of Mid-Infrared Chalcogenide Fibre Lasers.	66

2.6.3 Dy³⁺ Doped Chalcogenide Glass Fibre Laser 68

2.6.4 Pr³⁺ Doped Chalcogenide Glass Fibre Laser 68

2.6.5 Fibre Lasers Based on Tb³⁺ Doping 69

2.6.6 Summary 70

2.7 Concluding Remarks 71

References 71

3 Guided Wave Interaction in Photonic Integrated Circuits — A Hybrid Analytical/Numerical Approach to Coupled Mode Theory 77

M. Hammer

3.1 Introduction 77

 3.1.1 Hybrid Analytical/Numerical Coupled Mode Theory 79

3.2 Theoretical Background 80

 3.2.1 Straight Waveguides 81

 3.2.2 Bent Channels, or Curved Interfaces 82

 3.2.3 Cavities 84

 3.2.4 Coupled Mode Field Template 85

 3.2.5 Projection and Algebraic Procedure 85

 3.2.6 Material Dispersion and Spectral Scans 86

 3.2.7 Eigenfrequencies of Composite Systems 87

3.3 Numerical Examples 88

 3.3.1 Single Waveguide 89

 3.3.2 Two Straight Parallel Waveguides 90

 3.3.3 Waveguide Crossing 91

 3.3.4 Microresonators with Circular Cavities 94

 3.3.5 A 3-Ring Photonic Molecule, Excited by a Straight Waveguide 98

3.4 HCMT in 3-D 101

3.5 Concluding Remarks 102

References 104

4 Rigorous Analysis of Acousto-Optic Interactions in Optical Waveguides 107

B.M.A. Rahman, M.M. Rahman, S. Sriratanavaree,
N. Kejalakshmy and K.T.V. Grattan

4.1 Introduction 107

4.2 Theory 109

4.3 Results 112

 4.3.1 Low-Index Contrast Silica Guide 112

 4.3.2 High-Index Contrast Acoustic Guide 118

 4.3.3 Optical Modes in Acoustic Guides 121

 4.3.4 Light-Sound Interactions 122

4.4	Concluding Remarks	127
	References	128
5	Photonic Crystals and Metamaterials with Gain	131
	S. Droulias, T. Koschny and C.M. Soukoulis	
5.1	Introduction	131
5.1.1	Photonic Crystals and Metamaterials: Importance and Applications	132
5.1.2	Incorporating Gain	133
5.2	Theory and Numerical Implementation	134
5.2.1	Theory of Four-Level Gain Systems Coupled with Maxwell's Equations	134
5.2.2	Numerical Implementation with the FDTD	136
5.2.3	Initiating Lasing and Measuring the Lasing Threshold	137
5.3	Realistic Systems	140
5.3.1	Photonic Crystals with Gain: Lasing Threshold Control	140
5.3.2	Metamaterials with Gain: Mechanism of the Gain Material Coupled with the MM	147
5.3.3	Lasing with Plasmons	155
5.4	Concluding Remarks	156
	References	156
6	Theory and Numerical Modelling of Parity-Time Symmetric Structures in Photonics: Introduction and Grating Structures in One Dimension	161
	S. Phang, T.M. Benson, H. Susanto, S.C. Creagh, G. Gradoni, P.D. Sewell and A. Vukovic	
6.1	Introduction of Parity and Time-Reversal (\mathcal{PT}) Symmetry	161
6.2	Parity-Time (\mathcal{PT}) Symmetric Scatterers in 1-D	163
6.2.1	Parity and Time-Reversal (\mathcal{PT}) Symmetry	163
6.2.2	Photonics System Analogue of Quantum Mechanics \mathcal{PT} -Symmetric Hamiltonian	165
6.2.3	Generalised Conservation Relations	166
6.2.4	Phases in a \mathcal{PT} Scattering System	169
6.2.5	Simultaneous Coherent Perfect Absorber and Lasing	172
6.2.6	Bragg Grating with a \mathcal{PT} -Symmetric Refractive Index Modulation	173
6.3	Modelling Parity-Time (\mathcal{PT}) Symmetric Bragg Grating with a Realistic Gain/Loss Material Model	179

