Optical Fiber Communications

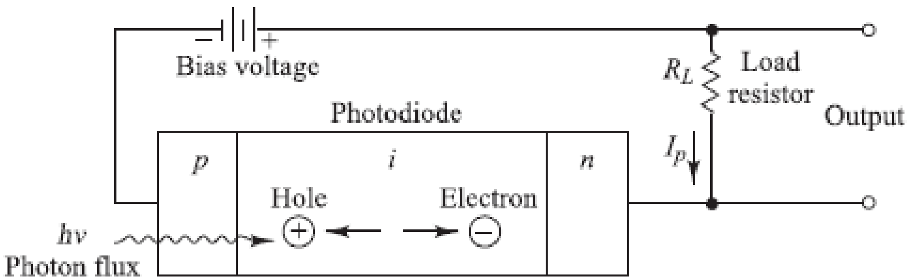
Chapter 6

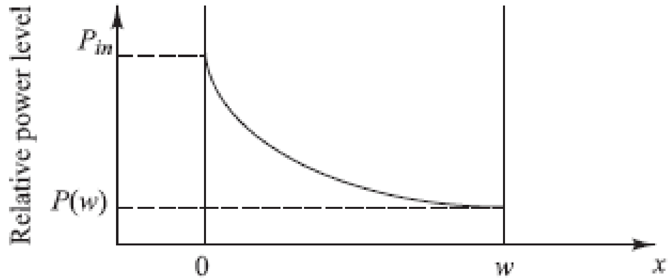
Photodetectors

Physical Principles of Photodiodes

- **As a photon flux Φ penetrates into a semiconductor, it will be absorbed as it progresses through the material.**
- **If $\alpha_s(\lambda)$ is the photon absorption coefficient at a wavelength λ, the *power level at a distance x into the material* is**

$$P(x) = P_{in}\exp(-\alpha_s x)$$





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?

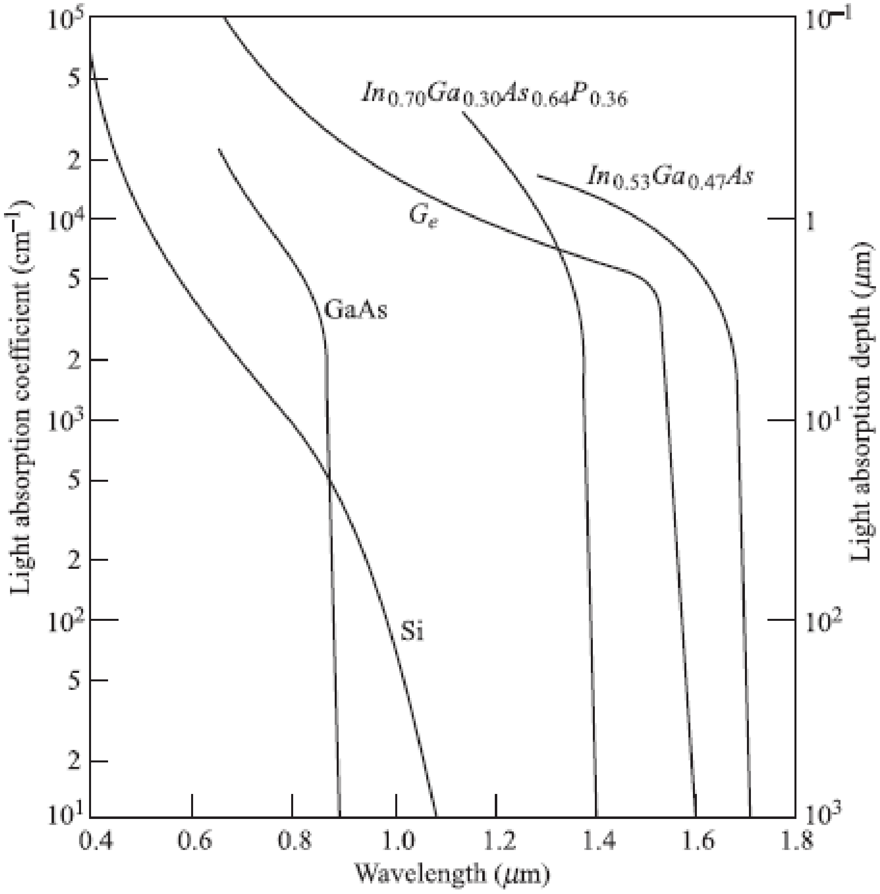
Solution: From Eq. (6.1), the optical power level at $x = 0.15\ \mu m$ relative to the incident power level is

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

Therefore only 20 percent of the incident photons are absorbed.

