
Optical Detectors and Human Vision

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Many photonics applications require the use of optical radiation detectors. Examples are optical radar, monitoring of laser power levels for materials processing, and laser metrology. Different types of optical detectors are available, covering the ultraviolet, visible, and infrared portions of the electromagnetic spectrum. Optical detectors convert incoming optical energy into electrical signals. The two main types of optical detectors are photon detectors and thermal detectors. Photon detectors produce one electron for each incoming photon of optical energy. The electron is then detected by the electronic circuitry. Thermal detectors convert the optical energy to heat energy, which then generates an electrical signal.

The detector circuit often employs a bias voltage and there is a load resistor in series with the detector. The incident light changes the characteristics of the detector and changes the current flowing in the circuit. The output signal is then the change in voltage drop across the load resistor.

In this module, we will describe some common optical detectors and their important characteristics. We shall not attempt to cover the entire field of light detection, which is very broad. Instead, we shall emphasize those detectors that are most commonly encountered in photonics applications.

Prerequisites

You should have the ability to solve algebraic equations, should understand basic trigonometric functions, and should have knowledge of laser safety procedures.

The following modules should have been completed previously or should be studied concurrently with this module:

Module 1-1 *Nature and Properties of Light*

Module 1-2 *Light Sources and Laser Safety*

Module 1-3 *Basic Geometric Optics*

Module 1-4 *Basic Physical Optics*

Module 1-5 *Lasers*

Objectives

When you finish this module, you will be able to:

1. Define important detector response characteristics, including responsivity, noise equivalent power, quantum efficiency, detectivity, rise time, and cutoff wavelength for a photon detector.
2. Define sources of detector noise, including shot noise, Johnson noise, $1/f$ noise, and photon noise. Explain methods employed to reduce the effect of these noise sources.
3. Describe and explain the operation of important types of photodetectors, including photon detectors, thermal detectors, photoemissive detectors, photoconductive detectors, photovoltaic detectors, and photomultiplier detectors. Describe the spectral response of each type.
4. Draw and explain a typical circuit for a photovoltaic detector.
5. Draw and explain a typical circuit for a photoconductive detector.
6. Describe important concepts related to human vision, including structure of the eye, the formation of images by the eye, and common defects of vision.
7. Given the necessary information, calculate the noise equivalent power of a detector.
8. Given the necessary information, calculate the detectivity of a detector.
9. Given the necessary information, calculate the quantum efficiency of a detector.
10. Given the necessary information, calculate the power reaching a detector after a laser beam is reflected from a Lambertian reflector.
11. Fabricate a circuit for operation of a photodiode. Use the circuit for detection of light in both photoconductive and photovoltaic modes of operation.
12. Determine the relative response of the detector circuit as a function of wavelength for several wavelengths in the visible spectrum.

Workplace Scenario

Maria is a senior photonics technician who uses detectors for infrared, visible, and ultraviolet light in many applications. Maria works in the advanced research laboratory of a large industrial company and has many years of photonics experience. She employs detectors for monitoring the output of lasers as she adjusts their mirrors. Working under the direction of a scientist, Maria has assembled equipment containing detectors for detecting the return signal in environmental monitoring applications and for controlling the progress of materials-processing applications. Her specific duties have included calibrating, cleaning, maintaining, testing, aligning, mounting, installing, operating, and demonstrating detectors for light.

Opening Demonstration

Materials

Helium-neon laser (few-milliwatt output)

Power meter (Coherent Fieldmaster LM-2 or equivalent)

Procedures

In this introductory demonstration, you will use a power meter to measure the output of a HeNe laser.

Assemble the equipment as shown in Figure 6-1. Turn on the HeNe laser, making sure to observe proper laser safety procedures. Direct the beam into the aperture of the power meter head. Observe the reading on the display.

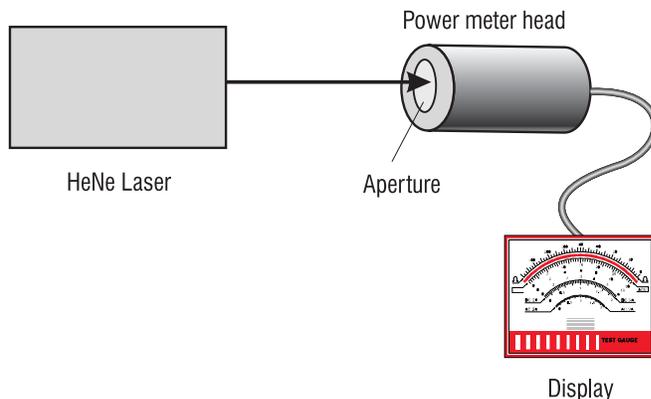


Figure 6-1 *Arrangement of equipment for introductory laboratory measurement of the output power of a HeNe laser*

Adjust the control for the output of the laser. Observe the changes in the power meter reading as the power of the laser is varied.

Basic Concepts

I. BASIC INFORMATION ON LIGHT DETECTORS

When light strikes special types of materials, a voltage may be generated, a change in electrical resistance may occur, or electrons may be ejected from the material surface. As long as the light is present, the condition continues. It ceases when the light is turned off. Any of the above conditions may be used to change the flow of current or the voltage in an external circuit and thus may be used to monitor the presence of the light and to measure its intensity.

A. Role of an optical detector

Many photonics applications require the use of optical detectors to measure optical power or energy. In laser-based fiber optic communication, a detector is employed in the receiver. In laser materials processing, a detector monitors the laser output to ensure reproducible conditions. In applications involving interferometry, detectors are used to measure the position and motion of interference fringes. In most applications of light, one uses an optical detector to measure the output of the laser or other light source. Thus, good optical detectors for measuring optical power and energy are essential in most applications of photonics technology.

Optical detectors respond to the power in the optical beam, which is proportional to the square of the electric field associated with the light wave. Optical detectors therefore are called “square-law detectors.” This is in contrast to the case of microwave detectors, which can measure the electric field intensity directly. All the optical detectors that we will describe have square-law responses.

