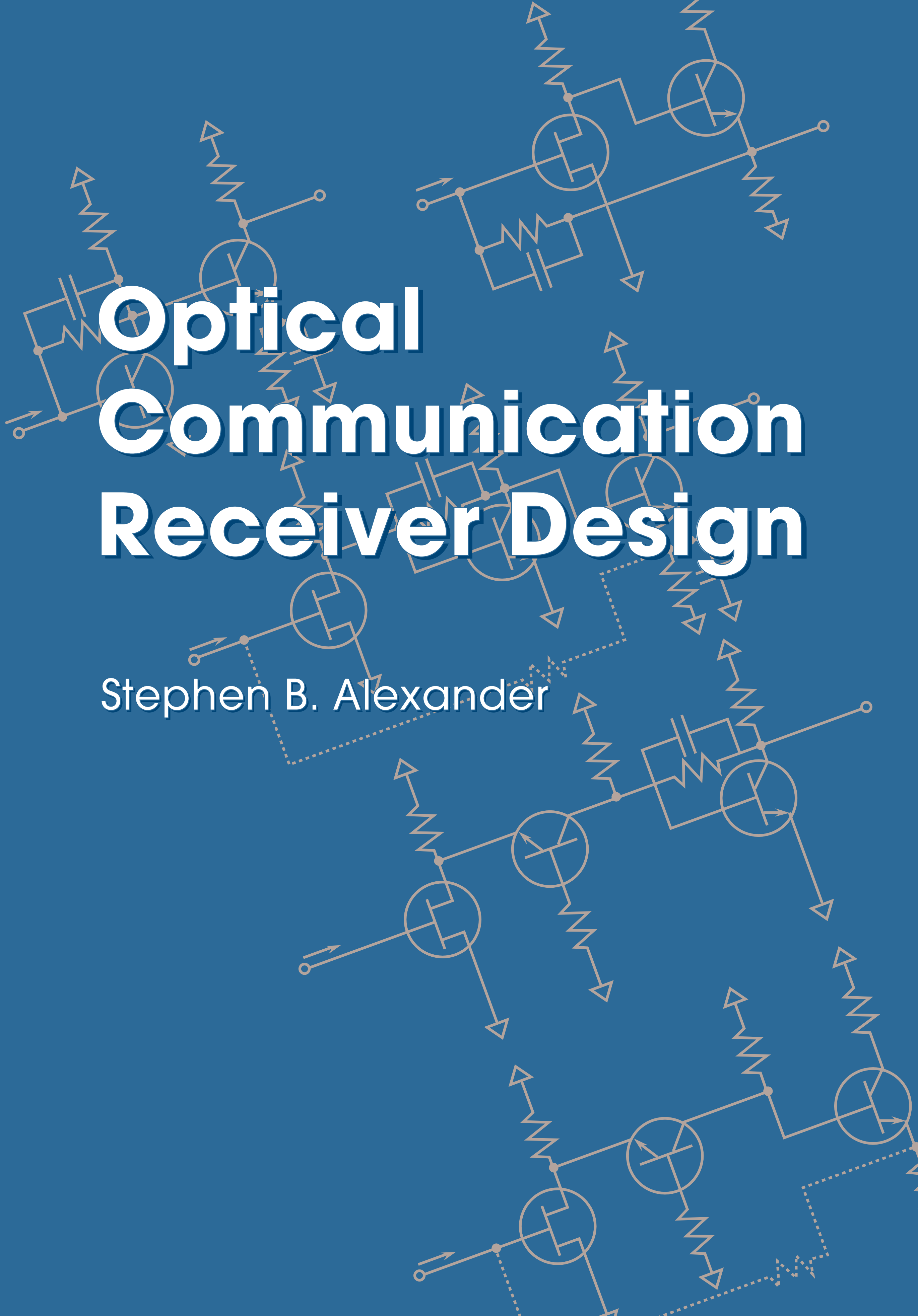
Optical Communication Receiver Design

Stephen B. Alexander



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Contents

Preface

We are surrounded by an ongoing revolution in optical communication. Fiber-optic networks carrying gigabits per second span oceans and continents, and devices such as optical amplifiers, which were once regarded only as laboratory curiosities, are now commonplace. The vast capacity of optical communication systems has enabled the development of information infrastructures of both national and global extent. Optical communication techniques are not restricted to fiber-optics. Free-space optical communication offers the possibility of high-data-rate links among satellites and the Earth, allowing even greater flexibility in terms of network connectivity and access.

