Figure 1.12: Components of an optical receiver.
PHOTODIODES

• PIN
• APD
I_p = R P_{in}, R = responsivity (A/W)
[square-law detector]
\eta = \text{electrons out/photons in}
= (I_p/q)/(P_{in}/h\nu) = (h\nu/q)R
R = \eta q/h\nu = \eta\lambda/1.24
1.24 = hc/q (\mu m/V)

\\Delta f = \left[2\pi(\tau_{tr} + \tau_{RC})\right]^{-1},
T_{tr} = \text{transit time} \sim W/v_d \sim 100 \text{ ps},
\tau_{RC} = \text{ckt response}

\textbf{Figure 4.1: A semiconductor slab used as a photodetector.}
Figure 4.2: Wavelength dependence of the absorption coefficient for several semiconductor materials. (After Ref. [2]; ©1979 Academic Press; reprinted with permission.)
Figure 4.3: (a) A $p$–$n$ photodiode under reverse bias; (b) variation of optical power inside the photodiode; (c) energy-band diagram showing carrier movement through drift and diffusion.
4.2 COMMON PHOTODETECTORS

Intrinsic, hi res Also DH structure (also waveguided)

\[ \eta \sim 1, \]
\[ W \sim 5\mu m \]

Figure 4.5: (a) A $p-i-n$ photodiode together with the electric-field distribution under reverse bias; (b) design of an InGaAs $p-i-n$ photodiode.
Figure 4.12: Equivalent circuit for (a) high-impedance and (b) transimpedance front ends in optical receivers. The photodiode is modeled as a current source in both cases.
# Table 4.1 Characteristics of common $p$–$i$–$n$ photodiodes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Si</th>
<th>Ge</th>
<th>InGaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>$\lambda$</td>
<td>$\mu$m</td>
<td>0.4–1.1</td>
<td>0.8–1.8</td>
<td>1.0–1.7</td>
</tr>
<tr>
<td>Responsivity</td>
<td>$R$</td>
<td>A/W</td>
<td>0.4–0.6</td>
<td>0.5–0.7</td>
<td>0.6–0.9</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>$\eta$</td>
<td>%</td>
<td>75–90</td>
<td>50–55</td>
<td>60–70</td>
</tr>
<tr>
<td>Dark current</td>
<td>$I_d$</td>
<td>nA</td>
<td>1–10</td>
<td>50–500</td>
<td>1–20</td>
</tr>
<tr>
<td>Rise time</td>
<td>$T_r$</td>
<td>ns</td>
<td>0.5–1</td>
<td>0.1–0.5</td>
<td>0.02–0.5</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>$\Delta f$</td>
<td>GHz</td>
<td>0.3–0.6</td>
<td>0.5–3</td>
<td>1–10</td>
</tr>
<tr>
<td>Bias voltage</td>
<td>$V_b$</td>
<td>V</td>
<td>50–100</td>
<td>6–10</td>
<td>5–6</td>
</tr>
</tbody>
</table>
Figure 4.7: Impact-ionization coefficients of several semiconductors as a function of the electric field for electrons (solid line) and holes (dashed line). (After Ref. [24]; ©1977 Elsevier, reprinted with permission.)
Figure 4.8: (a) An APD together with the electric-field distribution inside various layers under reverse bias; (b) design of a silicon reach-through APD.
### Table 4.2 Characteristics of common APDs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Si</th>
<th>Ge</th>
<th>InGaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>$\lambda$</td>
<td>$\mu$m</td>
<td>0.4–1.1</td>
<td>0.8–1.8</td>
<td>1.0–1.7</td>
</tr>
<tr>
<td>Responsivity</td>
<td>$R_{APD}$</td>
<td>A/W</td>
<td>80–130</td>
<td>3–30</td>
<td>5–20</td>
</tr>
<tr>
<td>APD gain</td>
<td>$M$</td>
<td>—</td>
<td>100–500</td>
<td>50–200</td>
<td>10–40</td>
</tr>
<tr>
<td>$k$-factor</td>
<td>$k_A$</td>
<td>—</td>
<td>0.02–0.05</td>
<td>0.7–1.0</td>
<td>0.5–0.7</td>
</tr>
<tr>
<td>Dark current</td>
<td>$I_d$</td>
<td>nA</td>
<td>0.1–1</td>
<td>50–500</td>
<td>1–5</td>
</tr>
<tr>
<td>Rise time</td>
<td>$T_r$</td>
<td>ns</td>
<td>0.1–2</td>
<td>0.5–0.8</td>
<td>0.1–0.5</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>$\Delta f$</td>
<td>GHz</td>
<td>0.2–1</td>
<td>0.4–0.7</td>
<td>1–10</td>
</tr>
<tr>
<td>Bias voltage</td>
<td>$V_b$</td>
<td>V</td>
<td>200–250</td>
<td>20–40</td>
<td>20–30</td>
</tr>
</tbody>
</table>
RECEIVER NOISE