Detection and measurement of optical and infrared radiation is a well-established area of technology. This technology has been applied to photonics applications. Detectors particularly suitable for use with lasers have been developed. Some detectors are packaged in the format of power or energy meters. Such a device is a complete system for measuring the output of a specific class of lasers, and includes a detector, housing, amplification if necessary, and a readout device.

B. Types of Optical Detectors

Optical detectors are usually divided into two broad classes: photon detectors and thermal detectors. In photon detectors, quanta of light energy interact with electrons in the detector material and generate free electrons. To produce free electrons, the quanta must have sufficient energy to free an electron from its atomic binding forces. The wavelength response of photon detectors shows a long-wavelength cutoff. If the wavelength is longer than the cutoff wavelength, the photon energy is too small to produce a free electron and the response of the photon detector drops to zero.

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Thermal detectors respond to the heat energy delivered by light. These detectors use some temperature-dependent effect, like a change of electrical resistance. Because thermal detectors rely on only the total amount of heat energy reaching the detector, their response is independent of wavelength.

The output of photon detectors and thermal detectors as a function of wavelength is shown schematically in Figure 6-2. This figure shows the typical spectral dependence of the output of photon detectors, which increases with increasing wavelength at wavelengths shorter than the cutoff wavelength. At that point, the response drops rapidly to zero. The figure also shows how the output of thermal detectors is independent of wavelength, and extends to longer wavelengths than the response of photon detectors.

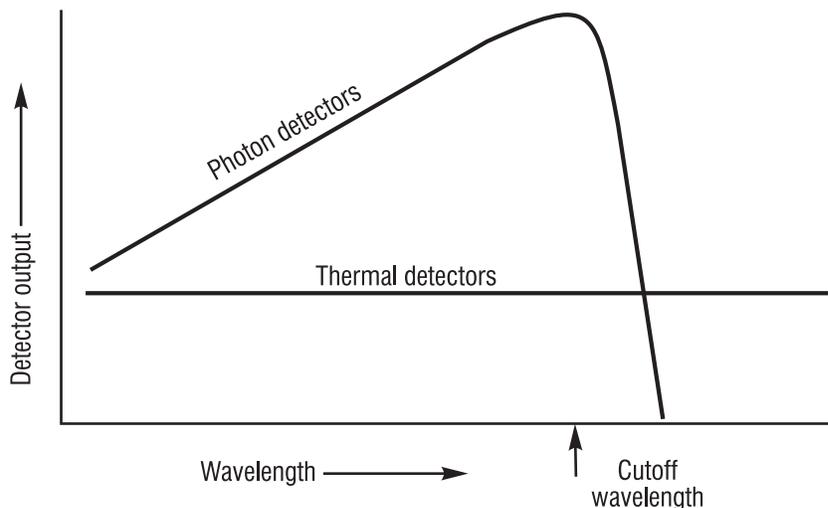


Figure 6-2 Schematic drawing of the relative output per unit input for photon detectors and thermal detectors as a function of wavelength. The position of the long-wavelength cutoff for photon detectors is indicated.

Figure 6-2 is intended to show only the relative shape of the output curves for these two types of detectors and is not intended to show quantitative values. Quantitative values will be presented in later figures for some specific detectors.

Photon detectors may be further subdivided according to the physical effect that produces the detector response. Some important classes of photon detectors are listed below.

- *Photoconductive.* The incoming light produces free electrons which can carry electrical current so that the electrical conductivity of the detector material changes as a function of the intensity of the incident light. Photoconductive detectors are fabricated from semiconductor materials such as silicon.
- *Photovoltaic.* Such a detector contains a junction in a semiconductor material between a region where the conductivity is due to electrons and a region where the conductivity is due to holes (a so-called pn junction). A voltage is generated when optical energy strikes the device.

- *Photoemissive*. These detectors are based on the photoelectric effect, in which incident photons release electrons from the surface of the detector material. The free electrons are then collected in an external circuit.

Photoconductive and photovoltaic detectors are commonly used in circuits in which there is a load resistance in series with the detector. The output is read as a change in the voltage drop across the resistor.

We shall discuss each of these effects in more detail later.

C. Detector characteristics

The performance of optical detectors is commonly characterized by a number of different parameters. It is important to define these parameters, sometimes called *figures of merit*, because manufacturers usually describe the performance of their detectors in these terms.

The figures of merit were developed to describe the performance of detectors responding to a small signal in the presence of noise. Thus, some of the figures of merit may not be highly relevant to the detection of laser light. For many laser applications, like laser metalworking, there is no question of detection of a small signal in a background of noise. The laser signal is far larger than any noise source that may be present. In other photonics applications, like laser communication, infrared thermal imaging systems, and detection of backscattered light in laser remote sensing, the signals are small and noise considerations are important.

Responsivity

The first term that we will define is *responsivity*. This is the *detector output per unit of input power*. The units of responsivity are either amperes/watt (alternatively milliamperes/milliwatt or microamperes/microwatt, which are numerically the same) or volts/watt, depending on whether the output is an electric current or a voltage.

The responsivity is an important parameter that is *usually specified by the manufacturer*. Knowledge of the responsivity allows the user to determine how much detector signal will be available for a specific application.

Noise Equivalent Power

A second figure of merit, which depends on noise characteristics, is the *noise equivalent power (NEP)*. This is defined as the *optical power that produces a signal voltage (or current) equal to the noise voltage (or current) of the detector*. The noise is dependent on the bandwidth of the measurement, so that bandwidth must be specified. Frequently it is taken as 1 Hz. The equation defining *NEP* is

$$\boxed{NEP = \frac{HA V_N}{V_S (\Delta f)^{1/2}}} \quad (6-1)$$

where H is the irradiance incident on the detector of area A ,
 V_N is the root mean square noise voltage within the measurement bandwidth Δf , and
 V_S is the root mean square signal voltage.

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The NEP has units of $\text{watts}/(\text{Hz})^{1/2}$, usually called “watts per root hertz.” From the definition, it is apparent that the lower the value of the NEP , the better are the characteristics of the detector for detecting a small signal in the presence of noise.

