

Contents

Foreword *XXIII*

Preface *XXV*

An Overview of Micro- and Nanophotonic Science and Technology *XXVII*

Part One From Research to Application 1

1	Nanophotonics: From Fundamental Research to Applications	3
	<i>François Flory, Ludovic Escoubas, Judikael Le Rouzo, and Gérard Berginc</i>	
1.1	Introduction	3
1.2	Application of Photonic Crystals to Solar Cells	5
1.3	Antireflecting Periodic Structures	8
1.4	Black Silicon	10
1.5	Metamaterials for Wide-Band Filtering	14
1.6	Rough Surfaces with Controlled Statistics	16
1.7	Enhancement of Absorption in Organic Solar Cells with Plasmonic Nano Particles	19
1.8	Quantum Dot Solar Cells	20
1.9	Conclusions	24
	Acknowledgments	24
	References	24
2	Photonic Crystal and Plasmonic Microcavities	29
	<i>Kazuaki Sakoda</i>	
2.1	Introduction	29
2.2	Photonic Crystal Microcavity	32
2.3	Purcell Effect	38
2.3.1	Purcell Factor	38
2.3.2	GaAs Quantum Dots in PC Microcavity	39
2.4	Plasmonic Microcavity	41
2.4.1	Enhanced MD Radiation	42
2.4.2	Enhanced ED Radiation	46

2.4.3	Multimode Cavity	47
	References	50
3	Unconventional Thermal Emission from Photonic Crystals	51
	<i>Hideki T. Miyazaki</i>	
3.1	Introduction	51
3.2	3D Photonic Crystals	52
3.3	2D Photonic Crystals	57
3.4	1D Photonic Crystals	60
3.5	Summary	61
	References	61
4	Extremely Small Bending Loss of Organic Polaritonic Fibers	65
	<i>Ken Takazawa, Hiroyuki Takeda, and Kazuaki Sakoda</i>	
4.1	Introduction	65
4.2	Exciton–Polariton Waveguiding in TC Nanofibers	66
4.2.1	Synthesis and Characterization of TC Nanofibers	66
4.2.2	Mechanism of Active Waveguiding in TC Nanofibers	67
4.3	Miniaturized Photonic Circuit Components Constructed from TC Nanofibers	69
4.3.1	Asymmetric Mach–Zehnder Interferometers	69
4.3.2	Microring Resonators	71
4.3.3	Microring Resonator Channel Drop Filters	74
4.4	Theoretical Analysis	76
4.4.1	Dispersion Relation	76
4.4.2	Bending Loss	78
	References	80
5	Plasmon Color Filters and Phase Controllers	81
	<i>Yoshimasa Sugimoto, Daisuke Inoue, and Takayuki Matsui</i>	
5.1	Introduction	81
5.2	Optical Filter Based on Surface Plasmon Resonance	82
5.2.1	Light Transmission through Hole and Slit Arrays	83
5.2.1.1	Hole Arrays	83
5.2.1.2	Nanoslit Arrays	85
5.2.2	Fabrication and Measurement	87
5.2.3	Transmission Characteristics	89
5.2.3.1	Hole Arrays	89
5.2.3.2	Nanoslit Arrays	91
5.3	Transmission Phase Control by Stacked Metal–Dielectric Hole Array	92
5.3.1	Verification of Transmission Phase Control by a Uniform SHA	93
5.3.2	Numerical Study of Transition SHA for Inclined Wavefront Formation	95
5.3.3	Experimental Confirmation of Uniform SHA	95

