EE5706

Optical Communications

การสื่อสารทางแสง

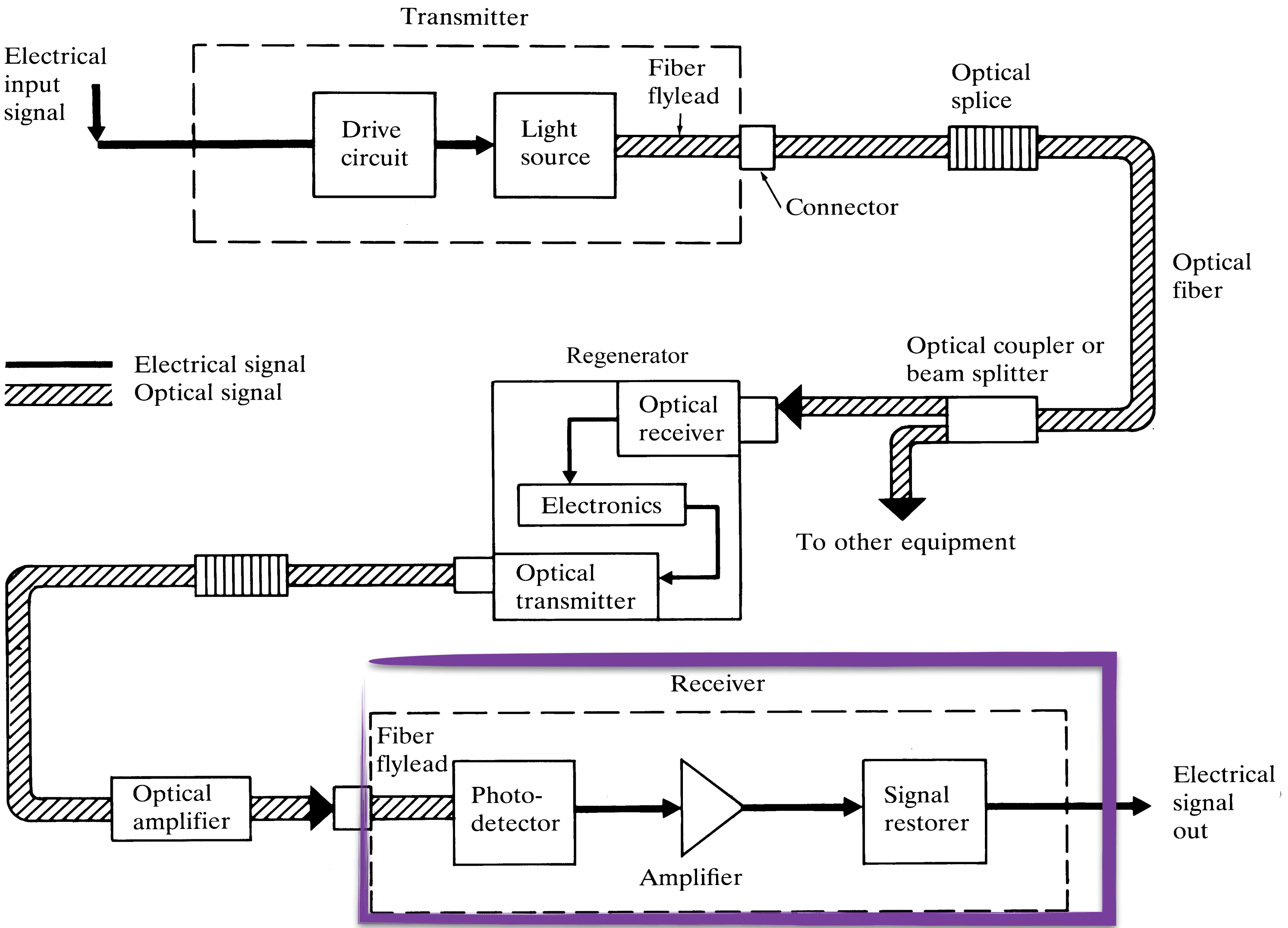
10:00 max 18:30

DATALEGREYA 17°c 11°c

23/07/2561

Optical Detectors
อุปกรณ์ตรวจจับแสง

Elements of Fiber Optic Link



Contents

- Physical Principles of Photodiodes
- pin-PD, APD
- Photodetectors characteristics (Quantum efficiency, Responsivity, S/N)
- Noise in Photodetector Circuits

