Applied Nanophotonics

With full color throughout, this unique text provides an accessible yet rigorous introduction to the basic principles, technology, and applications of nanophotonics. It explains key physical concepts such as quantum confinement in semiconductors, light confinement in metal and dielectric nanostructures, and wave coupling in nanostructures, and describes how they can be applied in lighting sources, lasers, photonic circuitry, and photovoltaic systems. Readers will gain an intuitive insight into the commercial implementation of nanophotonic components, in both current and potential future devices, as well as challenges facing the field. The fundamentals of semiconductor optics, optical material properties, and light propagation are included, and new and emerging fields such as colloidal photonics, Si-based photonics, nanoplasmonics, and bioinspired photonics are all discussed. This is the “go-to” guide for graduate students and researchers in electrical engineering and physics interested in nanophotonics, and students taking nanophotonics courses.

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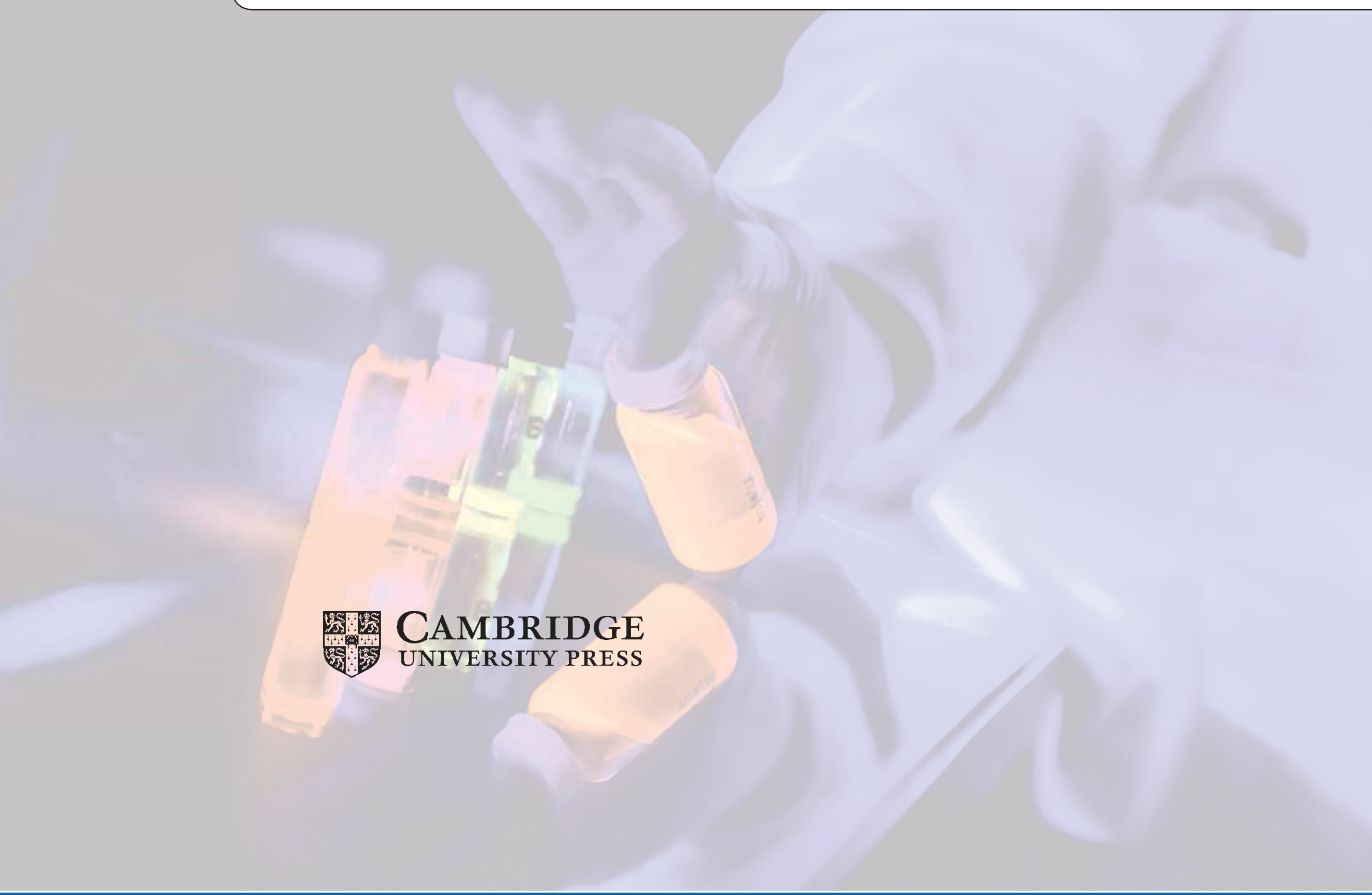

