CHAPTER

11

Receivers

About This Chapter

A fiber-optic receiver converts the optical signal transmitted through a fiber into an electronic form that can serve as input to other devices or communication systems at the receiver end of the system. This device contains two essential components—a detector, which converts an optical input into an electronic signal, and receiver electronics, which convert the raw detector output into a form usable by other equipment. In practice, this conversion may require some processing of the signal.

After defining the concept of receiver, this chapter first describes optical detectors, then covers their electronic functions. The chapter closes with examples of receiver circuits. Optical amplifiers and wavelength-division multiplexing, which sometimes are used at the receiver end of the system, are covered in Chapters 12 and 15, respectively.

Defining Receivers

Fiber-optic receivers detect optical signals and convert them to electronic signals usable by other equipment. In general, receivers include both optical and electronic devices.

Figure 11.1 shows major functions that receivers may perform. They fall into three general categories:

- *Optical pre-processing* of the input optical signal. This may include optical preamplification of the input signal to raise it to a level that improves receiver performance. If the input signal includes multiple optical channels, those must be separated by a *wavelength-division demultiplexer*, which directs each wavelength to a separate optical detector. This is vital because the detectors themselves are color-blind and cannot separate signals at different wavelengths. Like black-and-white film, detectors tell you the brightness of the input light, but not the color. Signals of different wavelengths must be separated before the detector, as shown

Detectors are color-blind.

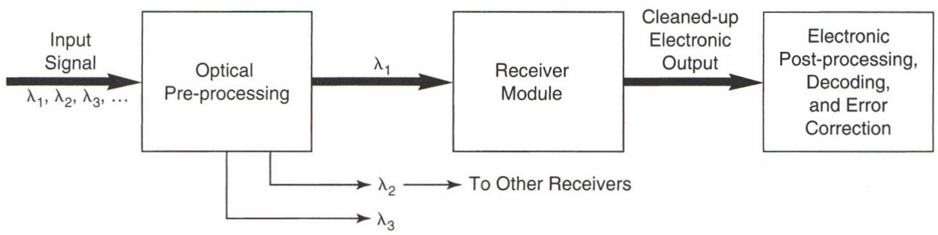


FIGURE 11.1 *Processing functions at the receiver end of a fiber system.*

in Figure 11.2. (This stage is not required if the input signal includes only one wavelength.) You'll learn about these functions in Chapters 12 and 15.

A digital receiver module produces a string of output bits.

- *Receiver module,* which converts the input light signal at one wavelength into an electronic form that represents either an analog signal or a series of input bits. The *detector* responds to input photons by producing a flow of electrons, so its raw output is an electrical current (with a few rare exceptions). All but the simplest receiver modules have electronic conversion and amplification stages that convert the current to a voltage, then amplify it to produce a stronger signal. Digital receivers include an additional stage that cleans up the output to produce a clear set of pulses. The output of the receiver module is a fresh signal, amplified and cleaned up. Figure 11.3 shows these stages. Note that the digital receiver includes an input analog section. You also can view the digital stage as an addition to an analog receiver. In either case, the digital version produces a string of output bits.

Electronic post-processing decodes bits from the receiver module.

- *Electronic post-processing* converts the raw output bits to the form needed by external systems. For digital systems, this can involve two stages: error correction and decoding. Error correction performs internal checks to verify that all bits have been received correctly, then tries to fix any mistakes. Decoding identifies how bits should be grouped and what they mean. These functions depend on the system, and usually are grouped with the system electronics rather than inside the receiver module. For

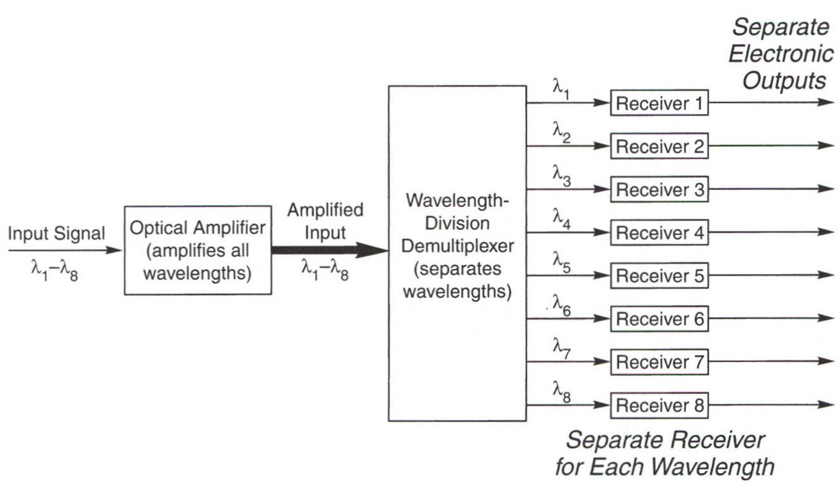


FIGURE 11.2 *Optical pre-processing amplifies and splits a WDM signal among receiver modules.*

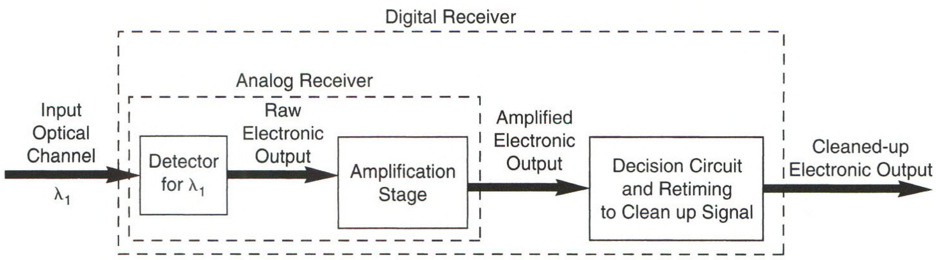


FIGURE 11.3
Receiver module includes analog and digital stages.

example, the receiver side of the XFP transceiver described in Chapter 10 produces a raw string of bits at a rate around 10 Gbit/s. Separate electronic post-processing circuits decode the signal to meet system requirements. The same receiver modules can be used for 10-Gigabit Ethernet and 10-Gbit/s telephone standards, but different post-processing is needed to decode the different signal formats. You'll learn more about those formats and standards in Chapters 19 and 20.

The receiver module, like the transmitter module, is often called an *opto-electronic* device because it converts optical signals into electronic form. As you learned in Chapter 10, the receiver module is often packaged with the transmitter module in a transceiver. We'll start by learning about detectors, then move on to the electronic side of the receiver module.

Detector Basics

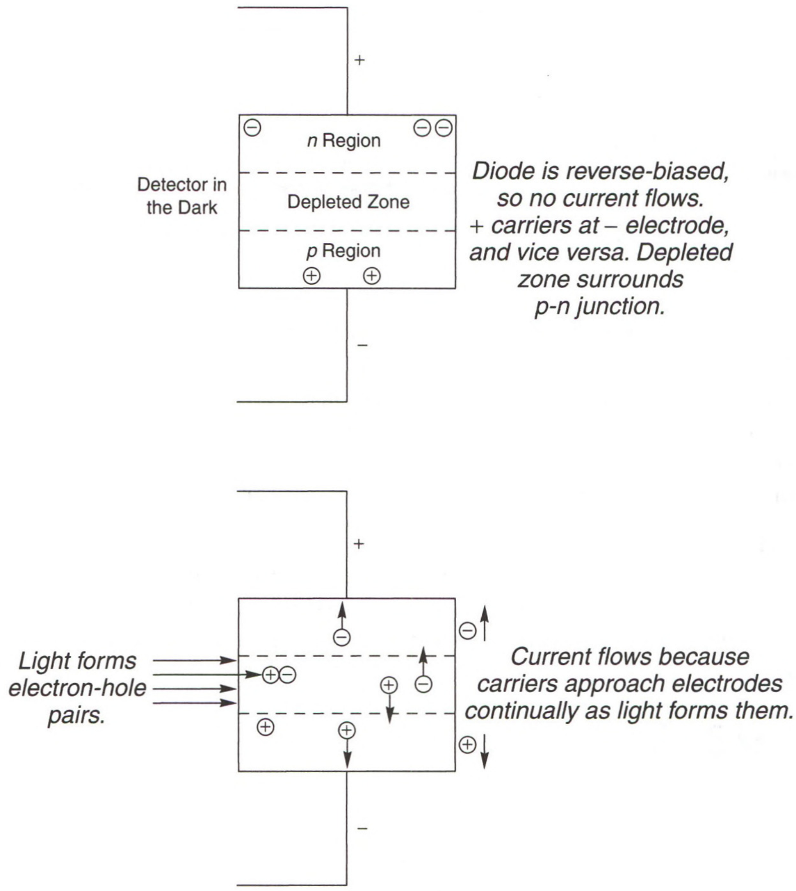
The detectors used in fiber-optic communications are semiconductor diodes that produce electron-hole pairs when illuminated by light. They are often called *photodiodes* or *photodetectors.* The incoming photons must have enough energy to raise electrons from the valence band to the conduction band. Because this bandgap energy depends on the material, the wavelength response also depends on the material. The diode also must be designed and operated so the current carriers can produce a signal that can be transmitted to other electronic devices.

