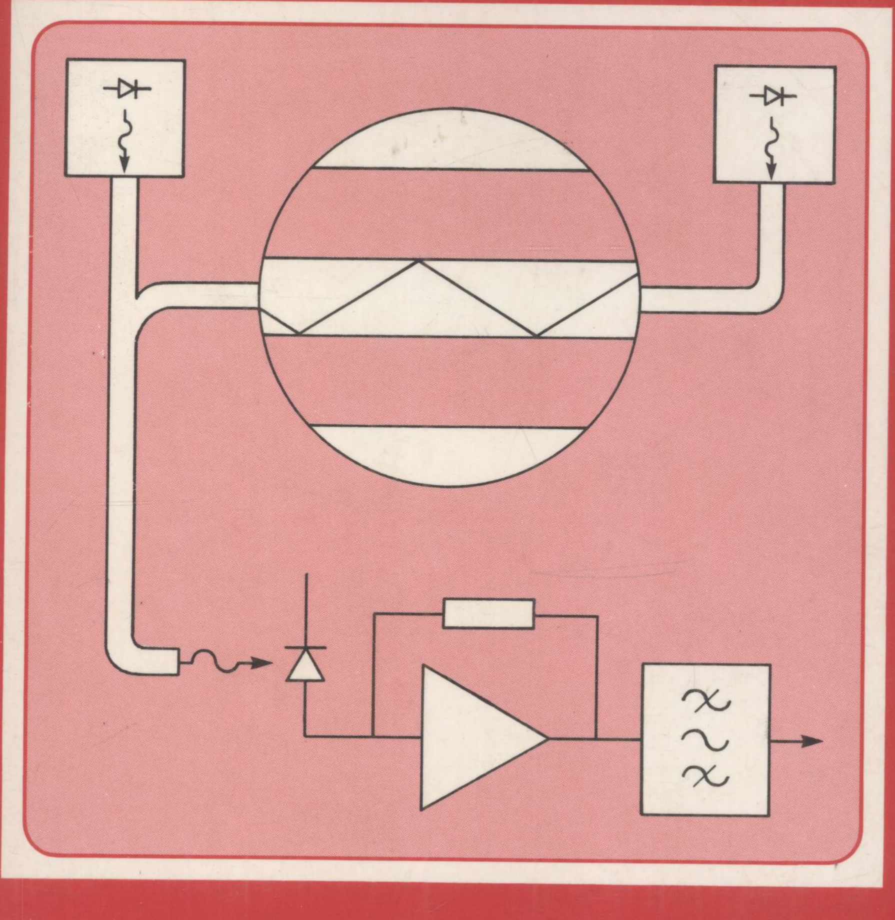
OPTICAL COMMUNICATIONS



M. J. N. SIBLEY

MACMILLAN NEW ELECTRONICS
INTRODUCTIONS TO ADVANCED TOPICS

Optical Communications

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Macmillan New Electronics
Introductions to Advanced Topics

MACMILLAN

First published 1990

Published by
MACMILLAN EDUCATION LTD
Houndmills, Basingstoke, Hampshire RG21 2XS
and London
Companies and representatives
throughout the world

Printed in Hong Kong

Typeset by TecSet Ltd, Wallington, Surrey.

British Library Cataloguing in Publication Data
Sibley, M. J. N.
Optical communications.
1. Optical communication systems
I. Title
621.38′0414

ISBN 0–333–47512–7
ISBN 0–333–47513–5 pbk

Optical Communications

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Series Editor's Foreword

The rapid development of electronics and its engineering applications ensures that new topics are always competing for a place in university and polytechnic courses. But it is often difficult for lecturers to find suitable books for recommendation to students, particularly when a topic is covered by a short lecture module, or as an 'option'.

Macmillan New Electronics offers introductions to advanced topics. The level is generally that of second and subsequent years of undergraduate courses in electronic and electrical engineering, computer science and physics. Some of the authors will paint with a broad brush; others will concentrate on a narrower topic, and cover it in greater detail. But in all cases the titles in the Series will provide a sound basis for further reading of the specialist literature, and an up-to-date appreciation of practical applications and likely trends.

