CHAPTER 7

OPTICAL DETECTORS AND FIBER OPTIC RECEIVERS

LEARNING OBJECTIVES

Upon completion of this chapter, you should be able to do the following:

1. Explain the principal properties of an optical detector and fiber optic receiver.
2. Detail semiconductor optical detector performance and capability requirements necessary for the successful implementation of fiber optic systems.
3. List the main components of a fiber optic receiver.
4. Discuss receiver sensitivity, dynamic range, and other key operational parameters used to define receiver performance.

INTRODUCTION TO OPTICAL DETECTORS AND FIBER OPTIC RECEIVERS

Chapter 6 taught you that a fiber optic transmitter is an electro-optic device capable of accepting electrical signals, converting them into optical signals, and launching the optical signals into an optical fiber. The optical signals propagating in the fiber become weakened and distorted because of scattering, absorption, and dispersion. The fiber optic device responsible for converting the weakened and distorted optical signal back to an electrical signal is a fiber optic receiver.

A **fiber optic receiver** is an electro-optic device that accepts optical signals from an optical fiber and converts them into electrical signals. A typical fiber optic receiver consists of an optical detector, a low-noise amplifier, and other circuitry used to produce the output electrical signal (see figure 7-1). The optical detector converts the incoming optical signal into an electrical signal. The amplifier then amplifies the electrical signal to a level suitable for further signal processing. The type of other circuitry contained within the receiver depends on what type of modulation is used and the receiver electrical output requirements.

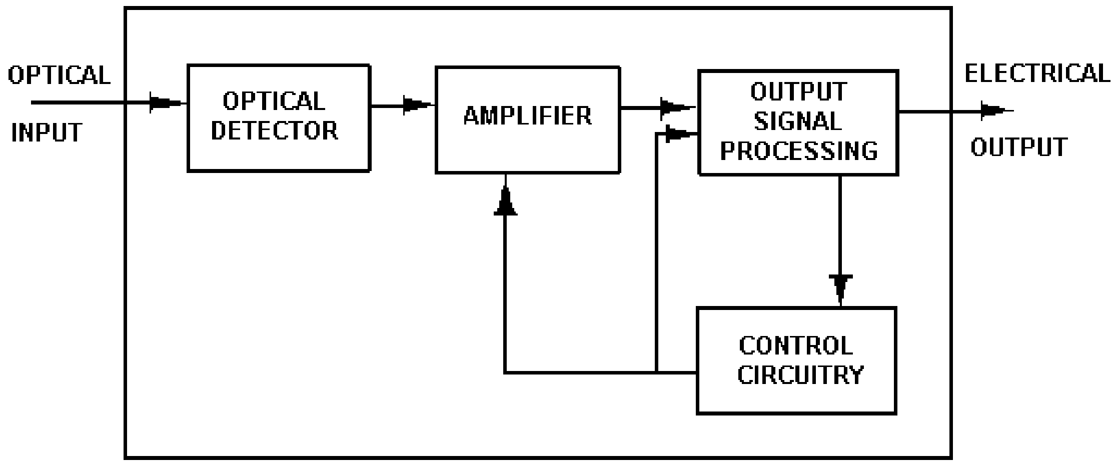

Figure 7-1.—Block diagram of a typical fiber optic receiver.

Receiver spectral response, sensitivity, frequency response, and dynamic range are key receiver performance parameters that can affect overall system operation. The choice of optical detector materials and structures determines the spectral response. Silicon (Si), gallium arsenide (GaAs), and gallium aluminum arsenide (GaAlAs) are typical detector materials used for receiver operation in the 850-nm wavelength region. germanium (Ge), indium phosphide (InP), and indium gallium arsenide (InGaAs) are examples of detector materials used for receiver operation in the 1300-nm and 1550-nm wavelength regions.

