Introduction to Nanophotonics

a subset

Sergey V. Gaponenko

National Academy of Sciences, Belarus



3/10

Contents

Preface p	
Notations and acronyms	xv
1 Introduction	1
1.1 Light and matter on a nanometer scale	1
1.2 What is nanophotonics?	2
1.3 Where are the photons in nanophotonics and in this book?	3
References	4
Part I Electrons and electromagnetic waves	
2 Basic properties of electromagnetic waves and quantum particles	9
2.1 Wavelengths and dispersion laws	9
2.2 Density of states	13
2.3 Maxwell and Helmholtz equations	16
2.4 Phase space, density of states and uncertainty relation	18
2.5 Wave function and the Schrödinger equation	20
2.6 Quantum particle in complex potentials	22
Problems	32
References	34
3 Wave optics versus wave mechanics I	35
3.1 Isomorphism of the Schrödinger and Helmholtz equations	35
3.2 Propagation over wells and barriers	37
3.3 Dielectric function of free electron gas and optical properties of metals	51
3.4 Propagation through a potential barrier: evanescent waves and tunneling	54
3.5 Resonant tunneling in quantum mechanics and in optics	65
3.6 Multiple wells and barriers: spectral splitting	70
3.7 Historical comments	73
Problems	76
References	77
4 Electrons in periodic structures and quantum confinement effects	79
4.1 Bloch waves	79
4.2 Reciprocal space and Brillouin zones	84

علقج

	4.3	Electron band structure in solids	86
	4.4	Quasiparticles: holes, excitons, polaritons	89
	4.5	Defect states and Anderson localization	93
	4.6	Ouantum confinement effects in solids	97
	4.7	Density of states for different dimensionalities	99
	4.8	Quantum wells, quantum wires and quantum dots	100
	Prob	lems	107
	Refe	rences	107
5	Sem	iconductor nanocrystals (quantum dots)	110
	5.1	From atom to crystal	110
	5.2	Particle-in-a-box theory of electron-hole states	112
	5.3	Quantum chemical theory	118
	5.4	Synthesis of nanocrystals	120
	5.5	Absorption spectra, electron-hole pair states and many-body effects	125
	5.6	Luminescence	130
	5.7	Probing the zero-dimensional density of states	133
	5.8	Quantum dot matter	133
	5.9	Applications: nonlinear optics	139
	5.10	Applications: quantum dot lasers	142
	5.11	Applications: novel luminophores and fluorescent labels	148
	5.12	Applications: electro-optical properties	155
	Prob	lems	157
	Refe	rences	158
6	Nan	oplasmonics I: metal nanoparticles	166
	6.1	Optical response of metals	166
	6.2	Plasmons	174
	6.3	Optical properties of metal nanoparticles	179
	6.4	Size-dependent absorption and scattering	187
	6.5	Coupled nanoparticles	191
	6.6	Metal-dielectric core-shell nanoparticles	192
	Prob	lems	195
	Refe	rences	196
7	Ligh	t in periodic structures: photonic crystals	199
	7.1	The photonic crystal concept	199
	7.2	Bloch waves and band structure in one-dimensionally periodic structures	200
	7.3	Multilayer slabs in three dimensions: band structure and omnidirectional	
		reflection	207
	7.4	Band gaps and band structures in two-dimensional lattices	210
	7.5	Band gaps and band structure in three-dimensional lattices	213
	7.6	Multiple scattering theory of periodic structures	215
	7.7	Translation to other electromagnetic waves	216

Contents
contents

	7.8	Periodic structures in Nature	217
	7.9	Experimental methods of fabrication	218
	7.10	Properties of photonic crystal slabs	225
	7.11	The speed of light in photonic crystals	232
	7.12	Nonlinear optics of photonic crystals	236
	Prob	lems	239
	Refe	rences	240
8	Ligh	t in non-periodic structures	246
	8.1	The 1/L transmission law: an optical analog to Ohm's law	246
	8.2	Coherent backscattering	251
	8.3	Towards the Anderson localization of light	253
	8.4	Light in fractal structures	258
	8.5	Light in quasiperiodic structures: Fibonacci and Penrose structures	270
	8.6	Surface states in optics: analog to quantum Tamm states	278
	8.7	General constraints on wave propagation in multilayer structures:	
		transmission bands, phase time, density of modes and energy localization	280
	8.8	Applications of turbid structures: Christiansen's filters and	
		Letokhov's lasers	289
	Prob	lems	290
	Refe	rences	291
9	Phot	tonic circuitry	295
	9.1	Microcavities and microlasers	295
	9.2	Guiding light through photonic crystals	298
	9.3	Holey fibers	303
	9.4	Whispering gallery modes: photonic dots, photonic	
		molecules and chains	305
	9.5	Propagation of waves and number coding/recognition	309
	9.6	Outlook: current and future trends	311
	Prob	lems	312
	Refe	rences	313
10	Tuni	neling of light	317
	10.1	Tunneling of light: getting through the looking glass	317
	10.2	Light at the end of a tunnel: problem of superluminal propagation	320
	10.3	Scanning near-field optical microscopy	330
	Prob	lems	334
	Refe	rences	334
11	Nan	oplasmonics II: metal-dielectric nanostructures	336
	11.1	Local electromagnetic fields near metal nanoparticles	336
	11.2	Optical response of a metal-dielectric composite beyond	
		Maxwell-Garnett theory	341