6.3.1	Time-Domain Modelling of Dispersive and Saturable Gain	179
6.3.2	Impact of Dispersion on the Properties of a \mathcal{PT} -Bragg Grating	186
6.3.3	Time-Domain Modelling of a PTBG Using the TLM Method	191
6.3.4	A Temporal Optical Switch Using the \mathcal{PT} -Symmetric Bragg Grating	192
6.4	Non-linear and Dispersive Parity-Time Bragg Grating for Optical Signal Processing Applications	194
6.4.1	TLM Model for Non-linear Medium	194
6.4.2	Non-linear \mathcal{PT} -Bragg Grating for a Memory Device	198
6.5	Concluding Remarks	202
	References	202
7	Theory and Numerical Modelling of Parity-Time Symmetric Structures in Photonics: Boundary Integral Equation for Coupled Microresonator Structures	207
	S. Phang, A. Vukovic, G. Gradoni, P.D. Sewell, T.M. Benson and S.C. Creagh	
7.1	Introduction	207
7.2	The Transmission-Line Modelling Method for Dispersive Gain (or Loss) in Two-Dimension	208
7.2.1	TLM Formalism in 2D Domain	208
7.2.2	TLM Shunt Node Model for Realistic Gain Medium	212
7.3	Parity-Time (\mathcal{PT}) Symmetric Coupled Resonators	214
7.3.1	Inter-Resonator Coupling Model by Boundary Integral Equation	214
7.3.2	Graf's Addition Theorem	215
7.3.3	Exact Solution Using Boundary-Integral Representation	215
7.3.4	Weak-Coupling Perturbation Approximation	222
7.3.5	\mathcal{PT} -Symmetric Threshold of Weakly-Coupled System	223
7.4	Symmetry Breaking in \mathcal{PT} -Microresonator Couplers	224
7.4.1	Impact of Gain/Loss Material Parameters on Threshold Behaviour in the Frequency Domain	224
7.4.2	Real Time Operation of \mathcal{PT} -Microresonator Couplers	227
7.5	\mathcal{PT} -Microresonator Photonic Molecules Array	229
7.6	Concluding Remarks	232
	References	232

8	Hydrodynamic Model for Coherent Nonlinear Plasmonics	235
	A.V. Krasavin, P. Ginzburg, G.A. Wurtz and A.V. Zayats	
8.1	Introduction	235
8.2	Hydrodynamic Model for the Free Electron Gas	237
8.3	Analytical Description of Nanoscale Plasmonic Nonlinear Phenomena	239
8.3.1	Nonlinear Coupling of Plasmonic Resonances in Metallic Nanoparticles	239
8.3.2	Cascaded Surface Plasmon-Solitons	243
8.4	Non-Perturbative Numerical Model of Nonlinear Dynamics in Plasmonic Nanostructures	248
8.4.1	Non-Perturbative Time Domain Finite Element Numerical Model	248
8.4.2	Second and Third Harmonic Generation from Plasmonic Nanorods	251
8.4.3	Nonlocal and Resonantly-Enhanced Nonlinear Phenomena	252
8.5	Conclusion	256
	References	257
9	Simulation of Second Harmonic Generation from Photonic Nanostructures Using the Discontinuous Galerkin Time Domain Method	261
	Y. Grynko and J. Förstner	
9.1	Introduction and Review of the Developments of the DGTD Method and Its Applications in Plasmonics	261
9.2	Parallel Implementation of the DGTD Method	263
9.2.1	Numerical Scheme Formulation	263
9.2.2	Parallel DGTD Solver	267
9.2.3	Incorporation of the Nonlinear Maxwell–Vlasov Hydrodynamic Model	270
9.3	Simulation of the Second Harmonic Generation in Selected Plasmonic Nanostructures	270
9.3.1	Second Harmonic Generation in Split-Ring Resonator Arrays	271
9.3.2	Second Harmonic Generation from Plasmonic Gap Antennas	277
9.4	Concluding Remarks	282
	References	282
10	All-Dielectric Nanophotonic Structures: Exploring the Magnetic Component of Light	285
	B. Hopkins, A.E. Miroshnichenko and Y.S. Kivshar	
10.1	Introduction	285

