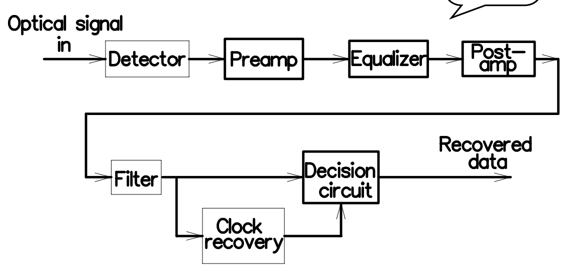
Optical Receivers

Optical Receivers

- ***Optical receiver* components**
  - ***Optical detector*: convert modulated light into electronic signal**
  - ***Preamp*: amplify weak electrical signal**
  - ***Equalizer*: recover bandwidth lost in preamp**
  - ***Postamplifier*: further amplifies signal**
  - ***Filter*: remove unwanted frequency components**
  - ***Clock recovery*: recover clock sent on optical signal**
  - ***Decision circuit*: sample signal and recover data**
- **Receiver design is complicated because…**
  - **Weak optical signal**
  - **Electronic noise present**

Fig. 6.1
p. 198



Noise

- Noise
  - Produces errors in data
  - Introduced by...
    - » Transmitter
    - » Channel
      - Fiber: zero channel noise
    - » Detector
    - » Electronic processing
  - Optical-detector noise different than radio and electronic detectors...
    - » Signal-dependent

Receivers: Preview

- Detectors
  - Physical operating principles of...
    - » Pin photodiode
    - » Avalanche photodiode (APD)
  - Operating parameters
  - Noise performance
  - Operating speed
- Digital receiver design in terms of...
  - Amplifier noise
  - Optimization of signal-to-noise ratio
  - Requirements for equalization amplifier
- Sensitivity of optical receiver is function of...
  - Detector noise and...
  - Preamplifier choice

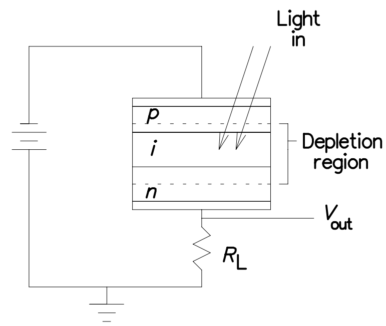
Receivers: Detector

- Converts optical input power to current output
- Photodetector properties
  - Efficiency
  - Noise
  - Spectral response
  - Speed
  - Linearity
  - IC-compatibility
  - Reliability
  - Price
- Semiconductor photodiodes
  - *pin* photodiode
  - Avalanche photodiode (APD)

Photodiodes: Physical Principles

- Reverse-biased *pin* junction

Fig. 6.2
p. 199



- *Depletion region* (no free carriers) around junction
- Portion of light absorbed *in depletion region*
- Hole-electron pair created
- Pair separated and swept out by electric field
- Sensed by outside circuitry
- Number of hole-electron pairs per second freed
  - Linearly dependent on optical power
  - Electric current proportional to optical power

Photodiodes: Spectral Response

- ***Bandgap energy***: energy required to free hole-electron pair

Material	E_g (eV)	λ_{max}(μm)
Si	1.14	1.09
Ge	0.67	1.85
GaAs	1.43	0.867
$In_{0.14}Ga_{0.86}As$	1.15	1.08
$In_{0.53}Ga_{0.47}As$	0.75	1.65

- **Long-λ response: no sensitivity at long λ**
  - **Photon energy**: $hc/\lambda \geq E_g$
  - ***Long wavelength cutoff***

$$\boxed{\lambda_{\text{max}} = hc/E_g} \Rightarrow 1.24/E_g' \,[\text{eV}]$$

» **Si: λ_{max} = 1.09 μm, short-λ (visible, 800-900 nm) detector**

» **InGaAs & Ge: long-λ (1300, 1550 nm) detectors**

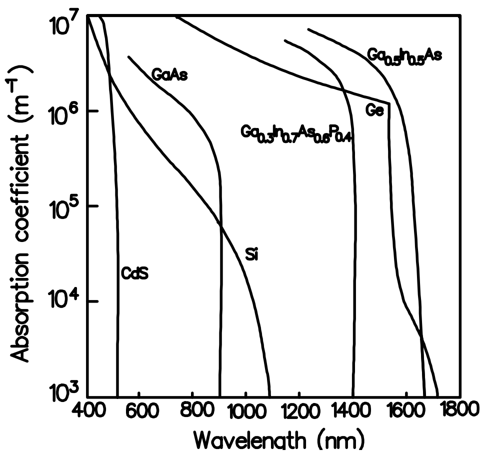
Photodiodes: Spectral Response (cont.)

- Short-λ response
  - No sensitivity at short λ
    - » Light penetration into depletion region...
      - Power absorbed in depletion region...

$$P(w) = P_i e^{-\alpha d}\left(1 - e^{-\alpha w}\right)\left(1 - R_f\right)$$

- Absorption coefficient: α
- Depletion region depth: w
- Region begins at depth: d
- Power reflectivity at detector surface: R_f

Fig. 6.3
p. 201



- Increase *w* with *i* layer of *pin*
- At short wavelengths
  - α rises dramatically
  - Strong surface absorption
  - Little power penetrates

Detectors: Sensitivity

- **Given by responsivity or quantum efficiency*:***
  - ***Responsivity:*** **output current per watt of optical power in**
  - ***Quantum efficiency:*** **number of hole-electron pairs generated per photon**

$$\Re = I_{\text{out}} / P_{\text{in}}$$

$$\eta = Ihc / qP_i\lambda = hc\Re / q\lambda$$

- **Spectral response...**

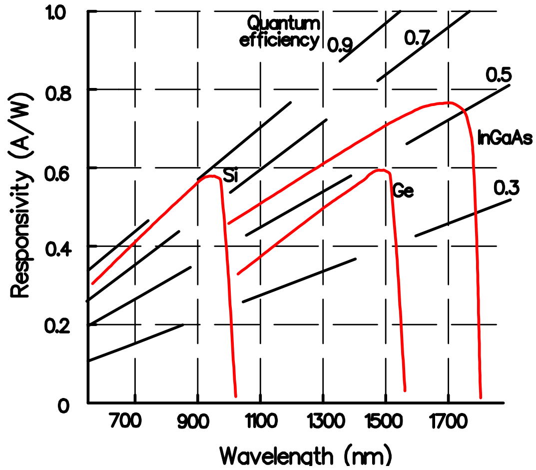


Fig. 6.5
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Detectors: Sensitivity - Probability Approach

- **Basic noise source: quantized nature of light**
- **Weak incident signal, output current <u>not</u> exact replica of ideal current**
  - **Random generation of charge-carrier pairs by photons**
    - » ***Poisson random process***
      - **Total carriers generated in time from *t* to *t+T* is random variable**
      - **Average number of carriers**

$$\bar{N} = (\eta\lambda/hc)\int_t^{t+T} p(t)\,dt = (\eta\lambda/hc)E$$

- **–*E:* total *energy* in interval *T***

- » **Probability that number of charges created, *N*, equals specific number, *n*,**

$$P(N = n) = \bar{N}^n e^{-\eta\lambda E/hc} / n!$$

Detectors: Probability Approach (cont.)