The level, scope and approach of the Series should also appeal to practising engineers and scientists encountering an area of electronics for the first time, or needing a rapid and authoritative update.

Paul A. Lynn

Preface

Since the mid 1970s, the field of optical communications has advanced considerably. Optical fibre attenuations have been reduced from over 1000 dB/km to below 0.5 dB/km, and light sources are now available that can launch several milli-watts of power into a fibre. Optical links are now to be found in short-haul industrial routes, as well as in long-haul telecommunications routes. In order to design and maintain these links, it is important to understand the operation of the individual system components, and it is my hope that this book will provide the relevant information.

I have tried to aim the level of this text so that it is suitable for students on the final year of undergraduate courses in Electrical and Electronic Engineering, and Physics, as well as for practising engineers requiring a knowledge of optical communications. The text should also serve as an introduction for students studying the topic at a higher level. The work presented here assumes that the reader is familiar with Maxwell's equations, and certain aspects of communications theory. Such information can be readily found in relevant textbooks.

The information presented has come from a wide variety of sources — many of which appear in the Bibliography at the end of the book. In order to keep the list of references down to manageable proportions, I have only selected certain key papers and books. In order to obtain further information, the interested reader should examine the references that these works themselves give. Most of the journals the papers appear in will be available from any well-equipped library; otherwise they can be obtained through an inter-library loan service. Because of the length of this book, the information obtained from these sources has been heavily condensed. In view of this, I regret any errors or omissions that may have arisen, and hope that they will not detract from this text.

I wish to acknowledge the assistance of Mr K. Fullard of the Joint European Torus project at Culham, England, for supplying the information about the optical LAN that appears in chapter 7. I also wish to thank the publisher, Mr M. J. Stewart of Macmillan Education for his guidance, and the Series Editor, Dr Paul A. Lynn, for his valuable comments on the text. During the compilation of this text, many of my colleagues at the Department of Electrical and Electronic Engineering, The Polytechnic of Huddersfield were party to several interesting discussions. In particular, I wish to acknowledge the help of Dr R. T. Unwin, who read the draft manuscript, offered constructive criticism, and showed a great deal of patience throughout the preparation of this book.

Finally, I would like to thank my family and friends for their continued support and encouragement.

List of Symbols

α	attenuation constant/absorption coefficient
α_e	electron ionisation coefficient
α_h	hole ionisation coefficient
$\boldsymbol{a}_x$, $\boldsymbol{a}_y$	unit vectors
A_0	total preamplifier voltage gain
$A(\omega)$	total voltage gain of receiver system
β	phase constant
B	bit-rate in digital or bandwidth in analogue systems
B_{eq}	noise equivalent bandwidth
c	velocity of light in a vacuum (3×10^8 m s^{-1})
C_π	base emitter capacitance
C_c	collector base capacitance
C_d	total diode capacitance
C_f	feedback resistance parasitic capacitance
C_{gd}	gate drain capacitance
C_{gs}	gate source capacitance
C_{in}	input capacitance of following amplifier
C_j	junction capacitance
C_s	stray input capacitance
C_T	total receiver input capacitance
δ_n	refractive index change
δE_c	conduction band step
δE_v	valence band step
ϵ_0	permittivity of free-space (8.854×10^{-12} F/m)
ϵ_r	relative permittivity
D_{mat}	material dispersion coefficient
D_{wg}	waveguide dispersion coefficient
E_g	band-gap difference
$F(M)$	excess noise factor
γ	propagation coefficient
g	gain per unit length
g_m	transconductance
h	Planck's constant (6.624×10^{-34} J s)
$h_f(t)$	pre-detection filter impulse response
$h_{out}(t)$	output pulse shape

