third edition

Optoelectronics

an introduction

John Wilson
John Hawkes

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THIRD EDITION

JOHN WILSON
UNIVERSITY OF NORTHUMBRIA AT NEWCASTLE

JOHN HAWKES
UNIVERSITY OF NORTHUMBRIA AT NEWCASTLE

PRENTICE HALL EUROPE
LONDON NEW YORK TORONTO SYDNEY TOKYO SINGAPORE
MADRID MEXICO CITY MUNICH PARIS

First published 1998 by
Prentice Hall Europe
Campus 400, Maylands Avenue
Hemel Hempstead
Hertfordshire, HP2 7EZ
A division of
Simon & Schuster International Group

Typeset in 10/12pt Times
by Mathematical Composition Setters Ltd, Salisbury, Wiltshire

Printed and bound in Great Britain

Library of Congress Cataloging-in-Publication Data

Wilson, J. (John), 1939–
Optoelectronics : an introduction / John Wilson, John Hawkes. — 3rd ed.
p. cm.
Includes bibliographical references and index.
ISBN 0-13-103961-X
1. Optoelectronics. I. Hawkes, J. F. B., 1942– . II. Title.
QC673.W54 1998
621.381'045—dc21 97-36547
CIP

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 0-13-103961-X

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2 3 4 5 02 01 00 99 98

Optoelectronics

Preface to the third edition

In the six or seven years which have elapsed since the second edition was published the importance of optoelectronics as a subject in its own right has continued to grow, and the applications of optoelectronic devices have increased significantly. Very few courses in physics or electronic engineering do not now include a discussion of optoelectronics.

Our interpretation of what is meant by optoelectronics has remained unaltered since the first edition was published in 1983. That is, we define optoelectronics as the interaction of light (in the wavelength range from about 100 nm to 20 μm) with matter in gaseous, liquid or solid form, and the devices which depend on these interactions. This definition is of course broader than that adopted by many authors who restrict their discussions to the ways in which light interacts with semiconductors. This, however, ignores the many important devices that depend on the behaviour of light in crystals subject to external force fields, and the majority of lasers.

Typical of the dramatic growth of optoelectronics is the staggering rise in fiber optic communications. Optical fibers with laser sources have enabled home subscribers to have access to an enormous amount of facilities and information, varying from telephone links, through many video channels, to information databases worldwide via the information superhighway. The so-called information superhighway has resulted from the development of very low dispersion fibers coupled with the enormous bandwidth provided by laser sources, and the availability of very fast light detectors. Similarly there has been an amazing continuation in the growth of laser applications, not least in the field of medicine.

The book was originally written very much with the final year UK undergraduate in mind. It has, however, been widely used as an introduction to optoelectronics for postgraduate students and those in industry, who require a treatment that is not too advanced, but which nevertheless gives a good introduction to the quantitative aspects of the subject. We see no reason to change this approach as the book has been used as a standard text by colleagues in very many institutions worldwide for both undergraduate and postgraduate students. We are grateful to those who, having used the book, have taken the time to point out minor errors and to make suggestions for improvements.

This edition then does not aim to cover all aspects of optoelectronics nor to deal with some topics in full theoretical rigour, which in many cases would require a formal quantum mechanical approach. It aims rather to put special emphasis on the fundamental principles which underlie the operation of devices and systems. This, it is anticipated, will enable the reader to appreciate the operation of devices not covered here and to understand future developments within the subject.

Optoelectronics relies heavily on the disciplines of optics and solid state physics and we expect the reader to have some background knowledge of these subjects. For those with little experience in these topics we have retained, after careful consideration, the original Chapters 1 and 2 with some modifications, which provide a review of some of the relevant topics in these areas.

Otherwise in this third edition, given the rapid developments mentioned earlier, we have taken the opportunity to update the material covered in all of the other chapters. We have also reduced the length of some sections and introduced new sections and topics to reflect the changing emphasis within the subject. Thus in Chapter 3 we have increased the emphasis on parametric oscillation, and introduced a section on solitons in Chapter 9.

The two chapters on lasers, Chapters 5 and 6, have been updated to include, for example, sections on the free electron laser, quantum well lasers, vertical emitting lasers and superluminescent diodes, fiber lasers and parametric lasers, together with a section on medical and industrial applications of lasers.

In Chapter 7 there is a reduced emphasis on thermal detectors but an increased emphasis on junction detectors, especially those operating in the near IR and on high speed devices.

Chapter 8 on optical fibers has been updated to emphasize the increased importance of single mode fibers and very low dispersion (high bandwidth) fibers. Fiber manufacture is updated and the production of long wavelength fibers discussed.

In Chapter 9 wavelength division multiplexing, optical amplifiers, solitons and coherent systems are all introduced, along with a consideration of the performance of systems which depend on these topics. The systems covered include local area networks (LANs) and worldwide telephone links. The section on integrated optoelectronics has been updated and expanded.