- **Application of Poisson results...**
  - **Want probability < 10^{-9} that "0" detected (*N* = 0) when "1" transmitted; what *E* is needed?**

$$P(N = n = 0) = \bar{N}^n e^{-\eta\lambda E/hc} \big/ n! \leq 10^{-9}$$

$$P(N = 0) = \bar{N}^0 e^{-\eta\lambda E/hc} \big/ 0! = 1 e^{-\eta\lambda E/hc} / 1 \leq 10^{-9}$$

$$E \geq 21 hc \big/ \eta\lambda \quad \text{(i.e., 21 photons)}$$

  - **Require reception of 21 or more photons during bit period when a "1" is transmitted to ensure detection with error probability <10^{-9}**
- **If number of "1"s and "0"s equal and bit period is T_B,**

$$P_{\text{average}} \geq \frac{21hc}{2\eta\lambda T_B} = \frac{21hcB_R}{2\eta\lambda} \qquad (\text{for } P_e \leq 10^{-9})$$

Generalization of BER Results

- For any desired **BER (*bit error rate*)**, need…

$$e^{\left(-\frac{\eta\lambda E}{hc}\right)} \le \text{BER} \qquad \text{or} \qquad E \ge \frac{hc}{\eta\lambda}\ln\left(\frac{1}{\text{BER}}\right)$$

- **Minimum required average *power* is...**

$$P_{\text{average}} = E_{\min}/2T_B = E_{\min}B_R/2$$

- **Theoretical power required to achieve desired BER when limited by light quantization into photons of energy *h*ν**

Avalanche Photodiode: Physical Principles

- Differences from *pin* diodes...
  - Dope *p* and *n* regions higher
  - Narrow *p* region added between *i* and n^+ region (see notes below)
    - » Electric field in this region larger than in depletion region
      - Field accelerates carriers to high velocities
      - Collisions create more hole-electron pairs (*impact ionization*)
- Operating physics
  - Light enters through p^+ region and (ideally) absorbed in *i* region
  - Generated carriers separate and drift across *i* region
  - When electrons enter *p* region, accelerated and impact other atoms, creating more carriers
  - Carriers are accelerated and, in turn, create more carriers (*avalanche effect*)

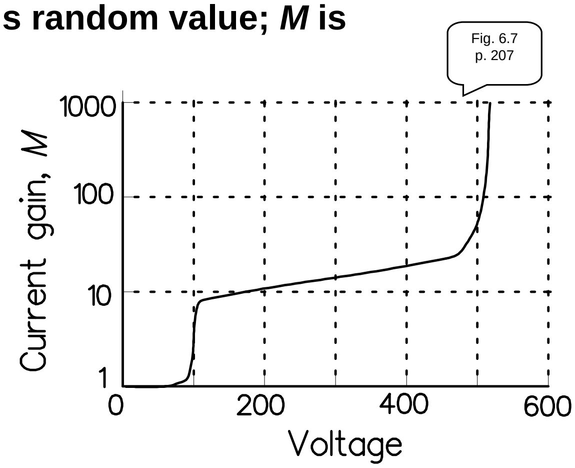
Avalanche Photodiode: Physical Principles(cont.)

- **Avalanche multiplies photocurrent**
  - ***Multiplication factor:*** $M = I_M / I$

    I: **output current <u>without multiplication</u>**
  - **Instantaneous multiplication is random value; *M* is *average* multiplication**
  - **Controlled by reverse bias**
    - » ***M=1*** **expensive pin diode**
- **APD responsivity**

$$\Re_{\mathrm{APD}} = \eta q \lambda M / hc = M \Re_0$$

$\Re_0$ **: responsivity at $M = 1$**



Detectors: Signal-to-Noise Ratio

- Use ***power signal-to-noise ratio***
  - ***"Signal"*** is signal ***power*** delivered to resistor by signal current
  - ***"Noise"*** is noise ***power*** delivered to same resistor
- ***Signal-to-noise ratio*, SNR**

$$\frac{S}{N}=\frac{P_{\text{signal}}}{P_{\text{noise}}}=\frac{\langle i_s^2\rangle R}{\langle i_N^2\rangle R}=\frac{\langle i_s^2\rangle}{\langle i_N^2\rangle}$$

  - **SNR independent of R; need only mean-square signal current and mean-square noise current**
- **Two noise mechanisms with photodiodes...**
  - **Shot noise and...**
  - **Thermal noise**

Detectors: Shot Noise

- Associated with quantization of charge or light
- Mean-square noise current:

$$\left\langle i_N^2 \right\rangle_{\text{shot noise}} = 2qIB \qquad (I = I_L + I_{\text{dark}})$$

  - *I*: dc current of device
  - *B:* electronic bandwidth
- *pin* diode dc current:
  - dc output current due to incident light ($I_L = \Re P$)
  - I_{dark}: *dark current*
    - » dc current with no input illumination (e.g., thermal generation and surface leakage currents)
    - » I_{dark} in long-λ detectors ~10x to 100x silicon short-λ detectors
    - » In APDs...
      - *Amplified* bulk dark current, I_{bulk}
      - *Unamplified* surface currents, $I_{surface}$
        - – Can be made zero with guard-ring design

APDs: *Excess* Shot Noise

- **Avalanche process contributes more noise described**

$$\left\langle i_N^2 \right\rangle_{\text{shot APD}} = 2q\, I\big|_{M=1} M^2 B F(M)$$

  - **–*F(M)*: *excess noise factor***
    - **» Extra noise added by avalanche process**
    - **» *D*epends on…**
      - **Detector material**
      - **Shape of *E* field**
      - **Relative ionization rates**
    - **» Modeled as...**

$$F(M) \approx kM + (1-k)\left(1+\frac{1}{M}\right) \approx M^x$$

Material	*k*	*x*
Silicon	0.02-0.04	0.3-0.5
Germanium	0.7-1.0	1.0
InGaAs	0.3-0.5	0.5-0.8

Detectors: Thermal Noise

- Any resistive load (or device with associated resistance) produces noise
- Mean-square thermal noise current...

$$\left\langle i_N^2 \right\rangle_{\text{thermal}} = \frac{4kTB}{R}$$

T: noise temperature

B: electronic bandwidth

R: resistance value

– Assumes power delivered to matched load ($R_L = R$)

Detectors: Signal-to-Noise Analysis

- **SNR of detector loaded by resistor R_L**

$$\frac{S}{N} = \frac{\left\langle i_s^2 \right\rangle\Big|_{M=1} M^2}{2q\left(I_L\big|_{M=1} + I_{Dark\ bulk}\right)M^2 F(M)B + 2qI_{\mathrm{surf}}B + \left(4kTB/R_L\right)}$$

  - **Numerator: mean-square signal current**
  - **Denominator**
    - » **(Amplified) shot noise due to**
      - **dc signal current (I_L) (*before* amplification)**
      - **Bulk dark current (I_D)**
    - » **Shot noise due to surface-leakage dark current I_{surf}**
    - » **Thermal noise due to load resistor**

SNR of pin Diode

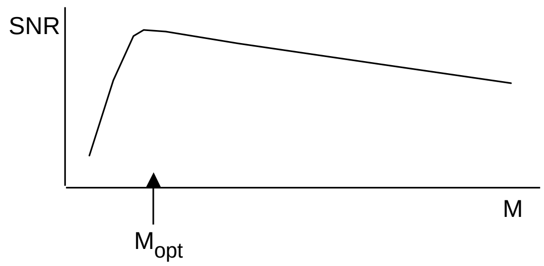
- For pin photodiode
  - *M* = *F(M)* = 1
  - Dominant noise source usually thermal noise
  - Constant input pulse...

$$i_s = \eta q \lambda P / hc = \Re P \qquad \langle i_s^2 \rangle = \Re^2 P^2$$

$$\mathrm{SNR}_{\text{pin diode}} \approx \frac{\Re^2 P^2}{4kTB/R_L}$$

SNR of APDs

- **For small *M*: thermal noise dominant; SNR increases with *M***
- **Large *M: M²F(M)* makes shot noise dominant; SNR decreases with *M***