The simplest photodetectors are solar cells, diodes in which internal structures generate electromagnetic fields that separate the electrons and holes produced by incident light. This separation generates a voltage without requiring any input electrical power. Solar cells work well for producing electricity, but are too slow and inefficient for use as detectors in communications.

Photodiodes are much faster and more sensitive if electrically reverse-biased, as shown in Figure 11.4. (Recall that LEDs and lasers are forward-biased to emit light.) The reverse bias draws current-carrying electrons and holes out of the junction region, creating a depleted region, which stops current from passing through the diode. Photons with enough energy can create electron-hole pairs in this region by raising an electron from the valence band to the conduction band, leaving a hole behind. The bias voltage causes these current carriers to move quickly away from the junction region, so a current flows proportional to the light illuminating the detector. Several types of detectors can be used in fiber-optic systems, as described below.

Semiconductor photodiodes are reverse-biased to detect light; they produce a current proportional to the illumination level.

FIGURE 11.4
Photodetector operation.



Composition and structure combine to determine the operational characteristics of photodetectors. We will start by looking at detector materials, then consider common structures. As you will see, the actual structures used are more complex than the simple example of Figure 11.4.

Detector Materials

The wavelengths at which detectors respond depend on their composition.

Photodetectors can be made of silicon, germanium, gallium arsenide, indium gallium arsenide, or other semiconductors. The wavelengths at which they respond to light depend on their composition. To produce a photocurrent, photons must have enough energy to raise an electron from the valence band to the conduction band—that is, their energy must equal or exceed the bandgap energy. The need to have at least this minimum energy means that photodetector sensitivity tends to drop steeply at the long-wavelength, low-energy end of the spectrum. Other effects, such as light absorption in other parts of the device, cause the response to drop more gradually for more energetic photons at shorter wavelengths.

Table 11.1 Typical operating ranges of important detectors

Material	Wavelengths (nm)
Silicon	400–1100
Germanium	600–1600
GaAs	400–900
InGaAs	900–1700
InGaAsP	800–1600

Table 11.1 lists approximate spectral ranges for important detector materials used in fiber-optic systems. Note that two of the most important semiconductor materials, silicon and gallium arsenide, are not sensitive at the 1280- to 1650-nm wavelengths used in long-distance fiber-optic systems. The band gaps in InGaAs and InGaAsP depend on the material composition, so the range of operating wavelengths may vary between devices. For example, while most fiber-optic InGaAs detectors are sensitive at 900 to 1700 nm, some InGaAs detectors respond to wavelengths longer than 2200 nm.

Silicon and GaAs have good response at 650 and 850 nm; InGaAs is used at 1250 to 1700 nm.

The response of each material also varies with wavelength. Figure 11.5 shows the relative response of silicon, germanium, GaAs, and InGaAs across the range of wavelengths normally used in fiber-optic systems. Silicon and GaAs have good response at the 650-nm

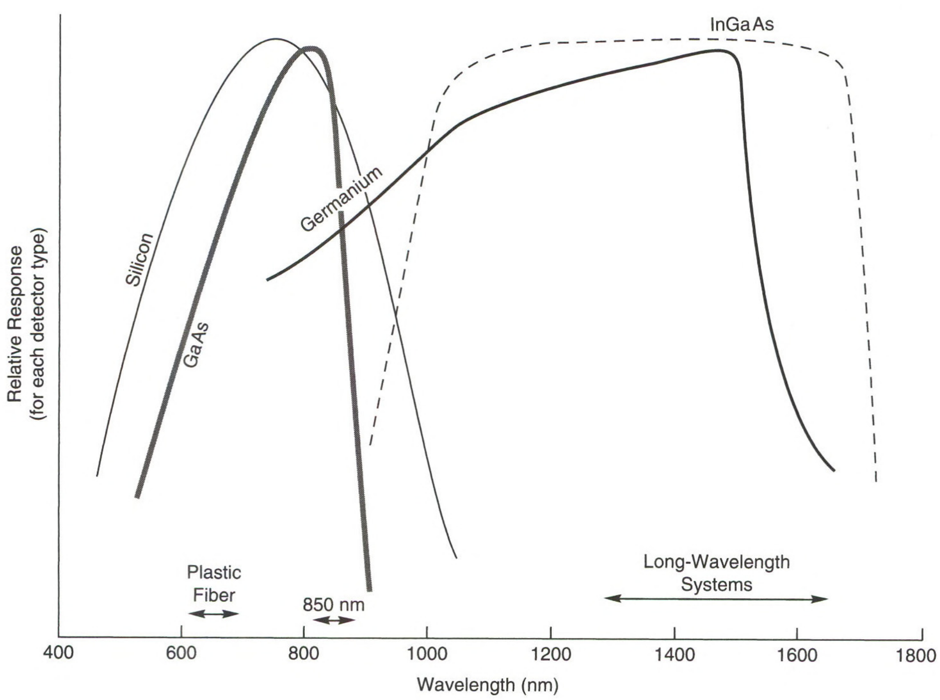


FIGURE 11.5
Detector response curves, showing quantum efficiency relative to the peak value for the material.

wavelength used in plastic fibers and the 850-nm wavelength used for short-distance transmission. Germanium has a very broad range, but response drops near 1550 nm and it suffers much higher noise levels than do other materials. InGaAs has response through the entire 1250 to 1700 nm range, making it the most common material for long-wavelength detectors. InGaAsP responds to similar wavelengths, depending on composition, but is not as widely used.

All these semiconductor materials also can be used in electronic circuits, allowing integration of detectors with amplifiers and other signal processing electronics in receivers. Detectors also can be combined with other electronic components to make hybrid receiver circuits.

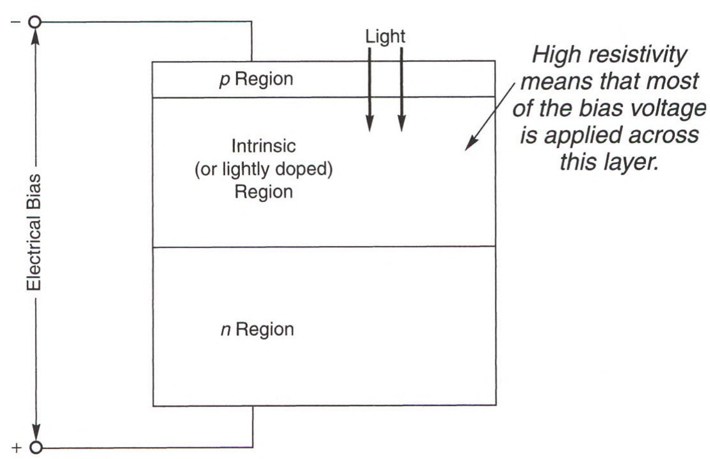
pn and *pin* Photodiodes

Photodiode sensitivity is improved by sandwiching an undoped intrinsic region between the *p* and *n* regions.

You saw earlier that photodetectors are reverse-biased diodes that generate current signals. They often are said to operate in a *photoconductive* mode because light changes the effective resistance of the device. However, they are not purely resistive devices because they contain *pn* junctions and function as diodes, which conduct current differently depending on the bias voltage. Purely resistive photoconductive detectors exist in which light produces current carriers that change the resistivity of a bulk semiconductor without a junction layer, but they are slow and not used as fiber-optic detectors.

Reverse biasing draws current carriers out of the central depleted region, blocking current flow unless light frees electrons and holes to carry current. The amount of current increases with the amount of light absorbed, and the light absorption increases with the thickness of the depleted region. Depletion need not rely entirely on the bias voltage. The same effect can be obtained if a lightly doped or undoped intrinsic semiconductor region is between the *p*- and *n*-doped regions shown in Figure 11.6. In a sense, such *pin* (*p*-intrinsic-*n*) photodiodes come predepleted because the intrinsic region lacks the impurities that can generate current carriers in the dark. This design has other practical advantages. By concentrating absorption in the intrinsic region, it avoids the noise and slow response that occur when the *p* region of ordinary *pn* photodiodes absorbs some light. The

FIGURE 11.6
A simple pin photodiode.



