LASERS

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PREFACE

This book presents a detailed and comprehensive treatment of laser physics and laser theory which can serve a number of purposes for a number of different groups. It can provide, first of all, a textbook for graduate students, or even well-prepared seniors in science or engineering, describing in detail how lasers work, and a bit about the applications for which lasers can be used. Problems, references and illustrations are included throughout the book.

Second, it can also provide a solid and detailed description of laser physics and the operational properties of lasers for the practicing engineer or scientist who needs to learn about lasers in order to work on or with them.

Finally, the advanced sections of this text are sufficiently detailed that this book will provide a useful one-volume reference for the experienced laser engineer or laser researcher's bookshelf. The discussions of advanced laser topics, such as optical resonators, Q-switching, mode locking, and injection locking, extend far enough into the current state of the art to provide a working reference on these and similar topics. References for further reading in the recent literature are included in nearly every section.

One unique feature of this book is that it removes much of the quantum mystique from "quantum electronics" (the generic label often applied to lasers and laser applications). Many people think of lasers as quantum devices. In fact, however, most of the basic concepts of laser physics, and virtually all the practical details, are classical in nature. Lasers (and masers) of all types and in all frequency ranges are simply electronic devices, of great interest and importance to the electronics engineer.

In the analogous case of semiconductor electronics, for example, the transistor is not usually thought of as a quantum device. Mental images of holes and electrons as classical charged particles which accelerate, drift, diffuse and recombine are used both by semiconductor device engineers to do practical device engineering, and by solid-state physics researchers to understand sophisticated physics experiments. These classical concepts serve to explain and make understandable what is otherwise a complex quantum picture of energy bands, Bloch wavefunctions, Fermi-Dirac distributions, and occupied or unoccupied quantum states. The same simplification can be accomplished for lasers, and laser devices can then be very well understood from a primarily classical viewpoint, with only limited appeals to quantum terms or concepts.

The approach in this book is to build primarily upon the classical electron oscillator model, appropriately extended with a descriptive picture of atomic energy levels and level populations, in order to provide a *fully accurate, detailed and physically meaningful* understanding of lasers. This can be accomplished without requiring a previous formal background in quantum theory, and also without attempting to teach an abbreviated and inadequate course in this subject on the spot. A thorough understanding of laser devices is readily available through this book, in terms of classical and descriptively quantum-mechanical concepts, without a prior course in quantum theory.

I have also attempted to review, at least briefly, relevant and necessary background material for each successive topic in each section of this book. Students will find the material most understandable, however, if they come to the book with some background in electromagnetic theory, including Maxwell's equations; some understanding of the concept of electromagnetic polarization in an atomic medium; and some familiarity with the fundamentals of electromagnetic wave propagation. An undergraduate-level background in optics and in Fourier transform concepts will certainly help; and although familiarity with quantum theory is *not* required, the student must have at least enough introduction to atomic physics to be prepared to accept that atoms do have quantum properties, especially quantum energy levels and transitions between these levels.

The discussions in this book begin with simple physical descriptions and then go into considerable analytical detail on the stimulated transition process in atoms and molecules; the basic amplification and oscillation processes in laser devices; the analysis and design of laser beams and resonators; and the complexities of laser dynamics (including spiking, Q-switching, mode locking, and injection locking) common to all types of lasers. We illustrate the general principles with specific examples from a number of important common laser systems, although this book does not attempt to provide a detailed handbook of different laser systems. Extensive references to the current literature will, however, guide the reader to this kind of information.

There is obviously a large amount of material in this book. The author has taught an introductory one-quarter "breadth" course on basic laser concepts for engineering and applied physics students using most of the material from the first part of the book on "Basic Laser Physics" (see the Table of Contents), especially Chapters 1–4, 6–8 and 11–13. A second-quarter "depth" course then adds more advanced material from Chapters 5, 9, 10, 30, 31 and selected sections from Chapters 24–29. A complete course on optical beams and resonators can be taught from Chapters 14 through 23.