  - **SNR has a maximum SNR at optimum *M***
- **Optimum *M*:**

$$M_{opt} = \left(\frac{2qI_{surf} + \left(4kT/R_L\right)}{xq\left(I_L + I_D\right)} \right)^{\frac{1}{2+x}}$$

- **Si APDs: M_{opt} = 80 → 100**
  - **SNR improves 40x → 50x (16 → 17 dB)**
  - **Excessive noise in long-λ APDs restricts use**

Analog Analysis

- **Modulated wave…**

$$p(t) = P\left(1 + m(t)\right)$$

$$i(t) = M\Re_0 P\left(1 + m(t)\right) = I_L\left(1 + m(t)\right)$$
$$I_{\text{DC}} = M\Re_0 P;$$
$$i_s(t) = M\Re_0 P m(t); \quad i_s(t)\Big|_{M=1} = \Re_0 P m(t)$$
$$\left\langle i_s^{\,2}(t)\right\rangle\Big|_{M=1} = \Re_0^{\,2} P^2 \left\langle m^2(t)\right\rangle$$

- **Need to assume a specific *m(t)* to proceed...**

Analog Analysis (cont.)

- **Assume…**

$$p(t) = P\left(1 + m\cos(\omega t)\right)$$

$$i(t) = M\Re_0 P\left(1 + m\cos(\omega t)\right) = I_L\left(1 + m\cos(\omega t)\right)$$

$$I_{\mathrm{DC}} = M\Re_0 P;$$

$$i_s(t) = M\Re_0 Pm\cos(\omega t); \quad i_s(t)\Big|_{M=1} = \Re_0 Pm\cos(\omega t)$$

$$\left\langle i_s^{\,2}(t)\right\rangle\Big|_{M=1} = \Re_0^{\,2} P^2 m^2 \underbrace{\left\langle \cos^2(\omega t)\right\rangle}_{1/2} = \frac{\Re_0^{\,2} P^2 m^2}{2}$$

- **Find SNR...**

Analog Analysis (cont.)

- SNR calculation…

$$\frac{S}{N}=\frac{\left\langle i_s^2\right\rangle\Big|_{M=1}M^2}{2q\left(I_L\big|_{M=1}+I_D\right)M^2F(M)B+2qI_{\text{surf}}B+\left(4kTB/R_L\right)}$$

$$=\frac{\dfrac{\Re_0{}^2P^2m^2M^2}{2}}{2q\left(\underbrace{I_L\big|_{M=1}}_{\Re_0P}\right)M^2F(M)B+2qI_DM^2F(M)B+2qI_{\text{surf}}B+\left(4kTB/R_L\right)}$$

$$=\frac{\dfrac{\Re_0{}^2P^2m^2M^2}{2}}{2q\left(\Re_0P\right)M^2F(M)B+2qI_DM^2F(M)B+2qI_{\text{surf}}B+\left(4kTB/R_L\right)}$$

- Make some simplifying assumptions...

Analog Analysis (cont.)

- **Pin diode (*M* =1) – assume that illumination is weak and, so, thermal noise is dominant…**

$$\frac{S}{N}=\frac{\dfrac{\Re_0{}^2P^2m^2}{2}}{2q\left(\Re_0P\right)B+2qI_DB+2qI_{\text{surf}}B+\left(4kTB/R_L\right)}$$

$$\approx\frac{\dfrac{\Re_0{}^2P^2m^2}{2}}{4kTB/R_L}=\frac{\left(1/2\right)\Re_0{}^2P^2m^2}{4kTB/R_L}$$

- **Maximize SNR by…**
  - **maximizing *m*, $\Re_0$, *P*, R_L**
  - **minimizing *T, B***

Analog Analysis (cont.)

- pin diode (*M* =1) – assume that illumination is strong and, so, signal-dependent shot noise is dominant…

$$\frac{S}{N} = \frac{\dfrac{\Re_0^{\,2} P^2 m^2}{2}}{2q\left(\Re_0 P\right)B + 2qI_D B + 2qI_{\text{surf}} B + \left(4kTB/R_L\right)}$$

$$\approx \frac{\dfrac{\Re_0^{\,2} P^2 m^2}{2}}{2q\left(\Re_0 P\right)B} = \frac{\Re_0 P m^2}{4qB}$$

- **"Quantum-limited" SNR**
- **Maximize SNR by…**
  - **maximizing *m*, $\Re_0$, *P***
  - **minimizing *B***

Analog Analysis (cont.)

- APD…
  - Same SNR expression as general expression

$$\frac{S}{N} = \frac{\left\langle i_s^2 \right\rangle\Big|_{M=1} M^2}{2q\left(I_L\big|_{M=1} + I_D\right)M^2 F(M)B + 2qI_{\text{surf}}B + \left(4kTB/R_L\right)}$$

$$= \frac{\dfrac{\Re_0{}^2 P^2 m^2 M^2}{2}}{2q\left(\Re_0 P\right)M^2 F(M)B + 2qI_D M^2 F(M)B + 2qI_{\text{surf}}B + \left(4kTB/R_L\right)}$$

- M_{opt} exists; same value as before (Eq. 6.42b on p. 200)

$$M_{\text{opt}} = \left(\frac{2qI_{\text{surf}} + \left(4kT/R_L\right)}{xq\left(\Re_0 P + I_{\text{Dark}}\right)}\right)^{\frac{1}{2+x}}$$

- $M_{opt} \rightarrow 1$ as power increases;
  - APDs have no advantage with strong illumination

Noise-Equivalent Power

- **Noise-Equivalent Power ("NEP")**
  - **Input power that makes the SNR = 1**
- **Ex. Pin diode with weak signal**

$$\frac{S}{N}=\frac{\dfrac{\Re_0{}^2P^2m^2}{2}}{2q\left(\Re_0P\right)B+2qI_DB+2qI_{\text{surf}}B+\left(4kTB/R_L\right)}$$

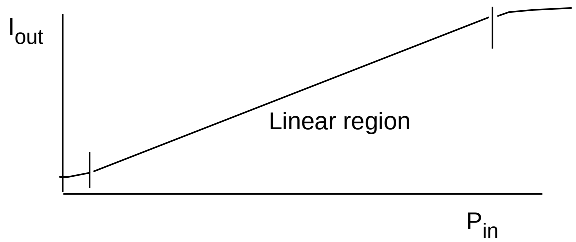
$$\approx\frac{\dfrac{\Re_0{}^2P^2m^2}{2}}{4kTB/R_L}=\frac{(1/2)\Re_0{}^2P^2m^2}{4kTB/R_L}$$

$$1=\frac{(1/2)\Re_0{}^2\text{NEP}^2m^2}{4kTB/R_L}\quad\Rightarrow\quad\text{NEP}=\frac{\sqrt{8kTB/R_L}}{\Re_0m}$$

- **Other cases are similar**
  - **Find SNR; set SNR= 1 and let *P* = NEP; solve for NEP**

Detectors: Linearity

- ***Linearity***: **of output current vs. optical input power curve**



- **Required for analog signal fidelity**
- **PIN diodes:**
  - **Excellent**
  - **Typically linear over 6 decades of input**
- **APDs:**
  - **Not quite as good**
  - **High linearity usually not required for weak signals**

PIN Diode: Speed of Response

- **Factors**
  1. ***Transit time***
     - » **Time to *drift* across depletion region: $\tau = w/\langle v \rangle$**
       - **$\langle v \rangle$:Scattering-limited velocity (Si: 1.0×10^5 m/s)**
       - **Depletion width of 10 μm; response time ≈ 0.1 ns (~10 GHz bandwidth)**
       - **Minimize by making *w* small (decreases sensitivity)**
  2. ***Diffusion time***
     - » **Time for carriers created in *p* or *n* material (close to depletion region boundary) to diffuse into depletion region**
       - **Diffusion process is *slow***
       - **Small fraction of carriers involved**
     - » **Minimize by ensuring that most of carriers generated in depletion region**
       - **Make *w* large ($w \gg 1/\alpha$)**
         - **[Increased depletion region increases transit time, however]**

PIN Diode: Speed of Response (cont.)

