

CONTENTS

Preface	xiii
Acknowledgment from I.T.	xix
1. Plasmonic Enhancement of Optical Properties by Isolated and Coupled Metal Nanoparticles	1
1. Introduction	2
2. Optical Enhancement due to Isolated Metal Nanospheres	4
2.1. Surface plasmon modes of an isolated metal sphere	4
2.2. Absorption enhancement	10
2.3. Electroluminescence enhancement	15
2.4. Photoluminescence enhancement	22
3. Enhancement due to Coupled Metal Nanoparticles	26
3.1. Coupled mode theory	28
3.2. Solution for the field enhancement	32
3.3. Enhancement results and discussion	34
4. Implications	39
2. Chiral Photonic and Plasmonic Structures	45
1. Introduction	45
2. Transfer Matrix Method for Anisotropic Medium	48
3. Chiral Media from Discrete Screw Operations	50
4. Chiral Media from Continuous Screw Operation	60
5. Conclusions	64

3.	Multipole Metamaterials	67
1.	Introduction	68
2.	Spatial Averaging for Meta-Molecules — Recalling the Role of Multipole Moments	68
3.	Light Propagation in Metamaterials Including Multipole Moments Up to the Second Order	78
4.	Multipolar Properties of Planar Meta-Molecules	87
5.	Multipole Near-Field Decomposition for Meta-Molecules	94
6.	Summary and Outlook	96
4.	Amplification and Lasing with Surface-Plasmon Polaritons	101
1.	Introduction	101
2.	Planar Metallic Surfaces	102
2.1.	Single metal-dielectric interface	103
2.2.	Thin metal film/stripe	110
2.3.	Metal-insulator-metal structure	116
3.	Metallic Nanocavities	117
4.	Metallic Nanoparticles	119
5.	Concluding Remarks	120
5.	Wavefront Engineering of Quantum Cascade Lasers Using Plasmonics	123
1.	Introduction	124
1.1.	Surface plasmons and Zenneck waves	124
1.2.	Quantum design and waveguide design of quantum cascade lasers	125
2.	Methods to Tailor the Dispersion Properties of Mid-IR and THz Surface Plasmon Polaritons	128
3.	One-Dimensional Collimators for Mid-IR QCLs	133
4.	Two-Dimensional Collimators for Mid-IR QCLs	138
5.	Multi-Beam QCLs	140
6.	Mid-IR QCLs with Integrated Plasmonic Polarizers	143
7.	Beam Shaping of THz QCLs Using Plasmonics	147
7.1.	Semiconductor plasmonic second-order grating collimator for THz QCLs	147
7.2.	Metasurface collimator for THz QCLs	149
7.3.	Reduction of the lateral beam divergence	156

7.4. Metasurface lens	158
8. Conclusions and Future Perspectives	159
6. Plasmonics for Ultrasensitive Nanospectroscopy and Optofluidic-Plasmonics Biosensors	167
1. Introduction	168
1.1. Plasmonic nano-biosensors	169
2. Mid-Infrared Plasmonics for Ultrasensitive Nanospectroscopy	172
2.1. Radiative engineering with collective plasmons on antenna arrays	173
2.2. Collectively enhanced infrared absorption spectroscopy	177
3. High Throughput Fabrication of Plasmonics with Nanostencil Lithography	180
3.1. Nanostencil lithography technique	181
3.2. High quality plasmonic resonances with NSL	182
3.3. High throughput nanofabrication with NSL	184
4. Integrated Nanoplasmonic-Nanofluidic Biosensors Molding the Flow of Light and Fluidics	185
4.1. Targeted versus conventional fluidics	187
4.2. Lift-off fabrication of plasmonic nanohole arrays	188
4.3. Active analyte delivery with sub-wavelength fluidics	189
5. Conclusion and Outlook	190
7. Long-Range Surface Plasmon Polariton Waveguides and Devices	197
1. Introduction	198
2. Dispersion Relations, Field Confinement and Propagation Loss	200
3. Fabrication	207
3.1. Metal stripe LRSPP waveguides	207
3.2. Nanowire plasmonic waveguides	209
3.3. Ultra-thin LRSPP waveguides with fluorescent polymer cladding	211
4. Optical Properties	213
4.1. Waveguide properties	213