I am very much indebted to many colleagues for help during the many years while this book was being written. I wish it were possible to thank by name all the students in my classes and my research group who lived through too many years of drafts and class notes. Special thanks must go to Judy Clark, who became a TEX and computer expert and did so much of the editing and manuscript preparation; to the Air Force Office of Scientific Research for supporting my laser research activities over many years; to Stanford University, and especially to Donald Knuth, for providing the environment, and the computerized text preparation tools, in which this book could be written; and to the Alexander von Humboldt Foundation and the Max Planck Institute for Quantum Optics in Munich, who supplied the opportunity for the manuscript at last to be completed. Finally, there are my wife Jeannie, and my family, who made it all worthwhile.

Anthony E. Siegman

UNITS AND NOTATION

The units and dimensions in this book are almost entirely mks, or SI, except for a few concessions to long-established habits such as expressing atomic densities N in atoms/cm^3 and cross sections σ in cm^2. Such non-mks values should of course always be converted to mks units before plugging them into formulas.

In general, lower-case symbols in bold-face type such as $\boldsymbol{\mathcal{E}}(\mathbf{r},t)$, $\mathbf{b}(\mathbf{r},\mathbf{t})$, $\mathbf{h}(\mathbf{r},\mathbf{t})$, and so on refer to electromagnetic field quantities as real vector functions of space and time, while $\mathcal{E}(r,t)$, $b(r,t)$, $h(r,t)$, etc., refer to the scalar counterparts of the same quantities. Bold-face capital letters **E**, **B**, **H**, etc., refer to the complex phasor amplitudes of the same vector quantities with $e^{j\omega t}$ variations, while $\tilde{E}$, $\tilde{B}$, $\tilde{H}$, etc., are the complex phasor amplitudes of the corresponding scalars. As illustrated here, complex quantities are sometimes, but not always, identified by a superposed tilde.

In writing sinusoidal signals and waves, waves propagating toward positive z are written in the "electrical engineer's form" of $\exp j(\omega t - \beta z)$ rather than the "physicist's form" of $\exp i(kz - \nu t)$. (This of course does *not* imply that $i \equiv -j$!) Linewidths Δf, $\Delta\omega$, $\Delta\lambda$ and pulsewidths Δt, τ or T, unless specifically noted, always mean the full width at half maximum (FWHM).

In contrast to much of the published literature, an attenuation or gain coefficient α in this book always refers to an *amplitude* or *voltage* growth rate, such as for example $\mathcal{E}(z) = \mathcal{E}(0)\exp \pm\alpha z$. Signal powers or intensities in this book, therefore, always grow or attenuate with exponential growth coefficients 2α rather than α.

The notation in the book has a few other minor idiosyncrasies. First, we are often concerned with signals and waves inside laser crystals, in which the host crystal itself has a dielectric constant ϵ and an index of refraction n even without any atomic transition present. To take the dielectric properties of a possible host medium into account, the symbols ϵ, c and λ in formulas in this text always refer to the dielectric permeability, velocity of light and wavelength of the radiation *in the dielectric medium* if there is one. We then use c_0 and λ_0 in the few cases where it is necessary to refer to these same quantities specifically in vacuum. The advantage of this choice is that all our formulas involving ϵ, c and λ remain correct with or without a dielectric host medium, without needing to clutter these formulas with different powers of the refractive index n.

The other special convention peculiar to this book is the nonstandard manner in which we define the complex susceptibility $\tilde{\chi}_{at}$ associated with a resonant atomic transition. In brief, we define the linear relationship between the induced polarization $\tilde{P}_{at}$ on an atomic transition in a laser medium and the electric field $\tilde{E}$ that produces this polarization by the convention that $\tilde{P}_{at} = \tilde{\chi}_{at}\epsilon\tilde{E}$ where ϵ is the dielectric permeability *of the host laser crystal* rather than the vacuum value ϵ_0 usually used in this definition. The merits of this nonstandard approach are argued in Chapter 2.