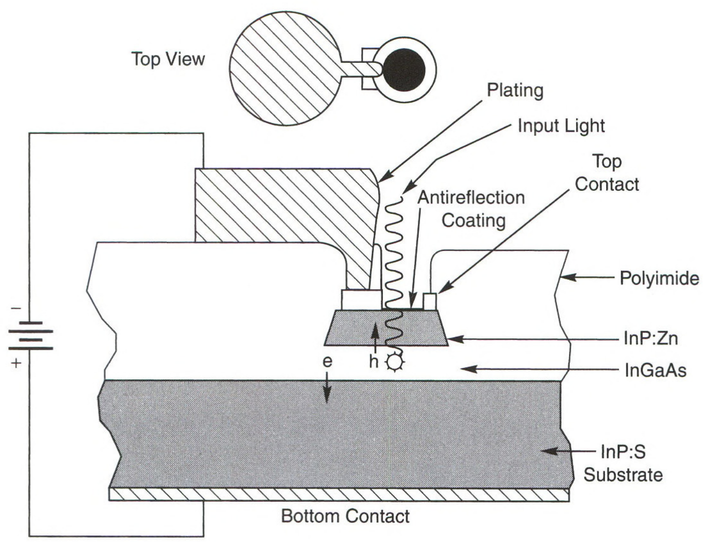


FIGURE 11.7
Structure of a multigigahertz pin *detector. (Copyright © 1993 Hewlett-Packard Company. Reproduced with permission.)*

bias voltage is concentrated across the intrinsic semiconducting region because it has higher resistivity than the rest of the device, helping raise speed and reduce noise.

The speed of *pin* photodiodes is limited by variations in the time it takes electrons to pass through the device. This time spread can be reduced in two ways—by increasing the bias voltage and/or by decreasing the thickness (and width) of the intrinsic layer. Reducing intrinsic layer thickness must be traded off against detector sensitivity because this reduces the fraction of the incident light absorbed. Typical biases are 3 to 20 V, although some devices have specified maximum bias above 100 V. Typical response times range from a few nanoseconds to about 5 ps. Sensitivity of *pin* detectors is measured as amperes of current generated per watt of light. For silicon, the peak sensitivity is about 0.7 A/W at 800 nm; InGaAs has a peak of around 1 A/W near 1600 nm. An important attraction of *pin* photodiodes is a large dynamic range; their output-current characteristics can be linear over 50 dB.

pin detectors can have response times well under 1 ns and dynamic ranges of 50 dB.

The speed and sensitivity of *pin* photodiodes are more than adequate for most fiber-optic applications, and they are widely used even in high-performance systems. Sending their electrical output directly to an electronic preamplifier can boost sensitivity.

pin photodiodes are widely used because of their high speed and good sensitivity.

The designs of actual *pin* photodiodes are more complex than this simple example, particularly in fast devices, like the multigigahertz detector in Figure 11.7. Light signals at 1200 to 1600 nm pass through the antireflection coating and upper layer of InP (which are transparent at those wavelengths) and are absorbed in the intrinsic InGaAs layer. Other designs direct light through the InP substrate, which is also transparent to the signal wavelengths.

Phototransistors

Phototransistors are used in low-cost, low-speed systems.

Some detectors have internal amplification, which increases their sensitivity. The simplest of these is a special type of transistor called a *phototransistor*, in which the incoming light

Table 11.2 Typical detector characteristics

Device	Responsivity	Rise Time	Dark Current
Phototransistor (Si)	18 A/W	2.5 μs	25 nA
Photodarlington (Si)	500 A/W	40 μs	100 nA
pin photodiode (Ge)	0.4 A/W	0.1–1 ns	100 nA
pin photodiode (Si)	0.5 A/W	0.1–5 ns	1–10 nA
pin photodiode (InGaAs)	0.8 A/W	0.005–5 ns	0.1–3 nA
Avalanche photodiode (Ge)	(voltage-dependent)	0.3–1 ns	400 nA (voltage-dependent)
Avalanche photodiode (Si)	10–125 A/W (voltage-dependent)	0.1–2 ns	10–250 nA (voltage-dependent)
Avalanche photodiode (InGaAs)	7–9 A/W (voltage-dependent)	0.1–0.5 ns	6–160 nA (voltage-dependent)

passes through the emitter region to illuminate the base, where it produces a photocurrent. The phototransistor amplifies the current generated in the base, just as an ordinary transistor amplifies its input base current.

The internal amplification stage gives the phototransistor much higher responsivity than a simple photodiode. However, this increase comes at a steep price in response time and linearity, and at some cost in noise, as you can see in Table 11.2. Most phototransistors are limited to speeds below the megahertz range. Commercial phototransistors normally are made of silicon. Their major uses are in sensors and in inexpensive fiber links.

Output of a phototransistor is fed to the base of a second transistor in a *photodarlington.* This is a simple, integrated darlington amplifier, which adds a second transistor to the phototransistor to increase the responsivity. This has the trade-offs of lowering speed and increasing noise. That constrains the photodarlington's uses even more narrowly than those of the phototransistor, but it offers higher responsivity for low-cost, low-speed applications.

Avalanche Photodiodes

Avalanche photodiodes are fast detectors with internal amplification.

The *avalanche photodiode* (APD) is another photodiode that provides internal amplification. It operates at much higher speeds, making it more useful for fiber-optic communications.

You can think of an APD as a two-stage device. The first stage is a conventional photodiode in which light generates current carriers. The second is an internal amplification stage based on avalanche multiplication in which a strong electric field accelerates the light-produced electrons so much that they can knock valence electrons out of the semiconductor lattice. At high voltage, the result is a near-avalanche of carriers—thus the name—that is still proportional to the amount of incident light. However, a further increase of the

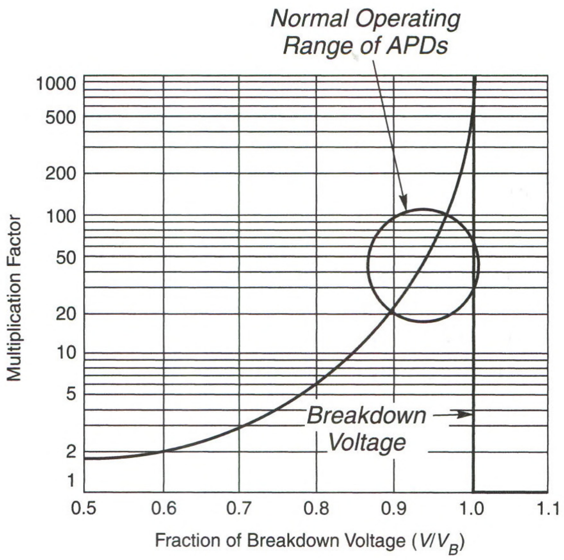


FIGURE 11.8
Increase of multiplication factor in APD.

voltage to a point called the *breakdown voltage,* V_B, causes current to flow freely through the semiconductor without regard to the amount of incident light; this can damage the device.

The factor by which each initial carrier is multiplied, called the *multiplication factor,* typically is 30 to 100. Multiplication factor M is defined as

The multiplication factor increases as bias voltage approaches the breakdown voltage.

$$M = \frac{1}{1 - \left(\dfrac{V}{V_B}\right)^n}$$

where V is the operating voltage, V_B is the breakdown voltage, and n is a number between 3 and 6, depending on the device characteristics. The multiplication factor can become very large as the operating voltage approaches the breakdown voltage. Care must be taken when increasing the operating voltage because reaching or exceeding the breakdown voltage can damage the device. A representative plot of multiplication factor as a fraction of breakdown voltage is shown in Figure 11.8. Note that multiplication factors of 100 require bias voltages within a few percent of breakdown. Typical APD operating voltages are 150 to 400 V in silicon but only 20 to 60 V in InGaAs, which has an inherently lower breakdown voltage.

APDs are fast, but the uneven nature of multiplication introduces noise. Avalanche gain is an average; not all photons are multiplied by the same factor. Signal power increases with roughly the square of the multiplication factor M, and at moderate values M increases faster than noise. However, as M reaches high levels, noise increases roughly as $M^{2.1}$, faster than M^2. As a result, APDs have an optimum multiplication factor to control noise; for silicon devices it is typically 30 to 100, but for InGaAs it is much lower.