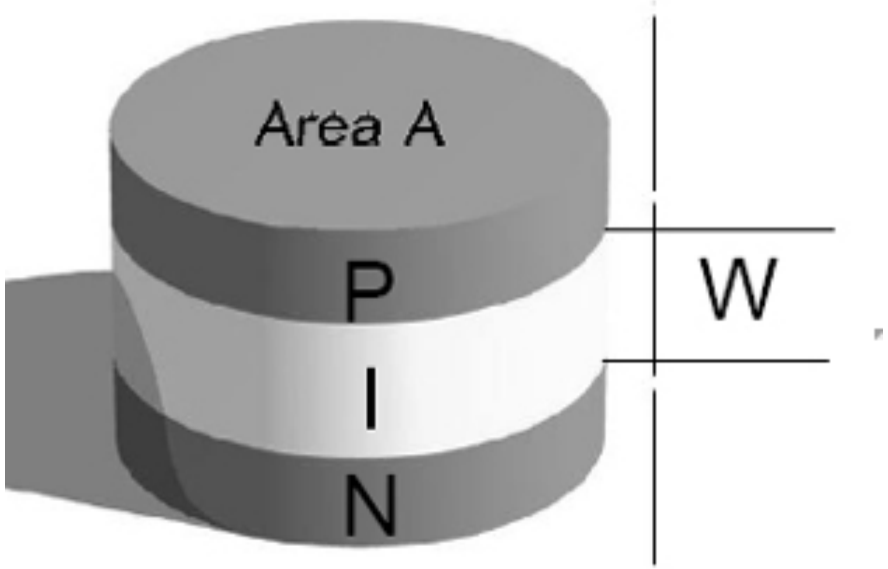
Requirements

- Compatible physical dimensions (small size)
- Low sensitivity (high responsivity) at the desired wavelength and low responsivity elsewhere wavelength selectivity
- Low noise and high gain
- Fast response time high bandwidth
- Insensitive to temperature variations
- Long operating life and low cost

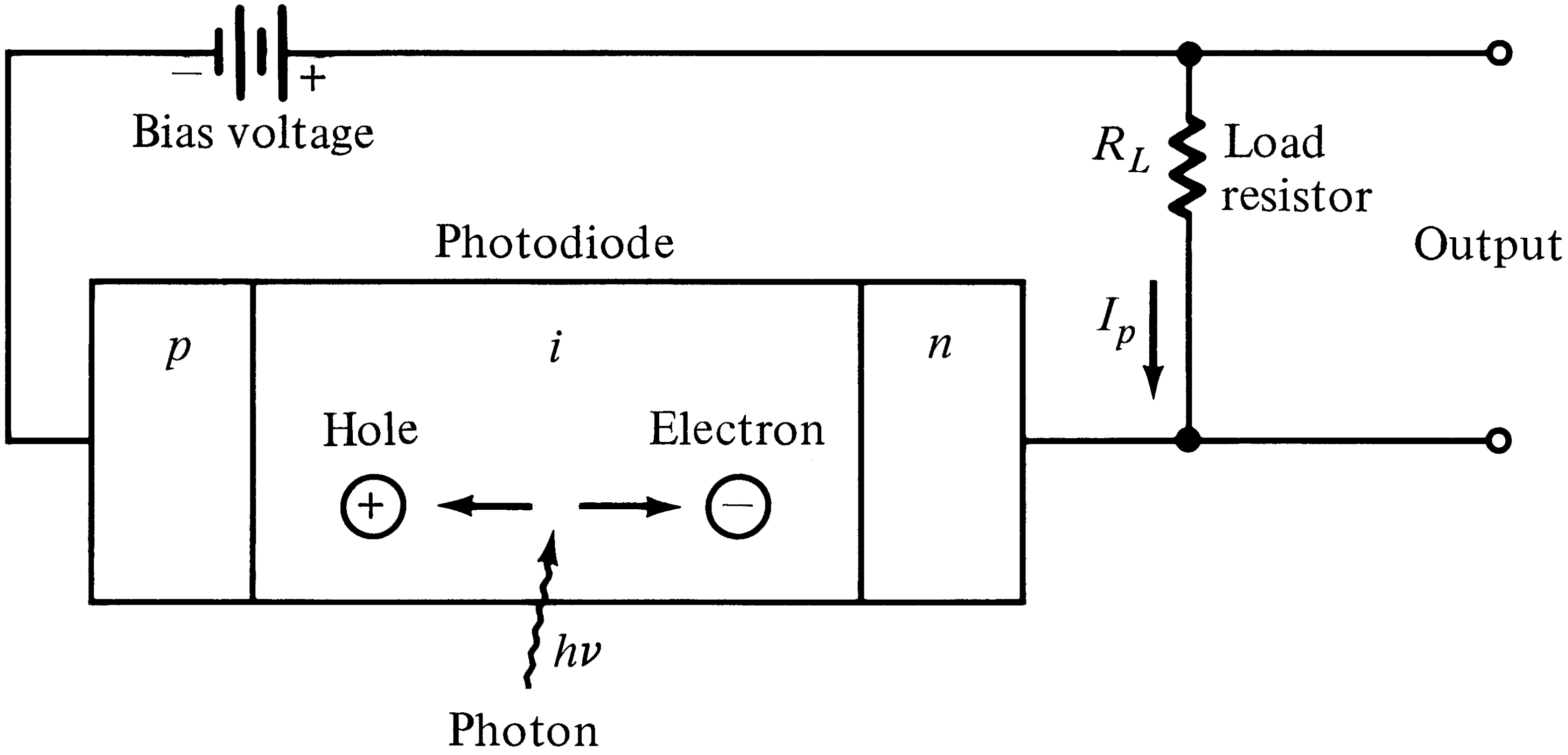
Photodiodes

- Photodiodes meet most the requirements, hence widely used as photo detectors.
- Positive-Intrinsic-Negative (pin) photodiode
  - No internal gain, robust detector
- Avalanche Photo Diode (APD)
  - Advanced version with internal gain M due to self multiplication process
- Photodiodes are sufficiently reverse biased during normal operation —> no current flow without illumination, the intrinsic region is fully depleted of carriers