3. **RC time constant of device and associated circuitry**

- **Bandwidth limitation:** $B_{max} = 1/2\pi RC_d$
  - **»** ***R*****: input resistance of preamplifier in parallel with load and device resistance** (keep small for fast receiver, R~50 Ω)
  - **»** C_d ***device capacitance:*** $= \varepsilon A/w$
    - **Reduce** C_d **by making A small** (decreased sensitivity) **and *w* large** (increases transit time, causing tradeoff)
      - **Usual compromise:** $w \approx 2/\alpha$
    - **Typical** $C_d < 1$ **pF**

- **Primary limit in well-designed, fast pin diode** (used in low-resistance circuit)**: transit time across depletion region**
- **Fast silicon devices have response <1 ns** (multi-GHz bandwidths)

APD: Speed of Response

- Response typically slower than fast *pin* diodes
  - Carriers must drift into avalanche region
  - Created carriers must drift back,
    - » Makes total transit time ~2x longer

- Constant gain-bandwidth product constraint
  - Caused by giving avalanche process time to occur
  - Typical value: $M \cdot BW \leq 200$ GHz

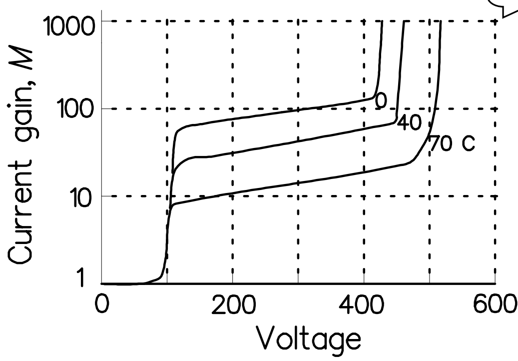
Detectors: Reliability

- No major problem
- Based on accelerated-temperature lifetime testing
  - Projected lifetime: ~10^8 hours

APDs: Temperature Sensitivity

- *M* quite temperature sensitive
- Use temperature-compensating feedback circuit to minimize effect

Fig. 6.9
p. 219



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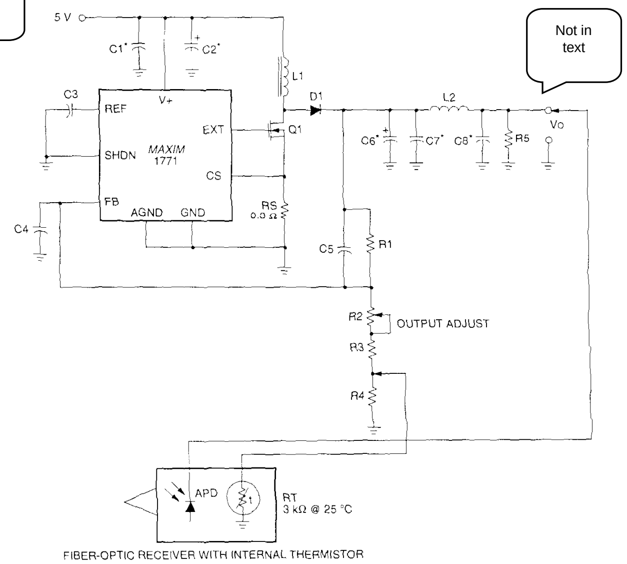


FIBER-OPTIC RECEIVER WITH INTERNAL THERMISTOR

* These capacitors must be low ESR types.

1-1002 (C)

Table 1. Component List for *Maxim* dc-dc APD Bias Circuit

Designation	Description	Source/Part No.
Q1	Power MOSFET $V_{BR(DSS)}$ = 100 V, I_D = 1.5 A	International Rectifier IRLL110
D1	Switching Diode V_R = 120 V, I_F = 400 mA	Central Semiconductor Corp. CMPD5001
L1*	Switching Inductor 330 µH Miniature Shielded, Surface Mount	Coilcraft Inc. DT1608C-334
L2	22 µH Surface-mount Inductor	Coilcraft Inc. 1812CS-223
C1, C7, C8	0.1 µF, 100 V Low ESR Ceramic	—
C2	330 µF, 10 V, Low ESR Ta	Sprague Electric Company 594D337X0010R2T
C3	0.1 µF Ceramic	—
C4	1000 pF NPO	—
C5	22 pF NPO	—
C6	47 µF, 100 V Low ESR	—
R1	432 kΩ Surface Mount	—
R2	5 kΩ Single-turn Potentiometer	—
R3	9.53 kΩ Surface Mount	—
R4	2.74 kΩ Surface Mount	—
R5	20 kΩ Surface Mount	—
RS	0.2 Ω, 1/4 W, Low Inductance, Surface Mount	Dale Electronics WSL1206R00FRE4

* Value not critical; 100 µH to 300 µH appears to work equally well.

Detector Power and Bit-Error-Rate Revisited

- **Digital receiver (left)**
  - **Detects optical signal and converts to electrical signal**
  - **Decides whether electrical output represents "1" or "0" (using decision circuit), and...**
  - **Generates logic voltage output**
- **Threshold voltage (decision level) critical to determining bit error rate (BER)**
  - **Threshold expressed as fraction *k* of expected output of "1"**
  - **Errors made due to noise (right)**

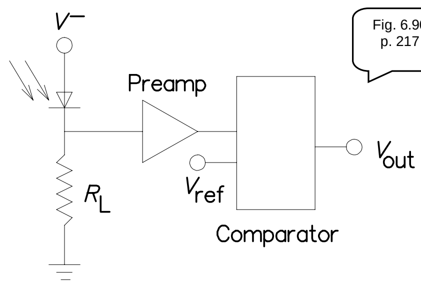


Fig. 6.90
p. 217

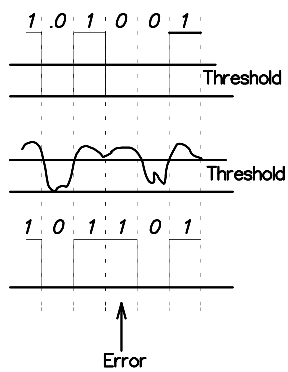


Fig. 6.11
p. 220

Receivers: Noise Models

- **Simplified noise assumptions...**
  - **Detector output currents are Gaussian random variables**

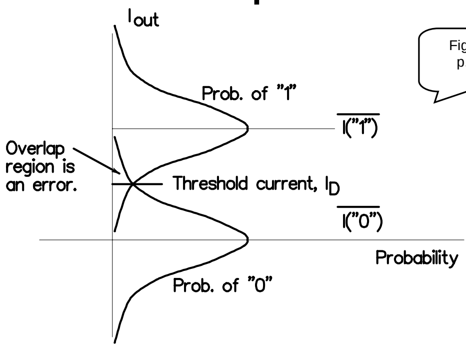


Fig. 6.12
p. 221

$$p(i_N)\,di_N = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(i_N-\bar{i})^2}{2\sigma^2}}\,di_N$$

  - **Mean value of current for logical "1": $\overline{i(1)}$**
  - **Mean value of output current for logical "0": $\overline{i(0)}$ (= 0, later)**
  - **Standard deviation σ is measure of width...**
    - » **Mean square noise current: $\langle i_N^2 \rangle = \sigma^2$**
    - » **Assume standard deviations σ_1 and σ_0 are equal**

Receivers: Noise Models (cont.)