Avalanche photodiodes require much higher operating voltages than the few volts normally used for *pin* photodiodes or other semiconductor electronics. The need for special circuits to provide this drive voltage, and to compensate for the temperature sensitivity of APD characteristics, makes APD receivers more complex than *pin* types. As Table 11.2 shows, APDs also suffer from higher dark currents and cannot match the rise times of the fastest *pin* detectors.

pin-FETs and Integrated Receivers

The distinction between detectors and the receivers that contain them sometimes can be hazy, especially when detectors are integrated on the same substrate with electronic circuits. One example is the *pin*-FET, which integrates a *pin* photodiode with an electronic amplifier circuit based on field-effect transistors. These devices are really *detector-amplifiers*, but they may be lumped together with detectors or simply called "detectors" themselves.

Performance Considerations

The factors that affect detector and receiver performance are complex and often interrelated. These considerations generally apply to both detectors and receivers, but some apply more to the detector. Remember that overall performance depends on the entire receiver system, and can be changed dramatically by replacing a detector or adding an optical preamplifier.

We can divide performance considerations into several broad categories. Four directly measure receiver performance: the strength of electrical signal generated in response to an optical input, internal noise levels, linearity, and the speed of the response. Signal coding and modulation format also play critical roles. Finally, the quality and power level of the optical input signal strongly influence performance. Let's look at each of these in turn.

Sensitivity

Sensitivity measures output signal produced for a given optical input.

Sensitivity measures the response to an optical input signal as a function of its intensity, in units such as amperes (of output signal intensity) per watt (of input light). Although sensitivity may sound like a simple concept, setting a precise definition can be tricky.

Detector sensitivity can be measured in two subtly different units. *Responsivity* is the ratio of electrical output from the detector to the input optical power. If the output current varies proportionally to the input, this is measured as amperes per watt (A/W). In practice, input powers usually are in the microwatt range, so responsivity is sometimes given as microamperes per microwatt (μA/μW), which is equivalent.

Quantum efficiency measures the fraction of incoming photons that generate electrons at the detector:

$$\text{Quantum efficiency} = \frac{\text{Electrons out}}{\text{Photons in}}$$

This sounds like the same thing as responsivity, but the two are not equivalent. Recall that the energy of a photon depends on the wavelength, so a 400-nm photon carries twice as much energy as an 800-nm photon. Suppose a detector generates one electron from every photon that reachs it at either wavelength. Then the input power at 400 nm would be twice the level at 800 nm, but the output current would be the same at both wavelengths. Thus responsivity—measured relative to power—at the shorter wavelength would be only half the level at the longer wavelength.

Both responsivity and quantum efficiency depend on the input wavelength, but their differences mean that the two curves are not interchangeable. The shape of the curve depends largely on the detector material, but the height also depends on the detector type and structure. Some curves, such as the one in Figure 11.5, show quantum efficiency at different wavelengths relative to the maximum value, rather than in absolute terms. You should always check the scales you're looking at.

Responsivity and quantum efficiency both depend on input wavelength and the detector material.

Typical values of responsivity from a *pin* detector alone are 0.4 to 1 A/W. InGaAs detectors typically have responsivity of 0.5 to 1 A/W in their long-wavelength range, and silicon has responsivity of 0.4 to 0.5 A/W at shorter wavelengths. (Note that according to the difference in wavelength, a silicon detector used at 800 nm should have about half the responsivity of an InGaAs detector used at 1600 nm.) Quantum efficiency of a detector with no internal amplification can approach 100%. Internal or external amplification can give much higher values by multiplying the number of electrons effectively generated by each incoming photon. Detector response also depends on operating temperature.

Receiver sensitivity is a different specification, the minimum optical input signal, usually in microwatts or dBm (decibels relative to one milliwatt) needed to operate at the required performance level. This quantity depends on the detector type as well as the receiver circuitry. For example, one receiver has sensitivity of −23 dBm with a *pin* detector, but −32 dBm with an avalanche photodiode as the detector. That reflects how internal amplification in the APD allows a receiver to process much weaker signals.

Dark Current and Noise-Equivalent Power

The electronic signal emerging from a detector includes noise as well as signal. The noise comes from many sources, including the optical input, the detector itself, and the amplification electronics. Electromagnetic interference can add noise by inducing currents in conductors in the receiver. The full complexities of noise are beyond the scope of this book, but you should understand two key concepts: dark current and noise-equivalent power.

An ideal detector generates an output signal that depends only on the input light, so in the dark it should produce no signal at all. Nature isn't that kind. Any detector generates some output current when it is operated in the normal manner but receives no light at all. This *dark current* measures the electrical noise inherent within the detector, which also is present when the detector is exposed to light. It's analogous to the low level of hiss you can hear during silent intervals on an analog tape cassette. It sets a floor on the minimum detectable signal, because a signal must produce more current than the dark current in order to be detected. Dark current depends on operating temperature, bias voltage, and the type of detector.

Dark current is the noise a detector generates in the dark.

Noise-equivalent power (NEP) is the input power needed to generate an electrical current equal to the root-mean-square noise from the detector (or receiver). This more directly measures the minimum detectable signal because it compares noise directly to optical power. NEP depends on the frequency of the modulated signal, the bandwidth over which noise is measured, the detector area, and the operating temperature. It's measured in the peculiar

Noise-equivalent power is the optical power needed to generate average detector noise.

units of watts divided by the square root of frequency (in hertz), or $W/Hz^{1/2}$. Specified values normally are measured with a 1-kHz modulation frequency and a 1-Hz bandwidth.

Speed and Bandwidth

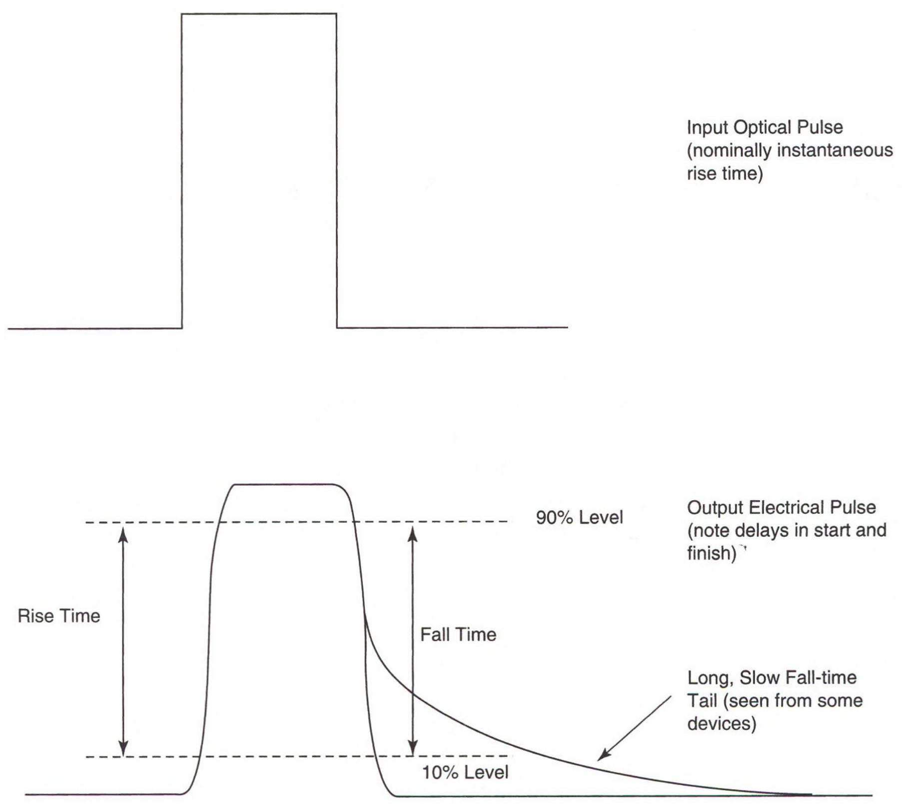
Detector bandwidth depends on rise time.

You can think of the speed of a detector in two ways. One is the time it takes to convert an input light signal into an output electronic signal. This measures how long the signal takes to pass through the detector, and has little impact on system operation because it does not change the shape of the pulses passing through. However, how fast the detector output responds to a change in the optical input changes the shape of the signal pulse, which does impact system performance. This can be measured as *rise time* or *bandwidth.*

Rise time is the time the output signal takes to rise from 10% to 90% of the final level after the input is turned on instantaneously, as shown in Figure 11.9. The *fall time* is how long the output takes to drop from 90% to 10% of the peak value after the input turns off abruptly. The two are not always symmetrical; some devices have long, slow-falling tails. Both are shown in Figure 11.9. Very slow fall times are undesirable because they can limit the detector's response speed more severely than can slow rise times.