pin Photodetector



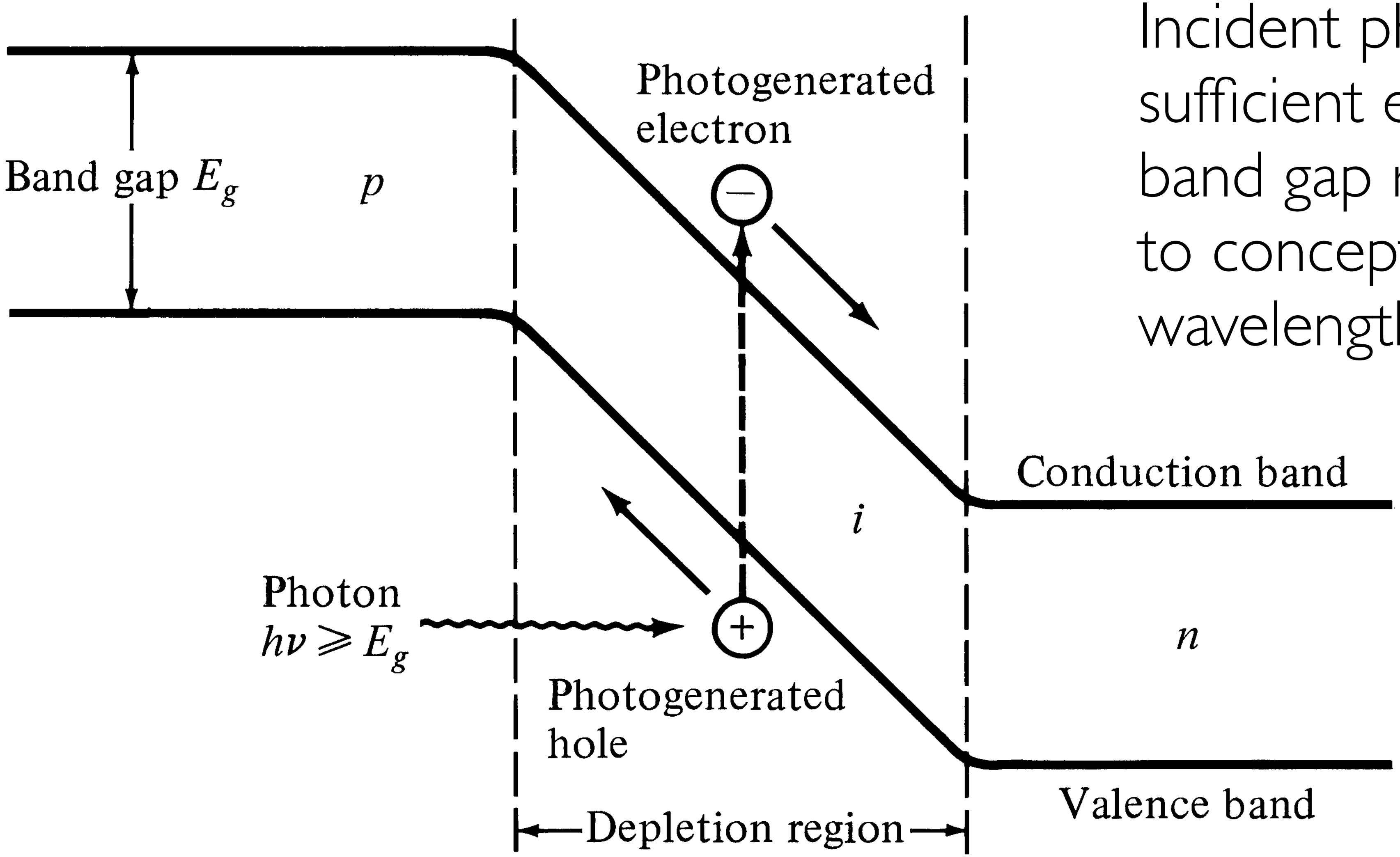
pin Photodetector



Bias voltage usually needed to fully deplete the intrinsic "i" region for high speed operation

The high electric field present in the depletion region causes photo-generated carriers to separate and be collected across the reverse –biased junction. This gives rise to a current flow in an external circuit, known as **photocurrent (I_p)**.

Energy-Band diagram for a *pin* photodiode



Incident photons must have sufficient energy to meet the band gap requirement. Leads to concept of cut-off wavelength.