	11.3	Extraordinary transparency of perforated metal films	344
	11.4	Metal-dielectric photonic crystals	346
	11.5	Nonlinear optics with surface plasmons	348
	11.6	Metal nanoparticles in a medium with optical gain	350
	11.7	Metamaterials with negative refractive index	353
	11.8	Plasmonic sensors	361
	11.9	The outlook	363
	Problems		363
	Refer	ences	364
12	Wave	e optics versus wave mechanics II	368
	12.1	Transfer of concepts and ideas from quantum theory of	
		solids to nanophotonics	368
	12.2	Why quantum physics is ahead	370
	12.3	Optical lessons of quantum intuition	370
	Problems		372
	Refer	ences	373

Part II Light-matter interaction in nanostructures

13	Light	 matter interaction: introductory quantum electrodynamics 	377
	13.1	Photons	377
	13.2	Wave-particle duality in optics	381
	13.3	Electromagnetic vacuum	382
	13.4	The Casimir effect	384
	13.5	Probability of emission of photons by a quantum system	385
	13.6	Does "Fermi's golden rule" help to understand	
		spontaneous emission?	389
	13.7	Spontaneous scattering of photons	390
	Proble	ms	392
	Refere	ences	392
14	Densi	ty of states effects on optical processes in mesoscopic structures	395
14	Densi 14.1	ty of states effects on optical processes in mesoscopic structures The Purcell effect	395 396
14	Densi 14.1 14.2	ty of states effects on optical processes in mesoscopic structures The Purcell effect An emitter near a planar mirror	395 396 400
14	Densi 14.1 14.2 14.3	ty of states effects on optical processes in mesoscopic structures The Purcell effect An emitter near a planar mirror Spontaneous emission in a photonic crystal	395 396 400 401
14	Densi 14.1 14.2 14.3 14.4	ty of states effects on optical processes in mesoscopic structures The Purcell effect An emitter near a planar mirror Spontaneous emission in a photonic crystal Thin layers, interfaces and stratified dielectrics	395 396 400 401 404
14	Densi 14.1 14.2 14.3 14.4 14.5	ty of states effects on optical processes in mesoscopic structures The Purcell effect An emitter near a planar mirror Spontaneous emission in a photonic crystal Thin layers, interfaces and stratified dielectrics Possible subnatural atomic linewidths in plasma	395 396 400 401 404 407
14	Densi 14.1 14.2 14.3 14.4 14.5 14.6	ty of states effects on optical processes in mesoscopic structures The Purcell effect An emitter near a planar mirror Spontaneous emission in a photonic crystal Thin layers, interfaces and stratified dielectrics Possible subnatural atomic linewidths in plasma Barnett-Loudon sum rule	395 396 400 401 404 407 408
14	Densi 14.1 14.2 14.3 14.4 14.5 14.6 14.7	ty of states effects on optical processes in mesoscopic structures The Purcell effect An emitter near a planar mirror Spontaneous emission in a photonic crystal Thin layers, interfaces and stratified dielectrics Possible subnatural atomic linewidths in plasma Barnett–Loudon sum rule Local density of states: operational definition and conservation law	395 396 400 401 404 407 408 410
14	Densi 14.1 14.2 14.3 14.4 14.5 14.6 14.7 14.8	ty of states effects on optical processes in mesoscopic structures The Purcell effect An emitter near a planar mirror Spontaneous emission in a photonic crystal Thin layers, interfaces and stratified dielectrics Possible subnatural atomic linewidths in plasma Barnett–Loudon sum rule Local density of states: operational definition and conservation law A few hints towards understanding local density of states	395 396 400 401 404 407 408 410 411
14	Densi 14.1 14.2 14.3 14.4 14.5 14.6 14.7 14.8 14.9	ty of states effects on optical processes in mesoscopic structures The Purcell effect An emitter near a planar mirror Spontaneous emission in a photonic crystal Thin layers, interfaces and stratified dielectrics Possible subnatural atomic linewidths in plasma Barnett–Loudon sum rule Local density of states: operational definition and conservation law A few hints towards understanding local density of states Thermal radiation in mesoscopic structures	395 396 400 401 404 407 408 410 411 413

تلاج

xi

2.50

1	4.11 Directional emission and scattering of light defined by partial	
	density of states	416
Р	roblems	419
R	References	419
15 L	ight-matter states beyond perturbational approach	424
1	5.1 Cavity quantum electrodynamics in the strong coupling regime	424
1	5.2 Single-atom maser and laser	428
1	5.3 Light-matter states in a photonic band gap medium	429
1	5.4 Single photon sources	431
Р	roblems	433
F	References	433
16 P	lasmonic enhancement of secondary radiation	436
1	6.1 Classification of secondary radiation	436
1	6.2 How emission and scattering of light can be enhanced	437
1	6.3 Local density of states in plasmonic nanostructures	439
1	6.4 "Hot spots" in plasmonic nanostructures	441
1	6.5 Raman scattering enhancement in metal-dielectric nanostructures	444
1	6.6 Luminescence enhancement in metal-dielectric nanostructures	447
P	roblems	452
F	References	452
Auth	or index	455
Subie	ect index	458

..