Rise and fall times are a measure of bandwidth, the range of frequencies that a detector can reproduce in a signal. Detectors themselves can reproduce extremely low frequencies,

FIGURE 11.9
Rise time of a pulse.



although receiver electronics may limit low-frequency response. The most important limitation in fiber optics is the way detector response falls off at higher frequencies. If you study electronics, you will learn that the highest frequencies are responsible for the sharp edges on a square-wave function like the input digital pulse of Figure 11.9. Lose those high frequencies, and the edges of the signal pulse become rounded, and the pulse takes longer to rise and fall, as shown in the output of Figure 11.9.

Detector bandwidth usually is defined as the frequency at which the output signal has dropped to 3 dB (50%) below the power at a low frequency. This means that only half as much signal is getting through the detector at the higher frequency. Frequencies higher than the upper bound of the bandwidth are attenuated even more. As bandwidth decreases, the higher frequencies fade away, and the pulses become more rounded.

Loss of high frequencies rounds the edges of digital pulses.

If rise and fall times are equal, the 3-dB bandwidth can be estimated from the rise time using the formula

$$\text{Bandwidth} = \frac{0.35}{\text{Rise time}}$$

Thus a detector with 1-ns rise time has a 3-dB bandwidth of 350 MHz, while one with 10-ps rise time has a 3-dB bandwidth of 35 GHz. You can also flip the formula to estimate rise time if you know bandwidth:

$$\text{Rise time} = \frac{0.35}{\text{Bandwidth}}$$

Device geometry, material composition, electrical bias, and other factors all combine to determine bandwidth and rise time. For relatively slow devices, the rise time is proportional to the RC time constant—the photodiode capacitance multiplied by the sum of the load resistance and the diode's internal resistance. Reducing the equivalent capacitance can increase speeds. At higher speeds, two other factors limit rise time, the diffusion of current carriers and the time needed for carriers to cross the depletion region.

Linearity of Response

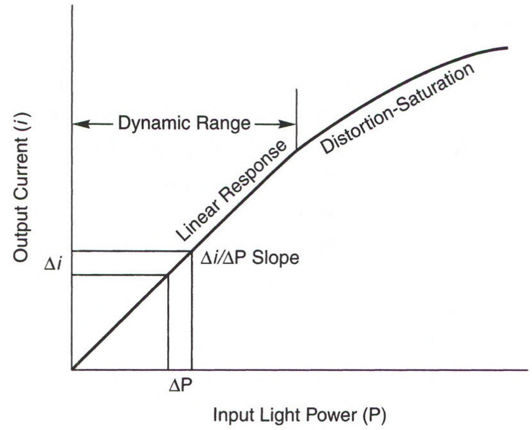
In an ideal detector, the output current would be a constant multiplied by the input power. This is called a *linear response*, and in practice it is available only over a limited range of input powers, called the *dynamic range*. Once the input exceeds that range, the output does not increase as rapidly, and the signal becomes distorted.

A detector has a linear response over a limited dynamic range.

As you can see in Figure 11.10, an increase of Δp in the input light produces an increase of Δi in the output current for a receiver or a detector. In the lower portion of the curve, where response is linear, $\Delta i/\Delta p$ is a constant. Once the power exceeds the detector's dynamic range, each additional photon no longer produces as many electrons in the output current, so the device starts to saturate. This happens every time the signal reaches this level, which could be every pulse in a digital system.

The result is distortion, much as when an audio speaker is driven with more power than it can handle. Exceeding the dynamic range in a digital receiver increases the bit error rate. In either case, inserting attenuators in front of the detector can reduce average signal intensity to a level within the dynamic range so the detector responds linearly.

FIGURE 11.10
Receiver output as a function of input light power. Both the detector and the receiver electronics affect dynamic range.



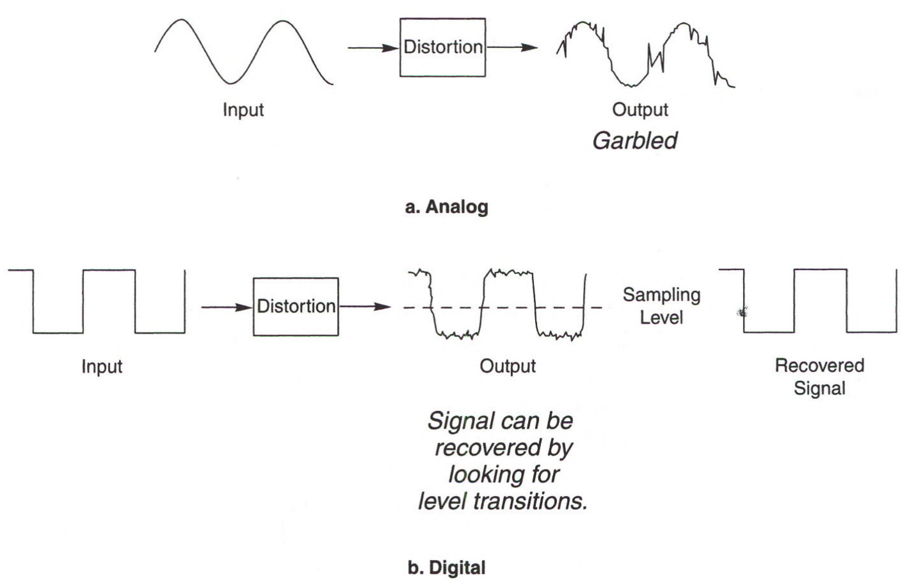
Receiver circuits also impact dynamic range, so you should consider their properties as well as those of the detector.

Detectors also need to receive a minimum level of input power, so the signal levels will exceed the background noise or dark current mentioned earlier.

Signal Coding and Modulation

Signal formats also affect detector and receiver performance. Analog modulation looks simple, because it only requires replicating the input signal. It also uses bandwidth efficiently. However, perfectly replicating the signal is difficult because detectors are not perfectly linear. Other complications include noise from the signal and the detector itself, and signal intensity. Figure 11.11 shows how distortion can affect analog signals.

FIGURE 11.11
Effects of distortion on (a) analog and (b) digital signals.



Digital signals can withstand the effects of noise and distortion better than analog signals. Conventional digital signals are binary codes in which the light is either "on" or "off"—corresponding to digital 1s and 0s. To interpret this type of input, a digital receiver needs only to tell whether the signal is "off" or "on," not to reproduce the input signal level. Digital receivers do this by deciding if pulses exceed a minimum discrimination level, as shown in Figure 11.11. Pulses that cross this threshold level are considered "on"; those that don't are considered "off." The decision is done by circuits in the receiver electronics.

Digital signals are more robust than analog signals, and can be extracted from noise.

Figure 11.3 shows that a digital receiver actually consists of an analog receiver followed by a set of circuits that clean up the digital output. First the circuits decide at what point the power crosses the threshold of being "on" or "off." Then they adjust the timing of the pulse to fit it into the right time interval. Sometimes called *regeneration* or *pulse recovery*, this process produces a fresh new signal for the next stage of transmission.

The analog receiver has to reproduce an analog input signal very accurately or the output will be distorted, as shown in Figure 11.11(a). The analog stages of the digital receiver don't have to be that good. A digital receiver is like a sound monitor that only needs to be sensitive enough to tell if someone is talking in a room. An analog receiver is like a sound monitor that lets you understand conversations in the room. If you've ever tried to understand the announcements in an airport, rail station, or bus terminal, you know there's a big difference between sound and intelligible speech. In a sense, a digital receiver is really a cheap and dirty analog receiver with a digital back end.

Analog receivers must reproduce signals much more accurately than digital receivers.

It's worth noting that the "off" state is not completely off in many fiber-optic systems, because many transmitters generate a very weak optical signal for 0 and a much stronger signal for a 1. That would pose a problem if the digital signal had to be reproduced precisely. However, decision circuits can easily tell if binary signals are in either an "on" or "off" state. In that way, noise can be removed from digital signals, something that is impossible with analog signals.

Digital transmission does not have to be binary. Some digital systems may have a series of steps in energy level, so the pulse may have, for example, four rather than two possible levels. That can carry more information, but requires telling the difference between four rather than two energy levels. Such systems have been demonstrated in the laboratory, but are not in practical use.