Light Absorption Coefficient

- The upper wavelength cutoff is determined by the bandgap energy E_g of the material.
- At the lower-wavelength end, the photoresponse cuts off as a result of the very large values of α_s at the shorter wavelengths.



Quantum Efficiency

- **The *quantum efficiency* η is the number of the electron–hole carrier pairs generated per incident–absorbed photon of energy hν and is given by**

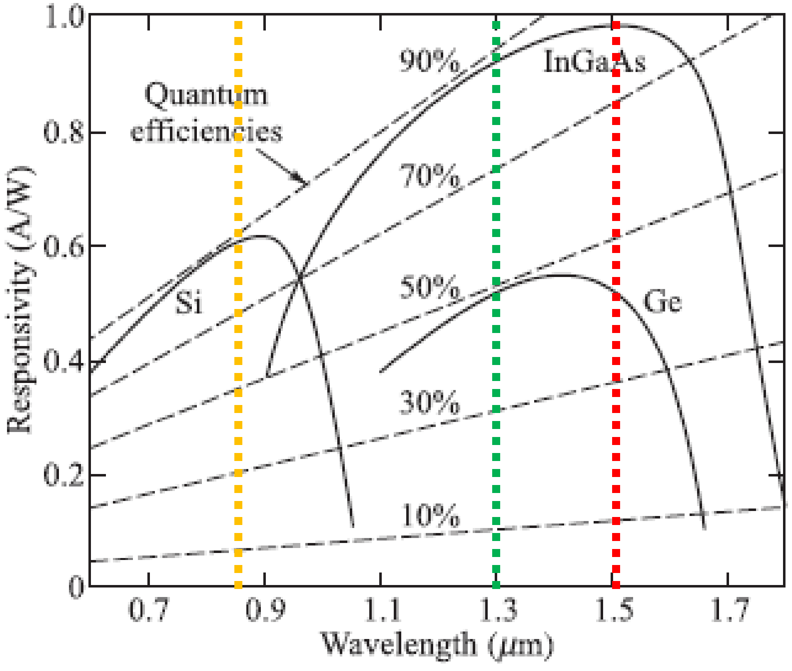
$$\boxed{\eta = \frac{\text{number of electron–hole pairs generated}}{\text{number of incident–absorbed photons}} = \frac{I_p / q}{P_{in} / h\nu}}$$

I_p is the photocurrent generated by a steady-state optical power P_{in} incident on the photodetector.

Responsivity

- The performance of a photodiode can be characterized by the ***responsivity*** $\mathcal{R}$. This is related to the quantum efficiency by

$$\boxed{\mathcal{R} = \frac{I_p}{P_{in}} = \frac{\eta q}{h\nu}}$$



I_p : Photocurrent

P_{in} : Optical power

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**

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

Noise Sources

- **If a modulated signal of optical power P(t) falls on the detector, the *primary photocurrent* is**

$$i_{\mathrm{ph}}(t) = \frac{\eta q}{h\nu} P(t)$$

- **The *quantum* or *shot noise current* arises from the statistical nature of the production and collection of photoelectrons**

$$\left\langle i_{\mathrm{shot}}^2 \right\rangle = \sigma_{\mathrm{shot}}^2 = 2qI_p B_e M^2 F(M)$$

- **The *bulk dark current* arises from electrons/holes that are thermally generated in the photodiode pn junction**

$$\left\langle i_{DB}^2 \right\rangle = \sigma_{DB}^2 = 2qI_D M^2 F(M) B_e$$

- **The photodetector load resistor contributes a *thermal noise current***

$$\left\langle i_T^2 \right\rangle = \sigma_T^2 = \frac{4k_B T}{R_L} B_e$$

M is the gain and F(M) is a noise figure associated with an APD

Noise Calculation Example

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),

$$\begin{aligned} I_p &= \mathscr{R}P_{in} = \frac{\eta q}{h\nu}P_{in} = \frac{\eta q \lambda}{hc}P_{in} \\ &= \frac{(0.90)(1.6\times10^{-19}\text{ C})(1.3\times10^{-6}\text{ m})}{(6.625\times10^{-34}\text{ J}\cdot\text{s})(3\times10^{8}\text{ m/s})}3\times10^{-7}\text{ W} \\ &= 0.282\ \mu\text{A} \end{aligned}$$

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

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

$$\begin{aligned} &= 2(1.6\times10^{-19}\text{ C})(0.282\times10^{-6}\text{ A})(20\times10^{6}\text{ Hz}) \\ &= 1.80\times10^{-18}\text{ A}^2 \end{aligned}$$

