Introduction to Nanophotonics

Nanophotonics is where photonics merges with nanoscience and nanotechnology, and where spatial confinement considerably modifies light propagation and light–matter interaction. Describing the basic phenomena, principles, experimental advances and potential impact of nanophotonics, this graduate-level textbook is ideal for students in physics, optical and electronic engineering and materials science.

The textbook highlights practical issues, material properties and device feasibility, and includes the basic optical properties of metals, semiconductors and dielectrics. Mathematics is kept to a minimum and theoretical issues are reduced to a conceptual level. Each chapter ends in problems so readers can monitor their understanding of the material presented.

The introductory quantum theory of solids and size effects in semiconductors is considered to give a parallel discussion of wave optics and wave mechanics of nanostructures. The physical and historical interplay of wave optics and quantum mechanics is traced. Nanoplasmonics, an essential part of modern photonics, is also included.

Sergey V. Gaponenko is Head of the Laboratory for Nano-optics at the Stepanov Institute of Physics, National Academy of Sciences of Belarus. He is also Chairman of the Association of Lasers and Optics and Vice-president of the Laser Association.

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Sergey V. Gaponenko
National Academy of Sciences, Belarus

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To Olga

Contents

Preface

It is an extraordinary paradox of Nature that, being seemingly the only creatures capable of understanding its harmony, we naively attempt to chase its very essence through our daily experience based on mass-point mechanics and ray optics, while its elusive structure is mainly contained in wave phenomena. It may be nanophotonics where many pathways happily merge that promises not only mental satisfaction in our scientific quest but also an extra bonus in the form of new technologies and devices.

In this book I have tried to give a consistent description of the basic physical phenomena, principles, experimental advances and potential impact of light propagation, emission, absorption, and scattering in complex nanostructures. Introductory quantum theory of solids and quantum confinement effects are considered to give a parallel discussion of wave optics and wave mechanics of complex structures as well as to outline the beneficial result of combined electron wave and light wave confinements in a single device. Properties of metal nanostructures with unprecedented capability to concentrate light and enhance its emission and scattering are discussed in detail.

Keeping mathematics to a reasonable minimum and reducing theoretical issues to a conceptual level, the book is aimed at assisting diploma and senior students in physics, optical and electronic engineering and material science. The contents include a vast diversity of phenomena from guiding and localization of light in complex dielectrics to single molecule detection by surface enhanced spectroscopy. The physical and historical interplay of wave optics and quantum mechanics is traced whenever possible to highlight the internal concordance inherent in physics and nature. Nanophotonics is presented as an open field of science and technology which has been conceived as an organic junction of quantum mechanics, quantum electrodynamics, optical physics, material science and engineering to offer an impressive impact on information and communication technology.

The book is principally based upon scientific experience the author gained while working at the Institute of Molecular and Atomic Physics in Minsk, Belarus, in the decade from 1997 to 2007. I am indebted to many colleagues from this institute for the creative atmosphere and high research grade. I gratefully acknowledge the fruitful cooperation and ongoing discussions with many colleagues in Belarus, Russia and other countries with special thanks to the European network of excellence "PHOREMOST" (Nanophotonics to realize molecular scale technologies) which has been organized and successfully driven for several years by Clivia Sotomayor Torres within the 6th Framework Programme of the European Union. Many of my PhD students have made their theses in nanophotonics and their results have been included in this book. I would specially acknowledge that Chapter 3 has been seriously influenced by cooperation with Sergey Zhukovsky and Chapter 16 has been written

based on continuous discussions with Dmitry Guzatov. I am grateful to these colleagues as well as to Dmitry Mogilevtsev, Maxim Ermolenko, Andrey Lutich, Maxim Gaponenko, and Andrey Nemilentsau for reading selected chapters and critical comments on their style and content. My colleague and friend Andrey Lavrinenko made a strong influence on my understanding of wave phenomena in complex structures and kindly provided the cover image for this book based on his calculations of light propagation in a photonic crystal with guiding defects. Great efforts by Tamara Chystaya for arranging the compuscript of the book are deeply appreciated.

This book would never have been accomplished without fruitful cooperation with Cambridge University Press, mainly with John Fowler, Lindsay Barnes and Caroline Brown. I am also indebted to the referees for encouraging comments and helpful advice in the early stages of this book project.