4.2. LRSPP mode coupling	215
4.3. Reflection gratings	218
4.4. Interferometric devices	221
4.5. Extinction modulators	224
4.6. LRSPP amplification	225
5. Conclusions and Outlook	227
8. Surface Plasmon Biosensing with 3D Plasmonic Crystals	231
1. Introduction	231
1.1. Label-free sensing	232
1.2. Surface plasmon sensing	232
2. Engineered Surfaces for Biosensing: Plasmonic Crystals with 3D Unit Cells	238
3. Bulk Refractive Index Sensitivity and Dependence on Angle of Incidence	239
4. Molecular Sensing Using 3D Plasmonic Crystals	242
4.1. Nanopyramidal gratings: sensing under reflection conditions	242
4.2. 3D Nanohole arrays: sensing under transmission conditions	244
5. Biosensing with 3D Plasmonic Crystals in Real-Time	246
6. Conclusions and Outlook	249
9. Tunable and Active Optical Negative Index Metamaterials	255
1. Introduction	255
2. Negative Index Metamaterials in the Optical Range	257
2.1. Sample fabrication	258
2.2. Simulations	261
3. Active Optical Negative Index Metamaterials	263
3.1. Sample fabrication	265
3.2. Sample characterization	268
3.3. Simulations	270
4. Tunable Optical Metamaterials	275
4.1. Sample fabrication	276
4.2. Tunable behavior	279
4.3. Simulations	280
5. Conclusions and Outlook	281

10. Manipulation of Plasmonics from Nano to Micro Scale	285
1. Introduction	285
2. Form-Birefringent Metal and Its Plasmonic Anisotropy	286
3. Plasmonic Photonic Crystal	290
4. Fourier Plasmonics	294
5. Nanoscale Optical Field Localization	297
6. Conclusions and Outlook	301
11. Dielectric-Loaded Plasmonic Waveguide Components	305
1. Introduction	306
2. Design of Waveguide Dimensions	307
2.1. Mode confinement and propagation loss	308
3. Sample Preparation and Near-Field Characterization	310
3.1. Sample configuration and fabrication method	310
3.2. Near-field imaging of DLSPPW components	311
4. Excitation and Propagation of Guided Modes	313
4.1. Mode confinement and propagation loss	314
5. Waveguide Bends and Splitters	316
6. Coupling between Waveguides	319
6.1. Near-field characterization	323
6.2. Design of wavelength selective DC	326
7. Waveguide-Ring Resonators	327
8. Bragg Gratings	329
9. Discussion	331
12. Manipulating Nanoparticles and Enhancing Spectroscopy with Surface Plasmons	335
1. Introduction	335
2. Propulsion of Gold Nanoparticles with Surface Plasmon Polaritons	337
3. Double Resonance Substrates for Surface-Enhanced Raman Spectroscopy	344
4. Conclusions and Outlook	352
13. Analysis of Light Scattering by Nanoobjects on a Plane Surface via Discrete Sources Method	355
1. Introduction	356

2.	Light Scattering by a Nanorod	358
2.1.	Introduction	358
2.2.	Asymmetrical DSM model for nanorod	358
2.3.	DSM numerical scheme	362
2.4.	Numerical results	365
2.5.	Conclusion	371
3.	Light Scattering by a Nanoshell	372
3.1.	Introduction	372
3.2.	DSM model for nanoshell	372
3.3.	Numerical scheme of the DSM	377
3.4.	Results and discussion	379
3.5.	Conclusion	385
4.	Summary	386
14.	Computational Techniques for Plasmonic Antennas and Waveguides	389
1.	Introduction	389
2.	Time Domain Solvers	392
2.1.	Eigenvalue problems	393
2.2.	Dispersive materials	393
2.3.	Periodic symmetries	394
2.4.	Grid refinement	395
2.5.	Finite differences and finite integrals	396
2.6.	Finite volume	396
2.7.	FEM and DG-FEM	397
3.	Frequency Domain Solvers	398
3.1.	Finite differences	399
3.2.	Finite elements	400
3.3.	Method of moments	401
3.4.	BEM	402
3.5.	Semi-analytic boundary discretization	402
4.	Plasmonic Antennas	404
4.1.	Metallic patch antenna with small groove	406
4.2.	Axisymmetric antenna structures	407
4.3.	Chains of plasmonic particles	411
5.	Plasmonic Waveguides	419
5.1.	Axisymmetric, cylindrical waveguide	421
5.2.	Non-axisymmetric, cylindrical waveguide	424
5.3.	Periodic, cylindrical waveguide	428

5.4. Periodic, axisymmetric waveguide	429
6. Advanced Structures	432
7. Conclusions	436
Index	441