5.3.4	Experimental Confirmation of Transition SHA	97
5.4	Summary	99
	References	100
6	Entangled Photon Pair Generation in Naturally Symmetric Quantum Dots Grown by Droplet Epitaxy	103
	<i>Takashi Kuroda</i>	
6.1	Introduction	103
6.2	Quantum Dot Photon-pair Source	105
6.3	Natural Growth of Symmetric Quantum Dots	108
6.4	Droplet Epitaxy of GaAs Quantum Dots on AlGaAs(1 1 1)A	109
6.5	Characterization of Entanglement	112
6.6	Violation of Bell's Inequality	115
6.7	Quantum-state Tomography and Other Entanglement Measures	118
	References	121
7	Single-Photon Generation from Nitrogen Isoelectronic Traps in III-V Semiconductors	125
	<i>Yoshiki Sakuma, Michio Ikezawa, and Liao Zhang</i>	
7.1	Introduction	125
7.2	What is Isoelectronic Trap?	126
7.3	GaP:N Case	127
7.3.1	Macro-PL from Bulk GaP:N	127
7.3.2	μ -PL of NN Pairs in δ -Doped GaP:N	127
7.3.3	Single-Photon Emission from δ -Doped GaP:N	130
7.4	GaAs:N Case	131
7.4.1	Overview of Isoelectronic Traps in GaAs	131
7.4.2	NX Centers in δ -Doped GaAs:N	132
7.4.2.1	Growth Conditions and Macro-PL	132
7.4.2.2	μ -PL of NX Centers and Single-Photon Emission	132
7.4.3	Energy-Defined N-Related Centers in δ -Doped GaAs:N	134
7.4.3.1	Growth Conditions and Macro-PL	134
7.4.3.2	μ -PL of NN_A and Single-Photon Emission	135
7.5	Summary	138
	References	138
8	Parity-Time Symmetry in Free Space Optics	143
	<i>Bernard Kress, PhD and Mykola Kulishov, PhD</i>	
8.1	Parity-Time Symmetry in Diffractive Optics	143
8.1.1	Spectral, Angular, and Polarization Selectivity	143
8.1.2	Time Multiplexing: Dynamic Gratings and Holograms	144
8.1.3	From Conventional Amplitude/Phase Modulations to Phase/Gain/Loss Modulations	145
8.1.4	Implementation of Parity-Time Symmetry in Optics	145

8.1.4.1	Thick and Thin Gratings	147
8.2	Free Space Diffraction on Active Gratings with Balanced Phase and Gain/Loss Modulations	148
8.2.1	Raman–Nath PT-Symmetric Diffraction	148
8.2.1.1	Raman–Nath Diffraction Regime	150
8.2.1.2	Intermediate and Bragg Diffraction Regimes	151
8.2.1.3	Summary	155
8.3	PT-Symmetric Volume Holograms in Transmission Mode	156
8.3.1	Second-Order Coupled Mode Equations	157
8.3.2	Two-Mode Solution for $\theta = \theta_B$	160
8.3.3	Analytic Solution for Balanced PT-Symmetric Grating for Arbitrary Angle of Incidence	162
8.3.4	Filled Space PT-Symmetric Grating	166
8.3.5	Symmetric Slab Configuration	167
8.3.6	Asymmetric Slab Configurations	168
8.3.6.1	Light Incident from the Substrate Side: $\varepsilon_3 = 1$	168
8.3.6.2	Light Incident from the Air: $\varepsilon_1 = 1$	170
8.3.6.3	Reflective Setup	170
8.3.7	Discussion	171
8.4	Analysis of Unidirectional Nonparaxial Invisibility of Purely Reflective PT-Symmetric Volume Gratings	174
8.4.1	Introduction	174
8.4.2	Analytic Solution for First Three Bragg Orders for a Balanced PT-Symmetric Grating	174
8.4.3	Zeroth Diffractive Orders in Transmission and Reflection	177
8.4.4	Higher Diffractive Orders	178
8.4.4.1	First Diffraction Orders	178
8.4.4.2	Second Diffraction Orders	179
8.4.5	Filled Space PT-Symmetric Gratings	180
8.4.5.1	Filled Space PT-Symmetric Grating Implies $\varepsilon_1 = \varepsilon_2 = \varepsilon_3$	180
8.4.6	Reflective PT-Symmetric Gratings with Fresnel Reflections	185
8.4.6.1	Symmetric Geometry $\varepsilon_1 = \varepsilon_3 = 1; \varepsilon_2 = 2.4$	185
8.4.6.2	Asymmetric Slab Configuration	186
8.5	Summary and Conclusions	189
	References	191
9	Parity–Time Symmetric Cavities: Intrinsically Single-Mode Lasing	193
	<i>Mykola Kulishov and Bernard Kress</i>	
9.1	Introduction	193
9.2	Resonant Cavities Based on two PT-Symmetric Diffractive Gratings	194
9.2.1	PT-Symmetric Bragg Grating	194
9.2.2	Concatenation of Two Gratings	195
9.2.3	Temporal Characteristics	202
9.2.4	Summary	204