Photocurrent

- Optical power absorbed, $P(x)$ in the depletion region can be written in terms of incident optical power, P_0 :

$$P(x) = P_0(1 - e^{-\alpha_s(\lambda)x})$$

- Absorption coefficient, $\alpha_s(\lambda)$,strongly depends on wavelength. The upper wavelength cutoff for any semiconductor can be determined by its energy gap as follows:

$$\lambda_c(\mu\mathrm{m}) = \frac{1.24}{E_g(\mathrm{eV})}$$

Examples of Photon Absorption

Example 6.1 If the absorption coefficient of $In_{0.53}Ga_{0.47}As$ is 0.8 μm^{-1} at 1550 nm, what is the penetration depth at which $P(x)/P_{in} = 1/e = 0.368$?

Solution: From Eq. (6.1),

$$\frac{P(x)}{P_{in}} = \exp(-\alpha_s x) = \exp[(-0.8)x] = 0.368$$

Therefore

$$-0.8\,x = \ln 0.368 = -0.9997$$

which yields $x = 1.25\ \mu m$.

Example 6.2 A high-speed $In_{0.53}Ga_{0.47}As$ *pin* photodetector is made with a depletion layer thickness of 0.15 μm. What percent of incident photons are absorbed in this photodetector at 1310 nm if the absorption coefficient is 1.5 μm^{-1} at this wavelength?

Solution: From Eq. (6.1), the optical power level at $x = 0.15\ \mu m$ relative to the incident power level is

$$\frac{P(0.15)}{P_{in}} = \exp(-\alpha_s x) = \exp[(-1.5)0.15] = 0.80$$

Therefore only 20 percent of the incident photons are absorbed.

- The primary photocurrent resulting from absorption is:

$$I_p = \frac{q}{h\nu} P_0 (1 - e^{-\alpha_s(\lambda) w})(1 - R_f)$$

- External Quantum Efficiency:

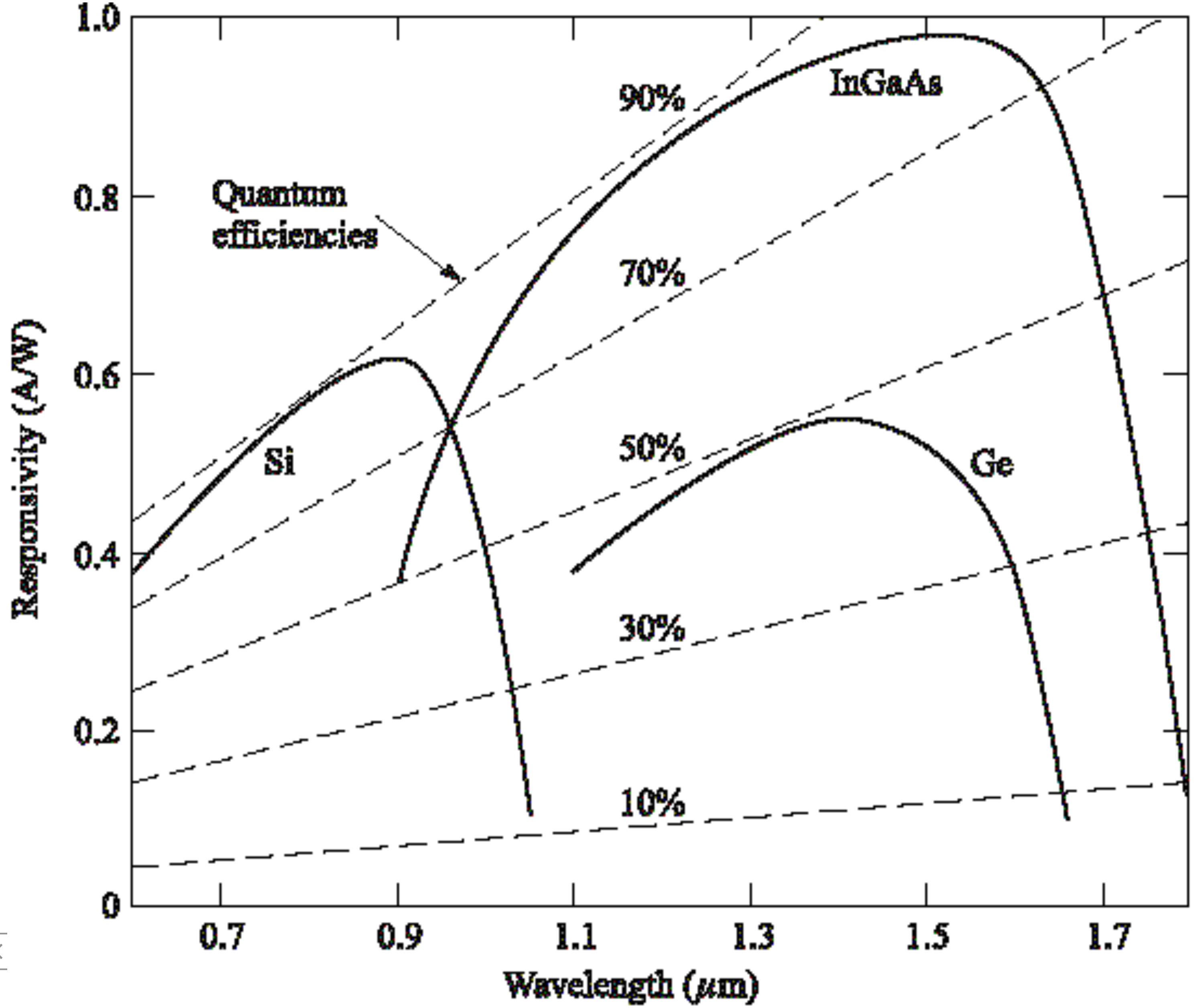
$$\eta = \frac{\text{\# of electron - hole photogenerated pairs}}{\text{\# of incident photons}}$$