- **Errors**
  - **"0" sent: error if i_N positive and $i_N > k\overline{i_N(1)} = I_D$**
  - **"1" sent: error if i_N negative and $|i_N| > (1-k)\overline{i_N(1)}$**

  - **Total probability of error is…**

$$P_e = P(\mathbf{0}|\mathbf{1})\,P(\mathbf{1}) + P(\mathbf{1}|\mathbf{0})\,P(\mathbf{0})$$

  - **If P(1) = 1/2 and P(0) = 1/2**
    - » **Combined error probability is...**

$$P_e = (1/2)\,P\left[i_N < -(1-k)\overline{i(\mathbf{1})}\right] + (1/2)\,P\left[i_N > k\overline{i(\mathbf{1})}\right]$$

Detectors: Threshold Location and BER

- **Substituting Gaussian distribution, can show that probability of error is...**

$$P_e = \text{BER} = \frac{1}{4}\left[\text{erfc}\left(\frac{\bar{i}(1) - I_D}{\sigma_1\sqrt{2}}\right) + \text{erfc}\left(\frac{I_D - \bar{i}(0)}{\sigma_0\sqrt{2}}\right) + \right] \qquad \left(I_D \equiv k\,\bar{i}(1)\right)$$

- **Optimum threshold location to minimize BER is…**

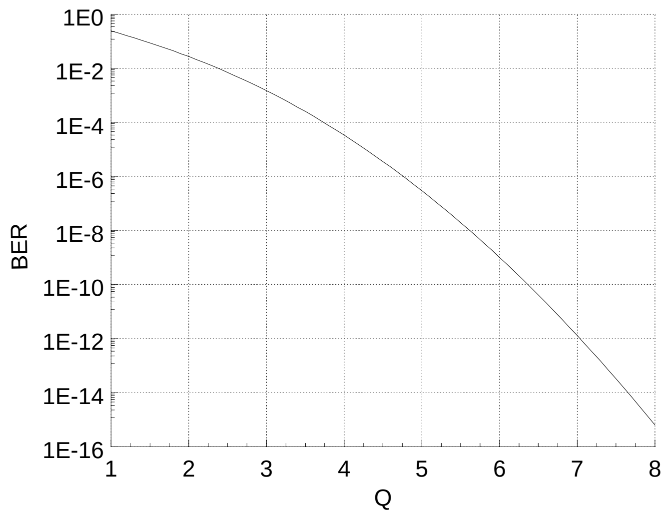
$$\frac{\bar{i}(1) - I_D}{\sigma_1} = \frac{I_D - \bar{i}(0)}{\sigma_0} = Q \quad \Rightarrow \quad I_D = \frac{\sigma_0 \bar{i}(1) + \sigma_0 \bar{i}(0)}{\sigma_0 + \sigma_1}$$

- **BER with optimized threshold is...**

$$\text{BER} = \frac{1}{2}\text{erfc}\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{e^{-\frac{Q^2}{2}}}{Q\sqrt{2\pi}} \quad \left(\text{for } Q > 3\right)$$

BER vs. *Q*

Fig. 6.13
p. 223



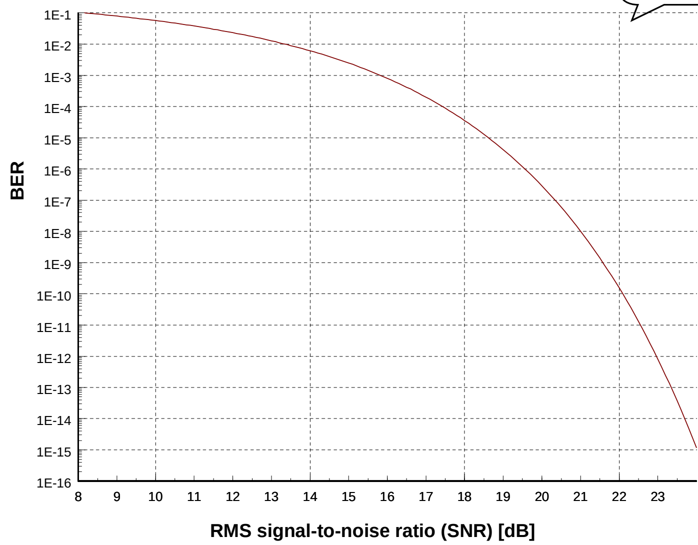
- **Benchmarks:**
  - **Q= 4.76 (BER =10^{-6})**
  - **Q = 6.00 (BER =10^{-9})**
  - **Q= 7.04 (BER =10^{-12})**

BER vs. SNR

- **Assume**
  - $\sigma_0 = \sigma_1 = \sigma = \sqrt{\langle i_N^2 \rangle}$
  - $I_D = [\overline{i(1)}+\overline{i(0)}]/2$ **(i.e., midway)**
  - **then...**

$$\text{BER} = \frac{1}{2}\text{erfc}\left(\frac{\sqrt{\text{SNR}}}{2\sqrt{2}}\right)$$

Fig. 6.14
p. 224



Receivers: Minimum Required Power (cont.)

- **Sample example** **(pp. 187–188, but BER = 10^{-9})**
- **Begin with desired BER; find required SNR...**
  - » **BER = 10^{-9} needs** $\sqrt{\text{SNR}} = \sqrt{\langle i_s^2 \rangle} \Big/ \sqrt{< i_N^2 >} = 21.5\ \text{dB} \Rightarrow 11.89$

Limiting noise (e.g., thermal noise for pin diode or shot noise for APD), and calculate...

$$\sqrt{< i_N^2 >} = \sqrt{\frac{4kTB}{R_L}} = \sqrt{\frac{(4)(1.38\times10^{-23})(400)(10^7)}{50}} = 6.65\times10^{-8}$$

– **From required SNR, find** $\sqrt{\langle i_s^2 \rangle}$ **...**

$$\sqrt{\langle i_s^2 \rangle} = \sqrt{\text{SNR}}\sqrt{< i_N^2 >} = (11.89)(6.65\times10^{-8}) = 7.90\times10^{-7}\,\text{A}$$

– **Find the optical power required at the detector to achieve specified BER..**

$$P_{\min} = \sqrt{< i_s^2 >} \Big/ \Re = 7.90\times10^{-7} \big/ 0.4 = 1.976\times10^{-6}\ \text{W} = 1.976\ \mu\text{W}$$

Receivers: Noise and Sensitivity

- ***Receiver front-end*:**
  - **Combination of detector and preamplifier**
- **Receiver noise properties set by...**
    - » **Detector**
    - » **Amplifier**
      - **Not detector alone**
- **Generally three common receiver implementations**
  1. ***Low-impedance front-end***
  2. ***Integrating front-end***
  3. ***Transimpedance amplifier front-end***
  - **(Some do *not* fall into these categories)**

Receivers: 1. Low-impedance Front-End

- Detector operates into low-impedance amplifier
  - Usually 50 Ω impedance
  - Ready availability of wideband RF amplifiers
- Choose R_L equal to amplifier input resistance
  - e.g., 50 Ω amplifier calls for 50 Ω load
- Poor preamplifier (not recommended)
  - Low sensitivity...
    - Small voltage across amplifier & load resistance
    - High thermal noise from small load/amplifier resistance