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To our wives and parents:
To Olga, Vasily, and Alina Gaponenko,
To Çiğdem Gündüz, Rahşan, and Salih Demir

CONTENTS

PREFACE

Nanophotonics looks at light–matter interactions at the nanoscale – covering all of the processes of light propagation, emission, absorption, and scattering in complex nanostructures. We found that looking at nanophotonics starting from the very basics and taking it all the way to the applications, which would be important and very useful for practitioners of nanophotonics, has been missing from the literature. The idea for this book, *Applied Nanophotonics*, was born at NTU Singapore as a result of our long discussions of how academic education and technical training in the field of nanophotonics should be. This book is therefore intended to be a self-contained textbook that can be used for both graduate and undergraduate students as well as engineers, scientists, and R&D experts who would like to have a complete treatment of nanophotonics.

This book was made possible as a result of the research work carried out by the authors over the period 2000–2018 at Stanford University, Bilkent University, NTU Singapore, and the Belarussian National Academy of Sciences. For that we are grateful to all of our colleagues, collaborators, and students, with whom we have explored the world of nanophotonics and learned a great deal in this joyful and fun adventure. To this end, special thanks go to Prof. D. A. B. Miller and Prof. J. Harris of Stanford University. At the final stage of this book project the critical reading of the selected chapters by Dr. A. Baldycheva, Dr. P. L. Hernandez-Martinez, Dr. S. Golmakaniyoon, and Dr. R. Thomas was of great help, as was the assistance of K. Güngör, who helped to produce the cover design. S. V. G. gratefully acknowledges the creative atmosphere and promotional support from NTU in 2014–2016.

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H. V. Demir and S. V. Gaponenko
Singapore, Ankara, Minsk
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NOTATION

A	spontaneous emission probability (rate), the Einstein coefficient
A	size of a quantum well; length; period in space
$\mathbf{a}$	acceleration
a_B^*	exciton Bohr radius
a_B	$= 5.2917\ldots \cdot 10^{-2}$ nm, electron Bohr radius
a, b, c	periods of a three-dimensional lattice
a_L	crystal lattice period
$\mathbf{B}$	magnetic induction vector
B	stimulated emission factor (the Einstein coefficient)
C	concentration
c	$= 299{,}792{,}458\ldots$ m/s, speed of light in vacuum
$\mathbf{D}$	electric displacement vector
D	density of modes, density of states
D	optical density (–lg(transmission))
$\mathbf{d}$	dipole moment; unit vector along dipole moment
d	dimensionality of space; thickness
e	$= 1.6021892 \ldots \cdot 10^{-19}$ C, elementary electric charge
$\mathbf{E}$	electric field vector
E	kinetic energy
E_F	Fermi level (energy)
E_g	band gap energy
$\mathbf{F}$	force
f	volume-filling factor; fraction
f_{BE}	Bose–Einstein distribution function
f_{FD}	Fermi–Dirac distribution function
G	Green's function
h	$= 6.626069\ldots \cdot 10^{-34}$ J·s, Planck constant
$\hbar$	$\equiv h/2\pi$
$\mathbf{H}$	Hamiltonian
$\mathbf{H}$	magnetic field vector
I	intensity
i	imaginary unit
$\mathbf{J}$	electric current density
$\mathbf{k}$, k	wave vector, wave number

k_B	= 1.380662 … · 10^{-23} J/K, Boltzmann constant
l	orbital quantum number
$\mathbf{L}$, L	angular momentum
L, l	thickness
ℓ	mean free path
$\mathbf{M}$	magnetic polarizations
M	exciton mass
M	mass
m_0	= 9.109534 · 10^{-31} kg, the rest mass of an electron
m^*	effective mass
$\mathbf{n}$	unit vector
N, n	concentration; integer number
nr	refractive index; real part of complex refractive index for absorbing materials
$\mathbf{P}$	electric polarization
P	hole concentration in a semiconductor
$\mathbf{p}$, p	momentum, quasi-momentum
Q	quantum efficiency; quantum yield
R	reflection coefficient for intensity
r	reflection coefficient for amplitude
$\mathbf{r}$	radius vector
R, r	radius, distance
r, ϑ, φ	spherical coordinates
Ry	= 13.605 … eV, Rydberg energy
Ry^*	exciton Rydberg energy
$\mathbf{S}$	pointing vector
$\mathbf{T}$	translation vector
T	time period; temperature; transmission coefficient
t	time; transmission coefficient for amplitude
U	potential energy; energy
u	spectral energy density per unit volume
V	volume
$\mathbf{v}$, v	velocity
$\mathbf{v}_g$, v_g	group velocity
W	emission rate
x, y, z	coordinates
α	absorption coefficient
Γ	dephasing rate
γ	decay rate
$\gamma_{\mathrm{rad}}^{\mathrm{vacuum}} \equiv \gamma_0$	radiative (spontaneous) decay rate in vacuum
ε	relative dielectric permittivity; molar absorption coefficient