$$\eta = \frac{I_P / q}{P_0 / h\nu}$$

- Responsivity:

$$\Re = \frac{I_P}{P_0} = \frac{\eta q}{h\nu} \quad [\text{A/W}]$$

Responsivity vs. Wavelength

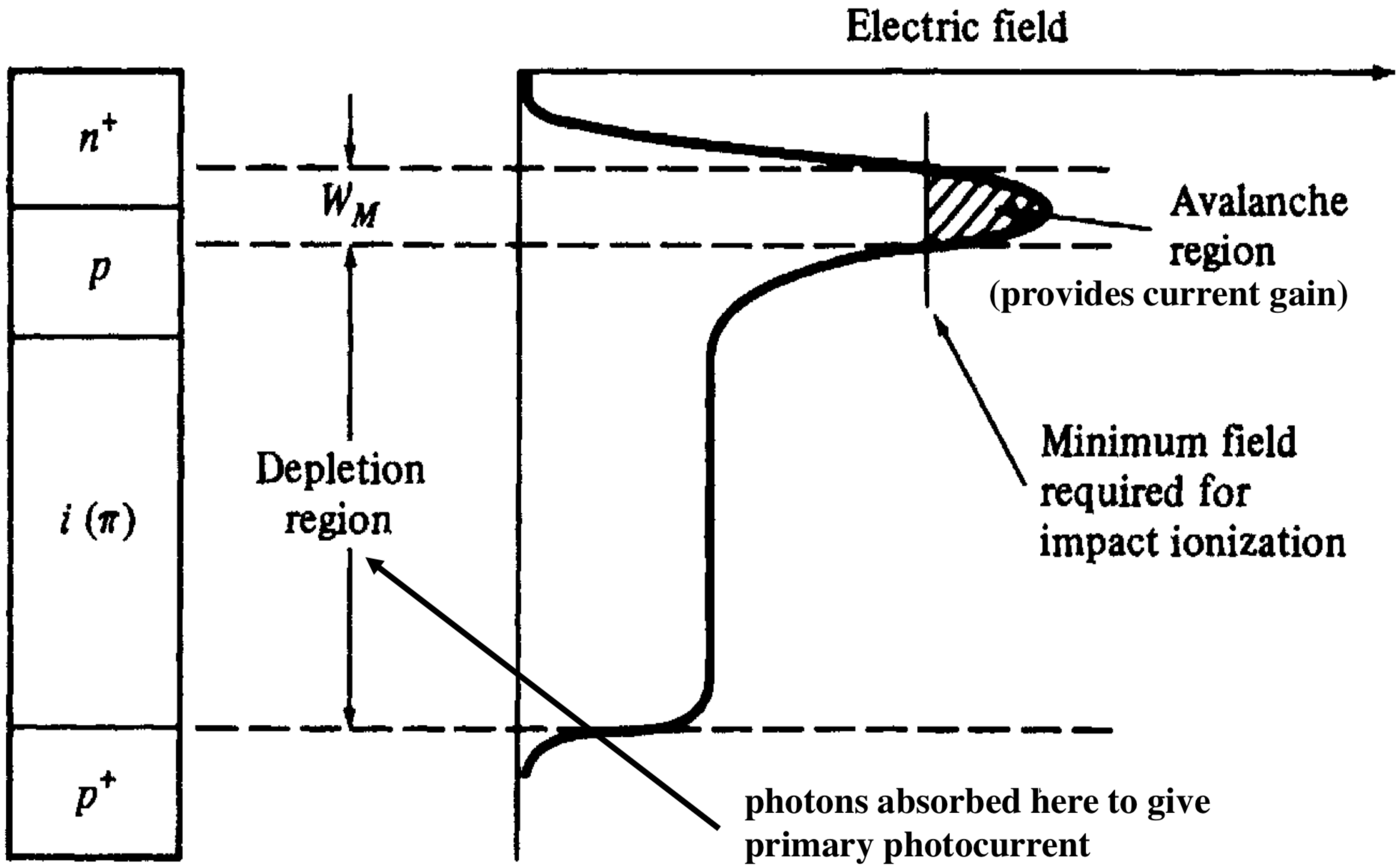


- Increases with wavelength until cut-off
- Maximum value of quantum efficiency is unity, which places an upper limit on responsivity

Avalanche Photodiode (APD)

- APD has an **internal gain M**, which is obtained by having a high electric field that energizes photo-generated electrons.
- These electrons ionize bound electrons in the valence band upon colliding with them which is known as impact ionization.
- The newly generated electrons and holes are also accelerated by the high electric field and gain energy to cause further impact ionization.
- This phenomena is the **avalanche effect**.