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LIST OF SYMBOLS

Throughout this text we attempt to follow a consistent notation for subscripts, using the conventions that:

a = either *atomic*, as in atomic transition frequency ω_a or homogeneous atomic linewidth $\Delta\omega_a$; or sometimes *absorption*, as in absorption coefficient α_a.

c = *cavity*, as in cavity decay time τ_c or cavity energy decay rate γ_c; also, *carrier*, as in carrier frequency ω_c.

d = *doppler*, as in doppler broadening with linewidth $\Delta\omega_d$, and by extension any other kind of inhomogeneous broadening.

e = *external*, as in cavity external coupling factor δ_e or external decay rate γ_e; also, sometimes, *effective*, as in effective lifetime or pumping rate.

m = *molecular* or *maser*, generally used to refer to atomic or maser or laser quantities, e.g., laser gain coefficient α_m or laser growth rate γ_m.

o = *ohmic*, referring generally to internal ohmic and/or scattering losses, as in the ohmic loss coefficient α_0 or ohmic cavity decay rate γ_0. Also used in several other ways, generally to indicate an initial value; a thermal equilibrium value; a small-signal or unsaturated value; a midband value; or a free-space (vacuum) values, as in c_0, ϵ_0, and λ_0.

p = *pump*, as in pumping rate R_p or pump transition probability W_p.

We also frequently use *ax* ≡ *axial*; *avail* ≡ *available*; *circ* ≡ *circulating*; *eff* ≡ *effective*; *eq* ≡ *equivalent*; *inc* ≡ *incident*; *opt* ≡ *optimum*; *out* ≡ *output*; *refl* ≡ *reflected*; *rt* ≡ *round-trip*; *sat* ≡ *saturation*; *sp* ≡ *spontaneous* or *spiking*; *ss* ≡ *small-signal* or *steady-state*; and *th* ≡ *threshold* as compound subscripts.

A partial list of symbols used in the text then includes:

α = exponential gain or loss coefficient for amplitude (or voltage); also, amplitude parameter for gaussian optical pulse

α'' = second derivative of $\alpha(\omega)$ with respect to ω

$\tilde{\alpha}_n$ = complex amplitude of n-th order Hermite-gaussian mode

α_m = maser/laser/molecular gain (or loss) coefficient

α_0 = ohmic and/or scattering loss coefficient

β = propagation constant, including host dielectric effects, but usually not loss or atomic transition effects; also, chirp parameter for gaussian pulse; relaxation-time ratio in multilevel laser pumping systems; Bohr magneton

β_I = Nuclear magneton

β', β'' = first and second derivatives of $\beta(\omega)$ with respect to ω

$\Delta\beta_m$ = added propagation constant term due to reactive part of an atomic transition