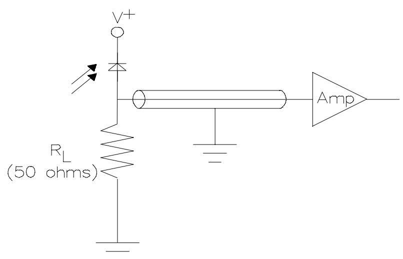


Fig. 6.16a
p. 227

Receivers: 2. High-impedance Front-End

- **Amplifier has high R_{in}**
  - $R_L = R_{in}$
- **Larger signal voltage and less thermal noise**
  - **Amplifier can use FET input for large R_{in}**
- **Capacitances in parallel with load/amplifier resistance:**
  - **Total: C_T**
    - » **Detector capacitance plus...**
    - » **Amplifier input capacitance plus...**
    - » **Parasitic capacitances**
- **Current generator driving parallel *RC* circuit**
  - **Integrator *(integrating front-end)***

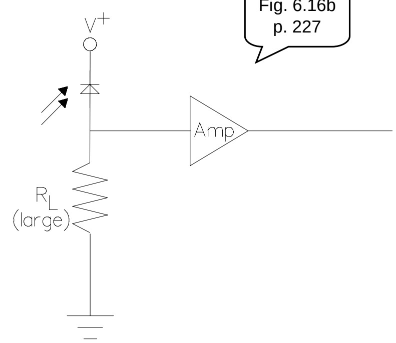


Fig. 6.16b
p. 227

Receivers: 2. High-impedance Front-End (cont.)

- **Bandwidth: 1/2π$R_{parallel}$ C_T**
  - » **$R_{parallel}$: 100s kΩ → few MΩ**
  - » **C_T: few pF or less**
  - » **Bandwidth ≤ kHz range**
    - **Too low for high bit-rate**
- ***Equalization amplifier*** **compensates for low bandwidth (see example)**
  - **Choose R_1 & C ⇒ $1/R_1C = 1/R_LC_T$**
    - » **Equalizer zero cancels front-end pole**
    - » **Combined bandwidth > front-end bandwidth**

$$\frac{V_{out}}{V_{amp}} = \frac{R_2(1 + j\omega R_1 C)}{R_1 + R_{amp} + R_2 + j\omega R_1 C(R_{amp} + R_2)}$$

$$f_{combined} = \frac{1}{R_1 C} \frac{R_1 + R_{amp} + R_2}{R_{amp} + R_2}$$

- **Pro: best sensitivity of all configurations**
- **Con:**
  - **Requires additional circuit**
  - **Limits dynamic range**
  - **Limits dc response**
    - » **Integrated low-frequency components saturate preamp**

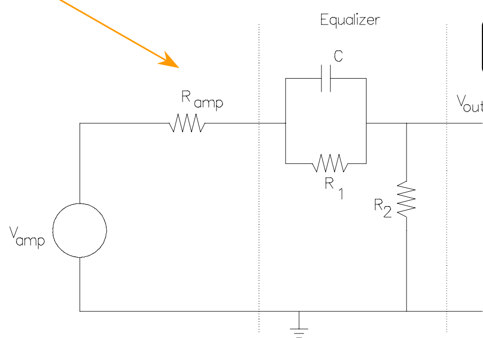
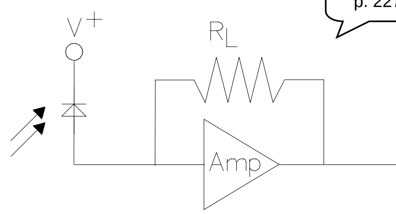


Fig. 6.17
p. 228

Receivers: 3. Transimpedance Front-End

- **Current-to-voltage convertor** (gain of R_L)
  - **Bandwidth:** A (amplifier gain)$/2\pi R_L C_T$
  - **No equalization amp**
- **Low-frequency components reduced by** $1/(A+1)$
  - **Reduces amplifier saturation**
  - **Increases dynamic range**
- **Pros:**
  - **Simple** (no equalization amp)
  - **Good bandwidth**
  - **Good dynamic range**
- **Cons:**
  - **More noise** (less sensitivity) **than integrating front-end**

Fig. 6.16c
p. 227



Receivers: Amplifier Noise Effects

- Actual receivers: amplifier noise dominates detector noise
- How to account for amplifier noise?
  - Amplifier *noise figure* F_n
    - » Describes noise added by amplifier (see notes)
    - » Usually specified in dB; convert to numerical value for formulas
    - » Good low-noise amplifier: F_n < 3 dB; otherwise, ≥ 6 dB
  - SNR:

$$\frac{S}{N} = \frac{G^2 \Re^2 P^2 M^2}{2q(\Re P + I_{\text{dark}})G^2 M^2 F(M) B + 2qI_{\text{surf}} BG^2 + \left(4kTBF_n G^2 / R_L\right)}$$

Additional noise due to amplifier

- » *pin* diode: *M* = *F(M)* = 1
- » APD: SNR maximum at M_{opt}

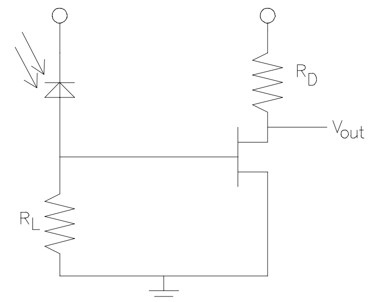
$$M_{\text{opt}} = \left(\frac{2qI_{\text{surf}} + \left(4kTF_n / R_L\right)}{xq\left(\Re P + I_{\text{dark}}\right)} \right)^{\frac{1}{2+x}}$$

Receivers: FET Front-Ends

2. FET front-ends

- Can use either FETs or bipolar junction transistors
  - FETs: superior noise properties
  - GaAs microwave FETs for high-data-rate

Fig. 6.19
p. 232



- Representative common-source preamp
  - Principal sources of noise
    - » Thermal noise from
      - FET channel resistance
      - Load resistor R_L
    - » Shot noise due to FET gate leakage current
    - » Electronic *1/f* noise of FET
    - » See next page

Receivers: FET Front-Ends (cont.)

- **Mean-square noise current of amplifier**

Eq. 6.95 p. 232

$$\langle i_N^2 \rangle_{\text{amp}} = (4kT/R_L)\underbrace{I_2 B_R}_{\text{Bandwidth}} + 2qI_{\text{gate}} I_2 B_R + (4kT\Gamma/g_m)(2\pi C_T^2) f_c I_f B_R^2 + (4kT\Gamma/g_m)(2\pi C_T^2) I_3 B_R^3$$

- I_1, I_2, I_3, and I_f : *Personick integrals* (constants depending on input/output pulse shapes)
- B_R: bit rate
- R_L: load or feedback resistor
- I_{gate}: FET gate leakage current
- g_m: FET transconductance
- C_T: total input capacitance
- f_c: FET 1/*f*-noise corner frequency
- Γ: FET channel noise factor
- Channel-noise factor Γ describes noise contribution from channel resistance and gate-induced noise

- $C_T = C_d + C_s + C_{gs} + C_{gd}$
  - » C_d: detector capacitance
  - » C_s: stray capacitance,
  - » C_{gs}: FET gate-to-source capacitance
  - » C_{gd}: gate-to-drain capacitance
- Corner frequency f_c of 1/*f* noise
  - » FET parameter
  - » Frequency where device 1/*f* electronic noise equals thermal noise of channel (characterized by Γ)
- Typical values shown in text and notes

Receivers: FET Front-End Noise (cont.)