κ	imaginary part of the complex refractive index; evanescence parameter in tunneling
λ	wavelength
μ	reduced mass; chemical potential; relative magnetic permeability
μ_0	permeability of a vacuum
ν	frequency
ξ	set of all coordinates of the particles in a quantum system
ρ	electric charge density
σ	absorption cross-section
τ	time constant in various processes (decay, transfer, scattering)
$\Gamma\vartheta$, φ	spherical coordinates
χ	dielectric susceptibility
χ_{nl}	roots of the spherical Bessel functions
Ψ	wave function, time-dependent
ψ	wave function, time-independent
ω	circular frequency
ω_{p}	plasma circular frequency

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More Information

ACRONYMS

Terms

2DPC	two-dimensional photonic crystal
3DPC	three-dimensional photonic crystal
AFM	atomic force microscope
CCD	charge-coupled device
CCT	correlated color temperature
CD	compact disk
CD-ROM	compact disk read-only memory
CFLs	compact fluorescent lamps
CIS	copper indium sulfide
CMOS	complementary metal-oxide-semiconductor (technology)
CQD	colloidal quantum dot
CQS	color quality scale
CRI	color rendering index
CVD	chemical vapor deposition
CW	continuous wave
DBR	distributed Bragg reflector
DFB	distributed feedback
DOM	density of modes
DOS	density of states
DVD	digital versatile disk
DWDM	dense wavelength division/multiplexing
EBL	electron blocking layer
EQE	external quantum efficiency
ESU	electrostatic unit
ETL	electron injection layer
FCC	face-centered cubic
FMN	flavin mononucleotide
FRET	Förster resonance energy transfer
FTTH	fiber to the home
HOMO	highest occupied molecular orbital
HTL	hole injection layer
ICP	inductively coupled plasma

IJE	injection efficiency
IQE	internal quantum efficiency
IR	infrared
ITO	indium tin oxide
LAN	local area network
LCD	liquid crystal display
LDOS	local density of states
LED	light-emitting diode
LEE	light extraction efficiency
LER	luminance efficacy of optical radiation
LUMO	lowest unoccupied molecular orbital
MBE	molecular beam epitaxy
MDM	mode division multiplexing
MEG	multiple exciton generation
MIXSEL	mode-locked integrated external-cavity surface-emitting laser
MOCVD	metal–organic chemical vapor deposition
MOVPE	metal–organic vapor-phase epitaxy
NP	nanoparticle
NW	nanowire
OLED	organic light-emitting diode
PC	personal computer
PC	photonic crystal
PECVD	plasma-enhanced chemical vapor deposition
PL	photoluminescence
PON	passive optical network
PSS	patterned sapphire substrate
RDE	radiative efficiency
RET	resonance energy transfer
RIE	reactive ion etching
RIU	refractive index unit
ROM	read-only memory
SAM	saturable absorber mirror
SDL	semiconductor disk laser
SEM	scanning electron microscope
SERS	surface enhanced Raman scattering
SESAM	semiconductor saturable absorber mirror
SOI	silicon-on-insulator
TAC	time-to-amplitude converter
TCO	transparent conducting oxide
TEM	transmission electron microscope
TNT	trinitrotoluene

UV	ultraviolet
VCSEL	vertical cavity surface-emitting laser
VECSEL	vertical external-cavity surface-emitting laser
VTE	voltage efficiency
WDM	wavelength division/multiplexing
WPE	wall-plug efficiency
XRD	x-ray diffraction
YAG	yttrium aluminum garnet

Companies and Organizations

AAAS	American Association for the Advancement of Science
ACS	American Chemical Society
AIP	American Institute of Physics
APS	American Physical Society
CIE	Commission Internationale de l'Éclairage
EPFL	École Polytechnique Fédérale de Lausanne
ETHZ	Swiss Federal Institute of Technology at Zurich
IBM	International Business Machines
MIT	Massachusetts Institute of Technologies
NREL	National Renewable Energy Laboratory
NTSC	National Television System Committee
OSA	Optical Society of America
RCA	Radio Corporation of America
RSC	Royal Society of Chemistry