• Shot noise
• Thermal noise
Figure 4.13: Ideal and degraded eye patterns for the NRZ format.
Example of Typical Link Experiment

Eye diagram

-35 -30 -25 -20
1E-3 1E-4 1E-5 1E-6 1E-7 1E-8 1E-9
Bit Error Ratio
Received Optical Power (dBm)

Some distance of fiber
Back to back
SHOT NOISE

• $I(t) = I_p + i_s(t)$

• *White noise*

• $\sigma_s^2 = \langle i_s^2(t) \rangle = 2qI_p\Delta f$

• $I_p \to I_p + I_d$
Figure 10-4 Random electron flow between two electrodes. This basic configuration is used in the derivation of shot noise.
THERMAL NOISE

• $I(t) = I_p + I_s(t) + I_{T}(t)$

• $\sigma_T^2 = \langle i_T^2(t) \rangle = \left( 4k_B T / R_L \right) \Delta f$

• White noise

• $\sigma_T^2 = (4k_B T / R_L) F_n \Delta f$

• $F_n = (S/N)_{in} / (S/N)_{out} = \text{Amplifier noise figure}$
4.3. RECEIVER DESIGN

Figure 4.11: Diagram of a digital optical receiver showing various components. Vertical dashed lines group receiver components into three sections.
SIGNAL TO NOISE RATIO

• SNR = avg signal pwr/noise pwr
  \[ = \frac{I_p^2}{\sigma^2} \]

• \( I_p = R_p P_{\text{in}} \), \( R_p = \eta q/h \nu \)

• \( \sigma^2 = \sigma_s^2 + \sigma_T^2 \), \( \sigma_T^2 \gg \sigma_s^2 \) in practice

• \( (\text{SNR})_T = R_L R_p^2 P_{\text{in}}^2 / 4k_B T F_n \Delta f \)

• \( \text{NEP} = P_{\text{in}} / (\Delta f)^{1/2} = \left( 4k_B T F_n / R_L R_p^2 \right)^{1/2}, \quad \text{SNR} = 1 \)

• \( (\text{SNR})_s = R_p P_{\text{in}} / 2q \Delta f \)
Figure 10-2 The intermingling of noise power with that of a signal causes the total power to fluctuate. The rms fluctuation $\Delta P$ limits the accuracy of power measurements.
1.3. Electrical Signals

Figure 1.9: (a) Transmitted digital signal, (b) distorted and noisy electrical signal at the receiver, and (c) reconstructed digital signal. The thin solid line in the middle shows the decision level.
Figure 10-19 An ideal noiseless pulse train (a) is contaminated by noise as in (b). A reconstruction using a threshold decision level $k_iS$ leads to (c). Note that the reconstruction of the last "1" pulse is in error because of a large negative noise fluctuation.
Figure 4.18: (a) Fluctuating signal generated at the receiver. (b) Gaussian probability densities for 1 and 0 bits. The dashed region shows the probability of incorrect identification.
BIT ERROR RATE

• BER = \( \frac{1}{2} \left[ P(0/1) + P(0/1) \right] \)

• \( \text{min BER for} \)
  \[
  \frac{(I_D - I_0)}{\sigma_0} = \frac{(I_1 - I_D)}{\sigma_1} = Q
  \]

• \( I_D = \frac{(\sigma_0 I_1 + \sigma_1 I_0)}{(\sigma_0 + \sigma_1)} \)