- 9.3 Distributed Bragg Reflector Structures Based on PT-Symmetric Coupling with Lowest Possible Lasing Threshold 204
- 9.3.1 Grating-Assisted Codirectional Coupler with PT Symmetry 205
- 9.3.2 Threshold Condition in DBR Lasers 208
- 9.3.3 DBR Lasers with PT-Symmetrical GACC Output 209
- 9.3.4 Transfer Matrix Description of the DBR Structure with PT-Symmetrical GACC Output 210
- 9.4 Unique Optical Characteristics of a Fabry–Perot Resonator with Embedded PT-Symmetrical Grating 215
- 9.4.1 Transfer Matrix for Fabry–Perot Cavity with a Single PT-SBG 216
- 9.4.2 Absorption and Amplification Modes along with Lasing Characteristics 220
- 9.4.2.1 Fully Constructive Cavity Interaction 220
- 9.4.2.2 Partially Constructive Cavity Interaction 223
- 9.4.2.3 Partially Destructive Cavity Interaction 228
- 9.4.2.4 Fully Destructive Cavity Interaction 230
- 9.5 Summary and Conclusions 230
- References 231

10 Silicon Quantum Dot Composites for Nanophotonics 233

Hiroshi Sugimoto and Minoru Fujii

- 10.1 Introduction 233
- 10.2 Core–Shell Type Nanocomposites 234
- 10.3 Polymer Encapsulation 239
- 10.4 Micelle Encapsulation 241
- 10.5 Summary 243
- Acknowledgments 243
- References 243

Part Two Breakthrough Applications 247

11 Ultrathin Polarizers and Waveplates Made of Metamaterials 249

Masanobu Iwanaga

- 11.1 Concept and Practice of Subwavelength Optical Devices 249
- 11.1.1 Conceptual Classification of Polarization–Controlling Optical Devices 249
- 11.1.2 Construction of Optical Devices Using Jones Matrices 250
- 11.1.3 UV NIL 252
- 11.2 Ultrathin Polarizers 254
- 11.3 Ultrathin Waveplates 258
- 11.3.1 Ultrathin Waveplates Made of Stratified Metal–Dielectric MMs 259
- 11.3.2 Ultrathin Waveplates of Other Structures 262
- 11.4 Constructions of Functional Subwavelength Devices 264