10.2	Modeling All-Dielectric Nanoparticle Systems	286
10.2.1	Magnetism in Nanophotonics	286
10.2.2	Radiation by Internal Current Distributions	288
10.2.3	Dipole Models	289
10.3	Eigenmodes of Nanoparticle Oligomers	292
10.3.1	Resonances, Polarizability, and Eigenmodes	292
10.3.2	Modal Interference and Fano Resonances	295
10.3.3	Eigenmodes of Nanoparticle Dimers	299
10.3.4	Dimensionless Eigenvalues	306
10.4	Observation of Fano Resonances in Nanoparticle Oligomers . . .	307
10.5	Concluding Remarks	310
	References	311
11	Computational Plasmonics: Theory and Applications	315
	F. Mohammed, R. Warmbier and A. Quandt	
11.1	Introduction	315
11.2	Theoretical Background	317
11.2.1	Optical Properties of Solids	317
11.2.2	Plasmons and Plasmonics	323
11.2.3	Example: Gold Nanoparticles	329
11.3	Applications in Photovoltaics	330
11.3.1	Solar Cell Design	331
11.3.2	Plasmon Enhanced Solar Cells	333
11.3.3	Example: Heating of Plasmonic Layers	334
11.4	New Research Directions	336
11.4.1	Plasmonic Resonances in Non-metallic Nanostructures	336
11.4.2	Interactions of Plasmons with Other Electronic Transition Processes	337
11.5	Concluding Remarks	338
	References	338
12	Computational Plasmonics: Numerical Techniques	341
	F. Mohammed, R. Warmbier and A. Quandt	
12.1	Introduction	341
12.2	Frequency Domain Methods for Periodic Systems	343
12.2.1	Photonic Band Structures	343
12.2.2	Numerical Details	344
12.2.3	Example: Honeycomb Lattice	346
12.3	Time Domain Methods	347
12.3.1	Outline of the FDTD Method	347
12.3.2	Numerical Details	350
12.3.3	Example: Cross Sections Using FDTD	350
12.4	Ab Initio Dielectric Functions	352

12.4.1	Density Functional Theory	352
12.4.2	Linear Response and the Time Dependent Density Functional Theory	355
12.4.3	Example: ZnO	358
12.5	Plasmonic Photonic Crystals	360
12.5.1	Perturbation Theory	361
12.5.2	Example: Plasmonic Photonic Band Structure	362
12.6	Open Questions	363
12.6.1	Missing Numerical Tools	363
12.7	Concluding Remarks	366
	References	367
13	Engineering of Hybrid Photonic-Plasmonic Devices for Enhanced Light-Matter Interactions	369
	M. Mossayebi, G. Bellanca, A. Parini, A.J. Wright and E.C. Larkins	
13.1	Introduction	369
13.2	Description of the Hybrid Device and Modeling Method	372
13.2.1	The Final Hybrid Structure Design	372
13.2.2	The Numerical Model	373
13.3	Optimization of the Hybrid Device	375
13.3.1	L3 Photonic Crystal Cavity	375
13.3.2	Bowtie Nanoantenna	376
13.3.3	Silicon Dioxide Spacing Layer	378
13.4	Characteristics of the Hybrid Device	381
13.4.1	Optical Intensity Profile	381
13.5	Integration of the Hybrid Device with a Photonic Crystal Waveguide	384
13.6	Concluding Remarks	388
	References	388
	Index	391