Example 1

The noise equivalent power of a detector with area 1 cm^2 is measured to be $2 \times 10^{-8} \text{ watts}/(\text{Hz})^{1/2}$ with a bandwidth of 1 Hz. What power is incident on the detector if the ratio of the noise voltage to the signal voltage is 10^{-6} ?

Solution:

According to Equation 6-1, the irradiance H at the detector must be

$$H = \frac{NEP}{A \left(\frac{V_N}{V_S} \right) (\Delta f)^{1/2}} = 2 \times 10^{-8} / \{ (1) \times (10^{-6}) \times (1) \} = 0.02 \text{ W/cm}^2$$

Because the area of the detector was 1 cm^2 , the power is 0.02 W.

Detectivity

The NEP of a detector is dependent on the area of the detector. To provide a figure of merit that is dependent on the intrinsic properties of the detector, not on how large it happens to be, a term called detectivity is defined. Detectivity is represented by the symbol D^* , which is pronounced as D-star. It is defined as the *square root of the detector area per unit value of NEP*.

$$D^* = A^{1/2}/NEP \quad (6-2)$$

Since many detectors have NEP proportional to the square root of their areas, D^* is independent of the area of the detector. The detectivity thus gives a measure of the intrinsic quality of the detector material itself.

When a value of D^* for an optical detector is measured, it is usually measured in a system in which the incident light is modulated or chopped at a frequency f so as to produce an AC signal, which is then amplified with an amplification bandwidth Δf . These quantities must also be specified. The dependence of D^* on the wavelength λ , the frequency f at which the measurement is made, and the bandwidth Δf are expressed by the notation $D^*(\lambda, f, \Delta f)$. The reference bandwidth is often 1 Hertz. The units of $D^*(\lambda, f, \Delta f)$ are $\text{cm}\cdot\text{Hz}^{1/2}/\text{watt}$. A high value of $D^*(\lambda, f, \Delta f)$ means that the detector is suitable for detecting weak signals in the presence of noise. Later, in the discussion of noise, we will describe the effect of modulation frequency and bandwidth on the noise characteristics.

Example 2

A detector has a noise equivalent power of 3×10^{-9} watts/(Hz)^{1/2} and an area of 0.4 cm². What is its value of D^* ?

Solution:

$$\begin{aligned} \text{According to equation 6-2, } D^* \text{ is } & (0.4 \text{ cm}^2)^{1/2} / 3 \times 10^{-9} \text{ watts}/(\text{Hz})^{1/2} \\ & = 0.632 \text{ cm} \times 0.333 \times 10^9 \text{ Hz}^{1/2}/\text{watt} \\ & = 2.11 \times 10^8 \text{ cm-Hz}^{1/2}/\text{watt} \end{aligned}$$

Quantum efficiency

Another common figure of merit for optical detectors is the *quantum efficiency*. Quantum efficiency is defined as the *ratio of countable events produced by photons incident on the detector to the number of incident photons*. If the detector is a photoemissive detector that emits free electrons from its surface when light strikes it, the quantum efficiency is the number of free electrons divided by the number of incident photons. If the detector is a semiconductor pn-junction device, in which hole-electron pairs are produced, the quantum efficiency is the number of hole-electron pairs divided by the number of incident photons. If, over a period of time, 100,000 photons are incident on the detector and 10,000 hole-electron pairs are produced, the quantum efficiency is 10%.

The quantum efficiency is basically another way of expressing the *effectiveness of the incident optical energy for producing an output of electrical current*. The quantum efficiency Q (in percent) may be related to the responsivity by the equation:

$$Q = 100 \times R_d \times (1.2395/\lambda) \quad (6-3)$$

where R_d is the responsivity (in amperes per watt) of the detector at wavelength λ (in micrometers).

Example 3

A detector has a quantum efficiency of 10% at a wavelength of 500 nm. At a wavelength of 750 nm, the responsivity is twice the responsivity at 500 nm. What is the quantum efficiency at 750 nm?

Solution:

From Equation 6-3, we see that the increase in responsivity from 500 to 750 nm will increase the quantum efficiency Q by a factor of 2, but the increase in wavelength will decrease the quantum efficiency Q by a factor of 2/3, so that the net change in quantum efficiency will be an overall increase by a factor of 4/3, from 10% to 13.33%.

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Detector response time

Another useful detector characteristic is the *speed of the detector response* to changes in light intensity. If a light source is instantaneously turned on and irradiates an optical detector, it takes a finite time for current to appear at the output of the device and for the current to reach a steady value. If the source is turned off instantaneously, it takes a finite time for the current to decay back to zero. The term *response time* refers to the *time it takes the detector current to rise to a value equal to 63.2% of the steady-state value* which is reached after a relatively long period of time. (This value is numerically equal to $1 - 1/e$, where e is the base of the natural logarithm system.) The *recovery time* is the *time it takes for the photocurrent to fall to 36.8% of the steady-state value* when the light is turned off instantaneously.

Because optical detectors often are used for detection of fast pulses, another important term, called *rise time*, is often used to describe the speed of the detector response. *Rise time* is defined as the *time difference between the point at which the detector has reached 10% of its peak output and the point at which it has reached 90% of its peak response*, when it is irradiated by a very short pulse of light. The *fall time* is defined as the *time between the 90% point and the 10% point on the trailing edge of the pulse waveform*. This is also called the decay time. We should note that the fall time may be different numerically from the rise time.

Of course, light sources are not turned on or off instantaneously. To make accurate measurements of rise time and fall time, the source used for the measurement should have a rise time much less than the rise time of the detector being tested. Generally, one should use a source whose rise time is less than 10% of the rise time of the detector being tested.