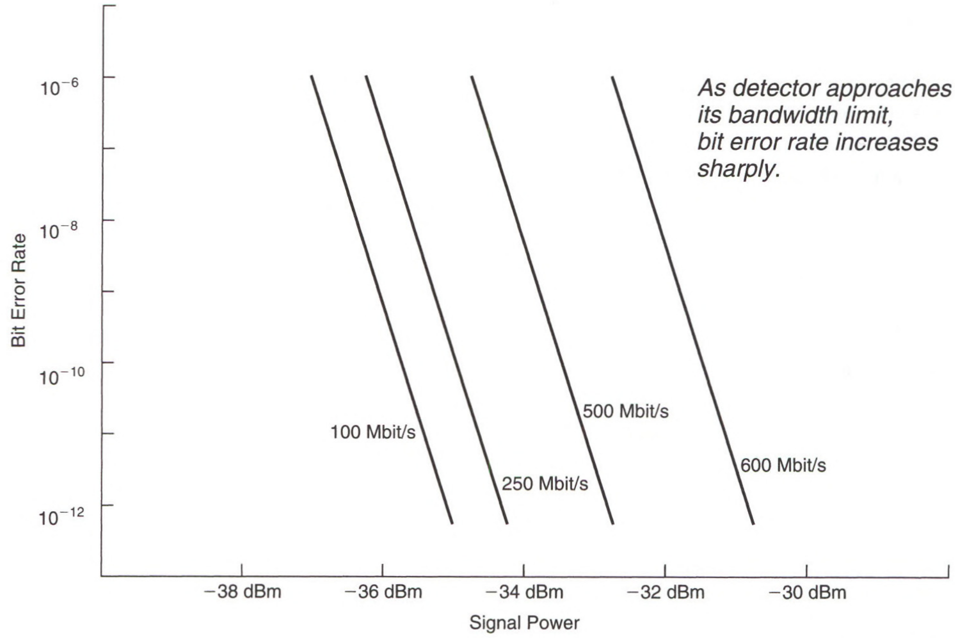
Signal Quality and Power

Power and quality of the input optical signal are important in detector and receiver response. The input consists of two components—the signal and the noise. The larger the difference between them, the better the signal quality. Usually the difference between the signal and the noise matters more than the absolute values of either. The ringing of someone else's cell phone is annoying if you're listening to a quiet passage of classical music, but you'd never hear the same ring if a heavy-metal band was playing full blast.

Signal-to-noise ratio measures analog signal quality.

Analog signal quality is measured as *signal-to-noise* ratio, usually in decibels. Normally average powers are used for both signal and noise. A 30-dB signal-to-noise ratio (or S/N ratio) means the signal amplitude is 1000 times higher than that of the noise. Whether or not that is acceptable depends on the situation, the type of signal, and who's measuring or listening. Many systems specify a minimum acceptable signal-to-noise ratio—for example, at certain points in a cable television network.

FIGURE 11.12
Bit error rate increases as average power drops and data rate increases.



Bit error rate measures quality of digital signals.

Digital signal quality normally is measured as *bit error rate,* the fraction of bits received incorrectly. Specified values depend on the application. For telephone and digital data transmission, the target normally is 10^{-12}, or no more than one incorrect bit in every trillion. Other applications may allow more errors.

The error rate depends on the number of photons received in a pulse. As the number of photons decreases, the chance of error increases. As you would expect, this means that the error rate increases as power decreases. This effect can be quite dramatic in certain power ranges. The plots in Figure 11.12 show how a 1-dB decrease in received power causes the bit error rate to jump from 10^{-12} to 10^{-9}.

Photons received per bit decreases for shorter pulses.

Increases in signal speed also can decrease the number of photons received per bit because shorter pulses have less time to deliver photons. Signal power measures the number of photons delivered per unit time, so the shorter the pulse, the fewer photons delivered during it. Suppose, for example, your laser transmitter delivers an average power of one microwatt at a wavelength of 1 μm, which equals roughly 5×10^{12} (five trillion) photons a second. At a data rate of 1 Gbit/s, that comes to roughly 5000 photons per bit interval. Raise the data rate to 10 Gbit/s and you have an average of only 500 photons per bit.

That's an average, and since there are both "on" and "off" bits, it might sound pretty easy to tell the bits apart: No photons should arrive during an "off" bit, so 1000 photons should arrive during an "on" bit. However, detectors don't sense every photon; they sense noise during the "off" pulses, and the goal is to have very low error rates, in the range of 10^{-12}—one error in a trillion bits. The more the power is reduced, the more likely an error is to occur. You can see this effect in Figure 11.12, where a small increase in data rate or power causes a large increase in error rate. The effect is strongest as the detector approaches its bandwidth limit.

Electronic Functions

Converting an optical signal into electrical form is only the first part of a receiver's job. The raw electrical signal generally requires some further processing before it can serve as input to a terminal device at the receiver end. Typically, photodiode signals are weak current signals that require amplification and conversion to voltage. In addition, they may require such cleaning up as squaring off digital pulses, regenerating clock signals for digital transmission, or filtering out noise introduced in transmission. The major electronic functions are as follows:

Detector output must be processed before other equipment can use the electronic signal.

1. Preamplification
2. Amplification
3. Equalization
4. Filtering
5. Discrimination or decision
6. Timing

If you're familiar with audio or other electronics, you will recognize some of these functions. Not all are required in every receiver, and even some of those included may not be performed by separate, identifiable devices. A phototransistor, for example, both detects and amplifies. And many moderate-performance digital systems don't need special timing circuits. Nonetheless, each of these functions may appear on block diagrams such as in Figure 11.3. Their operation is described briefly below.

Preamplification and Amplification

Typical optical signals reaching a fiber-optic receiver are 1 to 10 μW and sometimes lower. If a *pin* photodiode with 0.6 to 0.8 A/W responsivity detects such signals, its output current is in the microampere range and must be amplified for most uses. In addition, most electronics require input signals as voltage, not current. Thus, detector output must be amplified and converted.

Microampere-level *pin* detector outputs must be converted to logic-level voltages.

Receivers may include one or more amplification stages. Often the first is called preamplification because it is a special low-noise amplifier designed for weak input. (An optical amplifier placed in front of a detector also may be called a preamplifier.) In some cases, as mentioned earlier, the preamplifier may be packaged with the detector. The preamplifier output often goes into an amplifier, much as the output of a tape-deck or CD preamplifier goes to an audio amplifier that can produce the power needed to drive speakers.

Equalization

Detection and amplification can distort the received signal. For example, high and low frequencies may not be amplified by the same factor. The equalization circuit evens out these differences, so the amplified signal is closer to the original. Much the same is done in analog high-fidelity equipment, where standard equalization circuits process signals from tape heads and phonograph cartridges so they more accurately represent the original music.

Filtering blocks noise while transmitting the signal.

Filtering

Filtering helps increase the S/N ratio by selectively attenuating noise. This can be important when noise is at particular frequencies (e.g., a high-frequency hiss on analog audio tapes). It is most likely to be used in fiber optics to remove undesired frequencies close to the desired signal, such as harmonics.

Discrimination circuits generate digital pulses from an analog input.

Discrimination

Pulse regeneration requires circuitry to decide if the input is on or off.

So far, the functions you've looked at are needed to reproduce the original waveform for both analog and digital receivers. However, a further stage is needed to turn a received analog signal back into a series of digital pulses—decoding and discrimination. Rectangular pulses that started with sharp turn-on and turn-off edges have been degraded into unboxy humps, as shown in Figure 11.13. Dispersion may have blurred the boundaries between pulses.

As mentioned earlier, this rounding of square pulses represents loss of high frequencies, which make up the sharp rising and falling edges of the pulse, so if they are lost, the pulses lose their square edges. The remaining low-frequency components contain most of the