γ = in general, an energy or population decay rate
γ_c = decay rate for cavity stored energy ($\equiv 1/\tau_c$)
γ_i = total downward population decay rate from energy level E_i
γ_{ij} = population decay rate from upper level E_i to lower level E_j
γ_{nr} = nonradiative part of total decay rate for a classical oscillator or an atomic transition
γ_{rad} = radiative decay rate for classical electron oscillator or real atomic transition
$\tilde{\gamma}$ = complex eigenvalue for optical resonator or lensguide
$\tilde{\gamma}_{mn}$ = complex eigenvalue for mn-th order transverse eigenmode
$\Gamma = \alpha + j\beta$ = complex propagation constant for an optical wave
$\Gamma = \alpha - j\beta$ = complex gaussian pulse parameter
δ = coefficient of (logarithmic) fractional power gain or loss, per bounce or per round trip
δ_c = total (round-trip) power loss coefficient due to cavity losses plus external coupling
δ_e = cavity loss coefficient due to external coupling only
δ_m = power gain coefficient due to laser atoms
δ_0 = cavity loss coefficient due to internal (ohmic) losses only
Δ_m = AM or FM modulation index
ϵ = dielectric permeability of a medium
ϵ_0 = dielectric permeability of free space (vacuum)
η = efficiencies of various sorts; also, characteristic impedance $\sqrt{\mu/\epsilon}$ of a dielectric medium
η_0 = characteristic impedance of free space (vacuum)
λ = optical wavelength (in a medium); also, eigenvalue for optical ray matrix
λ_0 = optical wavelength in vacuum
λ_a, λ_b = eigenvalues of periodic lensguide or $ABCD$ matrix
Λ = spatial period of optical grating
μ = electric or magnetic dipole moment; also, magnetic permeability of a magnetic medium
μ_e = electric dipole moment
μ_m = magnetic dipole moment
μ_0 = magnetic permeability of free space
ρ = amplitude reflection or transmission of optical mirror or beamsplitter; also, distance between two points; $\rho(\omega)$ = cavity mode density
$\tilde{\rho}$ = complex amplitude reflection or transmission of optical mirror or beamsplitter
σ = ohmic conductivity; also, transition cross section, standard deviation
σ_{ij} = cross section for stimulated transition from level E_i to E_j
τ = lifetime or decay time
τ_c = cavity decay time due to all internal losses plus external coupling
τ_i = total lifetime (energy decay time) for energy level E_i
θ, ϕ, ψ = phase shifts and phase angles of various sorts
$\psi(\mathbf{r}, t)$ = Schrödinger wave function

ψ_{mn} = Guoy phase shift for an mn-th order gaussian beam
$\tilde{\chi}$ = susceptibility of a dielectric or magnetic medium = $\chi' + j\chi''$
χ', χ'' = real and imaginary parts of $\tilde{\chi}$
$\tilde{\chi}_{at}$ = susceptibility of a resonant atomic transition
$\tilde{\chi}_e, \tilde{\chi}_m$ = electric (magnetic) dipole susceptibilities
ω = frequency (in radians/second)
ω' = in general, a frequency that has been shifted, pulled, or modified in some small manner
ω_a = atomic transition frequency
ω_b = a beat frequency (between two signals)
ω_c = cavity or circuit resonant frequency; also, carrier frequency
$\omega_i(t)$ = instantaneous frequency of a phase-modulated signal
ω_m = generally, a modulation frequency of some sort
ω_q = resonant frequency of q-th axial mode
ω_R = Rabi frequency on an atomic transition
ω_{sp} = Spiking or relaxation-oscillation frequency
$\delta\omega_q$ = frequency pulling of axial mode frequency ω_q
$\Delta\omega$ = linewidth, or frequency tuning, in radians/sec
$\Delta\omega_a$ = atomic linewidth (FWHM)nin radians/sec
$\Delta\omega_{ax}$ = axial mode spacing between adjacent axial modes
Ω = solid angle; also, radian frequency or rotation rate

$\tilde{a}_i, \tilde{b}_i$ = normalized wave amplitudes
A = area
A_{ji} = Einstein A coefficient on $E_j \rightarrow E_i$ transition
$ABCD$ = matrix elements for optical ray matrix or paraxial optical system
b = magnetic field as real function of space and time; also, confocal parameter for gaussian beam
$\boldsymbol{b}$ = magnetic field as real vector function of space and time; also, confocal parameter for gaussian beam
B = magnetic field; also, pressure-broadening coefficient or "B integral" for nonlinear interaction
$\tilde{B}$ = phasor amplitude of sinusoidal B field
c = velocity of light in a material medium
c_0 = velocity of light in vacuum
C = in general, an unspecified constant; also, electrical capacitance; coupling coefficient in mode competition analysis
CC = complex conjugate (of preceding term)
CEO = classical electron oscillator model
d = electric displacement as real function of space and time; also, distance or displacement
$\boldsymbol{d}$ = electric displacement as real vector function of space and time
D = dimensionless dispersion parameter
$\tilde{D}$ = phasor amplitude of sinusoidal electric displacement
e = magnitude of electronic charge
$\mathcal{E}$ = electric field; usually, real field $\mathcal{E}(x,t)$ as function of space and time