The intrinsic response time of an optical detector arises from the transit time of photogenerated charge carriers within the detector material and from the inherent capacitance and resistance associated with the device. The measured value of response time is also affected by the value of the load resistance that is used with the detector, and may be longer than the inherent response time. There is a tradeoff in the selection of a load resistance between speed of response and high sensitivity. It is not possible to achieve both simultaneously. Fast response requires a low load resistance (generally 50 ohms or less), whereas high sensitivity requires a high value of load resistance. It is also important to keep any capacitance associated with the circuitry, the electrical cables, and the display devices as low as possible. This will help keep the RC (resistance \times capacitance) time constant low. Manufacturers often quote nominal values for the rise times of their detectors. These should be interpreted as minimum values, which may be achieved only with careful circuit design and avoidance of excess capacitance and resistance in the circuitry.

Linearity

Yet another important characteristic of optical detectors is their *linearity*. Detectors are characterized by a response in which the *output is linear with incident intensity*. The response may be linear over a broad range, perhaps many orders of magnitude. If the output of the detector is plotted versus the input power, there should be no change in the slope of the curve. Noise will determine the lowest level of incident light that is detectable. The upper limit of the input/output linearity is determined by the maximum current that the detector can produce without becoming saturated. *Saturation* is a condition in which there is *no further increase in detector response as the input light intensity is increased*. When the detector becomes saturated,

one can no longer rely on its output to represent the input faithfully. The user should ensure that the detector is operating in the range in which it is linear.

Manufacturers of optical detectors often specify maximum allowable continuous light level. Light levels in excess of this maximum may cause saturation, hysteresis effects, and irreversible damage to the detectors. If the light occurs in the form of a very short pulse, it may be possible to exceed the continuous rating by some factor (perhaps as much as 10 times) without damage or noticeable changes in linearity.

Spectral response

The *spectral response* defines how the *performance of a detector (responsivity or detectivity) varies with wavelength*. The spectral response is defined by curves such as shown in Figure 6-2, which presents generalized curves showing relative spectral response as a function of wavelength for photon detectors and thermal detectors. The exact shape of the spectral response and the numerical values depend on the detector type and the material from which the detector is fabricated. Many different types of detectors are available, with responses maximized in the ultraviolet, visible, or infrared spectral regions. Again, the manufacturer usually specifies the spectral response curve. One should choose a detector that responds well in the spectral region of importance for the particular application.

D. Noise considerations

Noise in optical detectors is a complex subject. In this module we will do no more than present some of the most basic ideas. *Noise is defined as any undesired signal*. It masks the signal that is to be detected.

Noise can be external and internal. *External noise* involves disturbances that appear in the detection system because of factors outside the system. Examples of external noise could be pickup of hum induced by 60-Hz electrical power lines and static caused by electrical storms. *Internal noise* includes all noise generated within the detection system itself. Every electronic device has internal sources of noise, which represent an ever-present limit to the smallest signal that may be detected by the system.

Noise cannot be described in the same manner as usual electric currents or voltages. We think of currents or voltages as functions of time, such as constant direct currents or sine-wave alternating voltages. The noise output of an electrical circuit as a function of time is completely erratic. We cannot predict what the output will be at any instant. There will be no indication of regularity in the waveform. The output is said to be random.

Now we will consider some of the sources of noise encountered in optical detector applications. A complete description of all types of noise would be very long. We will describe four noise sources often encountered in connection with optical detectors.

- Johnson noise
- Shot noise
- $1/f$ noise
- Photon noise

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Johnson noise

Johnson noise is generated by thermal fluctuations in conducting materials. It is sometimes called thermal noise. *It results from the random motion of electrons in a conductor.* The electrons are in constant motion, colliding with each other and with the atoms of the material. Each motion of an electron between collisions represents a tiny current. The sum of all these currents taken over a long period of time is zero, but their random fluctuations over short intervals constitute Johnson noise.

To reduce the magnitude of Johnson noise, one may cool the system, especially the load resistor. One should reduce the value of the load resistance, although this is done at the price of reducing the available signal. One should keep the bandwidth of the amplification small; one Hz is a commonly employed value.

Shot noise

The term *shot noise* is derived from *fluctuations in the stream of electrons in a vacuum tube.* These variations create noise because of the random fluctuations in the arrival of electrons at the anode. The shot noise name arises from the similarity to the noise of a hail of shots striking a target.

In semiconductors, the major source of shot noise is random variations in the rate at which charge carriers are generated and recombine. This noise, called generation-recombination or *gr noise*, is the semiconductor manifestation of shot noise.

Shot noise may be minimized by keeping any DC component to the current small, especially the dark current, and by keeping the bandwidth of the amplification system small.

1/f noise

The term *1/f noise* (pronounced *one over f*) is used to describe a number of types of noise that are present when the modulation frequency f is low. This type of noise is also called excess noise because it exceeds shot noise at frequencies below a few hundred Hertz.

The mechanisms that produce $1/f$ noise are poorly understood. The noise power is inversely proportional to f , the modulation frequency. This dependence of the noise power on modulation frequency leads to the name for this type of noise.

To reduce $1/f$ noise, an optical detector should be operated at a reasonably high frequency, often as high as 1000 Hz. This is a high enough value to reduce the contribution of $1/f$ noise to a small amount.

Photon noise

Even if all the previously discussed sources of noise could be eliminated, there would still be some noise in the output of an optical detector because of the random arrival rate of photons in the light being measured and from the background. This contribution to the noise is called *photon noise*; it is a noise source external to the detector. It imposes the ultimate fundamental limit to the detectivity of a photodetector.

The photon noise associated with the fluctuations in the arrival rate of photons in the desired signal is not something that can be reduced. The contribution of fluctuations in the arrival of photons from the background, a contribution that is called background noise, can be reduced.

The background noise increases with the field of view of the detector and with the temperature of the background. In some cases it is possible to reduce the field of view of the detector so as to view only the source of interest. In other cases it is possible to cool the background. Both these measures may be used to reduce the background noise contribution to photon noise.

The types of noise described here, or a combination of them, will set an upper limit to the detectivity of an optical detector system.

II. TYPES OF DETECTORS

We now return to the discussion of different types of detectors and present more detail on the various available optical detectors.