This text provides an overview of the design principles for receivers used in optical communication systems. The technology and techniques that are discussed are similar to those used in conventional microwave communication receivers; however, there are also significant differences because of the unique characteristics of the photodetection process. The text grew out of the notes for a short course in receiver design. The level of the material is targeted at the practicing engineer and the text contains some 500 references to provide a reader with pointers to the wide variety of work that is available in the open literature.

The material is organized into seven chapters, with Chapter 1 providing a brief review of the technologies used to construct optical communication links. Following the technology introduction, Chapter 2 illustrates the flow of system performance specifications into receiver requirements and is illustrated by the use of system link and receiver sensitivity budgets. Chapter 3 introduces the fundamentals of photodetection and the associated statistics. Semi-classical techniques are used, with appropriate references to quantum mechanical considerations as needed. The signal-to-noise ratio for both direct and coherent detection receivers is derived and the concept of a shot-noise-limited receiver is introduced. The characteristics and performance of photodetectors are reviewed in Chapter 4. The *p-i-n*, avalanche photodiode, and metal-semiconductor-metal photodetectors are covered in detail and a series of equivalent circuit models are developed so that the impact of device characteristics on achievable receiver performance can be determined.

The circuit analysis techniques used with electrical noise are omitted in many engineering curricula, and Chapter 5 provides a quick tutorial on the general subject of noise analysis and also serves to describe the specific analysis techniques needed to model optical receivers. In particular, we illustrate the concept of an equivalent input current-noise model for the receiver. Chapter 6 reviews the design of the receiver front end, covering the resistor terminated voltage amplifier, high-impedance amplifier, and transimpedance amplifier. Chapter 7 concludes the text with examples of receiver performance analysis. Direct detection, coherent detection, and optically preamplified receivers are discussed, as well as analog systems. Particular attention is given to the detection statistics associated with the various photodetectors and receiver structures.

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Acknowledgments

A tutorial text of this kind is clearly not the result of the efforts of a single individual. We are all indebted to the pioneers in this field. The works of Personick, Smith, Goell, Hullett, and Muoi form the foundation for much of what is contained in this text.

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Glossary

Symbols

α	absorption length of a material - usually in cm^{-1}
α_{dB}	attenuation constant of fiber - usually in dB/km
ε_o	permittivity of vacuum (8.85×10^{-12} F/m)
ε_r	relative permittivity
$\gamma(\omega)$	complex correlation coefficient
η	quantum efficiency
η_{AC}	AC quantum efficiency
η_{DC}	DC quantum efficiency
λ	wavelength
$\lambda(t)$	photon rate parameter - photons per second as a function of time
τ	transit-time
τ_a	transit-time for electrons in the absorbing region
τ_h	transit-time for holes
A	area
$A_v(\omega)$	voltage gain transfer function
B	bandwidth (Hz)
c	speed of light in a vacuum (3×10^8 m/s)
C_d	detector capacitance
C_j	junction capacitance

C_b	bonding-pad capacitance
C_p	package capacitance
C_t	total capacitance
E	energy (J)
$E(t)$	electric field
E_b	energy per bit
f	electrical frequency (Hz)
f_a	amplifier bandwidth
F	noise factor
$F(M)$	excess noise factor for multiplication gain
$F(\omega)$	noise figure (or factor) as a function of frequency
G_a	antenna (or aperture) gain
h	Planck's constant (6.626×10^{-34} J/s)
$\bar{i}$	time averaged DC photocurrent
i_{du}	unmultiplied dark current
i_{dm}	multiplied dark current
i_{dark} i_{dk}	dark current
i_{elec}	current-noise density of receiver electronics-noise
i_n or $i_n(\omega)$	current-noise density
$i_{n\text{-}d}$	dark current noise
$i_{n_{eq}}$ or $i_{n_{eq}}(\omega)$	equivalent input current-noise density $i_{n_{eq}}^2 = i_{shot}^2 + i_{rcvr}^2$
i_{rcvr}	current-noise density of receiver excluding signal shot-noise
$i_s(\omega)$ or $i_s(t)$	input signal current as a function of frequency or time
i_{shot}	current-noise density from photocurrent shot-noise
I_1, I_2, I_3, I_f	normalized noise bandwidth integrals
I_n	total current-noise
$I_{n_{eq}}$	total equivalent input current-noise
I_{shot}	total current-noise from shot-noise
I_a	length of absorbing region
L_b	bond-wire inductance