Finally, while the optical fiber sensor which rivals the ubiquitous thermocouple does not yet appear to have been developed, there is a continued high level of interest in optical fiber sensors and some recent developments, particularly on distributed systems, have been included in Chapter 10.

Many readers of the previous editions have indicated the usefulness of the in-chapter examples and we have retained these and introduced several more. These, we believe, give students a feel for the subject and of the orders of magnitude of the parameters involved, and provide a better understanding of the text. We have also included more end-of-chapter problems. A teachers' manual containing solutions to these problems can be obtained from the publisher. The book again uses SI units throughout with the exception of the occasional use of the electron volt (eV).

Glossary of symbols

$\mathcal{A}$	Source strength
A	area, electric field amplitude, spontaneous transition rate (A_{21})
a	Richardson–Dushman constant, fiber radius, periodicity of lattice
B	magnetic flux density, Einstein coefficient (B_{21}, B_{12}), electron–hole recombination parameter, luminance, 'flicker' noise constant, birefringence
BER	bit error rate
C	capacitance, waveguide coupling factor
D	diffusion coefficient (D_e, D_h)
d	mode volume thickness
$\mathcal{E}$	electric field
E	energy, bandgap (E_g), donor/acceptor energy level (E_d, E_a), phonon energy (E_p), exciton binding energy (E_e), Young's modulus
F	fractional transmission, lens f number, force, APD excess noise factor ($F(M)$), Fermi–Dirac distribution function ($F(E)$), solar cell fill factor, electric field decay factor ($F(y)$)
f	modulation frequency, cut-off frequency (f_c), focal length
G	thermal conductance, gain
g	degeneracy, electron–hole generation rate, lineshape function ($g(\nu)$)
$\mathcal{H}$	magnetic field
H	heat capacity, system frequency response ($H(f)$)
h	polarization holding parameter, normalized impulse response ($h(f)$)
h_{fe}	transistor common emitter current gain
$\mathcal{I}$	radiant or luminous intensity
I	irradiance
i	current, reverse bias saturation current (i_0), photoinduced current (i_λ)
i	$\sqrt{-1}$
$\boldsymbol{i}$	unit vector (x direction)
$\mathcal{J}$	molecular rotational quantum number
J	current density
$\boldsymbol{j}$	unit vector (y direction)
$\mathcal{K}$	diffraction factor
K	Kerr constant, electron beam range parameter
$\boldsymbol{k}$, k	wavevector, wavenumber, small signal gain coefficient
$\mathcal{L}$	inductance

L	diffusion length (L_e, L_h), beat length (L_p), radiance, insertion loss (L_{ins}), excess loss (L_e)
l_c	coherence length
M	mass, avalanche multiplication factor
m	mass, effective mass (m_e^*, m_h^*), image magnification
$\mathcal{N}$	number of photons
N	population inversion, donor/acceptor densities (N_d, N_a), effective density of states in conduction/valence band (N_c, N_v), number of photons (N_p), number of modes, group refractive index (N_g)
NA	numerical aperture
NEP	noise equivalent power
n	electron concentration, intrinsic carrier concentration (n_i), refractive index, quantum number, mode number
O_d	detector output
$\mathcal{P}$	phase factor
P	power, dipole moment, electrical polarization, quadratic electro-optic coefficient
p	hole concentration, momentum, probability, photoelastic coefficient (p_c)
Q	charge, 'quality factor', trap escape factor, profile dispersion parameter, radiant or luminous energy
R	electrical resistance, load resistor (R_L), radius of curvature, reflectance, frequency response ($R(f)$), Stokes to anti-Stokes scattering ratio, responsivity, electron range (R_e), Fresnel reflection loss (R_F)
r	linear electro-optic coefficient, ratio of electron to hole ionization probabilities, electron–hole generation/recombination rates (r_g, r_r), reflection coefficient
S_R	Rayleigh scattering fraction
S/N	signal-to-noise ratio
T	transmittance, temperature, Curie temperature (T_c), period
t	time, active region thickness
$U_0(x, y)$	electric field amplitude
$\mathcal{V}$	fringe visibility
V	voltage, potential energy, Verdet constant, normalized film thickness, eye relative spectral response
v	velocity, group velocity (v_g), molecular vibration quantum number, Poisson ratio
W	power, total depletion layer width, spectral radiant emittance
$x_{n,p}$, x	n, p depletion layer widths, coordinate distance
y	coordinate distance
Z	depth of field, density of states ($Z(E)$)
z	coordinate distance
α	absorption coefficient, temperature coefficient of resistance, transistor common base current gain, angle, fiber profile parameter
β	diode ideality factor, electron–hole generation efficiency factor, propagation constant, isothermal compressibility, refractive index temperature coefficient
γ	loss coefficient, mutual coherence function (γ_{12})
Δ	fiber refractive index ratio

