

The background of the cover is a dark blue color. It is filled with a complex, light-colored circuit diagram. The diagram consists of various electronic components such as resistors (zigzag lines), capacitors (two parallel lines), inductors (coiled lines), and transistors (circles with arrows). These components are interconnected by a network of lines, some of which are solid and others dashed, creating a dense and intricate pattern that suggests a sophisticated electronic design.

Optical Communication Receiver Design

Stephen B. Alexander

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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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Glossary

Symbols

| | |
|------------------|--|
| α | absorption length of a material - usually in cm^{-1} |
| α_{dB} | attenuation constant of fiber - usually in dB/km |
| ϵ_0 | 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-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 |
| ν | 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_r or $Z_t(\omega)$ | transimpedance gain |

Abbreviations

| | |
|------------------|--------------------------------------|
| AGC | automatic gain control |
| AFC | automatic frequency control |
| APD | avalanche photodiode |
| ASE | amplified spontaneous emission |
| ASE \times 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 |
| $S \times ASE$ | 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 |