A. Photon detectors

We have defined photon detectors and thermal detectors briefly. We begin a more detailed discussion of detector types with photon detectors. In photon detectors, quanta of light energy produce free electrons. The photon must have sufficient energy to exceed some threshold. In other words, the wavelength must be shorter than the cutoff wavelength. We will consider three types of photoeffects that are often used for detectors. These are the *photovoltaic effect*, the *photoemissive effect*, and the *photoconductive effect*.

Photovoltaic effect

The *photovoltaic effect* occurs at a junction in a semiconductor. The junction is the boundary between a region where the conductivity is due to electrons and a region where the conductivity is due to holes (the absence of electrons). This is called a pn junction. At the junction, an electric field is present internally because there is a change in the level of the conduction and valence bands. This change leads to the familiar electrical rectification effect produced by such junctions. The photovoltaic effect is the generation of a voltage when light strikes a semiconductor pn junction.

The photovoltaic effect is measured using a high-impedance voltage-measuring device, which essentially measures the open-circuit voltage produced at the junction.

In the dark, no open circuit voltage is present. When light falls on the junction, the light is absorbed and, if the photon energy is large enough, it produces free hole-electron pairs. The electric field at the junction separates the pair and moves the electron into the n-type region and the hole into the p-type region. This leads to an open circuit voltage that can be measured externally. This process is the origin of the photovoltaic effect. We note that the open-circuit voltage generated in the photovoltaic effect may be detected directly and that no bias voltage nor load resistor is required.

If the junction is short-circuited by an external conductor, current will flow in the circuit when the junction is illuminated. One may measure either the open-circuit voltage or the short-circuit current. Both these quantities will give measures of the light falling on the junction.

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Photoemissive effect

Now we turn to the *photoemissive effect*. The photoemissive effect involves the emission of electrons from a surface irradiated by quanta of light energy. A photoemissive detector has a cathode coated with a material that emits electrons when light of wavelength shorter than the cutoff wavelength falls on the surface. The electrons emitted from the surface are accelerated by a voltage to an anode, where they produce a current in an external circuit. The detectors are enclosed in a vacuum environment to allow a free flow of electrons from anode to cathode. These detectors are available commercially from a number of manufacturers. They represent an important class of detectors for many applications.

Some spectral response curves for photoemissive cathodes are shown in Figure 6-3. The cathodes are often mixtures containing alkali metals, such as sodium and potassium, from which electrons can easily be emitted. The responsivity in mA/watt of these devices is shown in the figure from the ultraviolet to the near infrared. At wavelengths longer than about 1000 nm, no photoemissive response is available. The short-wavelength end of the response curve is set by the nature of the window material used in the tube that contains the detector. The user can select a device that has a cathode with maximum response in a selected wavelength region. An important variation of the photoemissive detector is the photomultiplier, which will be described later.

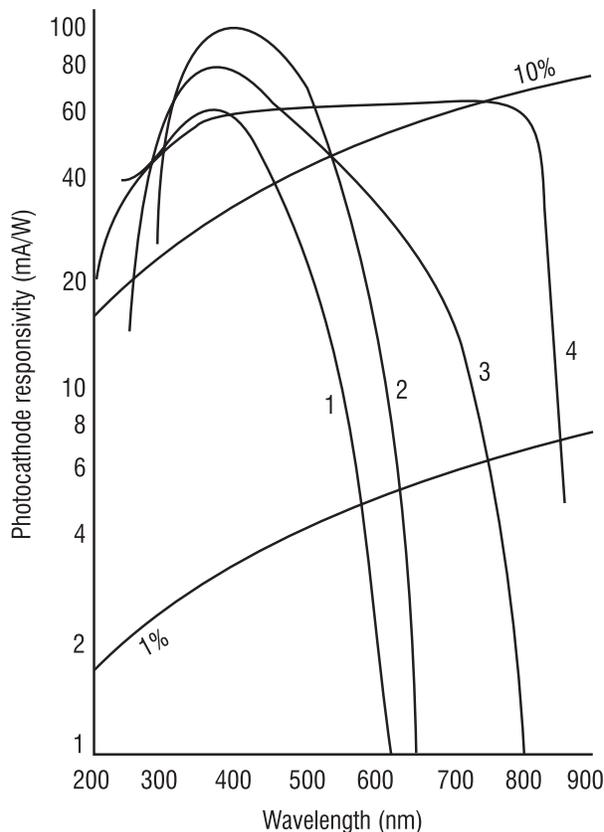


Figure 6-3 Response as a function of wavelength for a number of photoemissive surfaces. Curve 1 is the response of a bi-alkali type of cathode with a sapphire window; curve 2 is for a different bi-alkali cathode with a lime glass window; curve 3 is for a multi-alkali cathode with a lime glass window; and curve 4 is for a GaAs cathode with a 9741 glass window. The curves labeled 1% and 10% denote what the response would be at the indicated value of quantum efficiency.

Photoconductivity

A third phenomenon used in optical detectors is *photoconductivity*. A semiconductor in thermal equilibrium contains free electrons and holes. The concentration of electrons and holes is changed if light is absorbed by the semiconductor. The light must have photon energy large enough to produce free electrons within the material. The increased number of charge carriers leads to an increase in the electrical conductivity of the semiconductor. The device is used in a circuit with a bias voltage and a load resistor in series with it. The change in electrical conductivity leads to an increase in the current flowing in the circuit, and hence to a measurable change in the voltage drop across the load resistor.

Photoconductive detectors are most widely used in the infrared region, at wavelengths where photoemissive detectors are not available. Many different materials are used as infrared photoconductive detectors. Some typical values of detectivity (in $\text{cm}\cdot\text{Hz}^{1/2}/\text{watt}$) as a function of wavelength for some devices operating in the infrared are shown in Figure 6-4, along with values of detectivity for some other detectors to be discussed later. The photoconductive detectors are denoted PC. The exact value of detectivity for a specific photoconductor depends on the operating temperature and on the field of view of the detector. Most infrared photoconductive detectors operate at a cryogenic temperature (frequently liquid nitrogen temperature, 77 K) which may involve some inconvenience in practical applications.