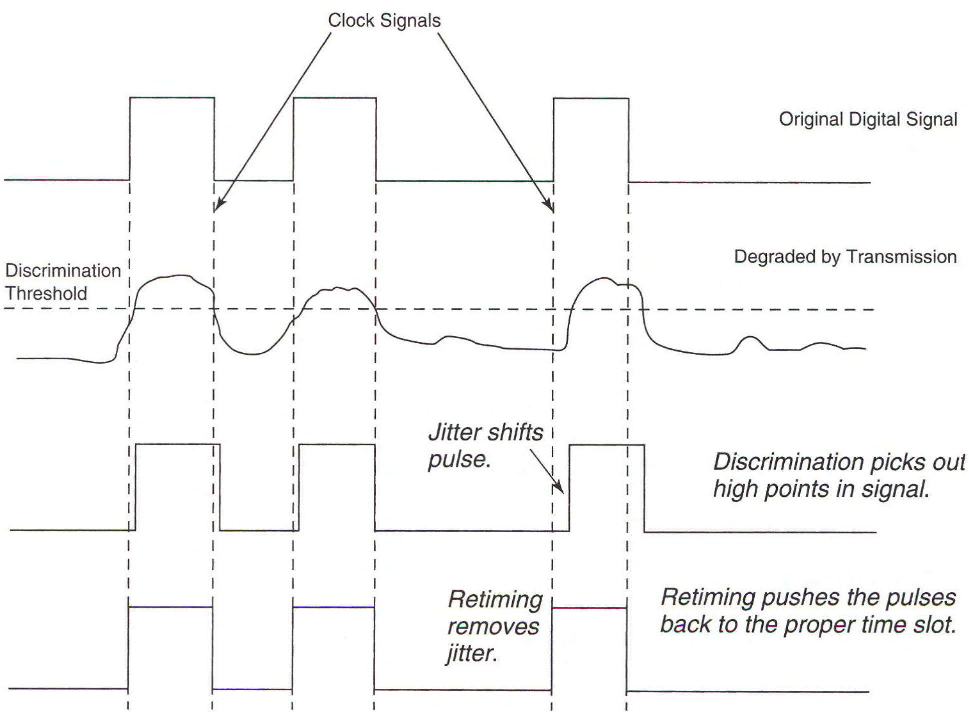


FIGURE 11.13 *Discrimination and retiming regenerate digital pulses.*

information needed, but they are not clean enough to serve as input to other electronic devices. Regeneration of clean pulses requires circuitry that decides whether or not the input is in the on or off state by comparing it to an intermediate threshold level. The decision circuit generates an "on" pulse if the power is above the threshold; otherwise it produces an "off" signal. Care must be taken in selecting this threshold level to avoid misinterpreting input; too low a threshold, for example, could turn noise spikes in the off state into signal pulses.

Timing

Another essential task in many receivers, particularly in high-performance systems, is resynchronizing the signal. Digital signals are generated at a characteristic clock rate, such as once every nanosecond for a 1-Gbit/s data stream. You can see in Figure 11.13 that discrimination circuits do not necessarily spot the exact times the pulses start and end. These random errors, called *jitter*, can cause the signal to drift from the clock rate, introducing errors.

Timing of digital pulses often must be resynchronized.

Timing synchronization recreates the clock signal (the dashed vertical lines in Figure 11.13) and puts the regenerated pulses in the right time slots. It is an essential part of cleaning up signals at a sophisticated receiver.

Packaging Considerations

As with transmitters, packaging is important for receivers. The basic requirements are electronic, mechanical, and optical interfaces that are simple and easy to use. The main mechanical issues are mounts. Electronic interfaces must allow for input of bias voltage and amplifier power (where needed) and for output of signals in the required format. Details can vary significantly.

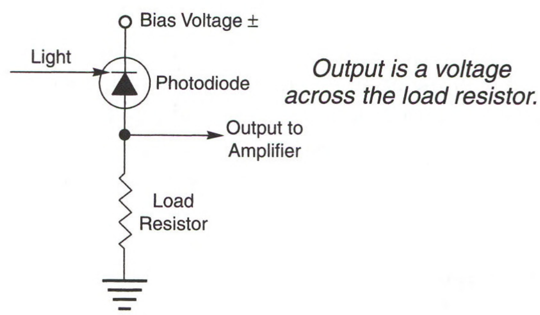
Optical interface requirements are simpler than for transmitters because mechanical tolerances for aligning fibers with detectors generally are looser. The active areas of detectors are larger than the cores of single-mode fibers. Larger-core multimode fibers transmit signals at slower speeds, so they normally are used only with slower detectors with larger active areas. In practice, receivers are assembled with integral fiber pigtails or connectors that collect light from the input fiber and deliver it to the detector.

In general, packaged receivers look very much like transmitters, and often the two are packaged together as a transceiver. You may have to read the labels to tell them apart. Detector modules are packaged inside receivers just as light-source modules are put inside transmitters. Internal design constraints become increasingly severe at high frequencies because of the problems inherent in high-frequency electronic transmission.

Sample Receiver Circuits

Details of receiver circuitry vary widely with the type of detector used and with the purpose of the receiver. For purposes of this book, I will show only a few simple circuits for important devices and avoid detailed circuit diagrams.

FIGURE 11.14
Basic circuit for photoconductive pin *or* pn *photodiode.*



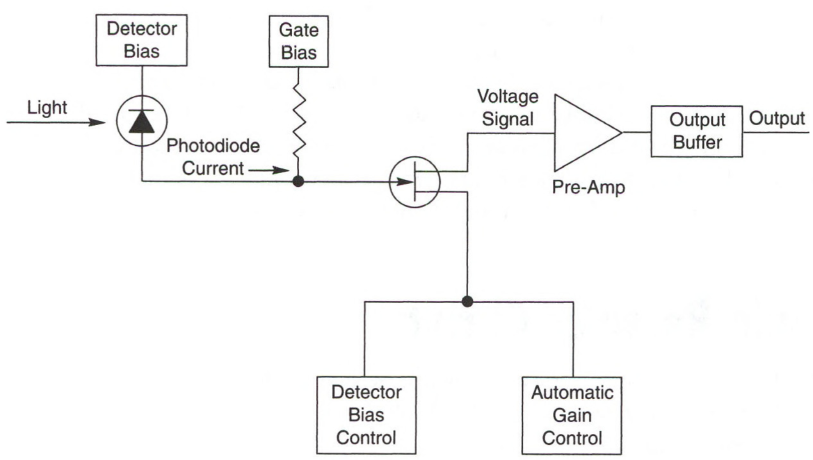
Photoconductive Photodiodes

Photoconductive photodiodes have a load resistor in series with the bias voltage.

The typical *pin* or *pn* photodiode used in a fiber-optic receiver is used in a circuit with a reverse-bias voltage applied across the photodiode and a series load resistor, such as that shown in Figure 11.14. In this mode, the photodiode is photoconductive because the photocurrent flowing is proportional to the nominal resistance of the illuminated photodiode. This simple circuit converts the photocurrent signal from a photodiode into a voltage signal.

The division of the bias voltage between the photodiode and the fixed resistor depends on illumination level. The higher the illumination of the photodiode, the more current it will conduct and, thus, the larger the voltage drop across the load resistor. In the simple circuit shown, the signal voltage is the drop across the load resistor. Most circuits are more complex, with amplification stages beyond the load resistor, as in *pin*-FET and detector-preamplifier circuits. Figure 11.15 is a block diagram of one circuit that includes automatic gain control, which can increase dynamic range by turning down the amplification factor before any other components are overloaded.

FIGURE 11.15
Block diagram of pin-FET receiver circuit.



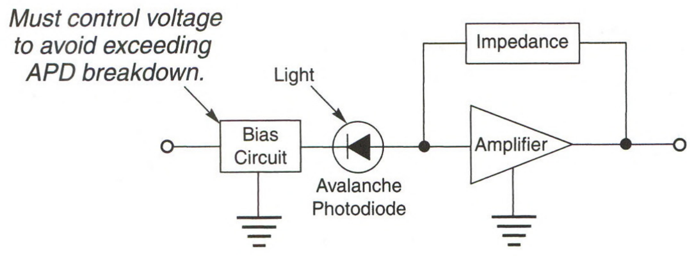


FIGURE 11.16
Basic receiver circuit for avalanche photodiode.

Avalanche Photodiode Circuits

The circuits used for avalanche photodiodes are conceptually similar to those used for photoconductive *pin* photodiodes. However, because of the high bias voltages required and the sensitivity of the photodiode to bias voltage, care must be taken to assure stable bias voltage. This adds to circuit complexity, as shown in the block diagram of Figure 11.16.

10-Gbit/s Receiver Module

Designs for 10-Gbit/s receivers are highly modularized, as shown in the block diagram of Figure 11.17. Optical input is directed to a *pin* photodiode, then amplified in a preamplifier before being transmitted (in electronic form) to an automatic gain-control circuit. Outputs from that circuit go to a clock and regeneration circuit and to a separate circuit that detects service outages and triggers external alarms. The clock and regeneration chip interfaces with a voltage-controlled oscillator and delivers two output signals: one containing the data, the other a clock signal. That clock can be used by electronic demultiplexer circuits (not shown here) to step the electronic data rate to slower speeds.

The receiver module shown in Figure 11.17 is a simple one that converts an optical input at 10 Gbit/s into a raw electronic signal at 10 Gbit/s. It does not include such electronic functions as forward error correction or demultiplexing to lower speeds for signal distribution. Such modules can be combined with transmitters to make the transceivers you learned about in Chapter 10.