$h_p(t)$	input pulse shape
$H_{eq}(\omega)$	equalising network transfer function
$H_f(\omega)$	pre-detection filter transfer function
$H_{out}(\omega)$	Fourier transform (FT) of output pulse
$H_p(\omega)$	FT of received pulse
$H_T(\omega)$	normalised transimpedance
$<i_n^2>_0$	mean square (m.s.) noise current for logic 0 signal
$<i_n^2>_1$	m.s. noise current for logic 1 signal
$<i_n^2>_c$	m.s. equivalent input noise current of preamplifier
$<i_n^2>_{DB}$	m.s. photodiode bulk leakage noise current
$<i_n^2>_{DS}$	m.s. photodiode surface leakage noise current
$<i_n^2>_{pd}$	m.s. photodiode noise current
$<i_n^2>_Q$	quantum noise
$<i_n^2>_T$	total signal-independent m.s. noise current
$<i_s^2>$	m.s. photodiode signal current
$i_s(t)$	photodiode signal current
I_2, I_3	bandwidth type integrals
I_b	base current
I_c	collector current
I_d	total dark current
I_{diode}	total diode current
I_g	gate leakage current
I_m	multiplied diode current
I_{max}	maximum signal diode current
I_{min}	minimum signal diode current
I_s	signal-dependent, unmultiplied photodiode current
$<I_s>$	average signal current
$<I_s>_0$	average signal current for a logic 0
$<I_s>_1$	average signal current for a logic 1
I_{th}	threshold current
I_{DB}	photodiode bulk leakage
I_{DS}	photodiode surface leakage current
ISI	inter-symbol interference
J	current density
J_{th}	threshold current density
k	Boltzmann's constant (1.38×10^{-23} J/K)
λ	wavelength
L_n	diffusion length in p-type
m	modulation depth
M	multiplication factor
M_{opt}	optimum avalanche gain

η	quantum efficiency
n	refractive index
$\langle n^2 \rangle_{\mathrm{T}}$	total m.s. output noise voltage
μ_0	permeability of free-space ($4\pi \times 10^{-7}$ H/m)
μ_{r}	relative permeability
N	mode number (integer)
N_{D}	donor atom doping level
N_{g}	group refractive index
N_{max}	maximum number of modes
NA	numerical aperture
P	average received power
P_{e}	total probability of error
q	electron charge (1.6×10^{-19} C)
r_{π}	base emitter resistance
$r_{\mathrm{bb'}}$	base-spreading resistance
r_{e}	reflection coefficient
R_1, R_2	reflectivity in resonator
R_{b}	photodiode load resistor
R_{f}	feedback resistor
R_{in}	preamplifier input resistance
R_{j}	photodiode shunt resistance
R_{L}	load resistor
R_0	photodiode responsivity
R_{s}	photodiode series resistance
R_{T}	low frequency transimpedance
σ	r.m.s. width of Gaussian distribution (line-width, etc.)
σ_{mat}	material dispersion per unit length
σ_{mod}	modal dispersion per unit length
σ_{off}	r.m.s. output noise voltage for logic 0
σ_{on}	r.m.s. output noise voltage for logic 1
σ_{wg}	waveguide dispersion per unit length
S	surface recombination velocity
$\mathbf{S}$	instantaneous power flow (Poynting vector)
$\mathbf{S}_{\mathrm{av}}$	average power flow
S_{E}	series noise generator (V^2/Hz)
$S_{\mathrm{eq}}(f)$	equivalent input noise current spectral density (A^2/Hz)
S_{I}	shunt noise generator (A^2/Hz)
S/N	signal-to-noise ratio
τ	time constant
τ_{nr}	non-radiative recombination time
τ_{r}	radiative recombination time
t_{e}	transmission coefficient
T	absolute temperature (Kelvin)
v_{g}	group velocity

v_{max}	maximum output signal voltage
v_{min}	minimum output signal voltage
v_p	phase velocity
V	normalised frequency in a waveguide
V_{br}	reverse breakdown voltage
V_s	output signal voltage
V_T	threshold voltage
y	normalised frequency variable
Z	impedance of dielectric to TEM waves
Z_0	impedance of free space
$Z_0(s)$	open loop transimpedance
$Z_c(s)$	closed loop transimpedance
$Z_f(s)$	feedback network transimpedance
Z_{in}	total input impedance
$Z_T(\omega)$	transimpedance

Contents

1 Introduction

Although the subject of this book is optical communications, the field encompasses many different aspects of electronic engineering: electromagnetic theory, semiconductor physics, communications theory, signal processing, and electronic design. In a book of this length, we could not hope to cover every one of these different fields in detail. Instead, we will deal with some aspects in-depth, and cover others by more general discussion. Before we start our studies, let us see how modern-day optical communications came about.

