LASER ELECTRONICS

Joseph T. Verdeyen

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PREFACE

This book originates from a set of class notes prepared for seniors or beginning graduate students in electrical engineering, physics, or chemistry at the University of Illinois. It is an attempt to adapt the student's background in electronics at radio or microwave frequencies to some of the techniques, components, and problems associated with this new source—the laser—at the higher-frequency domain.

Therefore, the book begins with Maxwell's equations, examines electromagnetic issues that play a major role in laser oscillation, and then discusses the basic phenomena in atomic physics which lead to amplification and, with feedback, to oscillation. While the discussion is intended to be applicable to all types of lasers, there is a considerable bias exhibited towards the gas laser as being the *simplest* system which exemplifies the principles discussed. The book concludes with a preliminary discussion of quantum detectors and detection systems, a subject which could be covered first or last, but in any case, should be covered, to appreciate some of the possibilities and problems of laser communications.

All theoretical developments are presented using the SI system of units, however, most of the discussion and examples involving numerical values use the centimeter as the unit of length.

The underlying philosophy of the entire text is that laser technology is, for the most part, a natural extension of low-frequency electronics. Lasers are quantum devices—so be it, so are transistors! The student should enjoy, rather than be intimidated by the quantum nature of the laser.

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During the past twenty-two years, I have had the honor of participating in the Department of Electrical Engineering at the University of Illinois. This department is superbly administered, is staffed by colleagues who are industrious, competent, and most congenial, and furthermore, manages to attract some of the brightest students in the world. It is a pleasure and an inspiration to work under such circumstances.

I am very grateful for the advice, encouragement, and education provided by my colleagues in physical electronics—Professors Paul Coleman, Tom DeTemple, J. Gary Eden, Oscar Gaddy, Ladislas Goldstein, Charles Hendricks, Nick Holonyak, Marv Krasnow, Greg Stillman, Ben Streetman, and Bob Turnbull. I would also like to express my deep appreciation and thanks to former colleagues Dr. Blake E. Cherrington, Dr. James B. Gerardo, and Dr. Paul A. Miller for their professional criticisms, valuable suggestions and aid, and, most of all, for their long-term personal friendship.

It is also a pleasure to acknowledge the many friends who have contributed to my research efforts on lasers and thus to the production of this book—Keith Kuehl, whose master glassblowing skills have contributed so much to my research effort, A. Wilson and E. Boose for their skill in vacuum technology and chemical processing, Mrs. Katharine Flessner who typed the original manuscript, and Mr. G. Morris for his skill in the production of the illustrations.

Finally, none of this would have been possible without my family's constant encouragement and love. However, their aid was not limited to merely moral support. My wife typed most of the final version of the manuscript and labored many hours checking the galley and page proofs. My daughter and son contributed their time to the proofreading and indexing. Hence, I would like to dedicate this book to my wife Katie, my daughters Mary and Jean, and my sons Joe and Mike.

JOSEPH T. VERDEYEN

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ROMAN SYMBOLS

A^*	Complex conjugate of A
$\mathbf{a}_n$	Unit vector in direction of n
a	Attachment rate per unit of drift
$[A]$	Density of A
A_{21}	Einstein coefficient for spontaneous emission
A, B, C, D	Components of ray matrix
$\mathbf{b}, \mathbf{B}$	Magnetic induction vector
B_e	Rotational constant
B_{21}	Einstein coefficient for stimulated emission
B_{12}	Einstein coefficient for absorption $B_{12} = g_2 B_{21}/g_1$
c	Velocity of light in vacuum
$\mathbf{d}, \mathbf{D}$	Displacement vector
D_T	Transverse diffusion coefficient
$D_{n(p)}$	Diffusion coefficients for electrons (holes)
E	Energy
e	Electronic charge
$\mathbf{e}, \mathbf{E}$	Electric field intensity
$E_{c(v)}$	Energy of the conduction (valence) band
E_F	Fermi Energy
$\bar{e}^2, \bar{i}^2$	Equivalent noise generators
F	Finesse = FSR/$(\Delta\nu_{1/2})$
f	Focal lengths
$F(\epsilon)$	Electron distribution function per unit of energy
$f(E)$	Fermi function
$F(J)$	Rotational energy
$F_{n(p)}$	Quasi-Fermi level for electrons (holes)
FSR	Free spectral range $= c/2d$
$F(z)$	Forward wave
$F(v)$	Electron distribution function per unit of velocity
FWHM	Full width at half maximum
f_{12}	Absorption oscillation strength
$g(\nu)$	Lineshape
$\bar{g}(\nu)$	Lineshape normalized to unity at line center, i.e., $\bar{g}(\nu_0) = 1$
$G(v)$	Vibrational energy
G	Power gain
$1/q(z)$	Complex beam parameter $= 1/R(z) - j\lambda/[\pi w^2(z)]$
$g_{1,2}$	$(1 - d/R_{1,2})$, the g parameter of a cavity
g	$2J + 1$, the degeneracy of a quantum state
h	Planck's constant
$\hbar$	Planck's constant divided by 2π
$\mathbf{h}, \mathbf{H}$	Magnetic field intensity