$\tilde{E}$ = phasor amplitude of sinusoidal E field
$E_n(t)$ = amplitude of n-th mode in a normal mode expansion
f = frequency in Hz ($\equiv$ cycles/sec); also, lens focal length
$f^{\#}$ = lens f-number
Δf = linewidth, or frequency detuning, in Hz
Δf_a = atomic transition linewidth (FWHM) in Hz
Δf_d = doppler or inhomogeneous linewidth (FWHM) in Hz
F = oscillator strength for an atomic transition; also, lens f-number
$\mathcal{F}$ = finesse, of interferometer or laser cavity
$\tilde{F}(x)$ = Fresnel integral function
F_{ji} = oscillator strength of $E_j \rightarrow E_i$ atomic transition $\equiv \gamma_{\text{rad},ji}/3\gamma_{\text{rad,ceo}}$
g = amplitude (or voltage) gain, as a number; also, gaussian stable resonator parameter; magnetic resonance g value
$g(v), g(\omega)$ = normalized lineshapes
$\tilde{g}$ = complex amplitude (or voltage) gain, as a (complex) number
g_i, g_j = degeneracy factors for quantum energy levels E_i and E_j
g_I = nuclear magnetic resonance g value
$\tilde{g}_{rt}$ = round-trip voltage gain inside an optical cavity
G = power gain (as a number); also, electrical conductance
G_{dB} = power gain in decibels
h = magnetic intensity as real function of space and time; also, Planck's constant
$\hbar$ = $h/2\pi$
$\boldsymbol{h}$ = magnetic $\boldsymbol{H}$ field as real vector function of space and time
h_n = n-th order polynomial function
$\tilde{H}$ = phasor amplitude of sinusoidal H field
H_n = n-th order hermite polynomial
I = intensity (power/unit area) of an optical wave; also sometimes, loosely, total power in the wave
I_m = modified Bessel function of order m
I_{sat} = amplifier (or absorber) saturation intensity
j = current density as real function of space and time; also, $\sqrt{-1}$
$\boldsymbol{j}$ = current density as real vector function of space and time
$\tilde{J}$ = phasor amplitude of sinusoidal current density
J_m = Bessel function of order m
k = propagation vector of optical wave $= \omega/c$
K = scalar constant in various equations (especially coupled rate equations); also, spring constant in classical oscillator model
L = length; electrical inductance
m = electron mass; also, magnetization (magnetic dipole moment per unit volume) as real function of time
$\boldsymbol{m}$ = magnetization (magnetic dipole moment per unit volume) as real vector function of space and time
$m, \tilde{m}$ = half-trace parameter for ray or $ABCD$ matrix
M = proton mass; molecular mass

$\tilde{M}$ = phasor amplitude of sinusoidal magnetic dipole moment

$\boldsymbol{M}$ = optical ray matrix or $ABCD$ matrix

n = refractive index; also, photon number $n(t)$ (number of photons per cavity mode)

n_2 = optical Kerr coefficient n_{2E} or n_{2I}

N = atomic number or level population; usually interpreted as atoms per unit volume, sometimes as total number of atoms

ΔN = population difference, or population difference density, on an atomic transition ($\Delta N_{ij} \equiv N_i - N_j$)

N = Fresnel number $a^2/L\lambda$ for an optical beam or resonator

N_c = collimated Fresnel number for an unstable optical resonator

N_{eq} = equivalent Fresnel number for an unstable optical resonator

N_i = population, or population density, in atomic energy level E_i

p = perimeter, period or round-trip path length, for cavities or periodic lensguides; also, electric polarization (electric dipole moment per unit volume) as real function of time, and laser mode density or mode number

