Field Guide to

Light–Matter Interaction

Galina Nemova

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Introduction to the Series

2022 is a landmark year for the SPIE *Field Guide* series. It is our 19th year of publishing *Field Guides*, which now includes more than 50 volumes, and we expect another four titles to publish this year. The series was conceived, created, and shaped by Professor John Greivenkamp from the University of Arizona. John came up with the idea of a 100-page handy reference guide for scientists and engineers. He wanted these books to be the type of reference that professionals would keep in their briefcases, on their lab bench, or even on their bedside table. The format of the series is unique: spiral-bound in a 5″ by 8″ format, the book lies flat on any page while you refer to it.

John was the author of the first volume, the seminal *Field Guide to Geometric Optics*. This book has been an astounding success, with nearly 8000 copies sold and more than 72,000 downloads from the SPIE Digital Library. It continues to be one of the strongest selling titles in the SPIE catalog, and it is the all-time best-selling book from SPIE Press. The subsequent several *Field Guides* were in key optical areas such as atmospheric optics, adaptive optics, lithography, and spectroscopy. As time went on, the series explored more specialized areas such as optomechanics, interferometry, and colorimetry. In 2019, John created a sub-series, the *Field Guide to Physics*, with volumes on solid state physics, quantum mechanics, and optoelectronics and photonics, and a fourth volume on electromagnetics to be published this year. All told, the series has generated more than $1.5 million in print sales and nearly 1 million downloads since eBooks were made available on the SPIE Digital Library in 2011.

John's impact on the profession through the *Field Guide* series is immense. Rival publishers speak to SPIE Press with envy over this golden nugget that we have, and this is all thanks to him. John was taken from us all to early, and to honor his contribution to the profession through this series, he is commemorated in the 2022 Field Guides.

We will miss John very much, but his legacy will go on for decades to come.

Vale John Greivenkamp!

J. Scott Tyo
Series Editor, SPIE Field Guides
Melbourne, Australia, March 2022

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Preface

The interaction of light and matter has been a subject of scientific research since the 5th century BC. Its investigation has resulted in the evolution from the ancient corpuscular theory to the wave theory and finally to the quantum theory. Application of the theoretical research on light–matter interaction has led to numerous scientific achievements, including lasers, optical trapping, and optical cooling, among others. Indeed, it has brought into existence the entire field of photonics.

The primary objective of *Field Guide to Light–Matter Interaction* is to provide an overview of the basic principles of light and matter interaction using classical, semiclassical, and quantum approaches. The book covers basic photonics concepts using classical electrodynamics. A vast majority of light–matter interaction problems can be treated to a high accuracy within the semiclassical theory, where atoms with quantized energy levels interact with classical electromagnetic fields. The concepts involved in these problems are all addressed. The book also considers the interaction of matter with quantized electromagnetic fields consisting of photons. This approach gives a complete account of light–matter interaction, explaining many effects (such as the photoelectric effect) that cannot be explained using classical electromagnetic fields. The book elucidates the interaction of electromagnetic waves with atoms, molecules, solids, and plasma. It also covers the main concepts of optical pressure.

Field Guide to Light–Matter Interaction can also serve as a complement to *Field Guide to Laser Cooling Methods*, published by SPIE Press in 2019.

I would like to thank SPIE Director of Publications Patrick Franzen and Field Guide Series Editor Scott Tyo for the opportunity to write a Field Guide for one of the most interesting areas of current scientific research. I also wish to thank the anonymous reviewers for their many useful suggestions and comments on the draft of this Field Guide.

Preface

Finally, I wish to thank SPIE Press Sr. Editor Dara Burrows for her help.

This book is dedicated to my mom, Albina.