l_d	length of depletion region
L_{max}	maximum length
$L_N\{x\}$	Laguerre polynomial
L_p	loss during propagation
L_T	total loss
M	multiplication gain
M_e	multiplication gain for electrons
M_h	multiplication gain for holes
v	optical frequency (Hz)
n	number of photons, index of refraction
$n(f)$	noise spectral density
n_b	number of background photons
n_p	number of photons per bit
n_s	number of signal photons
N	total noise
N_o	noise density (W/Hz)
P	power (W)
P_{in}	input power
P_{rcvd}	received optical power
P_{sig} P_s	detected signal power
P_{noise} P_n	noise power
P_{out}	output power
$P(x)$	probability of occurring
$P(x\|y)$	probability of occurring given that has occurred
r	photon arrival rate in photons per second
R	responsivity, reflectivity, resistance, data rate
R_j	junction resistance
R_l	load resistance
R_s	series resistance or source resistance
RC	resistor-capacitor

V_n	total current-noise
v_n or $v_n(\omega)$	voltage-noise density
$v_o(\omega)$ or $v_o(t)$	output voltage as a function of frequency or time
v_s	saturation velocity
v_e	velocity of an electron
v_h	velocity of a hole
ω	electrical frequency (rad/s)
ω_c	cutoff frequency (usually 3-dB point)
ω_p	frequency of a pole
ω_z	frequency of a zero
X_s	source reactance
$Y_c(\omega)$	correlation admittance
$Y_s(\omega)$	source admittance
z	propagation distance
$Z_{in}(\omega)$	input impedance
Z_o	characteristic impedance
Z_t or $Z_t(\omega)$	transimpedance gain

Abbreviations

AGC	automatic gain control
AFC	automatic frequency control
APD	avalanche photodiode
ASE	amplified spontaneous emission
ASE × ASE	ASE-cross-ASE noise
ASK	amplitude shift keying
AWGN	additive white Gaussian noise
BER	bit-error rate
BLIP	background limited IR photodetection
BJT	bipolar junction transistor
CB	common base
CC	common collector

CCD	charge-coupled device
CE	common emitter
CNR	carrier-to-noise ratio
CNDR	carrier-to-noise density ratio
CPFSK	continuous-phase FSK
CSO	composite second order
CTB	composite triple beat
CW	continuous wave
dBc	decibels relative to the carrier power
dBi	decibels relative to an isotropic radiator
dBm	decibels relative to 1.0 mW
DBR	distributed Bragg reflector
dBW	decibels relative to 1.0 W
DFB	distributed feedback
DPSK	differential phase shift keying
EDFA	erbium-doped fiber amplifier
FET	field-effect transistor
fF	femto-Farads
FM	frequency modulation
FP	Fabry-Perot
FSK	frequency shift keying
GBW	gain bandwidth
GEO	geosynchronous-Earth orbit
G-R	generation-recombination
HBT	heterojunction bipolar transistor
HEMT	high-electron-mobility transistor
HEO	high-Earth orbit
HFET	heterojunction FET
IF	intermediate frequency
ISI	intersymbol interference
JFET	junction FET
lasercom	laser communication
LED	light-emitting diode

LEO	low-Earth orbit
LO	local oscillator
MAP	maximum a posteriori
MESFET	metal-semiconductor FET
ML	maximum likelihood
MOPA	master-oscillator power-amplifier
MOSFET	metal-oxide-semiconductor FET
MMIC	monolithic microwave integrated circuit
MSM	metal-semiconductor-metal
NEB	noise equivalent bandwidth
NF	noise figure
NRZ	nonreturn to zero
OEIC	optoelectronic integrated circuit
OOK	on-off keying
PDFA	praseodymium doped fiber amplifier
pF	pico-Farads
PLL	phase-locked loop
PM	polarization maintaining
PMD	polarization mode dispersion
PMT	photomultiplier tube
PPM	pulse position modulation
PSD	power spectral density
PSK	phase shift keying
QE	quantum efficiency
QOS	quality of service
QPSK	quadrature phase shift keying
RIN	relative intensity noise
RAPD	reach-through APD
RC	resistance-capacitance
RF	radio frequency
RMS	root mean square
RZ	return to zero
S × ASE	signal-cross-ASE noise

SAM	separate absorption and multiplication
SAGM	separate absorption and grading multiplication
SAW	surface acoustic wave
SLA	semiconductor laser amplifier
SL-APD	superlattice APD
SMSR	side-mode suppression ratio
SNR	signal-to-noise ratio
SNDR	signal-to-noise density ratio
TDRSS	Tracking and Data Relay Satellite System
TE	transverse electric
TM	transverse magnetic
WDM	wavelength-division multiplexing