Field Guide to

Laser Cooling Methods

Galina Nemova

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Preface

Cooling or refrigeration is based on heat removal and dates back thousands of years to when people tried to preserve their food using ice and snow. The laser—a groundbreaking scientific achievement of the 20th century— has revolutionized the cooling process. The advent of lasers brought laser cooling, also known as optical refrigeration, into existence. Today, laser cooling and its applications represent one of the major subfields of atomic, molecular, and solid state physics.

This Field Guide provides an overview of the basic principles of laser cooling of atoms, ions, nanoparticles, and solids, including Doppler cooling, polarization gradient cooling, different sub-recoil schemes of laser cooling, forced evaporation, laser cooling with anti-Stokes fluorescence, hybrid laser cooling, and Raman and Brillouin cooling. It also covers radiation-balanced lasers and Raman lasers with heat mitigation, and considers the basic principles of optical dipole traps, magnetic traps, and magneto-optical traps. This Field Guide will serve both to introduce students, scientists, and engineers to this exciting field, and to provide a quick reference guide for the essential math and science.

I would like to thank SPIE Press Manager Timothy Lamkins and Series Editor John Greivenkamp for the opportunity to write a Field Guide for one of the most interesting areas of photonics, as well as SPIE Press Sr. Editor Dara Burrows for her help.

This book is dedicated to my mom, Albina.

Galina Nemova
September 2019

Glossary

Fundamental constants

$\mu_B = 9.27400899 \times 10^{-24}$ (J·T^{-1})	Bohr magneton
$k_B = 1.3806503 \times 10^{-23}$ (J·K^{-1})	Boltzmann constant
$\varepsilon_0 = 8.854187817 \times 10^{-12}$ (F·m^{-1})	vacuum permittivity or electric constant
$m_e = 9.10938188 \times 10^{-31}$ (kg)	electron mass
$g_s = 2.0023193043737$	electron spin g-factor
$e = 1.6021766208 \times 10^{-19}$(C)	elementary charge
$\alpha = 7.297352533 \times 10^{-3}$	fine structure constant
$\mu_0 = 4\pi \times 10^{-7}$ (H·m^{-1})	permeability of vacuum
$h = 6.62606876 \times 10^{-34}$ (J·s)	Planck's constant
$\hbar = h/2\pi = 1.054571596 \times 10^{-34}$ (J·s)	reduced Planck's constant
$c = 299792458$ (m·s^{-1})	speed of light in vacuum
$\sigma = 5.67 \times 10^{-8}$ (Wm^{-2}K^{-4})	Stefan–Boltzmann constant

Units of measure

C	coulomb	kg	kilogram
F	farad	m	meter
H	henry	s	second
J	joule	T	tesla
K	kelvin		

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.

Γ	Landau–Zener parameter
Δ	detuning
η	efficiency
κ	thermal conductivity
λ	wavelength
λ_{deB}	de Broglie wavelength
$\boldsymbol{\mu}$	magnetic dipole moment (also known as a magnetic moment or magnetic dipole)
ν	frequency

Glossary of Symbols and Acronyms

ρ	density operator
σ_a	absorption cross section
σ_e	emission cross section
ψ	wave function
ω	angular frequency
$\mathbf{B}$	magnetic field
$\mathbf{E}$	electric field
E_F	Fermi energy
g_F	Landé g-factor
g_l	electron orbital g-factor
g_s	electron spin g-factor
$\mathbf{k}$	wave vector
k_r	restoring-force constant
t	time
T	temperature
v	velocity
v_s	speed of sound

Quantum mechanical symbols

$\mathbf{d}$	atomic dipole moment
F	total angular momentum quantum number (used by spectroscopists for atoms with an odd isotope number)
$\mathbf{F}$	total angular momentum (for atoms with an odd isotope number)
$\lvert\mathbf{F}\rvert$	magnitude of the total angular momentum $\mathbf{F}$
$\mathbf{I}$	nuclear spin angular momentum
j	total angular momentum quantum number (for a single particle)
J	total angular momentum quantum number (used by spectroscopists for atoms with an even isotope number)
$\mathbf{J}$	total angular momentum (for atoms with an even isotope number)
$\lvert\mathbf{J}\rvert$	magnitude of the total angular momentum $\mathbf{J}$
l	orbital angular momentum quantum number or orbital quantum number (for a single particle)
L	orbital angular momentum quantum number (for a system of several particles)

Glossary of Symbols and Acronyms

$\mathbf{L}$	orbital angular momentum (for a system of several particles)
$\|\mathbf{L}\|$	magnitude of the orbital angular momentum $\mathbf{L}$
m_l	magnetic quantum number
n	principal quantum number (for a single particle)
s	spin quantum number (for a single particle)
S	spin quantum number (for a system of several particles)
$\mathbf{S}$	spin angular momentum (for a system of several particles)
$\|\mathbf{S}\|$	magnitude of the spin angular momentum $\mathbf{S}$

Acronyms and Abbreviations

AC	alternating current
ASF	anti-Stokes fluorescence
BEC	Bose–Einstein condensate
BYF	BaY_2F_8
CARS	coherent anti-Stokes Raman scattering
CG	Clebsch–Gordan (coefficient)
CNBZn	CdF_2-$CdCl_2$-NaF-BaF_2-$BaCl_2$-ZnF_2
DC	direct current
ED	electrical dipole
EIT	electromagnetically induced transparency
EM	electromagnetic
ESA	excited-state absorption
EQ	electric quadrupole
f-factor	oscillator strength
FMHM	full width at half maximum
GEF	geometrical efficiency factor
IPTS	International Practical Temperature Scale
KPC	KPb_2Cl_5
LD	Lamb–Dicke (regime)
LO	longitudinal optical
MAT	minimum achievable temperature
MD	magnetic dipole
MOT	magneto-optical trap
ODT	optical dipole trap
PSD	phase-space density

Glossary of Symbols and Acronyms

QM	quantum model
RE	rare earth
RF	radiofrequency
rms	root-mean-square
RWA	rotating-wave approximation
SCM	semi-classical model
SHG	second harmonic generation
SLT	second law of thermodynamics
SNR	signal-to-noise ratio
SRAP	stimulated Raman adiabatic passage
SRE	selective resonant enhancement
SSRS	stimulated Stokes Raman scattering
STIRAP	stimulated Raman adiabatic passage
TA	transverse acoustic
TIR	total internal reflection
TO	transverse optical
TOF	time-of-flight
TOP	time-orbiting potential
VECSEL	vertical-external-cavity surface-emitting laser
VSCPT	velocity-selective coherent population trapping
VUV	vacuum ultraviolet
YAG	$Y_3Al_5O_{12}$ (yttrium aluminium garnet)
YLF	$YLiF_4$ (yttrium lithium fluoride)
ZBLAN	ZrF_4-BaF_2-LaF_3-AlF_3-NaF
ZBLANP	ZrF_4-BaF_2-LaF_3-AlF_3-NaF-PbF_3 (heavy-metal fluoride glass)