The **receiver sensitivity** is the minimum amount of optical power required to achieve a specific receiver performance. For digital transmission at a given data rate and coding, this performance is described by a maximum bit-error rate (BER). In analog systems, for a given modulation and bandwidth, it is described by a minimum signal-to-noise ratio (SNR). **Dynamic range** refers to the range of optical power levels over which the receiver operates within the specified values. It usually is described by the ratio of the maximum input power to the sensitivity. Before discussing receiver sensitivity, bandwidth, dynamic range, and frequency response in more detail, we discuss the main types of optical detectors used in fiber optics.

OPTICAL DETECTORS

A **transducer** is a device that converts input energy of one form into output energy of another. An **optical detector** is a transducer that converts an optical signal into an electrical signal. It does this by generating an electrical current proportional to the intensity of incident optical radiation. The relationship between the input optical radiation and the output electrical current is given by the detector responsivity. Responsivity is discussed later in this chapter.

OPTICAL DETECTOR PROPERTIES

Fiber optic communications systems require that optical detectors meet specific performance and compatibility requirements. Many of the requirements are similar to those of an optical source. Fiber optic systems require that optical detectors:

- Be compatible in size to low-loss optical fibers to allow for efficient coupling and easy packaging.
- Have a high sensitivity at the operating wavelength of the optical source.
- Have a sufficiently short response time (sufficiently wide bandwidth) to handle the system's data rate.
- Contribute low amounts of noise to the system.
- Maintain stable operation in changing environmental conditions, such as temperature.

Optical detectors that meet many of these requirements and are suitable for fiber optic systems are semiconductor photodiodes. The principal optical detectors used in fiber optic systems include semiconductor positive-intrinsic-negative (PIN) photodiodes and avalanche photodiodes (APDs).

SEMICONDUCTOR PHOTODIODES

Semiconductor photodiodes generate a current when they absorb photons (light). The amount of current generated depends on the following factors:

- The wavelengths of the incident light and the responsivity of the photodiode at those wavelengths
- The size of the photodiode active area relative to the fiber core size
- The alignment of the fiber and the photodiode

The optical fiber is coupled to semiconductor photodiodes similarly to the way optical sources are coupled to optical fibers. Fiber-to-photodiode coupling involves centering the flat fiber-end face over the photodiode active area. This is normally done directly by butt coupling the fiber up to the photodiode surface. As long as the photodiode active area is larger than that of the fiber core, fiber-to-detector coupling losses are very low. In some cases a lens may be used to couple the fiber end-face to the detector. However, this is not typically done.

SEMICONDUCTOR MATERIAL AND DEVICE PROPERTIES

The mechanism by which optical detectors convert optical power into electrical current requires knowledge of semiconductor material and device properties. As stated in chapter 6, providing a complete description of these properties is beyond the scope of this manual. In this chapter we only discuss the general properties of semiconductor PINs and APDs.

Semiconductor detectors are designed so that optical energy (photons) incident on the detector active area produces a current. This current is called a **photocurrent**. The particular properties of the semiconductor are determined by the materials used and the layering of the materials within the device. Silicon (Si), gallium arsenide (GaAs), germanium (Ge), and indium phosphide (InP) are the most common semiconductor materials used in optical detectors. In some cases aluminum (Al) and indium (In) are used as dopants in the base semiconductor material.

Responsivity

Responsivity is the ratio of the optical detector's output photocurrent in amperes to the incident optical power in watts. The responsivity of a detector is a function of the wavelength of the incident light and the efficiency of the device in responding to that wavelength. For a particular material, only photons of certain wavelengths will generate a photocurrent when they are absorbed. Additionally, the detector material absorbs some wavelengths better than others. These two properties cause the wavelength dependence in the detector responsivity. Responsivity is a useful parameter for characterizing detector performance because it relates the photocurrent generated to the incident optical power.