11.5	Summary and Prospects	267
	Acknowledgments	267
	References	267
12	Nanoimprint Lithography for the Fabrication of Metallic Metasurfaces	269
	<i>Yoshimasa Sugimoto, Masanobu Iwanaga, and Hideki T. Miyazaki</i>	
12.1	Introduction	269
12.2	UV-NIL	270
12.3	Large-Area SP-RGB Color Filter Using UV-NIL	273
12.3.1	Introduction	273
12.3.2	Device Design	274
12.3.3	Device Fabrication and Transmission Characteristics	275
12.4	Emission-Enhanced Plasmonic Metasurfaces Fabricated by NIL	278
12.4.1	Introduction	278
12.4.2	SC-PIC Structure	279
12.4.3	Fabrication and Optical Characterization of SC-PIC	279
12.5	Metasurface Thermal Emitters for Infrared CO ₂ Detection by UV-NIL	282
12.5.1	Introduction	282
12.5.2	Metasurface Design	282
12.5.3	Device Fabrication and Optical Properties	283
12.6	Summary	285
	References	287
13	Applications to Optical Communication	291
	<i>Philippe Gallion</i>	
13.1	Introduction	291
13.2	Optical Fiber and Propagation Impairments	294
13.2.1	Guiding Necessity	294
13.2.2	Multimode and Single-Mode Fibers	295
13.2.3	Rayleigh Diffusion as the Limiting Factor for Optical Fiber Attenuation	297
13.2.4	A Huge Available Bandwidth Resource	298
13.2.5	dispersions as the bit-rate limitations	299
13.2.5.1	Group Velocity Dispersion	299
13.2.5.2	Polarization Mode Dispersion	299
13.2.5.3	bit-rate limitations	301
13.2.5.4	Overcoming the Dispersion Limitations	302
13.2.6	Fiber Nonlinearity	302
13.2.7	New Fiber Materials and Structures	304
13.3	Basics of Functional Devices	305
13.3.1	Optical Sources	305
13.3.1.1	Light Emission in Semiconductor	305
13.3.1.2	Semiconductor Laser Single-Mode Operation	306

13.3.1.3	Interband Dynamics as Direct Modulation Limitation	308
13.3.1.4	Optical Frequency Chirping	308
13.3.1.5	Optical Frequency Tuning	309
13.3.1.6	Quantum Phase Diffusion and Linewidth	309
13.3.2	External Modulation	310
13.3.2.1	Electroabsorption Modulation	310
13.3.2.2	Electro-Optic Modulation	310
13.3.3	Optical Amplification	311
13.3.3.1	Needs of Optical Amplification	311
13.3.3.2	Today's Optical Amplifier Technologies	311
13.3.3.3	Heisenberg Indetermination and Quantum Noise	312
13.3.3.4	Spontaneous Emission Noise Description	313
13.3.3.5	Optical Amplifier Noise Figure	313
13.3.3.6	Noise in Cascaded Amplifications	313
13.3.4	Interfacing the Optical and the Electronics Domains	314
13.3.5	Module Packaging	314
13.4	Advanced Optical Communication Techniques	315
13.4.1	Managing the Color and Wavelength Division Multiplexing	315
13.4.2	Coherent Optical Communication	316
13.4.2.1	Coherent Optical Receiver	316
13.4.2.2	Quadrature Amplitude Modulations	317
13.4.3	Digital Communication and Signal Processing Techniques	318
13.5	Today's Optical Communication Systems	319
13.5.1	The Conquest of Submarine and Terrestrial Communication Infrastructures	319
13.5.2	Optical Fiber at Our Door	320
13.5.2.1	The Last-Mile Problem	320
13.5.2.2	Optical Connection to the End Users	320
13.5.3	Optical Wireless and Free Space Communications	322
13.5.4	Quantum Cryptography	322
13.6	Conclusions: Today's Challenges and Perspectives	323
	Acknowledgments	326
	List of Acronyms and Abbreviations	326
	References	328
14	Advanced Concepts for Solar Energy	333
	<i>Mikaël Hosatte</i>	
14.1	Introduction	333
14.2	Photon Management	334
14.2.1	Antireflection Techniques	334
14.2.2	Light Trapping	337
14.3	Spectral Optimization	339
14.3.1	Upconversion/Downconversion	339
14.3.2	Tandem Cells	340
14.4	Advanced Concepts	343