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

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

$$\begin{aligned} \langle i_{DB}^2 \rangle &= 2qI_DB_e \\ &= 2(1.6\times19^{-19}\text{ C})(4\times10^{-9}\text{ A})(20\times10^{6}\text{ Hz}) \\ &= 2.56\times10^{-20}\text{ A}^2 \end{aligned}$$

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

$$\begin{aligned} \langle i_T^2 \rangle &= \frac{4k_BT}{R_L}B_e = \frac{4(1.38\times10^{-23}\text{ J/K})(293\text{K})}{1\text{ k}\Omega}B_e \\ &= 323\times10^{-18}\text{ A}^2 \end{aligned}$$

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.

Signal-to-Noise Ratio

The signal-to-noise ratio at the input of the receiver amplifier is

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

when the average signal current is much larger than the leakage and dark currents, the signal-to-nose ratio becomes

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

Limiting Cases for SNR

- **When the optical signal power is relatively high, then the shot noise power is much greater than the thermal noise power. In this case the SNR is called *shot-noise limited* or *quantum noise limited*.**
- **When the optical signal power is low, then thermal noise usually dominates over the shot noise. In this case the SNR is referred to as being *thermal-noise limited*.**

Example 6.9 Consider the InGaAs *pin* photodiode described in Example 6.8. What is the SNR in decibels?

Solution: Since the dark current noise is negligible compared to the shot noise and thermal noise, we can substitute the numerical results into Eq. (6.18*b*) to get

$$\frac{S}{N} = \frac{(0.282 \times 10^{-6})^2}{1.80 \times 10^{-18} + 323 \times 10^{-18}} = 245$$

In decibels the SNR is

$$\frac{S}{N} = 10 \log 245 = 23.9$$

Noise-Equivalent Power

- **The sensitivity of a photodetector is describable in terms of the *minimum detectable optical power* to have SNR = 1.**
- **This optical power is the *noise equivalent power or NEP*.**
- **Example: Consider the thermal-noise limited case for a *pin* photodiode. Then** $$\mathrm{SNR} = \mathscr{R}^2 P^2 / (4k_B T B_e / R_L)$$

To find the NEP, set the SNR = 1 and solve for P:

$$\mathrm{NEP} = \frac{P_{\min}}{\sqrt{B_e}} = \sqrt{4k_B T / R_L} / \mathscr{R}$$

Example 6.11 For an InGaAs photodetector operating at 1550 nm, $\mathscr{R} = 0.90$ A/W. What is the NEP in the thermal-noise limited case if the load resistor is $R_L = 1000\ \Omega$ and $T = 300°\mathrm{K}$?

Solution: From the above expression for NEP we have

$$\begin{aligned}\mathrm{NEP} &= \sqrt{4(1.38\times10^{-23})(300)/1000}/0.90 \\ &= 4.52\times10^{-12}\ \mathrm{W}/\sqrt{\mathrm{Hz}}\end{aligned}$$

Comparisons of *pin* Photodiodes

Parameter	*Symbol*	*Unit*	*Si*	*Ge*	*InGaAs*
Wavelength range	λ	nm	400–1100	800–1650	1100–1700
Responsivity	$\mathcal{R}$	A/W	0.4–0.6	0.4–0.5	0.75–0.95
Dark current	I_D	nA	1–10	50–500	0.5–2.0
Rise time	τ_r	ns	0.5–1	0.1–0.5	0.05–0.5
Modulation (bandwidth)	B_m	GHz	0.3–0.7	0.5–3	1–2
Bias voltage	V_B	V	5	5–10	5

NOTE: The values were derived from various vendor data sheets and from performance numbers reported in the literature. They are guidelines for comparison purposes. Detailed values on specific devices for particular applications can be obtained from photodetector and receiver module suppliers.

Comparisons of APDs

Parameter	*Symbol*	*Unit*	*Si*	*Ge*	*InGaAs*
Wavelength range	λ	nm	400–1100	800–1650	1100–1700
Avalanche gain	M	—	20–400	50–200	10–40
Dark current	I_D	nA	0.1–1	50–500	10–50 @ $M = 10$
Rise time	τ_r	ns	0.1–2	0.5–0.8	0.1–0.5
Gain · bandwidth	$M \cdot B_m$	GHz	100–400	2–10	20–250
Bias voltage	V_B	V	150–400	20–40	20–30

NOTE: The values were derived from various vendor data sheets and from performance numbers reported in the literature. They are guidelines for comparison purposes. Detailed values on specific devices for particular applications can be obtained from photodetector and receiver module suppliers.