PIN PHOTODIODES

A **PIN photodiode** is a semiconductor positive-negative (p-n) structure with an intrinsic region sandwiched between the other two regions (see figure 7-2). It is normally operated by applying a reverse-bias voltage. The magnitude of the reverse-bias voltage depends on the photodiode application, but typically is less than a few volts. When no light is incident on the photodiode, a current is still produced. This current is called the **dark current**. The dark current is the leakage current that flows when a reverse bias is applied and no light is incident on the photodiode. Dark current is dependent on temperature. While dark current may initially be low, it will increase as the device temperature increases.

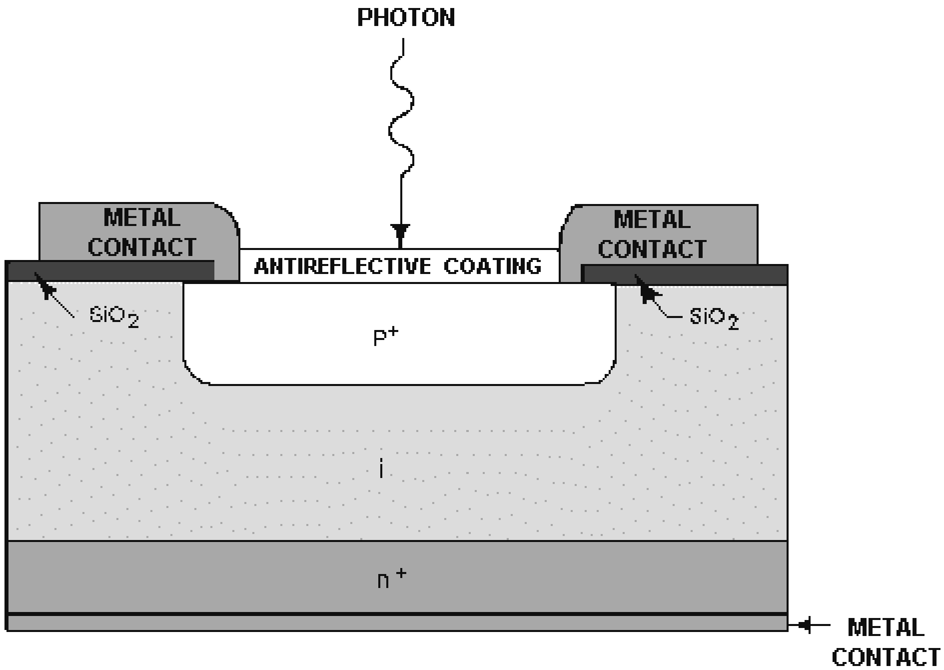

Figure 7-2.—The basic structure of a PIN photodiode.

Response Time

There are several factors that influence the response time of a photodiode and its output circuitry (see figure 7-3). The most important of these are the thickness of the detector active area and the detector RC time constant. The detector thickness is related to the amount of time required for the electrons generated to flow out of the detector active area. This time is referred to as the electron **transit time**. The thicker the detector active area, the longer the transit time will be.