Galina Nemova
March 2022

Glossary of Symbols and Acronyms

Fundamental Constants

$b = 2.897771955 \times 10^{-3}$ m · K	Wien's displacement constant
$c = 2.99793 \times 10^{8}$ m · s^{-1}	speed of light in vacuum
$e = -1.602176634 \times 10^{-19}$ C	electron charge
$h = 6.626 \times 10^{-34}$ J · s	Planck's constant
$\hbar = h/2\pi$	reduced Planck's constant
$m_e = 9.1096 \times 10^{-31}$ kg	mass of an electron
$\varepsilon_0 = 8.8541878128(13) \times 10^{-12}$ F · m^{-1}	vacuum permittivity
$\kappa_B = 1.380649 \times 10^{-23}$ J · K^{-1}	Boltzmann constant
$\mu_0 = 1.25663706212(19) \cdot 10^{-6}$ H · m^{-1}	vacuum permeability
$\mu_B = 0.927 \times 10^{-23}$ A · m^{-2}	Bohr magneton
$\sigma = 5.670373 \times 10^{-8}$ W · m^{-2} · K^{-4}	Stefan–Boltzmann (or Stefan's) constant

Units of Measure

A	ampere
C	coulomb
F	farad
H	henry
J	joule
K	kelvin
kg	kilogram
m	meter
s	second
T	tesla
V	volt
W	watt

Frequently Used Symbols

It is impossible to avoid using the same symbols for more than one quantity. A list of symbols denoting a single quantity is presented here. Other symbols are defined in the body of the book.

A	mass number
a_H	Bohr radius

Glossary of Symbols and Acronyms

$\vec{B}$	magnetic induction
$\vec{D}$	electric field displacement
$\vec{E}$	electric field strength
e	electron charge (a negative number)
g	degeneracy
$\vec{H}$	magnetic field strength
J	total angular momentum quantum number (for multi-electron atoms)
$\vec{J}$	total angular momentum (for multi-electron atoms)
j	total quantum number
$\vec{j}$	total angular momentum (for single-electron atoms)
$\tilde{j}$	surface current density
k	wave vector magnitude
$\vec{k}$	wave vector
k_0	vacuum wave vector magnitude ($k_0 = \omega/c$)
k_{sp}	spring constant
L	total orbital angular momentum quantum number (for multi-electron atoms)
$\vec{L}$	total orbital angular momentum (for multi-electron atoms)
l	orbital quantum number
$\vec{l}$	orbital angular momentum (for single-electron atoms)
l_l	longitudinal coherence length
l_t	transverse coherence length
m_l	magnetic quantum number
m_s	spin magnetic quantum number
N	neutron number
P	magnitude of the polarization vector ($P = \lvert\vec{P}\rvert$)
$\vec{P}$	polarization vector
p	photon momentum magnitude
r	radius
S	total spin quantum number (for multi-electron atoms)
$\vec{S}$	total electron spin (for multi-electron atoms)

Glossary of Symbols and Acronyms

s	spin quantum number
$\vec{s}$	spin (for single-electron atoms)
T	temperature
v	velocity
V_{coh}	coherence volume
Z	atomic or proton number
α	polarizability
Δ	detuning ($\Delta = \omega_0 - \omega$)
$\boldsymbol{\varepsilon}$	linear dielectric tensor
ε	dielectric permittivity
$\hat{\varepsilon}$	unit vector
λ	wavelength
μ	magnetic permeability
ν	frequency
ρ	density matrix
φ_p	phase angle
ω	angular frequency ($\omega = 2\pi\nu$)

Acronyms and Abbreviations

BCE	Before Common Era
c.c.	complex conjugate
CG	Clebsch–Gordon
CM	center of mass
DC	direct current
ED	electric dipole
EM	electromagnetic
FWHM	full width at half-maximum
h.c.	Hermitian conjugate
HWHM	half width at half-maximum
IR	infrared
LA	longitudinal acoustic
LO	longitudinal optical
LP	left polarization
MD	magnetic dipole
OPL	optical path length
RP	right polarization
RW	radio waves
RWA	rotating-wave approximation

Glossary of Symbols and Acronyms

RE	rare earth
SAM	spin angular momentum
SF	superfluorescence
SI	International System of Units
SPhP	surface phonon polariton
SR	superradiance
TA	transverse acoustic
TO	transverse optical
UV	ultraviolet