14.4.1	Third-Generation Concepts	343
14.4.2	Multiple Energy Level Solar Cells	344
14.4.3	Multiple Exciton Generation	345
14.4.4	Hot Carrier Solar Cells	348
14.4.5	Comparison of the Approaches	349
14.5	Conclusions	349
	References	350
15	The Micro- and Nanoinvestigation and Control of Physical Processes Using Optical Fiber Sensors and Numerical Simulations: a Mathematical Approach	355
	<i>Adrian Neculae and Dan Curticapean</i>	
15.1	Introduction	355
15.2	Temperature Measurement and Heat Transfer Evaluation in a Circular Cylinder by Considering a High Accurate Numerical Solution	360
15.2.1	Theoretical Background	361
15.2.2	Numerical Results for Conductive Transport	366
15.2.3	The SP ₁ Approximation Model	370
15.2.4	Numerical Results for the SP ₁ Model	370
15.3	Numerical Analysis of the Diffusive Mass Transport in Brain Tissues with Applications to Optical Sensors	372
15.3.1	Theoretical Background	373
15.3.2	Numerical Results	375
	Acknowledgment	380
	References	380
16	Laser Micronanofabrication	383
	<i>Sylvain Lecler, Joël J. Fontaine, and Frédéric Mermet</i>	
16.1	Introduction	383
16.2	Physical Issues	384
16.2.1	The Laser Mean Power	385
16.2.2	The Wavelength	385
16.2.3	Pulse Duration and Repetition Rate	385
16.2.4	Spatial Concentration and Beam Shaping	385
16.2.5	Material Response	386
16.3	Recent Technological Advances	387
16.3.1	Femtosecond Laser	387
16.3.2	Nondivergent Subwavelength Beams	388
16.3.3	Subwavelength Focusing of Light with Photonic Nanojet	389
16.3.4	Subwavelength Deposition by LIFT Technique	389
16.4	Laser Microprocesses	392
16.4.1	Material Deposition and Thin-Layer Control	392
16.4.2	Nanoparticle Fabrication	392
16.4.3	Microdrilling	393
16.4.4	Microcutting	393

- 16.4.5 Laser Microwelding 395
- 16.4.6 Surface Texturing 396
- 16.4.7 Additive Manufacturing 397
- 16.4.8 Waveguide Writing 399
- 16.5 Conclusions 399
- References 400

- 17 Ultrarealistic Imaging Based on Nanoparticle Recording Materials 403**
Hans I. Bjelkhagen
- 17.1 Introduction 403
- 17.1.1 Demands on a Holographic Emulsion 404
- 17.1.2 Silver Halide Emulsion Light Scattering 405
- 17.1.3 History of Ultrafine-grain Silver Halide Emulsions 406
- 17.2 Preperation of Silver Hailde Emulsions: Principle 407
- 17.2.1 General Description of the Photographic Emulsion Making Process 407
- 17.2.2 The Specification for the SilverCross Ultrafine-grain Emulsion 408
- 17.2.3 The Fabrication of a Basic Ultrafine-Grain Emulsion 409
- 17.2.3.1 Gelatin Concentration 410
- 17.2.3.2 Silver and Halide Concentrations 410
- 17.2.3.3 Silver to Halide Ratio 410
- 17.2.3.4 Jetting Methods and Jetting Time 410
- 17.2.3.5 Solution Temperatures 411
- 17.2.3.6 Concentration and Removal of Reaction By-products 411
- 17.2.3.7 Coating 412
- 17.3 Testing of the Emulsion 413
- 17.3.1 Sensitometric Tests 413
- 17.3.2 Color Holography Tests 414
- 17.4 Recording Museum Artifacts with Color Holography 417
- 17.4.1 Recording Holograms of Museum Artifacts 418
- 17.4.2 Holographic Recordings with Mobile Equipment 418
- 17.5 Conclusions 421
- Acknowledgments 421
- References 422

- 18 An Introduction to Tomographic Diffractive Microscopy: Toward High-Speed Quantitative Imaging Beyond the Abbe Limit 425**
Jonathan Bailleul, Bertrand Simon, Matthieu Debailleul, and Olivier Haeberlé
- 18.1 Introduction 425
- 18.2 Conventional Transmission Microscopy 426
- 18.2.1 Transmission Microscopy and Köhler Illumination 426
- 18.2.2 Dark-Field Microscopy 428
- 18.2.3 Phase-Contrast Microscopy 429
- 18.3 Phase Amplitude Microscopy 431