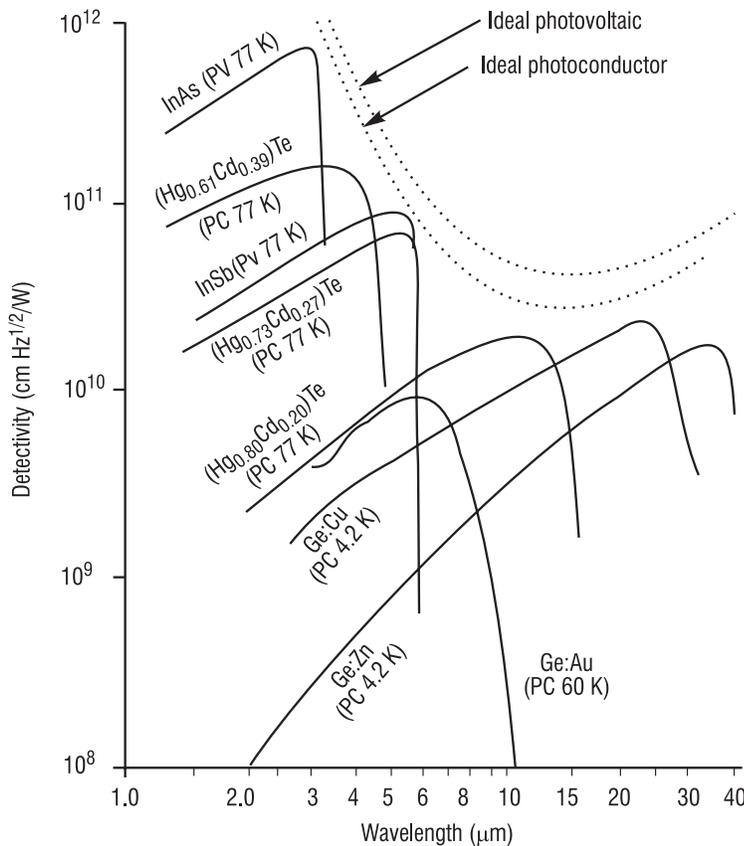


Figure 6-4 Detectivity as a function of wavelength for a number of different types of photodetectors operating in the infrared spectrum. The temperature of operation is indicated. Photovoltaic detectors are denoted PV; photoconductive detectors are denoted PC. The curves for ideal photodetectors assume a 2π steradian field of view and a 295 K background temperature.

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A photoconductive detector uses a crystal of semiconductor material that has low conductance in the dark and an increased value of conductance when it is illuminated. It is commonly used in a series circuit with a battery and a load resistor. The semiconductor element has its conductance increased by light. The presence of light leads to increased current in the circuit and to increased voltage drop across the load resistor.

We now consider two specific types of photon detectors that are especially useful in photonics, the photodiode and the photomultiplier.

Photodiodes

We have discussed the photovoltaic effect, for which no bias voltage is required. It is also possible to use a pn junction to detect light if one does apply a bias voltage in the reverse direction. The reverse direction is the direction of low current flow, that is, with the positive voltage applied to the n-type material. A pn junction detector with bias voltage is termed a photodiode.

Figure 6-5 shows the current-voltage characteristics of a photodiode. The curve marked dark shows the current-voltage relation in the absence of light. It shows the familiar rectification characteristics of a pn semiconductor diode. The other curves represent the current-voltage characteristics when the device is illuminated at different light levels. A photovoltaic detector, with zero applied voltage, is represented by the intersections of the different curves with the vertical axis. Figure 6-5 is intended to show qualitatively how a photodiode operates. No quantitative values are shown for the axes in this figure; these values will vary from one material to another.

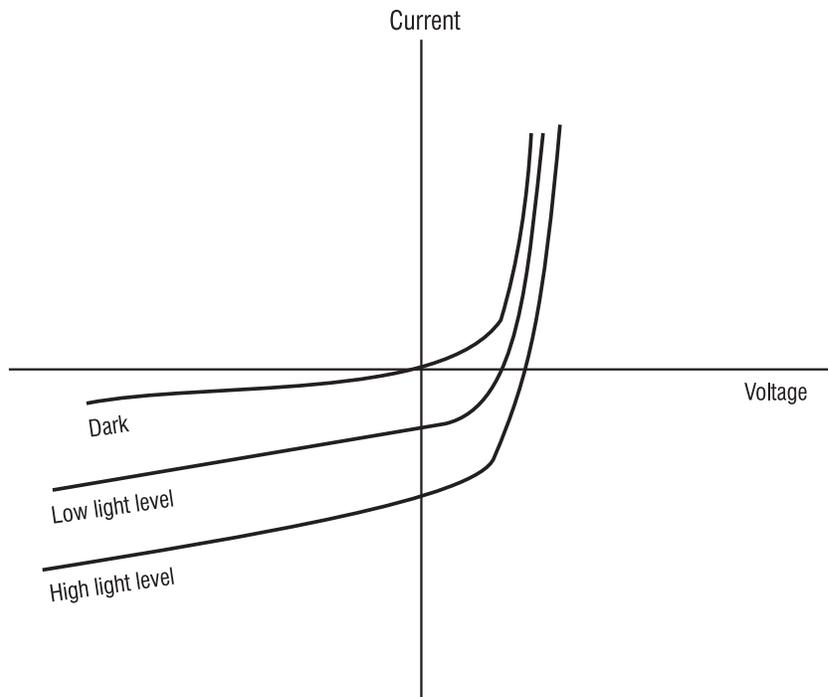


Figure 6-5 *Current-voltage characteristic for a photodiode*

A *photodiode detector* is operated in the lower left quadrant of this figure, where the current that may be drawn through an external load resistor increases with increasing light level. In practice, one measures the voltage drop appearing across the load resistor.