Avalanche Photodiode (APD)



Reach-Through APD structure (RAPD)
showing the electric fields in depletion region and multiplication region.

Responsivity of APD

- The multiplication factor (current gain) M for all carriers generated in the photodiode is defined as:

$$M = \frac{I_M}{I_p}$$

Where I_M is the average value of the total multiplied output current & I_P is the primary photocurrent.

- The responsivity of APD can be calculated by considering the current gain as:

$$\Re_{APD} = \frac{\eta q}{h\nu} M = \Re_0 M$$

Photodetector Noise

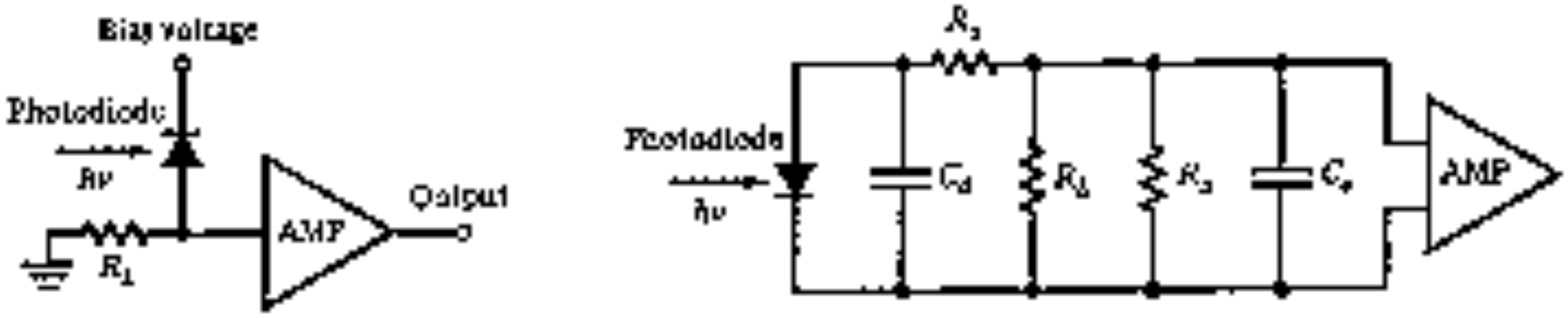
- In fiber optic communication systems, the photodiode is generally required to detect very weak optical signals.
- Detection of weak optical signals requires that the photodetector and its amplification circuitry be optimized to maintain a given signal-to-noise ratio.
- The power signal-to-noise ratio S/N (also designated by SNR) at the output of an optical receiver is defined by

$$SNR = \frac{S}{N} = \frac{\text{signal power from photocurrent}}{\text{photodetector noise power} + \text{amplifier noise power}}$$