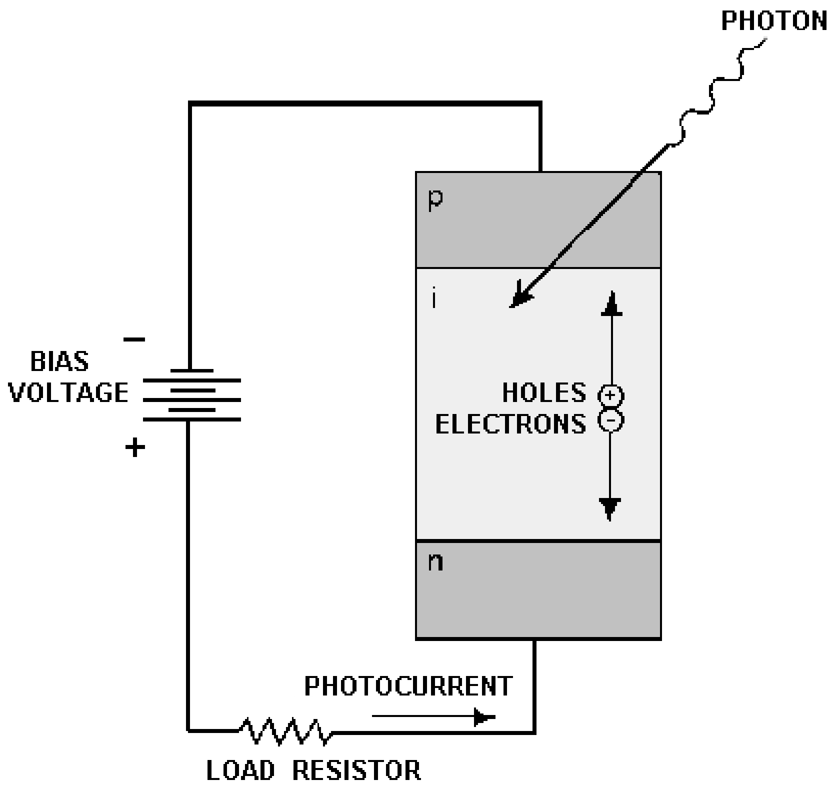

Figure 7-3.—A schematic representation of a photodiode.

The **capacitance** (**C**) of the photodiode and the **resistance** (**R**) of the load form the RC time constant. The capacitance of the photodetector must be kept small to prevent the RC time constant from limiting the response time. The photodiode capacitance consists mainly of the junction capacitance and any capacitance relating to packaging. The **RC time constant** is given by $t_{RC} = RC$.

Trade-offs between fast transit times and low capacitance are necessary for high-speed response. However, any change in photodiode parameters to optimize the transit time and capacitance can also affect responsivity, dark current, and coupling efficiency. A fast transit time requires a thin detector active area, while low capacitance and high responsivity require a thick active region. The diameter of the detector active area can also be minimized. This reduces the detector dark current and minimizes junction capacitance. However, a minimum limit on this active area exists to provide for efficient fiber-to-detector coupling.

Linearity

Reverse-biased photodetectors are highly linear devices. Detector **linearity** means that the output electrical current (photocurrent) of the photodiode is linearly proportional to the input optical power. Reverse-biased photodetectors remain linear over an extended range (6 decades or more) of photocurrent before saturation occurs. Output saturation occurs at input optical power levels typically greater than 1 milliwatt (mW). Because fiber optic communications systems operate at low optical power levels, detector saturation is generally not a problem.

AVALANCHE PHOTODIODES

An **avalanche photodiode (APD)** is a photodiode that internally amplifies the photocurrent by an avalanche process. Figure 7-4 shows an example APD structure. In APDs, a large reverse-bias voltage, typically over 100 volts, is applied across the active region. This voltage causes the electrons initially generated by the incident photons to accelerate as they move through the APD active region. As these electrons collide with other electrons in the semiconductor material, they cause a fraction of them to become part of the photocurrent. This process is known as **avalanche multiplication**. Avalanche multiplication continues to occur until the electrons move out of the active area of the APD.