• \( Q = \frac{(I_1 - I_0)}{(\sigma_1 + \sigma_0)} \)
Figure 4.19: Bit-error rate versus the $Q$ parameter.
Figure 10-20 Plot of Equation (10.9-4) for the error probability (BER) as a function of the (peak) signal to noise current ratio at the detector output.
Transmission Performance

• Bit Error Rate (BER) vs. Min. Ave. Received Power

\[ BER = \frac{1}{2} \text{erfc}\left(\frac{Q}{\sqrt{2}}\right) \]

\[ Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} = \text{Optical SNR} \]

\[ SNR = \frac{P_1 - P_0}{\sigma_1^2 + \sigma_0^2} \approx 2Q^2 \]

\[ BER \approx \frac{e^{-\left(\frac{Q^2}{2}\right)}}{Q\sqrt{2\pi}} \]

Q=6 \rightarrow BER=1e-9; Q=7 \rightarrow BER=1e-12
MINIMUM REC’D PWR

\( (P_{\text{rec}})_{\text{pin}} \sim Q \sigma_T / R \)

\( \sigma_T^2 = (4k_B T / R_L) \Delta f \)

\( \Delta f \sim B / 2 \)

\( Q \sim 6 \) for \( 10^{-9} \) BER

\( P_{\text{rec}} \sim 0.6 \mu W \) or \(-32.2 \) dBm for 

\( \lambda = 1550 \text{nm}, R = 1 \text{ A/W}, \)

\( \sigma_T \sim 100 \text{nA}, B \sim 10 \text{ Gb/s} \)
QUANTUM LIMIT

• quantum limit is $<N_p> = 10$ photons/bit, with $\sigma_0 = 0$ and BER $< 10^{-9}$

• $P_{rec} = <N_p> \ h \nu B$
  \[ = 13 \text{ nW or } -48.9 \text{ dBm at } B = 10 \text{ Gb/s} \]

• In practice, $P_{rec}$ is 20 dB larger, corresponding to 1000 photons/bit
POWER PENALTY

• Increases $P_{\text{rec}}$
• Transmission impairments
  • Chromatic dispersion
  • PMD
  • SPM, XPM
  • FWM
• Receiver impairments
  • Extinction ratio $P_0/P_1$
  • RIN
  • Timing jitter
Power Penalty – Extinction Ratio

\[ I_0 < I_{th} \rightarrow \frac{I_0}{P_0} \sim \text{spont. emission} \]
\[ I_0 \geq I_{th} \rightarrow \frac{I_0}{P_0} > 0 \]

\[ Q = \frac{I_1 - I_0}{\sigma_1 \tau_0} ; \quad I_1 = R P_1 ; \quad I_0 = R P_0 \]

\[ Q = \frac{R P_1 - R P_0}{\sigma_1 \tau_0} = \frac{R P_1 (1-r)}{\sigma_1 \tau_0} \frac{P_{rec}}{(1+r) \frac{P_{rec}}{\sigma_1 \tau_0}} \]

\[ Q = \frac{(1-r) \frac{2 R P_{rec}}{(1+r)}}{(1-r) \frac{2 R P_{rec}}{(1+r)}} \]

\[ \sigma_1 \tau_0 = \sigma_f \]

\[ \overline{P_{rec}}(r) = \frac{(1+r)}{(1-r)} \frac{\sigma_f Q}{2} \]

\[ \text{SNR Penalty} = \delta = 10 \log \left( \frac{\overline{P_{rec}}(r)}{\overline{P_{rec}}(0)} \right) \]

\[ \delta = 10 \log \left( \frac{1+r}{1-r} \right) \]

Fig. 4.10
Figure 4.20: Power penalty versus the extinction ratio $r_{ex}$. 
Figure 4.21: Power penalty versus the intensity noise parameter $\eta$. 
Figure 4.22: Power penalty versus the timing jitter parameter $B\tau_j$. 