Eq. 6.95
p. 232

$$\langle i_N^2 \rangle_{\text{amp}} = (4kT/R_L) I_2 B_R + 2qI_{\text{gate}} I_2 B_R + (4kT\Gamma/g_m)(2\pi C_T^2) f_c I_f B_R^2 + (4kT\Gamma/g_m)(2\pi C_T^2) I_3 B_R^3$$

- **First term**
  - **Thermal noise of load resistor**
  - **Make resistor large...**
    - » **But reduces receiver dynamic range**
- **Second term**
  - **Shot noise of gate leakage current**
  - **Choose FET with low value of I_{gate}**
- **Third term**
  - **1/f noise of preamp**
  - **Choose FET with low 1/f noise (low value of f_c)**
- **Fourth term**
  - **FET channel noise**
  - **Choose FET with maximum value of g_m/C_T^2**

Receivers: Noise in FET Front-Ends (cont.)

- **High-bit-rate designs**
  - ***Short-circuit common-source gain-bandwidth product***

$$f_T = \frac{g_m}{2\pi\left(C_{gs} + C_{gd}\right)}$$

    - » **Used to describe FET preamp wideband performance**
  - **Usually interested in optimizing receiver performance at high bit rates...**
    - » **Noise dominated by fourth term** **(due to B_R^3 dependence) so...**
    - » **Minimum noise current:**

$$\left\langle i_N^2 \right\rangle_{\text{amp min}} = (32kT)\frac{\Gamma(C_d + C_s)}{f_T} I_3 B_R^3 \quad (\text{for large } B_R)$$

Eq. 6.98
p. 233

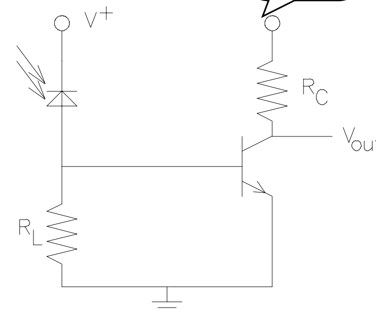
    - » **Lowest amplifier noise when FET chosen that has maximum figure of merit of...**

$$\text{FOM}_{\text{FET}} = \frac{f_T}{\Gamma\left(C_d + C_s\right)}$$

Receivers: Noise in BJT Front-Ends

- **Bipolar preamplifiers in some receiver front-ends**
  - **Low bit rates: noise higher than FETs (not recommended)**
  - **High bit rates: comparable noise**
- **Representative common-emitter preamp**

Fig. 6.20
p. 234



- **Principal noise sources:**
  - **Thermal noise from the load resistor R_L**
  - **Shot noise due to base and collector bias currents (I_b and I_C)**
  - **Thermal noise from base-spreading resistance $r_{bb'}$**
- **Amplifier mean-square noise current...**

Eq. 6.100
p. 234

$$\langle i_N^2 \rangle_{\text{amp}} = (4kT/R_L) I_2 B_R + 2qI_b I_2 B_R + (2qI_c/g_m^2)(2\pi C_T^2) I_3 B_R^3$$
$$+4kTr_{bb'}\left[2\pi (C_d + C_s)\right]^2 I_3 B_R^3$$

Receivers: Noise in BJT Front-Ends (cont.)

$$\langle i_N^2 \rangle_{\text{amp}} = (4kT/R_L) I_2 B_R + 2qI_b I_2 B_R + (2qI_c/g_m^2)(2\pi C_T^2) I_3 B_R^3$$
$$+4kT r_{bb'} \left[2\pi (C_d + C_s)\right]^2 I_3 B_R^3$$

Eq. 6.100
p. 234

- **Parameters...**
  - **β: transistor current gain**
  - **Transistor transconductance (depends on collector bias):**

    $g_m = I_c/V_T$ (with $V_T = kT/q$)
  - **Total capacitance:**

    $C_T = C_d + C_s + C_{b'e} + C_{b'c}$

    $C_{b'e}$ **and** $C_{b'c}$**: small-signal hybrid-pi model**
    - **Capacitances depend on bias current** (see notes or text)
  - f_T**: "short-circuit common-emitter bandwidth product**

- **There is optimum bias current to minimize noise**

  $I_{c\ \text{optimum}} = 2\pi C_0 f_T V_T\ \Psi(B_R)$

  Eq. 6.105
  p. 232

  where $\Psi(B_R) = 1\Big/\sqrt{1+\left(I_2 f_T^2/\beta I_3 B_R^2\right)}$ and

  C_0**: "total capacitance at zero bias"**

  $C_0 = C_d + C_s + C_{b'c} + C_{je}$

- **Mean-square amplifier noise current at optimum bias…**

  See Eq. 6.110 on p. 233 or in notes below

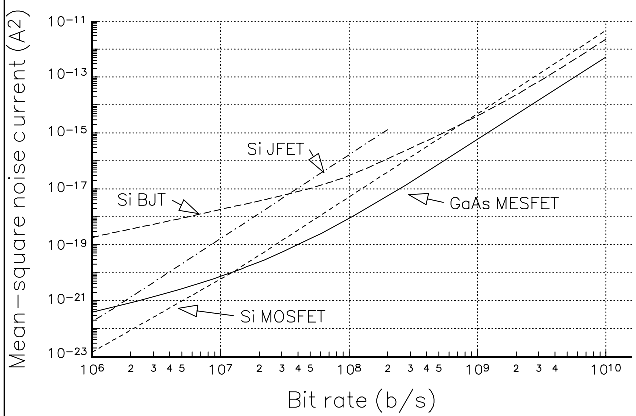
- **Minimize noise by maximizing...**

  Eq. 6.111
  p. 235

$$\text{FOM}_{\text{BJT}} = \frac{2 f_T}{C_0 + \pi f_T r_{bb'} (C_d + C_s)} \quad \text{(for large } B_R\text{)}$$
$$\approx \frac{2 f_T}{C_0} \quad \text{(for large } B_R \text{ and small } r_{bb'}\text{)}$$

Comparison of Noise: FET and BJT Front-Ends

Fig. 6.21
p. 236



- **Parameter values in notes**
- **Low B_R: FET front-end superior to BJT**
- **High B_R: BJT comparable to FET**
- **FET front-ends...**
  - **Low B_R: Si MOSFET slightly advantageous**
  - **High B_R:**
    - **» GaAs MESFET slightly superior**
    - **» Si JFETs not suitable**
      - **Relatively low gain-bandwidth product (lose gain above ~200 Mb/s)**

Receivers: Sensitivity of Detectors + Front-Ends

- **Power required on receiver**
  - **To achieve BER in presence of *both*...**
    - **Detector noise *and...***
    - **Amplifier noise**
- **First will consider pin receiver and, then, more-complicated case of APD receiver**

Receivers: PIN Diode/Preamp Sensitivity

- **>20 dB above quantum limit**
  - **Neglect signal-related shot noise**
- **Total mean-square noise current:** $\left\langle i_N^2 \right\rangle_{\text{Total}} = \left\langle i_N^2 \right\rangle_{\text{amp}} + 2qI_{\text{dark}} I_2 B_R$
- **Find required SNR for desired BER (from BER vs. SNR equation or curve)**
- **Detector power for pin diode receiver...**

$$P = \left(hc\sqrt{\text{SNR}} \,/\, \text{q}\lambda \right) \sqrt{\left\langle i_N^2 \right\rangle_{\text{Total}}}$$

- ***P* calculated and plotted as function of B_R,**
  - **Once pin diode parameters and...**
  - **Amplifier type and parameters are known**
- **Straight-forward application of SNR concepts**

Receivers: APD/Preamp Sensitivity

- More difficult since...
  - M is additional variable and...
  - Excess noise present
  - M_{opt} gives best sensitivity (depends on device, preamplifier noise, and B_R; find by computer modeling or measurement)
- ***At M=M_{opt},***
  - APD noise ≈ preamplifier noise
  - Dark-current shot noise: $\left\langle i_N^2 \right\rangle_{\text{dark}} \approx 2qI_{\text{surface}} I_2 B_R + 2qI_{\text{D bulk}} M^2 F\left(M\right) I_2 B_R$
  - Required power for an APD receiver is…

$$P \approx \left(\frac{hc}{q\lambda}\right) Q \left[QqB_R I_1 F(M) + \sqrt{\frac{\left\langle i_N^2 \right\rangle_{\text{Total}}}{M^2} + 2qI_{\text{D}} F(M) B_R I_2} \right]$$

Q: Q-parameter required by BER

I_1 and I_2: Personick integrals

$\langle i_N^2 \rangle_{Total} = \langle i_N^2 \rangle_{amp} + 2qI_{surf} I_2 B$

- ***Continue on next slide...***

Receivers: APD/Preamp Sensitivity (cont.)