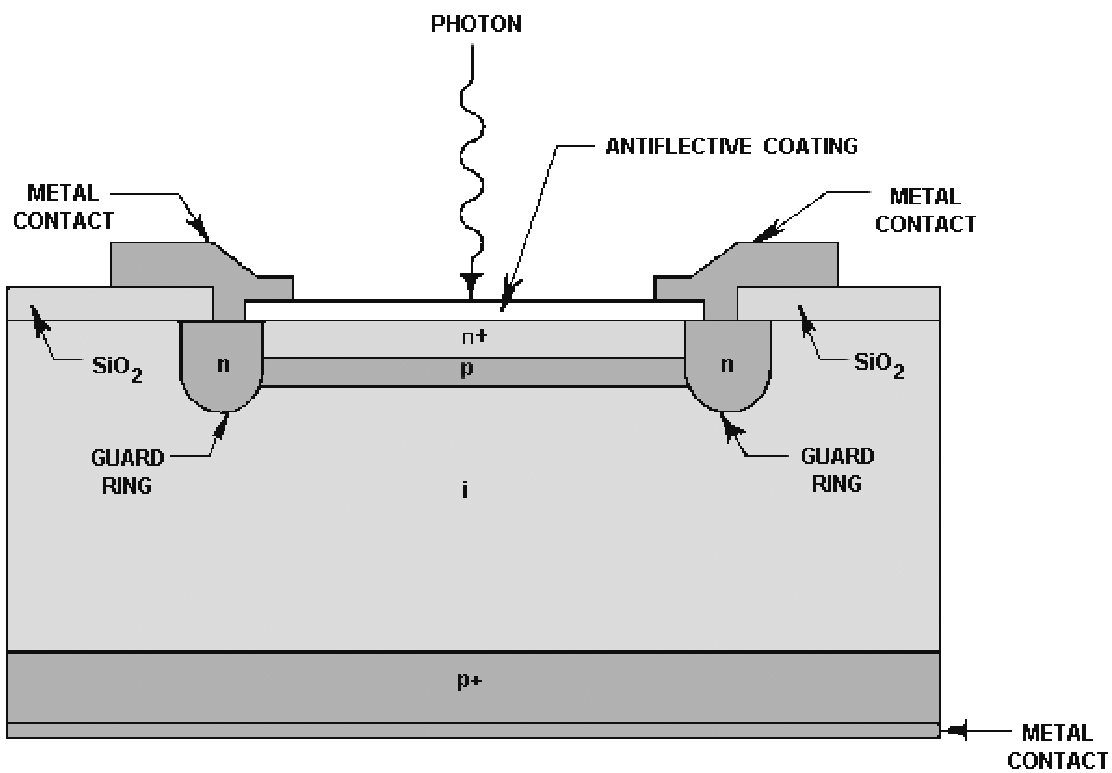

Figure 7-4.—The basic structure of an APD.

The gain of the APD can be changed by changing the reverse-bias voltage. A larger reverse-bias voltage results in a larger gain. However, a larger reverse-bias voltage also results in increased noise levels. Excess noise resulting from the avalanche multiplication process places a limit on the useful gain of the APD. The avalanche process introduces excess noise because every photogenerated carrier does not undergo the same multiplication. The noise properties of an APD are affected by the materials that the

APD is made of. Typical semiconductor materials used in the construction of low-noise APDs include silicon (Si), indium gallium arsenide (InGaAs), and germanium (Ge).

Trade-offs are made in APD design to optimize responsivity and gain, dark current, response time, and linearity. This chapter does not attempt to discuss trade-offs in APD design in more detail. Many aspects of the discussion provided on responsivity, dark current, and response time provided in the PIN photodiodes section also relate to APDs. The response time of an APD and its output circuitry depends on the same factors as PIN photodiodes. The only additional factor affecting the response time of an APD is the additional time required to complete the process of avalanche multiplication. To learn more about APD design trade-offs and performance parameters, refer to the reference material listed in appendix 2.

FIBER OPTIC RECEIVERS

In fiber optic communications systems, optical signals that reach fiber optic receivers are generally attenuated and distorted (see figure 7-5). The fiber optic receiver must convert the input and amplify the resulting electrical signal without distorting it to a point that other circuitry cannot use it.

