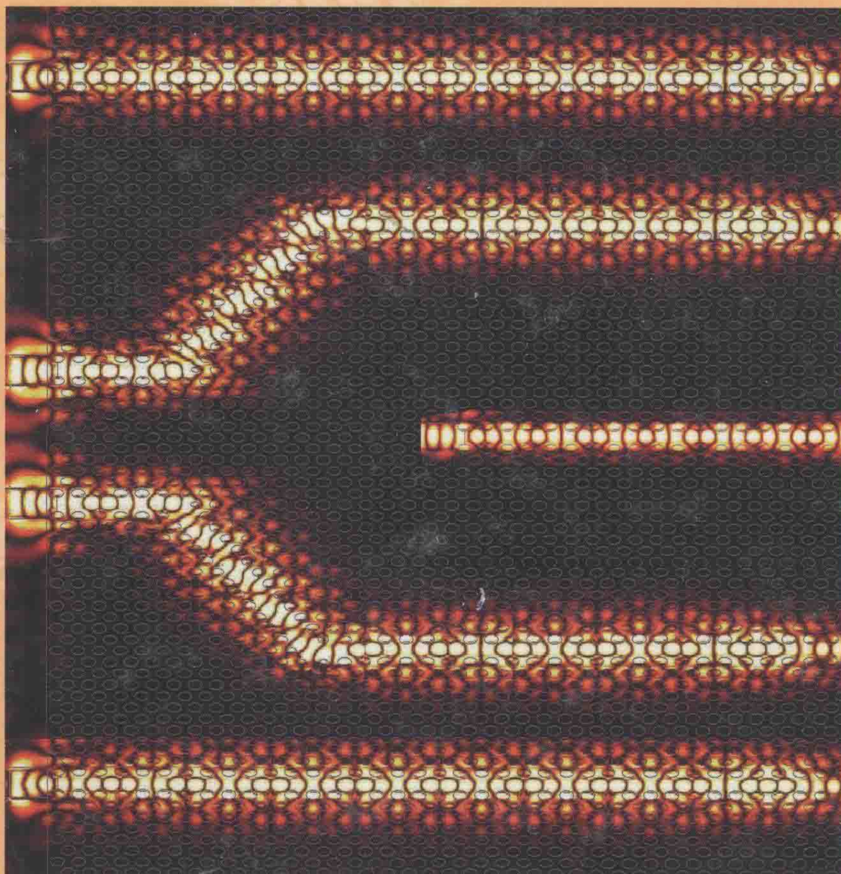
Introduction to
NANOPHOTONICS



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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, $a_B \approx a^0$ 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	$= 299\,792\,458$ 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 · 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

Contents

1 Introduction

1.1 Light and matter on a nanometer scale

The notion of "photonics" implies the science and technology related to generation, absorption, emission, harvesting, processing of light and their applications in various devices. Light is electromagnetic radiation available for direct human perception, in the wavelength range from approximately 400 to approximately 700 nanometers. Typically, adjacent far ultraviolet and near infrared ranges are also involved to give the approximate range of electromagnetic radiation from 100 nanometers to 1–2 micrometers as the subject of photonics. If the space has certain inhomogeneities on a similar scale to the wavelength of the light, then multiple scattering and interference phenomena arise modifying the propagation of light waves. Light scattering is the necessary prerequisite for vision. Shining colors in soap bubbles and thin films of gasoline on a wet road after rain are primary experiences of light-wave interference everybody gains in early childhood. To modifiy the conditions for light propagation, inhomogeneities in space which are not negligible as compared to the wavelength of the light, i.e. starting from the size range 10–100 nm to a few micrometers, become important. Space inhomogeneity for light waves implies inhomogeneity in dielectric permittivity.

Matter is formed from atoms which in turn can be subdivided into nuclei and electrons. An elementary atom of hydrogen has a radius for the first electron orbital of 0.053 nm. Atoms may form molecules and solids. Many typical organic molecules have sizes of the order of 1 nm. Typical crystalline solids feature a lattice period of approximately 0.5 nm. Interaction of light with matter actually reduces to the processes involved in the electron subsystem of molecules and solids. Therefore to understand light–matter interactions, electron properties must be examined in detail. Electrons are viewed as objects possessing wave properties in terms of wavelength, and corpuscular properties in terms of mass and charge. If an electron has gained kinetic energy as a result of acceleration in an electric field between a couple of plates with voltage 1 V (e.g. generated in a silicon photocell), then its kinetic energy of 1 eV results in an electron de Broglie wavelength close to 1 nm. For kinetic energies corresponding to a characteristic value of $k_B T = 27$ meV at room temperature, the electron de Broglie wavelength in solids is of the order of 10 nm. Here k_B is the Boltzman constant and T is temperature. When space inhomogeneities present which are not negligible as compared to the electron wavelength then scattering and interference of electrons develop modifying in many instances the interaction of light with matter. Space inhomogeneities for electrons means inhomogeneity in charge or mass displacement, electric or magnetic field variations.