- **If I_D is small enough that it adds negligible noise** (true for short-λ detectors)...
  - **Required receiver power simplifies to...**

$$P = \left(hcQ/q\lambda\right)\left(\frac{\sqrt{\left\langle i_N^2\right\rangle_{\text{Total}}}}{M} + qQB_R I_1 F(M)\right)$$

  - **Optimum gain**

$$M_{\text{opt}} = \left(1/\sqrt{k}\right)\sqrt{\left(\sqrt{\left\langle i_N^2\right\rangle_{\text{Total}}}/qI_1 B_R Q\right) - k + 1}$$

- **If I_D *not* negligible (long-λ detectors)...**
  - **M_{opt} smaller than value predicted** (M_{opt} found graphically or numerically at each B_R by finding M that minimizes receiver power)
  - **Calculate total noise and sensitivity as function of B_R**

Receivers: Extinction Ratio Effects

- ***Extinction ratio***: $r = P(0)/P(1)$
  - Indicates if source turned off for "0"
- Extinction ratio <1
  - Reduces receiver sensitivity *(sensitivity "penalty")*
    - » Shot noise associated with reception of "0"
    - » Not all of received optical power being modulated
  - PIN diode receiver
    - » Power for desired BER is $(1+r)/(1-r)$ *larger*
  - APD receiver
    - » Increases required power in complicated fashion
    - » r affects M_{opt} (found numerically)

Receivers: Eye Pattern Analysis

- Measures speed response and noise

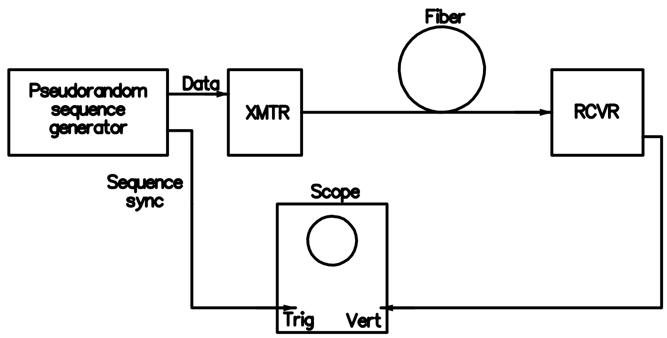


Fig. 6.22
p. 240

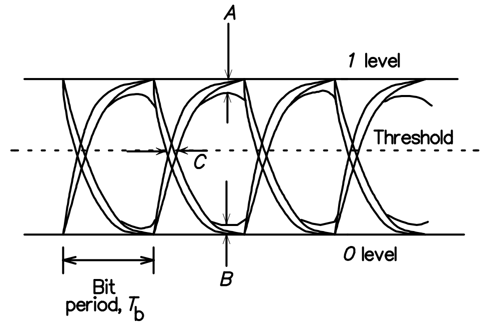
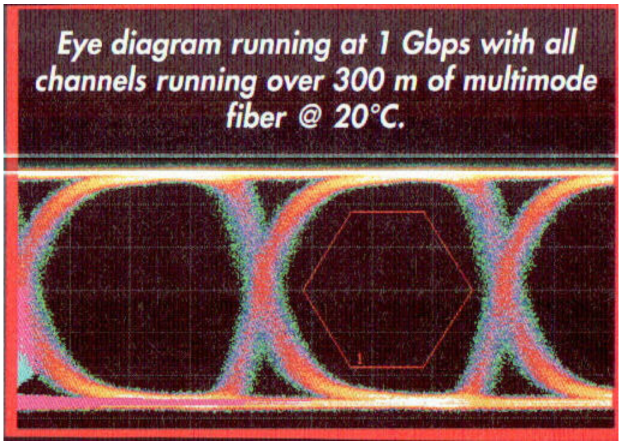


Fig. 6.23
p. 240

Example of Eye Pattern from Sampling 'Scope

- Experimental performance of high bit-rate link measured from *eye pattern*
- Time-domain measurement



- Pattern is superposition of outputs from pseudorandom stream of data pulses

Spec Sheets

- See web site for examples of spec sheets
- Receiver spec sheets
- Electronic receiver preamplifiers

Receivers: Summary

- Properties of pin diodes and APDs

Tabel 6.8
p. 241

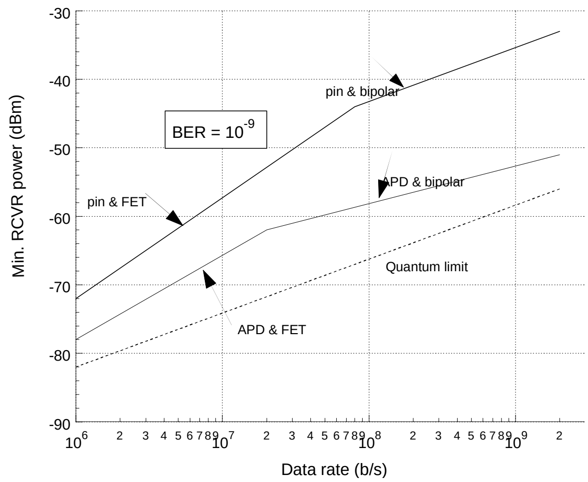
	Photodiodes			APDs	
	Si	Ge	InGaAs	Si	Ge
λ (nm)	400–1l00	500–1800	1000–1500	400–1100	500–1650
Quant. Eff	80%	50%	70%	80%	75%
t_{rise}(ns)	0.01	0.3	0.1	0.5	0.25
Bias (V)	15	6	10	170	40
$\Re_0$ (A/W)	0.5	0.7	0.4	0.7	0.6
M (gain)	1	1	1	80-150	80-150

- Silicon detectors
  - Mature technology
  - Operate close to theoretical limits in short-λ region
- InGaAs detectors
  - Useful in long-λ region
- Germanium-based detectors
  - Long-λ detector
  - Fundamental difficulties with
    - » Noise performance
    - » Noise in APDs and
    - » High dark current

Receivers: Summary (cont.)

- Noise contributions of preamplifier are important
  - High-impedance preamps
    - » Pro: best sensitivity
    - » Con: need equalization amplifier
  - Transimpedance preamps
    - » Pro:
      - Simple design/operation
      - Increased dynamic range
    - » Con: increased noise
    - » Frequently-used receiver
- Representative sensitivities for BER of 10^{-9}

Fig. 6.24
p. 242



Receivers: Summary (cont.)

- Observations...
  - Increased sensitivity required at higher B_R
  - Si FET receivers: good up to ~ 70 Mb·s^{-1}
  - GaAs MESFETs: higher B_R
- APDs
  - Pro: ~10 dB increased sensitivity
  - Cons:
    - » More operating power required
    - » Higher cost
    - » Require temperature compensation
- Best detector/preamplifier combination
  - ~10 dB from quantum-limited detection