1.1 Historical background

The use of light as a means of communication is not a new idea; many civilisations used sunlight reflected off mirrors to send messages, and communication between warships at sea was achieved using Aldis lamps. Unfortunately, these early systems operated at very low data-rates, and failed to exploit the very large bandwidth of optical communications links.

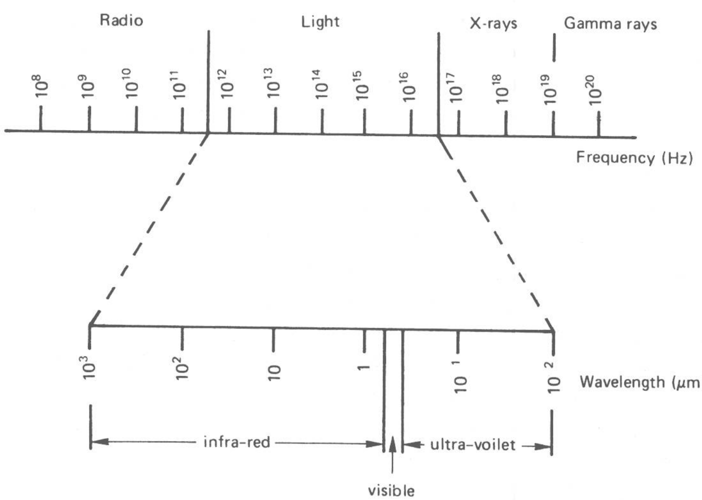

Figure 1.1 The electromagnetic spectrum

A glance at the electromagnetic spectrum shown in figure 1.1 reveals that visible light extends from 0.4 to 0.7 μm which converts to a bandwidth of 320 THz (1 THz = 10^{12} Hz). Even if only 1 per cent of this capability were available, it would still allow for 80 billion, 4 kHz voice channels! (If we could transmit these channels by radio, they would occupy the whole of the spectrum from d.c. right up to the far infra-red. As well as not allowing for any radio or television broadcasts, the propagation characteristics of the transmission scheme would vary tremendously.) The early optical systems used incandescent white light sources, the output of which was interrupted by a hand-operated shutter. Apart from the obvious disadvantage of a low transmission speed, a white light source transmits all the visible, and some invisible, wavelengths at once. If we draw a parallel with radio systems, this is equivalent to a radio transmitter broadcasting a single programme over the whole of the radio spectrum — very inefficient! Clearly, the optical equivalent of an oscillator was needed before light-wave communications could develop.

A breakthrough occurred in 1960, with the invention of the ruby laser by T. H. Maimon [1], working at Hughes Laboratories, USA. For the first time, an intense, coherent light source operating at just one wavelength was made available. It was this development that started a flurry of research activity into optical communications.

Early experiments were carried out with line-of-sight links; however, it soon became apparent that some form of optical waveguide was required. This was because too many things can interfere with light-wave propagation in the atomosphere: fog, rain, clouds, and even the occasional flock of pigeons.

Hollow metallic waveguides were initially considered but, because of their impracticality, they were soon ruled out. By 1963, bundles of several hundred glass fibres were already being used for small-scale illumination. However, these early fibres had very high attenuations (>1000 dB/km) and so their use as a transmission medium for optical communications was not considered.

It was in 1966 that C. K. Kao and G. A. Hockman [2] (working at the Standard Telecommunications Laboratories, UK) postulated the use of glass fibres as optical communications waveguides. Because of the high attenuation of the glass, the idea was initially treated with some scepticism; in order to compete with existing co-axial cable transmission lines, the glass fibre attenuation had to be reduced to less than 20 dB/km. However, Kao and Hockman studied the loss mechanisms and, in 1970, workers at the Corning glass works, USA, produced a fibre with the required attenuation. This development led to the first laboratory demonstrations of optical communications with glass fibre, in the early 1970s. A study of the spectral response of glass fibres showed the presence of low-loss transmission windows at 850 nm, 1.3 μm, and 1.55 μm. Although the early optical links