S. V. Gaponenko
Minsk, 2009

Notations and acronyms

A	amplitude
a	length, radius, width
a^0	$= 5.292\ldots \cdot 10^{-11}$ m, atomic length unit
a_B	Bohr radius of a hydrogen atom, $a_\mathrm{B} \approx a^0$ holds
a_B^*	Bohr radius of an exciton
$\mathbf{a}$	acceleration
$\mathbf{a_i}$	elementary translation vectors
a_L	crystal lattice constant
$\mathbf{b_i}$	elementary translation vectors in reciprocal space
b_i	reciprocal lattice constants
$\mathbf{B}$	magnetic induction vector
C	cross-section
C_abs	absorption cross-section
C_ext	extinction cross-section
C_scat	scattering cross-section
c	$= 299\,792\,458\ \mathrm{ms}^{-1}$, speed of light in vacuum
D	density of modes, density of states
D	diffusion coefficient
$\mathbf{D}$	electric displacement vector
d	thickness
d	dimensionality
e	$= 1.6021892\ldots \cdot 10^{-19}$ C, elementary electric charge
E	a particle energy
E_c	energy at the bottom of the conduction band
E_F	Fermi energy
E_g	band gap energy
E_v	energy at the top of the valence band
$\mathbf{E}$, E	electric field vector, amplitude
F	distribution function
$\mathbf{F}$	force
f	volume fraction
G	generator of a fractal structure
$\mathbf{H}$	magnetic field vector, Hamiltonian operator
h	$= 6.626069 \cdot 10^{-34}$ J $\cdot$ s, Planck constant
$\hbar$	$= h/2\pi$
I	intensity

$\mathbf{J}$	electric current density
k	wave number
$\mathbf{k}, \mathbf{K}$	wave vector
k_B	$= 1.380662\ldots \cdot 10^{-23}$ J/K, Boltzman constant
ℓ	mean free path
$\mathbf{L}$	angular momentum
L	length
m	mass
m_0	$= 9.109534\ldots \cdot 10^{-31}$ kg, an electron's rest mass
m^*	effective mass
M	exciton mass
$\mathbf{M}$	magnetic polarization vector
n	the principal quantum number
n	refractive index
n_1	real part of refractive index
n_2	imaginary part of refractive index
$p, \mathbf{p}$	momentum
$\mathbf{P}$	electric polarization vector
Q	efficiency factor
R	reflection coefficient for intensity
R, r	radius
r	reflection coefficient for amplitude
$\mathbf{r}$	radius vector
Ry	≈ 13.60 eV, Rydberg constant, Rydberg energy
Ry*	exciton Rydberg energy
$\mathbf{S}$	Poynting vector
t	transmission coefficient for amplitude
t	time
T	period of oscillations
T	temperature
T	transmission coefficient for intensity
$\mathbf{T}$	translation vector
U, u	potential energy
$v, \mathbf{v}$	velocity
$v_g, \mathbf{v_g}$	group velocity
V	volume
W	light energy
W_{abs}	light energy absorption rate
W_{ext}	light energy extinction rate
W_{scat}	light energy scattering rate
$W(\mathbf{r})$	spontaneous emission rate at point $\mathbf{r}$
W_0	spontaneous emission rate in vacuum
Y_{lm}	spherical Bessel functions
x, y, z	Cartesian coordinates

α	polarizability
α_{abs}	absorption coefficient
Γ	scattering rate
ε	relative dielectric permittivity
ε_0	$= 8.8541878 \cdot 10^{-12}$ F/m, dielectric constant (the dielectric permittivity of a vacuum)
κ	evanescence parameter
λ	wavelength
μ	relative magnetic permeability
$\mathrm{\mu}$	dipole moment, chemical potential
$\mathrm{\mu}_0$	$= 1.256637 \cdot 10^{-6}$ H/m, magnetic permeability of vacuum
μ_{eh}	electron–hole reduced effective mass
ν	frequency
ρ	electric charge density
ρ	material resistivity per unit area and unit length
σ	conductivity
τ	decay constant, scattering time, phase time
Φ	potential
φ	phase
χ_{nl}	roots of Bessel functions
χ	susceptibility
Ψ	time-dependent wave function
ψ	time-independent wave function
ω	circular frequency
ω_p	plasma circular frequency
AAAS	American Association for the Advancement of Science
AIP	American Institute of Physics
bcc	body-centered cubic (lattice)
CCD	charge coupled device
CD	compact disk
CIE	Comission Internationale de l'Eclairage (International Commission for Illumination)
CMOS	complementary metal-oxide-semiconductor (notation for modern microelectronics technology platform)
CNDO/S	complete neglect of differential orbital, spectroscopic version (a quantum chemical technique)
cw	continuous wave
DOS	density of states
EM	electromagnetic
fcc	face-centered cubic (lattice)
FTIR	frustrated total internal reflection
IR	infrared
LED	light emitting diode

LDOS	local density of states
MBE	molecular beam epitaxy
MOCVD	metal-organic chemical vapor deposition
MOVPE	metal-organic vapor phase epitaxy
NA	numerical aperture
RBG	red-blue-green
SEF	surface enhanced fluorescence
SEM	scanning electron microscopy
SERS	surface enhanced Raman scattering
SNOM	scanning near field optical microscope
SOI	silicon on insulator
SPP	surface plasmon polariton
TE	transverse electric (mode)
TEM	transmission electron microscopy
TIR	total internal reflection
TM	transverse magnetic (mode)
UV	ultraviolet