-4.6. SENSITIVITY DEGRADATION

173
FIGURE 2.76 Functional diagram of complete direct-detection receiver, including (from left to right) optical preamplifier with pump feedback loop, photoreceiver with photodiode and front-end amplifier, 3-dB signal tap, post-amplifier with equalizer, clock-recovery circuit with RF voltage-controlled oscillator (VCO) and phase-locked loop, clock phase adjust ($\Delta \phi$) and integration/decision circuit.
NRZ & RZ SPECTRAL DENSITY

\[ \text{[1111]}, \quad d = 0.5 \]

\[ \text{T T T T T} \quad T = \frac{1}{B-1} \]
\[ k = \frac{1}{T} = B \]

\[ \text{[1111]}, \quad d = 1.0 \]
\[ f = 0, \quad dc \]

\[ \text{[1010]} \]
\[ f = \frac{1}{2T} = B/2 \]

power density of random bit stream

\[ \delta(b) \]

\[ N \text{RZ} \quad [d = 1] \]

\[ \delta(b) \]

\[ R \text{Z} \quad [d = 0.5] \]
2.3. **Bit-Stream Generation**

![Graphs](image)

**Figure 2.5**: Power spectral density of (a) NRZ bit stream and (b) RZ bit stream with 50% duty cycle. Frequencies are normalized to the bit rate and the discrete part of the spectrum is shown by vertical arrows.
Figure 4.23: Measured receiver sensitivities versus the bit rate for $p-i-n$ (circles) and APD (triangles) receivers in transmission experiments near 1.3- and 1.55-$\mu$m wavelengths. The quantum limit of receiver sensitivity is also shown for comparison (solid lines).
Figure 4.24: BER curves measured for three fiber-link lengths in a 1.55-μm transmission experiment at 10 Gb/s. Inset shows an example of the eye diagram at the receiver. (After Ref. [110]; ©2000 IEEE; reprinted with permission.)
Performance Impairment

- Power penalty is typically due to:
  - Mode partition noise
  - Dispersion
  - Chirp
  - Noise
  - Jitter

Example of a closed eye
Forward Error Correcting Codes in Fiber Optic Systems

Motivation: Increase System Margin
»Increased System Capacity
»Decrease System Cost
»Longer Transmission Distances
»Increased Amplifier spacing
»Lower the optical power: less pump power, less nonlinear impairments
Forward error correction (FEC)

© J.Wiley & Sons, Inc., 2003

© J.Wiley & Sons, Inc., 2003
EXPERIMENTAL PROGRESS IN ERROR CORRECTION

Pioneers: Reed-Solomon, Viterbi,…

Source: C. Chandrasekhar (Lucent)
Block Turbo Code FEC*

Mitsubishi Electric Corporation   T. Mizuochi, et al., OFC2003 PD-21

Q-Factor \sim 6.3 \text{ dB}
ELECTRONIC DISPERSION EQUALIZATION in Enterprise Legacy LAN *(Scintera Networks)*

- Large legacy infrastructure of installed Multimode Fiber
  - Designed for “FDDI” at 300-m distance; supports 1GE
- Modal dispersion limits distance to 75 m at 10-Gb/s data rate
- LX4 uses CWDM: expensive and not commercially viable

Enables Cost-effective 10G over Enterprise Legacy LAN

*Source: A. Shanbhag (Scintera Networks)*
Electronic signal processing can mitigate PMD.

Fig. 1: DFL chip layout.

Moeller, Thiede et al. ECOC 99
the end
\[
\begin{align*}
\bar{i}_s^2 & = 2 \left( \frac{P_e \eta}{h \nu} \right)^2 \\
\bar{i}_{N_1}^2 & = \frac{3e^2(P + P_B) \eta \Delta \nu}{h \nu} + 2e i_d \Delta \nu \\
\bar{i}_{N_2}^2 & = \frac{4kT_e \Delta \nu}{R_L}
\end{align*}
\]

**Figure 11-21** Noise equivalent circuit of a photodiode operating in the direct (video) mode. The modulation index \( m \) is taken as unity, and it is assumed that the modulation frequency is low enough that the junction capacitance and transit-time effects can be neglected. The resistance \( R_L \) is assumed to be much smaller than the shunt resistance \( R_d \) of the diode, so the latter is neglected. Also neglected is the series diode resistance, which is assumed small compared with \( R_L \).