A variety of photodiode structures are available. No single photodiode structure can best meet all requirements. Perhaps the two most common structures are the *planar diffused photodiode*, shown in Figure 6-6a, and the *Schottky photodiode*, shown in Figure 6-6b. The planar diffused photodiode is fabricated by growing a layer of oxide over a slice of high-resistivity silicon, etching a hole in the oxide and diffusing boron into the silicon through the hole. This structure leads to devices with high breakdown voltage and low leakage current. The circuitry for operation of the photodiode is also indicated, including the load resistor.

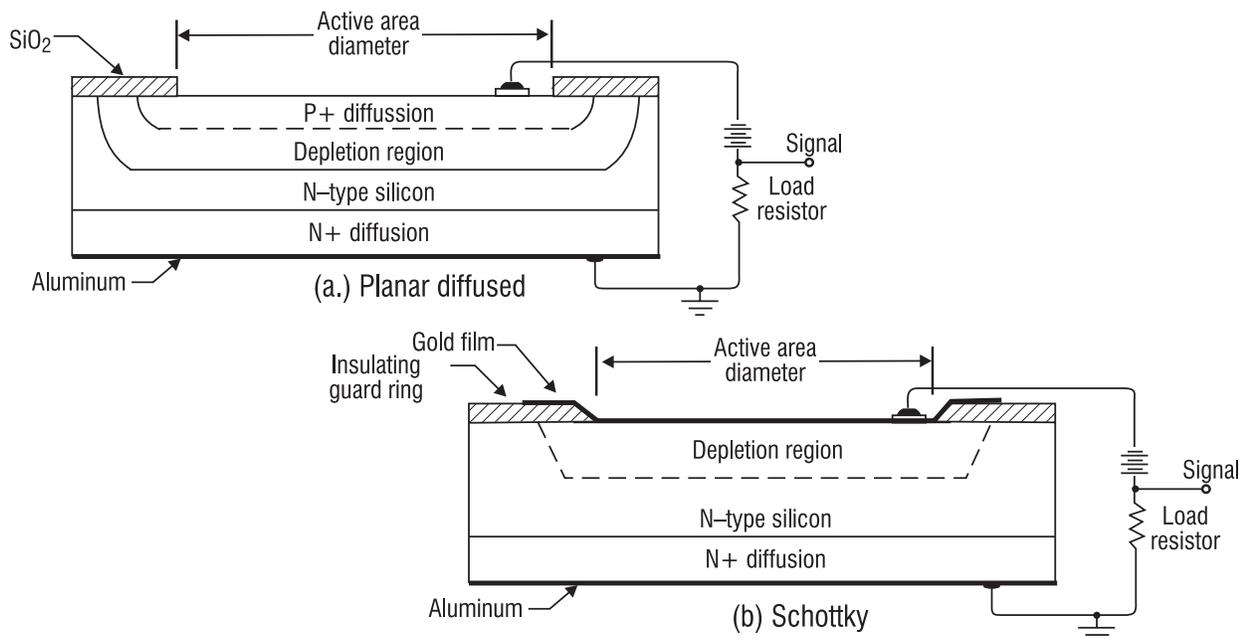


Figure 6-6 Photodiode structures: (a) Planar diffused photodiode; (b) Schottky photodiode

The Schottky barrier photodiode is formed at a junction between a metallic layer and a semiconductor. If the metal and the semiconductor have work functions related in the proper way, this can be a rectifying barrier. The junction is fabricated by oxidation of the silicon surface, then etching of a hole in the oxide, followed by the evaporation of a thin transparent and conducting gold layer. The insulation guard rings serve to reduce the leakage current through the device.

A number of different semiconductor materials are in common use as photodiodes. They include silicon for use in the visible, near ultraviolet, and near infrared; germanium and indium gallium arsenide in the near infrared; and indium antimonide, indium arsenide, mercury cadmium telluride, and germanium doped with elements like copper and gold in the longer-wavelength infrared.

The most frequently encountered type of photodiode is silicon. *Silicon photodiodes* are widely used as the detector elements in optical disks and as the receiver elements in optical fiber telecommunication systems operating at wavelengths around 800 nm. Silicon photodiodes

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respond over the approximate spectral range of 400–1100 nm, covering the visible and part of the near infrared regions. The spectral responsivity (in A/watt) of typical commercial silicon photodiodes is shown in Figure 6-7. The responsivity reaches a peak value around 0.7 amp/watt near 900 nm, decreasing at longer and shorter wavelengths. Optional models provide somewhat extended coverage in the infrared or ultraviolet regions. Silicon photodiodes are useful for detection of many of the most common laser wavelengths, including argon, HeNe, AlGaAs, and Nd:YAG.

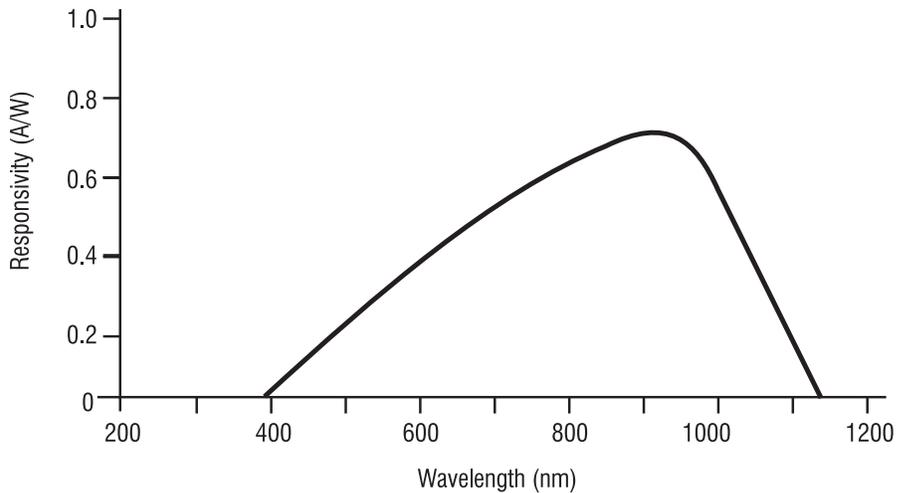


Figure 6-7 Responsivity as a function of wavelength for typical silicon photodiodes

In practice, *silicon photodiodes* have become the detector of choice for many photonics applications within their spectral range. They use well-developed technology and are widely available. They represent the most widely used type of detector for lasers operating in the visible and near infrared portions of the spectrum.