SNR Can NOT be improved by amplification

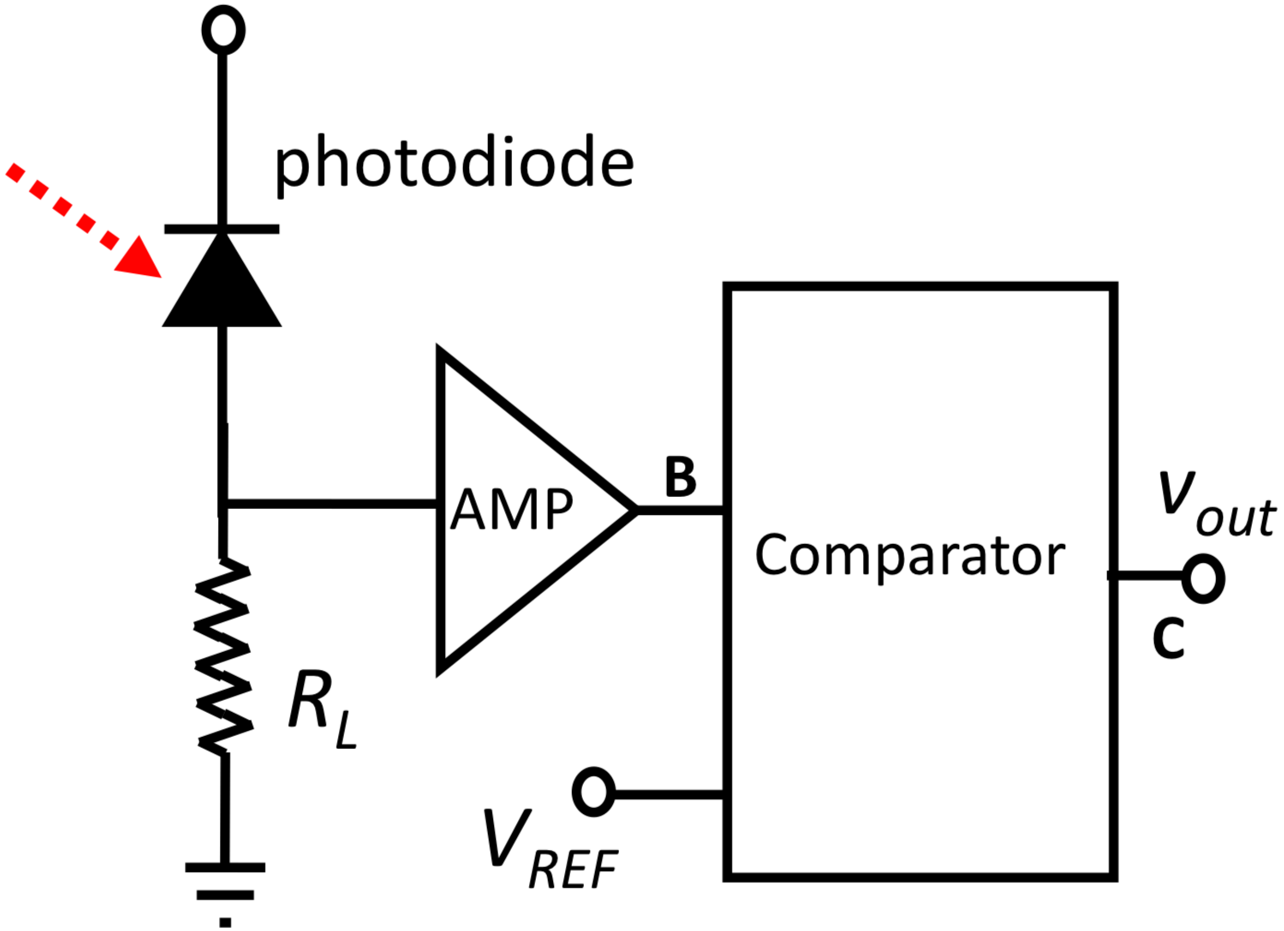
Photodetector Noise

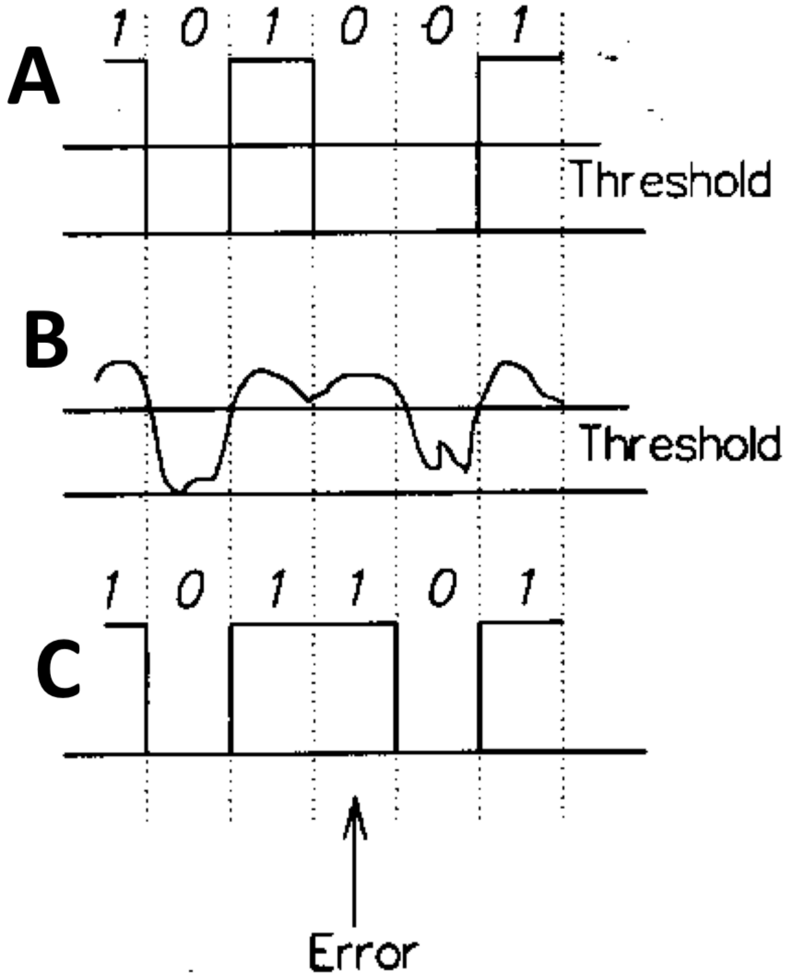
- Detection of weak optical signal requires that the photodetector and its following amplification circuitry be optimized for a desired signal-to-noise ratio.
- It is the noise current which determines the minimum optical power level that can be detected. This minimum detectable optical power defines the sensitivity of photodetector. That is the optical power that generates a photocurrent with the amplitude equal to that of the total noise current (S/N=1)



(a) (b)

Impact on digital reception





SNR performance of PIN photodiode

- Consider the modulated optical power signal P(t) falls on the photodetector with the form of:

$$P(t) = P_0[1 + ms(t)]$$

- Where s(t) is message electrical signal and m is modulation index. Therefore the primary photocurrent is (for pin photodiode M=1):

$$i_{\mathrm{ph}} = \frac{\eta q}{h\nu} MP(t) = I_P[\mathrm{DC\ value}] + i_p(t)[\mathrm{AC\ current}]$$