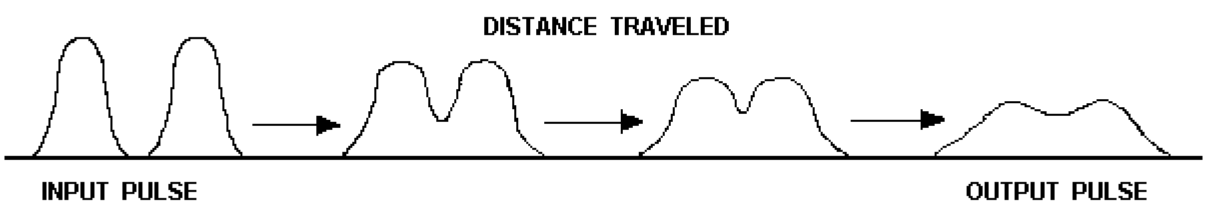

Figure 7-5.—Attenuated and distorted optical signals.

As stated previously, a fiber optic receiver consists of an optical detector, an amplifier, and other circuitry. In most fiber optic systems, the optical detector is a PIN photodiode or APD. Receiver performance varies depending on the type of detector used. The amplifier is generally described as having two stages: the preamplifier and the postamplifier. The **preamplifier** is defined as the first stage of amplification following the optical detector. The **postamplifier** is defined as the remaining stages of amplification required to raise the detector's electrical signal to a level suitable for further signal processing. The preamplifier is the dominant contributor of electrical noise in the receiver. Because of this, its design has a significant influence in determining the sensitivity of the receiver.

The output circuitry processes the amplified signal into a form suitable for the interfacing circuitry. For digital receivers, this circuitry may include low-pass filters and comparators. For analog receivers, this circuitry may also include low-pass filters.

Receiver sensitivity, bandwidth, and dynamic range are key operational parameters used to define receiver performance. One goal in designing fiber optic receivers is to optimize receiver sensitivity. To increase sensitivity, receiver noise resulting from signal-dependent shot noise and thermal noise must be kept at a minimum. A more detailed discussion of receiver shot and thermal noise is provided later in this chapter.

In addition to optimizing sensitivity, optical receiver design goals also include optimizing the bandwidth and the dynamic range. A receiver that has the ability to operate over a wide range of optical power levels can operate efficiently in both short- and long-distance applications. Because conflicts arise when attempting to meet each goal, trade-offs in receiver designs are made to optimize overall performance.

RECEIVER NOISE

Noise corrupts the transmitted signal in a fiber optic system. This means that noise sets a lower limit on the amount of optical power required for proper receiver operation. There are many sources of noise in fiber optic systems. They include the following:

- Noise from the light source
- Noise from the interaction of light with the optical fiber
- Noise from the receiver itself

Because the intent of this chapter is to discuss optical detector and receiver properties, only noise associated with the photodetection process is discussed. **Receiver noise** includes thermal noise, dark current noise, and quantum noise. Noise is the main factor that limits receiver sensitivity.

Noise introduced by the receiver is either signal dependent or signal independent. Signal dependent noise results from the random generation of electrons by the incident optical power. Signal independent noise is independent of the incident optical power level.

Thermal noise is the noise resulting from the random motion of electrons in a conducting medium. Thermal noise arises from both the photodetector and the load resistor. Amplifier noise also contributes to thermal noise. A reduction in thermal noise is possible by increasing the value of the load resistor. However, increasing the value of the load resistor to reduce thermal noise reduces the receiver bandwidth. In APDs, the thermal noise is unaffected by the internal carrier multiplication.

Shot noise is noise caused by current fluctuations because of the discrete nature of charge carriers. Dark current and quantum noises are two types of noise that manifest themselves as shot noise. **Dark current noise** results from dark current that continues to flow in the photodiode when there is no incident light. Dark current noise is independent of the optical signal. In addition, the discrete nature of the photodetection process creates a signal dependent shot noise called quantum noise. **Quantum noise** results from the random generation of electrons by the incident optical radiation. In APDs, the random nature of the avalanche process introduces an additional shot noise called excess noise. For further information on the excess noise resulting from the avalanche process, refer to the avalanche photodiode section.

RECEIVER DESIGN

The simplest fiber optic receivers consist of only the optical detector and a load resistor. However, the output signal of these simple receivers is not in a suitable form for most types of interfacing circuitry. To produce a suitable signal, a preamplifier, a post amplifier, and other circuitry are generally included in the receiver.