1.2 What is nanophotonics?

Nanophotonics is the recently emerged, but already well defined, field of science and technology aimed at establishing and using the peculiar properties of light and light–matter interaction in various nanostructures. Since it is the spatial confinement of light waves in complex media and electron waves in various nanostructured solids that determine multiple physical phenomena in nanophotonics, it is possible to characterize *nanophotonics as the science and technology of confined light waves and electron waves*. It can be tentatively divided into four sections.

The **first** section of nanophotonics is *electron confinement effects on the optical properties of matter*; mainly semiconductor and dielectric materials. These phenomena are typically referred to as *quantum confinement* effects since manifestations of *wavy properties of electrons are typically labeled as quantum phenomena*. The net optical manifestations of these effects are size-dependent optical absorption spectra, emission spectra and transition probabilities for solid matter purposefully structured on the scale of a few nanometers. Their potential applications are the variety of optical components with size-controlled, tuned and adjustable parameters including emitters, filters, lasers and components, optical switches, electro-optical modulators etc. This sub-field of nanophotonics has become the subject of systematic research since the 1970s. Different issues related to electron confinement phenomena and their optical manifestations have already been the subject of several books [1–3].

The **second** section of nanophotonics constitutes *light wave confinement phenomena* in structured dielectrics, including the fine concept of photonic solids in which light wave propagation is controlled in a similar manner to electron waves in solids. This subfield of nanophotonics is principally *classical* in its essence, i.e. it is based entirely on *wave optics* and does not imply any notion beyond classical Maxwell equations. It actually dates back to early identification of light interference phenomena by Isaac Newton in the eighteenth century and to genuine prediction by Lord Rayleigh of the remarkable reflective properties of periodic media in the 1880s. The main practical outcome for this field is ingenious photonic circuitry development, from ultrasmall but high-quality cavities to ultracompact waveguides. Different issues of light confinement phenomena and near-field optics have already been included in several books [4–8].

The **third** section of nanophotonics is essentially the *quantum optics of nanostructures*. It deals with modified light–matter interaction in nanostructures with confined light waves. Spontaneous emission and scattering of light essentially modifies and becomes controllable since spontaneous photon emission and spontaneous photon scattering can be promoted or inhibited by engineering photon density of states often referred to as electromagnetic mode density. The ultimate case of this modified light–matter interaction is the development of confined light–matter states in microcavities and photonic crystals. This section of nanophotonics is relatively new. It has its root in the seminal paper by E. Purcell in 1946 predicting the modified spontaneous decay rate of a quantum sytem (e.g. an atom) in a cavity. In the 1970s V. P. Bykov suggested freezing spontaneous decay of excited atoms in a periodic structure where no means is available to carry off the emitted radiation. Eventually these ideas evolved into the concept of *photonic crystals* and *photonic solids* through seminal papers in the 1980s by E. Yablonovitch who suggested thresholdless lasing in a device with inhibited spontaneous emission of radiation, and by S. John who indicated possible light wave localization in disordered structures. Modified light–matter interaction in microcavities and photonics crystals is the subject of a few books [9–11].

The **fourth** section of nanophotonics is optics and optical engineering based on *metal-dielectric nanostructures*. Typically metals are not considered an important subject in optical research and engineering. Our experience mainly reduces to everyday observation of ourselves in aluminium mirrors. However metal-dielectric nanostructures feature a number of amazing properties resulting from the development of electron excitations at metal–dielectric interfaces called *surface plasmons*. Structuring of metal-dielectric composites on the nanoscale (10–100 nm) makes surface effects dominant. Actually, the optical properties of metal nanoparticles have been used for many centuries in stained glass but nowadays the study of metal-dielectric composites in optics has evolved into the well-defined field of *nanoplasmonics*. High concentrations of electromagnetic radiation and modification of the rates of quantum transitions in the near vicinity of metallic singularities result in novel light emitting devices and ultrasensitive spectral analysis with ultimate detection of a single molecule by means of Raman scattering. A few issues of nanoplasmonics have been considered in books [12,13].

1.3 Where are the photons in nanophotonics and in this book?

The author takes the approach whereby temptation to use the term "photon" is purposefully avoided unless the concept of light quanta is essential in order to understand the phenomenon in question. It is anticipated by many scientists and has been clearly outlined by W. Lamb in his seminal paper entitled "Anti-photon" [14]. In nanophotonics photons become necessary when trying to understand the emission of light by an excited quantum system and the scattering of light when light frequencies change (Raman scattering). Then, eventually, *quantum electrodynamics* comes to the stage. Not all phenomena of light propagation need the involvement of photons and the vast majority of light absorption phenomena can be treated in a semiclassical way when the matter is described in terms of quantum mechanics (more accurately speaking, *wave mechanics*), but light is understood as classical electromagnetic waves.

The rest of the book is organized as follows. Fifteen chapters, from Chapter 2 to Chapter 16, are organized in the form of two large parts.

Part I is entitled "*Electrons and electromagnetic waves in nanostructures*" and contains Chapters 2 to 12. It considers electrons in complex media and nanostructures in terms of *wave mechanics*, and electromagnetic radiation in complex media and nanostructures in terms of *wave optics*. Parallel consideration of wave phenomena in the theory of matter and in the theory of light in complex structures is pursued purposefully to highlight the conformity of wave phenomena in nature, both for electrons in matter and for classical waves