$\boldsymbol{p}$ = electric polarization (electric dipole moment per unit volume) as real vector function of space and time

p_m = path length (round-trip) through an atomic or laser gain medium

P = power, in watts; also, pressure, in torr

$P_n(t)$ = polarization driving term for n-th order cavity mode in coupled-mode expansion

$\tilde{P}$ = phasor amplitude of sinusoidal electric polarization

q = axial mode index

$\tilde{q}$ = complex gaussian beam parameter or complex radius of curvature

$\hat{q}$ = reduced gaussian beam parameter, $\tilde{q}/n$

r = amplitude reflectivity of mirror or beamsplitter; also, dimensionless or normalized pumping rate; displacement off axis of optical ray

r' = reduced slope $n\,dr/dz$ for optical ray

$\boldsymbol{r}$ = shorthand for spatial coordinates x, y, z

$\tilde{r}_{ij}$ = complex scattering matrix element, or mirror or beamsplitter reflection coefficient

r_p = dimensionless pumping rate or inversion ratio, relative to threshold pumping rate or threshold inversion density

$d\boldsymbol{r}$ = volume element, dV or $dx\,dy\,dz$

R = power reflectivity of mirror or beamsplitter ($\equiv |r|^2$); also, electrical resistance; radius of curvature for mirror, dielectric interface, or optical wave

$\hat{R}$ = reduced radius of curvature R/n

R_p = pumping rate in atoms per second and, usually, per unit volume

s = spatial frequency (cycles/unit length)

$\boldsymbol{s}$ = shorthand for transverse spatial coordinates x, y

$d\boldsymbol{s}$ = transverse area element dA or $dx\,dy$

$\boldsymbol{S}$ = multiport scattering matrix (matrix elements S_{ij})

t = time; also, amplitude transmission through mirror, beamsplitter, or light modulator

$\tilde{t}$ = complex amplitude transmission coefficient through mirror, beamsplitter or light modulator

$\tilde{t}_{ij}$ = complex scattering matrix element, or mirror/beamsplitter transmission coefficient

T = power transmission of mirror or beamsplitter ($\equiv |t|^2$); also, cavity round-trip transit time, or temperature (K)

$\boldsymbol{T}$ = dimensionless susceptibility tensor

T_b = laser oscillation build-up time

T_{nr} = temperature of "nonradiative" surroundings

T_{rad} = temperature of radiative surroundings

T_1 = energy decay time, population recovery time, longitudinal relaxation time

T_2 = dephasing time, collision time, transverse relaxation time

T_2^* = effective T_2 or dephasing time for inhomogeneous (gaussian) transition

$\tilde{u}$ = complex (and usually normalized) optical wave amplitude

U = energy or, more commonly, energy density (energy per unit volume)

U_a = energy density in a collection of atoms or atomic energy level populations

U_{bbr} = energy density of blackbody radiation

v = velocity of an atom, an electron, or a wave

$\tilde{v}$ = complex spot size for Hermite-gaussian modes

v_g = group velocity

v_ϕ = phase velocity

V, V_c = volume (of a cavity mode or field pattern)

w = gaussian spot size parameter ($1/e$ amplitude point)

w_{ij} = total relaxation transition probability (per atom, per second) from level E_i to level E_j

W_{ij} = stimulated transition probability (per atom, per second) from level E_i to level E_j

W_p = pumping transition probability (per atom, per second)

$x(t)$ = displacement of electronic charge in classical electron oscillator model

z_D = dispersion length for dispersive pulse broadening

z_R = Rayleigh range for a gaussian or collimated optical beam

Z = atomic number

2^* = dimensionless population saturation factor, with values between $2^* = 1$ (lower level empties out rapidly) and $2^* = 2$ (lower level bottlenecked)

3^* = dimensionless polarization overlap factor for atomic interactions, with numerical value between 0 and 3

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LASER DYNAMICS AND ADVANCED TOPICS

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