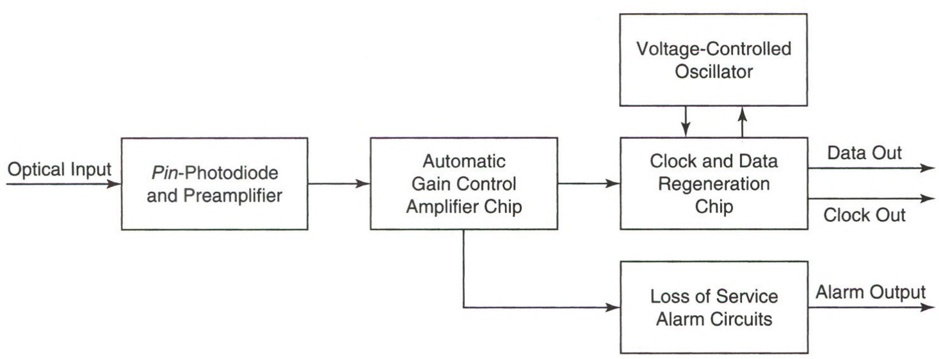


FIGURE 11.17
Elements of a 10-Gbit/s receiver.

What Have You Learned?

1. A receiver detects optical signals and converts them to electronic form.
2. A digital receiver includes an optical detector, an electronic amplifier, and circuits for retiming and regenerating the original digital signal. An analog receiver is similar, but lacks the retiming and regeneration circuits.
3. Wavelength-division demultiplexing must be performed before the optical detector because the detector is color-blind. One detector is needed for each optical channel.
4. Electronic post-processing corrects errors and decodes the sequence of incoming bits after the receiver module converts them to electronic form.
5. When a photon of sufficient energy strikes a semiconductor detector, it excites an electron from the valence band into the conduction band, producing an electron and a hole. This produces a current that flows through a reverse-biased semiconductor photodiode. Electronic circuits in the receiver convert this current signal into a voltage signal.
6. Detectors respond to photons that have enough energy to raise electrons from the valence band to the conduction band. The wavelengths at which they respond depend on composition. Silicon responds at 400 to 1000 nm. InGaAs responds at 800 to 1700 nm.
7. A high-resistivity intrinsic layer between the *p* and *n* layers of a *pin* photodiode absorbs light and improves its sensitivity. *pin* photodiodes are widely used for their high speed and sensitivity.
8. A high bias current creates an internal cascade of electrons in an avalanche photodiode, multiplying its electrical output to higher levels than those produced by *pin* photodiodes. However, APDs are slower than *pin* photodiodes and have higher noise.
9. Detector sensitivity is the output signal produced for a given input power. Responsivity is the current per watt of optical input. Quantum efficiency is the fraction of incoming photons that generate electrons.
10. Dark current and noise-equivalent power measure noise in detectors.
11. The bandwidth of a detector depends on its rise time in response to a signal. Loss of high frequencies reduces rise time and rounds sharp-cornered signal pulses.
12. Detectors operate best over a limited dynamic range, where their output depends linearly on the input signal.
13. Digital signals are more robust than analog signals because receivers do not have to reproduce digital signals as accurately.
14. Signal-to-noise ratio measures the quality of analog signals. Bit error rate measures the quality of digital signals.
15. A receiver's ability to detect pulses depends on the number of photons in the pulse.

What's Next?

In Chapter 12, I move on to optical amplifiers and to electro-optic repeaters and regenerators, which combine the functions of receivers and transmitters.

Further Reading

S. R. Forrest, "Optical detectors for lightwave communication," pp. 569–599 in Stewart E. Miller and Ivan P. Kaminow, eds., *Optical Fiber Telecommunications II* (Academic Press, 1988)

David A. Johnson, *Handbook of Optical Through the Air Communications* (*http://www.imagineeringezine.com/ttaoc/detector.html*)

Gerd Keiser, *Optical Fiber Communications* (McGraw-Hill, 2000), See Chapter 6 "Photodetectors" and Chapter 7 "Optical Receiver Operation".

Jim Rue and Bouchiab Nessar, "High speed avalanche photodiode optical receivers," *Fiberoptic Product News* (November 1999)

Questions to Think About

1. The input signal at a receiver is -30 dBm (1 μW), which is too low for your *pin* photodiode detector. What alternatives are there to increase receiver sensitivity?
2. An input signal is -30 dBm (1 μW). If its data rate is 1 Gbit/s, how much energy does each pulse contain, remembering that a power of one watt equals one joule per second? If the signal is at 1.5 μm, how many photons does that correspond to, using the following equation?

$$E = \frac{1.989 \times 10^{-19}(\text{joules}/\mu\text{m})}{\lambda(\mu\text{m})}$$

3. If a detector has a response of 1 μA/μW and the input is -30 dBm, what is the output current? How many electrons per second does this correspond to, recalling that 1 A = 6.24×10^{18} electron charges per second? How many electrons would be contained in a 1-nanosecond pulse?
4. A silicon *pin* detector has peak sensitivity of 0.7 A/W at 800 nm. If the input signal is -20 dBm, how many electrons does a 1-ns pulse produce? Use the equations and conversion factors from Questions 2 and 3.
5. The rise time of an InGaAs *pin* photodiode is 0.005 ns. The rise time of an InGaAs avalanche photodiode at the same wavelength is 0.1 ns. All other things being equal, how much larger is the bandwidth of the *pin* photodiode? If the rise time is all that limits the bandwidth of the two devices, what are their bandwidths?

6. The breakdown voltage of a silicon APD is 100 V. What voltage should it be operated at to have an electron multiplication factor of 20?
7. The dark current in a germanium *pin* photodiode is 100 nA, compared to 1 nA in an InGaAs *pin* photodiode. Suppose that all other things are equal, and the germanium detector has a sensitivity of −15 dBm, limited by dark current. What would be the sensitivity of the InGaAs detector?

Chapter Quiz

1. How many separate receivers are required for a 16-channel wavelength-division multiplexed system with an optical preamplifier that provides 15-dB gain on all channels?
   a. 1
   b. 4
   c. 8
   d. 16
   e. 32
2. When would an optical preamplifier be used at the receiver end of a system?
   a. always
   b. when input power is below 1 mW
   c. when the input signal contains multiple optical channels
   d. when input power is below receiver sensitivity
   e. never
3. What is present in a digital receiver that is not present in an analog receiver?
   a. nothing
   b. a detector
   c. thresholding and retiming circuits
   d. amplification circuits
   e. wavelength-division multiplexing
4. Photodiodes used as fiber-optic detectors normally are
   a. reverse-biased.
   b. thermoelectrically cooled.
   c. forward-biased.
   d. unbiased to generate a voltage like a solar cell.
   e. none of the above
5. Silicon detectors are usable at wavelengths of
   a. 800 to 900 nm.
   b. 1300 nm.

c. 1550 nm.

d. all of the above

6. Which detector material is most often used in the 1550-nm window?

a. silicon

b. InGaAs

c. GaAs

d. germanium

e. all of the above

7. A *pin* photodiode is a

a. point-contact diode detector in which a pin makes contact with the semiconductor.

b. semiconductor detector with an undoped intrinsic region between *p* and *n* materials.

c. circuit element used in receiver amplification.

d. photovoltaic detector.

e. hybrid detector-amplifier.

8. A phototransistor

a. has an internal amplification stage based on avalanche multiplication of electrons.

b. has an external amplification stage containing a single transistor.

c. generates a photocurrent in the base of a transistor, which amplifies the signal.

d. is an ordinary transistor that generates an optical signal under bright lights.

e. is the same as a photodarlington.

9. An avalanche photodiode

a. has an internal amplification stage based on avalanche multiplication of electrons.

b. has an external amplification stage containing a single transistor.

c. generates a photocurrent in the base of a transistor, which amplifies the signal.

d. is an ordinary transistor that generates an optical signal under bright lights.

e. is the same as a photodarlington.

10. What type of photodetector could have a responsivity of 20 amperes per watt?

a. silicon *pin* photodiode

b. silicon avalanche photodiode

c. InGaAs *pin* photodiode

d. InGaAs avalanche photodiode

e. none

11. What bit error rate is most often specified for digital telecommunications systems?

a. 40 dB

b. 10^{-4}

c. 10^{-6}

d. 10^{-12}

e. 10^{-18}

12. Noise equivalent power is

a. optical input power required to generate a signal equal to the noise.

b. noise required to equal the signal intensity.

c. the power of the current generated when a detector is in the dark.

d. noise present in the electrical output signal.

13. What happens when you increase the bias voltage above the breakdown voltage in an avalanche photodiode?

a. You stabilize the output current.

b. You stop the avalanche of electrons produced inside the semiconductor.

c. You get in trouble because that can damage the APD.

d. You increase signal-to-noise ratio to infinity.

14. What's the maximum value of quantum efficiency possible in a *pin* photodiode?

a. 0

b. 0.5

c. 0.9

d. 1.0

e. 100