The choice of an optical detector and the design of the preamplifier help determine the operational characteristics of the receiver. Fiber optic receivers using APDs have greater sensitivity than those using PIN photodiodes. In addition, trade-offs are made in preamplifier designs to increase sensitivity while optimizing bandwidth and dynamic range. The two basic types of amplifiers used in fiber optic receivers are the **high-impedance amplifier** and the **transimpedance amplifier**.

The high-impedance preamplifier is generally used with a large load resistor to improve sensitivity. The large load resistor is used to reduce thermal noise. Although the high-impedance preamplifier achieves high sensitivity, receiver bandwidth and dynamic range are limited. The transimpedance preamplifier uses a low-noise, high-input impedance amplifier with negative feedback. This design provides improvements in bandwidth and dynamic range with some degradation in sensitivity from an increase in noise. For more information on receiver performance and design, refer to the reference material listed in appendix 2.

FIBER OPTIC RECEIVER PACKAGES

Fiber optic receivers come in packages similar to those for fiber optic transmitters. For information on fiber optic receiver packages, refer back to the fiber optic transmitter packages section of chapter 6.

FIBER OPTIC RECEIVER APPLICATIONS

Fiber optic receivers can be classified into two categories: **digital** and **analog**. Digital receivers detect the input optical signal, amplify the digital photocurrent, and reshape the signal to produce an undistorted output electrical signal. Analog receivers detect the input optical signal and amplify the generated photocurrent.

Digital Applications

For most digital applications the designs of the digital fiber optic receivers are similar. For **low-data-rate** applications, PIN diodes and high impedance amplifiers are generally used. Receiver sensitivities are maximized by using large load resistors in the photodiode circuit. For **moderate-data-rate** applications, PIN diodes and either high impedance amplifiers with smaller load resistances or transimpedance amplifiers are used. For **high-data-rate** applications, PINs or APDs are used with transimpedance amplifiers. APDs are rarely used in low- or moderate-data-rate applications unless receivers with extremely low sensitivities are required.

For each digital application, the receiver will generally contain a low-pass filter. The pass-band of the filter depends on the data rate of the application. The filter is used to smooth the amplified signal to remove some of the high frequency noise before the signal is further processed. The digital receiver generally contains a comparator, which reshapes the amplified electrical signal to remove any distortions introduced in the transmission process. In some cases the receiver may also contain clock recovery circuitry, which retimes the output electrical signal as well.

Analog Applications

Analog receivers are similar in design to digital receivers with the exception that digital signal restoring circuitry is not used. The preamplifier and postamplifiers are designed to be more linear than those used in digital receivers in some cases.

For **low-frequency** applications, PIN diodes and high impedance amplifiers are generally used. For **moderate-frequency** applications, PIN diodes and either high impedance amplifiers or transimpedance amplifiers are used. For **high-frequency** applications, PINs or APDs are used with transimpedance amplifiers. As in digital applications, APDs are rarely used in low- or moderate-frequency applications unless receivers with extremely low sensitivities are required.

SUMMARY

Now that you have completed this chapter, let's review some of the new terms, concepts, and ideas that you have learned. You should have a thorough understanding of these principles before moving on to chapter 8.

A **FIBER OPTIC RECEIVER** is an electro-optic device that accepts optical signals from an optical fiber and converts them into electrical signals. A typical fiber optic receiver consists of an optical detector, a low-noise amplifier, and other circuitry used to produce the output electrical signal.

RECEIVER SPECTRAL RESPONSE, SENSITIVITY, FREQUENCY RESPONSE, and **DYNAMIC RANGE** are key receiver performance parameters that can affect overall system operation.