- The root mean square signal current is then:

$$\langle i_s{}^2 \rangle = \langle i_p{}^2 \rangle M^2 = \sigma_s{}^2$$

$$\langle i_p{}^2 \rangle = \sigma_p{}^2 = \frac{m^2 I_P^2}{2} \quad \text{for sinusoidal signal}$$

Quantum Noise Current (Shot Noise Current)

- Quantum noise arises due optical power fluctuation because light is made up of discrete number of photons

$$\boxed{\left\langle i_Q^2 \right\rangle = 2qI_pBM^2F(M)}$$

F(M): APD Noise Figure $F(M) \sim= M^x$ $(0 \le x \le 1)$
I_p: Mean Detected Current
B = Bandwidth
q: Charge of an electron

Dark/Leakage Current Noise

- There will be some (dark and leakage) current without any incident light. This current generates two types of noise:

Bulk Dark Current Noise:

$$\boxed{\left\langle i_{DB}^{2} \right\rangle = 2qI_{D}BM^{2}F(M)}$$

I_D: Dark Current

Surface Dark Current Noise:

$$\left\langle i_{DS}^{2} \right\rangle = 2qI_{L}B$$

(Surface Leakage Current Noise)

I_L: Leakage Current

Thermal Noise

- The photodetector load resistor RL contributes to thermal (Johnson) noise current.

$$\boxed{\left\langle i_T^2 \right\rangle = 4K_B TB / R_L}$$

K_B: Boltzmann's constant = 1.38054 X 10^(-23) J/K
T: Absolute temperature

- Quantum and Thermal are the significant noise mechanisms in all optical receivers.

Signal to Noise Ratio

Signal Power = $\langle i_p^2 \rangle M^2$

$$\boxed{SNR = \frac{\langle i_p^2 \rangle M^2}{2q(I_p + I_D)M^2 F(M)B + 2qI_L B + 4k_B TB / R_L}}$$

Typically not all the noise terms will have equal weight. Often thermal and quantum noise are the most significant.

$$\boxed{\frac{S}{N} = \frac{\langle i_p^2 \rangle M^2}{2qI_p M^2 F(M) B_e + 4k_B T B_e / R_L}}$$

*** *This formula is for APD but for pin photodiode M=1 and F(M)=1*

Example: Noise Calculation

Example: Noise Calculation

Example 6.8 An InGaAs *pin* photodiode has the following parameters at a wavelength of 1300 nm: $I_D = 4$ nA, $\eta = 0.90$, $R_L = 1000\ \Omega$, and the surface leakage current is negligible. The incident optical power is 300 nW (–35 dBm), and the receiver bandwidth is 20 MHz. Find the various noise terms of the receiver.

Solution: (*a*) First, we need to find the primary photocurrent. From Eq. (6.6),

$$I_p = \mathscr{R}P_{in} = \frac{\eta q}{h\nu}P_{in} = \frac{\eta q\lambda}{hc}P_{in}$$

$$= \frac{(0.90)(1.6\times10^{-19}\ \text{C})(1.3\times10^{-6}\ \text{m})}{(6.625\times10^{-34}\ \text{J}\cdot\text{s})(3\times10^{8}\ \text{m/s})}3\times10^{-7}\ \text{W}$$

$$= 0.282\ \mu\text{A}$$

(*b*) From Eq. (6.13), the mean-square shot noise current for a *pin* photodiode is

$$\langle i_{\text{shot}}^2\rangle = 2qI_pB_e$$

$$= 2(1.6\times10^{-19}\ \text{C})(0.282\times10^{-6}\ \text{A})(20\times10^{6}\ \text{Hz})$$

$$= 1.80\times10^{-18}\ \text{A}^2$$

or $\langle i_{\text{shot}}^2\rangle^{1/2} = 1.34\ \text{nA}$

(*c*) From Eq. (6.14), the mean-square dark current is

$$\langle i_{DB}^2\rangle = 2qI_DB_e$$

$$= 2(1.6\times19^{-19}\ \text{C})(4\times10^{-9}\ \text{A})(20\times10^{6}\ \text{Hz})$$

$$= 2.56\times10^{-20}\ \text{A}^2$$

or

$$\langle i_{DB}^2\rangle^{1/2} = 0.16\ \text{nA}$$

(*d*) The mean-square thermal noise current for the receiver is found from Eq. (6.17) as

$$\langle i_T^2\rangle = \frac{4k_BT}{R_L}B_e = \frac{4(1.38\times10^{-23}\ \text{J/K})(293\ \text{K})}{1\ \text{k}\Omega}B_e$$

$$= 323\times10^{-18}\ \text{A}^2$$

or

$$\langle i_T^2\rangle^{1/2} = 18\ \text{nA}$$

Thus for this receiver the rms thermal noise current is about 14 times greater than the rms shot noise current and about 100 times greater than the rms dark current.