- 18.3.1 Digital Holography 432
- 18.3.2 Wavefront Analyzer 433
- 18.4 Tomographic Diffractive Microscopy for True 3D Imaging 433
 - 18.4.1 Limits of Phase Microscopy 433
 - 18.4.2 Tomography by Illumination Variation 434
 - 18.4.3 Tomography by Specimen Rotation 436
- 18.5 Biological Applications 438
- 18.6 Conclusions 439
- References 439

- 19 Nanoplasmonic Guided Optic Hydrogen Sensor 443**
Nicolas Javahiraly and Cédric Perrotton
 - 19.1 Introduction 443
 - 19.2 Fiber Optic Sensor 448
 - 19.3 Pd Hydrogen Sensing Systems 451
 - 19.3.1 Bulk Palladium Film 451
 - 19.3.2 Thin Pd Film 453
 - 19.3.3 Metal Properties upon Hydrogenation 454
 - 19.4 Fiber Optic Hydrogen Sensors 455
 - 19.5 Fiber Surface Plasmon Resonance Sensor 457
 - 19.6 Sensitive Material for Hydrogen Sensing 460
 - 19.6.1 Pd Alloys 460
 - 19.6.2 Metal Hydrides and Rare-Earth Materials 461
 - 19.6.3 Tungsten Oxide 462
 - 19.7 Conclusions 464
 - Acknowledgment 466
 - References 466

- 20 Fiber Optic Liquid-Level Sensor System for Aerospace Applications 471**
Alex A. Kazemi, Chengning Yang, and Shiping Chen
 - 20.1 Introduction 471
 - 20.2 The Operation Principle and System Design 472
 - 20.2.1 Optical Fiber Long-Period Gratings 472
 - 20.2.2 Optical Time Domain Reflectometer 474
 - 20.2.3 Total Internal Reflection 474
 - 20.2.4 LPG Sensor Liquid-Level System 475
 - 20.2.5 TIR-Based Liquid-Level Detection System 476
 - 20.3 Experimental Results 478
 - 20.4 Liquid-Level Sensor Performance 485
 - 20.5 Conclusions 486
 - References 487

- 21 Tunable Micropatterned Colloid Crystal Lasers 489**
Seiichi Furumi, Hiroshi Fudouzi, and Tsutomu Sawada
 - 21.1 Introduction 489

21.2	Synthesis of Colloidal Microparticles and Reflection Features of CCs	493
21.3	Laser Action from CCs with Light-Emitting Planar Defects	495
21.4	Micropatterned Laser Action from CCs by Photochromic Reaction	498
21.5	Tunable Laser Action from CC Gel Films Stabilized by Ionic Liquid	498
21.6	Conclusions and Outlook	503
	Acknowledgments	504
	References	504
22	Colloidal Photonic Crystals Made of Soft Materials: Gels and Elastomers	507
	<i>Hiroshi Fudouzi and Tsutomu Sawada</i>	
22.1	Introduction	507
22.2	Colloidal Photonic Crystal Gels Consist of Nonclose-packed Particles	508
22.2.1	Highly Oriented Colloidal Photonic Crystals by Shear-Flow Effect	508
22.2.2	Structural Characterization of Crystals Oriented by Shear Flow	510
22.3	Colloidal Photonic Crystal Elastomer Consists of Close-packed Particles	515
22.3.1	A Uniaxially Oriented Opal Film by Crystal Growth under Silicone Liquid	515
22.3.2	Colloidal Photonic Crystal Elastomer Film Coated on a Rubber Sheet	518
22.4	Applications	520
22.4.1	Colloidal Photonic Crystal Gels	520
22.4.2	Colloidal Photonic Crystal Elastomers	521
22.5	Summary and Outlook	523
	References	524
23	Surveying the Landscape and the Prospects in Nanophotonics	527
	<i>David L. Andrews, Patrick L. Meyrueis, and Marcel Van de Voorde</i>	
23.1	Retrospective	527
23.2	Fundamental Developments	527
23.3	Futorology	528
23.4	Applications	529
23.5	Summing Up	529
	Index	531