RECEIVER SENSITIVITY is the minimum amount of optical power required to achieve a specific receiver performance. For digital transmission at a given data rate and coding, this performance is described by a maximum bit-error rate (BER). In analog systems, for a given modulation and bandwidth, it is described by a minimum signal-to-noise ratio (SNR).

DYNAMIC RANGE refers to the range of optical power levels over which the receiver operates within the specified values. It usually is described by the ratio of the maximum input power to the sensitivity.

A **TRANSDUCER** is a device that converts input energy of one form into output energy of another.

An **OPTICAL DETECTOR** is a transducer that converts an optical signal into an electrical signal. It does this by generating an electrical current proportional to the intensity of incident optical radiation.

The semiconductor **POSITIVE-INTRINSIC-NEGATIVE (PIN) PHOTODIODE** and **AVALANCHE PHOTODIODE (APD)** are the principal optical detectors used in fiber optic systems.

A **PHOTOCURRENT** is generated when photons are absorbed by a photodiode.

RESPONSIVITY is the ratio of the optical detector's output photocurrent in amperes to the incident optical power in watts.

DARK CURRENT, or reverse-leakage current, is the current that continues to flow in the photodetector when there is no incident light.

The **RESPONSE TIME** of a photodiode and its output circuitry depends primarily on the thickness of the detector active area and the detector RC time constant.

The **TRANSIT TIME** is the time it takes electrons to travel out of the detector active area.

The **RC TIME CONSTANT** is defined by the capacitance (C) of the photodiode and the resistance (R) of the load. The RC time constant is given by $t_{RC} = RC$.

A **HIGH-SPEED RESPONSE** requires short transit times and low capacitance. However, any change in photodiode parameters to optimize the transit time and capacitance can also affect quantum efficiency, dark current, and coupling efficiency.

Detector **LINEARITY** means that the output electrical current (photocurrent) of the photodiode is linearly proportional to the input optical power.

An **AVALANCHE PHOTODIODE (APD)** is a photodiode that internally amplifies the photocurrent by an avalanche process.

In **APDs**, a large **REVERSE-BIAS VOLTAGE**, typically over 100 volts, is applied across the active region.

AVALANCHE MULTIPLICATION occurs when accelerated electrons collide with other electrons in the semiconductor material, causing a fraction of them to become part of the photocurrent.

TRADE-OFFS are made in APD design to optimize responsivity and gain, dark current, response time, and linearity.

The **RESPONSE TIME** of APDs accounts for the avalanche build-up time in addition to transit time and RC time constant.

The **PREAMPLIFIER** is defined as the first stage of amplification following the optical detector.

The **POSTAMPLIFIER** is defined as the remaining stages of amplification required to raise the detectors electrical signal to a level suitable for further signal processing.

RECEIVER SENSITIVITY, BANDWIDTH, and **DYNAMIC RANGE** are key operational parameters used to define receiver performance.

NOISE is the main factor that determines receiver sensitivity.

RECEIVER NOISE includes thermal noise, dark current noise, and quantum noise.

THERMAL NOISE is the noise resulting from the random motion of electrons in a conducting medium.

SHOT NOISE is noise caused by current fluctuations due to the discrete nature of charge carriers.

DARK CURRENT NOISE results from dark current that continues to flow in the photodiode when there is no incident light.

QUANTUM NOISE results from the random generation of electrons by the incident optical radiation.

The **HIGH-IMPEDANCE AMPLIFIER** and the **TRANSIMPEDANCE AMPLIFIER** are the two basic types of amplifiers used in fiber optic receivers.

The **HIGH-IMPEDANCE PREAMPLIFIER** provides a high sensitivity, but limits receiver bandwidth and dynamic range.

The **TRANSIMPEDANCE PREAMPLIFIER** provides improvements in bandwidth and dynamic range with some degradation in sensitivity from an increase in noise.

PIN PHOTODIODES are used as the detector in most applications.

AVALANCHE PHOTODIODES are only used in high-speed applications and applications where detectors with extremely low sensitivities are required.