$H_n(u)$	Hermite polynomial of order n argument $n = [(-1)^n e^{u^2}]/du^n$
H_{op}	Operator corresponding to the Hamiltonian
I_ν	Intensity at a frequency ν
$I(\nu)$	Intensity per unit of frequency at ν
J	Angular momentum quantum number
j	The imaginary number $(-1)^{1/2}$
$\mathbf{j}$, $\mathbf{J}$	Conduction current
k	$2\pi n/\lambda$
$\mathbf{k}$	Wave vector $= k\mathbf{a}_n$
K.E.	Kinetic energy
$m_{c(v)}$	Effective mass in the conduction (valence) band
N	Density (number/volume)
n	Population difference $(N_2 - N_1)V$
n	Mode index
n	Index of refraction $(\epsilon_r)^{1/2}$
$n(\nu)$	Frequency dependent refractive index
$n_c(E)$	Density of electrons in conduction band per unit of energy
n_e	Electron density
n_{th}	Threshold value of population difference
N_ν	Number of modes in a volume V between 0 and ν
$N_2(v)$	Nitrogen in a vibrational state v
$N_{2(1)}$	Density of atoms in state 2(1)
$\langle P \rangle$	Average power (averaged over many cycles)
$\langle p \rangle$	Instantaneous power (averaged over a few cycles)
p	Pressure
$\mathbf{p}$, $\mathbf{P}$	Polarization vector
P_{el}	Power in electron gas
P_f	Fluorescence power
$p_v(E)$	Density of holes in the valence band per unit of energy
Q	Quality factor $= \omega W/(-dW/dt)$
q	Axial mode number of a resonant mode in a cavity, also the number of half-wavelengths between the mirrors
R	Resistance
R	If the numerical value > 1, radius of curvature; if < 1, power reflectivity
$\mathbf{r}$	Position vector $= x\mathbf{a}_x + y\mathbf{a}_y + z\mathbf{a}_z$
Re ( )	Real part of the quantity ( )
$R(z)$	Reverse wave
$R(z)$	Radius of curvature of phase front
$\mathbf{S}$	Poynting vector
S/N	Signal to noise ratio
$S_T(\nu)$	Power per unit of frequency
$\mathbf{T}$	Ray matrix

T	Temperature (°K)
T_e	Electronic term energy
TEM	Transverse electric and magnetic mode
V	Voltage or volume
$V_{m,n}$	Volume of the $TEM_{m,n}$ mode
v	Speed, velocity or vibrational quantum number
v_g	Group velocity
VSWR	Voltage standing wave ratio
W	Energy
w	Drift velocity (Chapter 11)
W_e	Energy of the electron gas
w_0	Minimum spot-size
w_s	Saturation energy
$w(z)$	Spot-size as a function of z
z_0	Characteristic length parameter of a Gaussian beam
Z	Impedance

GREEK SYMBOLS

α	Absorption coefficient (loss per length)
α	Townsend ionization coefficient (ionization rate per unit of drift) (Chapter 11)
α_e	Correction to the rotational constant due to vibration
β	Phase constant (rad/length) of a guided wave
β_0	A phase constant satisfying the Bragg condition
$\gamma_{1(2)}$	Decay rate of state 1 (or 2)
Γ	Photon flux ($I/h\nu$)
$\gamma_0(\nu)$	Small signal gain coefficient
$\gamma(\nu)$	Intensity dependent gain coefficient
δ	Secondary emission ratio
δ	Fraction of the electron's excess energy lost in an elastic collision
$\Delta\nu_D$	Doppler line width
$\Delta\nu_h$	Homogeneous line width
$\Delta\nu_n$	Natural line width
$\Delta\nu_H$	Hole line width
$\Delta\omega$	Line width in radian frequency units
$\Delta t_{1/2}$	Pulse wide (FWHM)
ϵ_k	Characteristic energy of electrons $= D_T/u$
ϵ_A	Characteristic energy of atoms or molecules
ϵ'	Real part of the relative dielectric constant
ϵ''	Imaginary part of the relative dielectric constant