Δt	coherence time
δ	phase angle, secondary electron emission coefficient, waveguide difference parameter
ε	relative permittivity/dielectric constant (ε_r), emissivity
η	efficiency, charge transfer efficiency (η_{ct})
θ, θ_B	angle, Brewster angle
Λ	acoustic wavelength, microbend wavelength, grating periodicity
λ	light wavelength, bandgap wavelength (λ_g), light wavelength in vacuum (λ_0)
μ	electron/hole mobility (μ_e, μ_h), relative permeability (μ_r)
ν	light wave frequency
ρ	charge density, radiation density (ρ_ν), resistivity
σ	conductivity, Stefan's constant, r.m.s. pulse width
τ	time constant, thermal time constant (τ_H), lifetime, minority carrier lifetime (τ_c), time
Φ	phase angle, light flux
ϕ	phase angle, work function
χ	electric susceptibility, electron affinity
Ψ	time-dependent wavefunction
ψ	time-independent wavefunction, phase change
Ω	solid angle, rotation rate
ω	angular frequency, mode field diameter (ω_0)

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CHAPTER 1

Light

In discussing the various topics which we have brought together in this text under the title *optoelectronics*, of necessity we rely heavily on the basic physics of light, matter and their interactions. In this and the next chapter we describe rather briefly those concepts of optics and solid state physics which are fundamental to optoelectronics. The reader may be familiar with much of the content of these two chapters though those who have not recently studied optics or solid state physics may find them useful. For a more detailed development of the topics included, the reader is referred to the many excellent texts on these subjects, a selection of which is given in refs 1.1 and 2. 1.

In this chapter we shall describe phenomena such as polarization, diffraction, interference and coherence; we have assumed that the basic ideas of the reflection and refraction of light and geometrical optics are completely familiar to the reader, though one or two results of geometrical optics are included for convenience. In this context it is worth noting that the term 'light' is taken to include the ultraviolet and near-infrared regions as well as the visible region of the spectrum.

1.1 Nature of light

During the seventeenth century two emission theories on the nature of light were developed, the wave theory of Hooke and Huygens and the corpuscular theory of Newton. Subsequent observations by Young, Malus, Euler and others lent support to the wave theory. Then in 1864 Maxwell combined the equations of electromagnetism in a general form and showed that they suggest the existence of transverse electromagnetic waves. The speed of propagation in free space of these waves was given by

$$c = \sqrt{\frac{1}{\mu_0 \varepsilon_0}} \tag{1.1}$$

where μ_0 and ε_0 are the permeability and permittivity of free space, respectively. Substitution of the experimentally determined values of μ_0 and ε_0 yielded a value for c in very close agreement with the value of the speed of light *in vacuo* measured independently. Maxwell therefore proposed that light was an electromagnetic wave having a speed c of approximately 3×10^8 m s^{-1}, a frequency of some 5×10^{14} Hz and a wavelength of about 500 nm. Maxwell's theory suggested the possibility of producing electromagnetic waves

TABLE 1.1 Electromagnetic spectrum

Type of radiation	Wavelength	Frequency (Hz)	Quantum energy (eV)
	100 km	3×10^3	1.2×10^{-11}
Radio waves			
	300 mm	10^9	4×10^{-6}
Microwaves			
	0.3 mm	10^{12}	4×10^{-3}
Infrared			
	0.7 μm	4.3×10^{14}	1.8
Visible			
	0.4 μm	7.5×10^{14}	3.1
Ultraviolet			
	0.03 μm	10^{16}	40
X-rays			
	0.1 nm	3×10^{18}	1.2×10^4
γ-rays			
	1.0 pm	3×10^{20}	1.2×10^6

Note: The divisions into the various regions are for illustration only; there is no firm dividing line between one region and the next. The numerical values are only approximate; the upper and lower limits are somewhat arbitrary.

with a wide range of frequencies (or wavelengths). In 1887 Hertz succeeded in generating non-visible electromagnetic waves, with a wavelength of the order of 10 m, by discharging an induction coil across a spark gap thereby setting up oscillating electric and magnetic fields. Visible light and Hertzian waves are part of the *electromagnetic spectrum* which, as we can see from Table 1.1, extends approximately over the wavelength range of 1.0 pm to 100 km. The wave theory thus became the accepted theory of light. However, while the wave theory, as we shall see below, provides an explanation of optical phenomena such as interference and diffraction, it fails completely when applied to situations where energy is exchanged, such as in the emission and absorption of light and the photoelectric effect. The photoelectric effect, which is the emission of electrons from the surfaces of solids when irradiated, was explained by Einstein in 1905. He suggested that the energy of a light beam is not spread evenly but is concentrated in certain regions, which propagate like particles. These 'particles' of energy subsequently became known as photons (G. N. Lewis, 1926).

Einstein was led to the concept of photons by the work of Planck on the emission of light from hot bodies. Planck found that the observations indicated that light energy is emitted in multiples of a certain minimum energy unit. The size of the unit, which is called a *quantum*, depends on the frequency ν of the radiation and is given by

$$E = h\nu \tag{1.2}$$

where h is Planck's constant. Planck's hypothesis did not require that the energy should be emitted in *localized* bundles and it could, with difficulty, be reconciled with the electromagnetic wave theory. When Einstein showed, however, that it seemed necessary to assume