ϵ_0	Permittivity of free-space
ϵ_r	Relative dielectric constant
ϵ	Electron energy
η_0	Wave impedance of free-space $(\mu_0/\epsilon_0)^{1/2}$
η_{qe}	Quantum efficiency
η_x	Extraction efficiency
Λ	Characteristic length
λ_q	Wavelength of the $TEM_{m,m,q}$ mode
λ_0	Free-space wavelength
λ	Wavelength λ_0/n
μ	Mobility
μ_{21}	Electric dipole moment
μ_0	Permeability of free-space
ν, f	Frequency (Hertz)
ν_i	Ionization rate (per electron)
ν_0	Line center
$\bar{\nu}$	Wave number (# of wavelengths per centimeter)
ν_c	Collision of frequency
$\rho(\nu)$	Energy per unit of volume per unit of frequency at ν
ρ_ν	Energy per unit of volume at a frequency ν
ρ	Reflection coefficient for the electric field
$\sigma(\nu)$	Stimulated emission cross-section
$\sigma_c(\epsilon)$	Collision cross-section
σ_i	Ionization cross-section
τ_1	Lifetime of state 1
τ_2	Lifetime of state 2
τ_{21}^{-1}	Decay rate of state 2 into state 1
τ_p	Photon lifetime
τ_r	Radiative lifetime
ϕ, θ	Phase shift or geometric angles
ϕ_p	Number of photons in a cavity
ϕ_{12}	Branching ratio
ψ	Wave function
ω	Radian frequency $= 2\pi\nu$
Ω	Rabi frequency $(\mu_{21}E/2\hbar)$

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PRELIMINARY COMMENTS

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Prior to the 1960s, optics formed the basis for a relatively small industry involving rather sedate and mature topics such as optical instruments, cameras, microscopes, and scientific applications. Then the laser came on the scene, first the solid-state (ruby) laser, then the gas laser, then the semiconductor injection laser—and now optics forms the basis for many more functions, products, and services.

At first, the standard joke was: "The laser is a solution in search of a problem." More seriously, almost everybody recognized the potential of the laser in communications, in data processing, storage, and retrieval, and even in eye surgery. The question to be answered was: Could the laser do things that had not been done before, or could it do things better and more economically than had previous devices and technologies? It is interesting to observe that the initial applications of the laser have not been in the rather obvious fields listed above but in new applications by ingenious people who understood the principles of the laser and who understood the problems to be solved. Hence, we have laser transits, laser pattern cutting, laser cutting of steel, and laser fusion, and we are starting to make inroads in optical communications. The history of the laser in the field of communications is a good one to follow to illustrate a point about "obvious" applications.

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The frequency of the ruby laser at $\lambda = 694.3$ nm is 4.32×10^{14} Hz, a quantity that is of interest to any communication engineer. If only 1% of this carrier frequency is used for the information bandwidth, we have a communication channel that has two to three orders of magnitude (10^2 to 10^3) more capacity than the widest band channel in existence. Some of the microwave radio-relay links used by the telephone company have channel widths as large as 10% of the carrier frequency. Consequently, one laser beam should be able to carry a huge number of telephone conversations (bandwidth required per telephone conversation, 4 kHz) and many television programs (bandwidth, ~5 MHz) simultaneously.

There are, however, a few problems. We do not know how to modulate this carrier at a 4×10^{12} Hz rate; nor does the technology exist to demodulate at this rate; nor could our terminal equipment handle information at this rate. If that is not enough, we are not overly confident of being able to transmit the information from point A to a distant point B with the reliability afforded by microwave links. Finally, there was some doubt as to the reliability of the laser. Consequently, communications by lasers with the same degree of sophistication as is done at microwave frequencies lies in the future, but some inroads are being made.

The invention of glass fibers exhibiting very low loss has made laser communications a viable alternative to wired links. After all, the world has practically exhausted high-grade copper ore supplies, but we have not really touched the primary ingredient of glass—SiO_2 (i.e., sand). Thus, the first "obvious" application of the laser, communications, had to wait until 1977 for trial runs over short-haul links.

The point to be made by the above is that obvious applications are not so straightforward and simple. Most often, it is the materials that are the major impediment, but this should not stop one from looking for other uses. For instance, a first major use of the ruby laser was in the "trimming" of solid-state circuit components. In that case, one uses the ability to focus the energy of the laser onto a very small spot so as to vaporize the excess material.

In view of the above, then, we will not look at a laser from an applications standpoint. Rather, we will try to introduce the elementary and *simple* principles of the laser itself, the propagation of its radiation, and the elements of the detection problem. The word "simple" was underlined to emphasize the goal of this textbook: to make you feel comfortable with the following issues:[1]

1. What physical principles are involved in *generation* of laser radiation? (2)

[1]The numbers in parentheses represent the order of the topics covered in this book.

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