Figure 6-4 shows the spectral D^* (or detectivity) for a number of commercially available detectors operating in the infrared spectrum. The figure includes both photovoltaic detectors (denoted PV) and photoconductive detectors (denoted PC). The choice of detector will depend on the wavelength region that is desired. For example, for a laser operating at 5 μm , an indium antimonide photovoltaic detector would be suitable.

Figure 6-4 also indicates the detectivity for “ideal” detectors, that is, detectors whose performance is limited only by fluctuations in the background of incident radiation, and that do not contribute noise themselves. Available detectors approach the ideal performance limits fairly closely.

PIN photodiodes

Another common type of semiconductor structure used in photodiodes is the so-called *PIN structure*. This structure was developed to increase the frequency response of photodiodes. The device has a layer of nearly intrinsic semiconductor material bounded on one side by a relatively thin layer of highly doped p-type semiconductor and on the other side by a relatively thick layer of n-type semiconductor. Hence it is called a PIN device.

Light that is absorbed in the intrinsic region produces free electron-hole pairs, provided that the photon energy is high enough. These carriers are swept across the region with high velocity and are collected in the heavily doped regions. The frequency response of PIN photodiodes can be very high, of the order of 10^{10} Hz. This is higher than the frequency response of pn junctions without the intrinsic region.

Avalanche photodiodes

Another variation of the photodiode is the *avalanche photodiode*. The avalanche photodiode offers the possibility of internal gain; it is sometimes referred to as a “solid-state photomultiplier.” The most widely used material for avalanche photodiodes is silicon, but they have been fabricated from other materials, such as germanium.

An avalanche photodiode has a diffused pn junction, with surface contouring to permit high reverse bias voltage without surface breakdown. A large internal electric field leads to multiplication of the number of charge carriers through ionizing collisions. The signal is thus increased, to a value perhaps 100–200 times greater than that of a nonavalanche device. The detectivity is also increased, provided that the limiting noise is not from background radiation. Avalanche photodiodes cost more than conventional photodiodes and they require temperature-compensation circuits to maintain the optimum bias, but they represent an attractive choice when high performance is required.

Photomultipliers

Previously, we described photoemissive detectors in which current flows directly from a photocathode to an anode. We turn now to an important photoemissive detector that provides for amplification of the current. This is the *photomultiplier*. This device has a photoemissive cathode and a number of secondary emitting stages called dynodes. The dynodes are arranged so that electrons from each dynode are delivered to the next dynode in the series. Electrons emitted from the cathode are accelerated by an applied voltage to the first dynode, where their impact causes emission of numerous secondary electrons. These electrons are accelerated to the next dynode and generate even more electrons. Finally, electrons from the last dynode are accelerated to the anode and produce a large current pulse in the external circuit. The photomultiplier is packaged as a vacuum tube.

Figure 6-8 shows a cross-sectional diagram of a typical photomultiplier tube structure. This tube has a transparent end window with the underside coated with the photocathode material.

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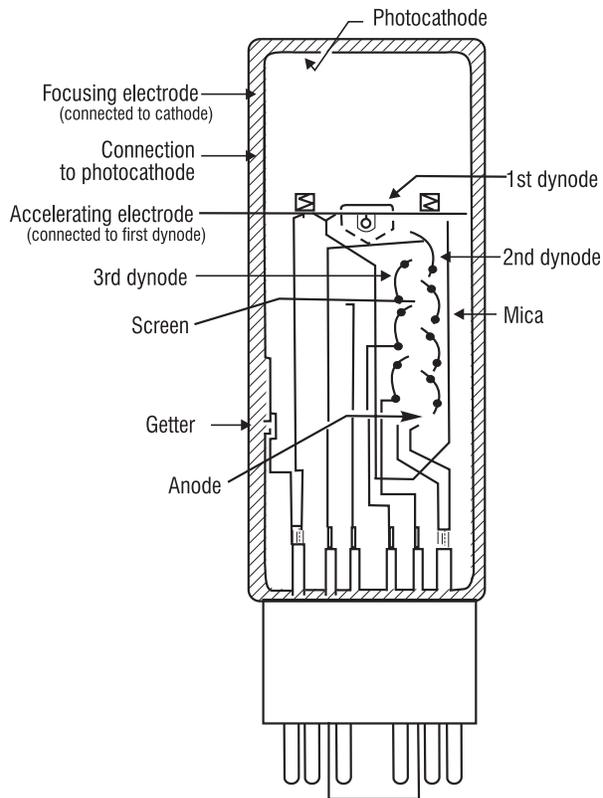


Figure 6-8 Diagram of typical photomultiplier tube structure

Figure 6-9 shows the principles of operation of the tube. Photoelectrons emitted from the cathode strike the first dynode, where they produce 1 to 8 secondary electrons per incident electron. These are accelerated to the second dynode, where the process is repeated. After several such steps the electrons are collected at the anode and flow through the load resistor. Voltages of 100 to 300 volts accelerate electrons between dynodes, so that the total tube voltage may be from 500 to 3000 volts from anode to cathode, depending on the number of dynodes.

The *current gain* of a photomultiplier is the *ratio of anode current to cathode current*. Typical values of gain may be in the range 100,000 to 1,000,000. Thus 100,000 or more electrons reach the anode for each photon striking the cathode. Photomultiplier tubes can in fact detect the arrival of a single photon at the cathode.

Figure 6-10 shows the gain as a function of the voltage from the anode to the cathode for a typical photomultiplier tube. This high gain process means that photomultiplier tubes offer the highest available responsivity in the ultraviolet, visible, and near infrared portions of the spectrum. But their response does not extend to wavelengths longer than about 1000 nm.

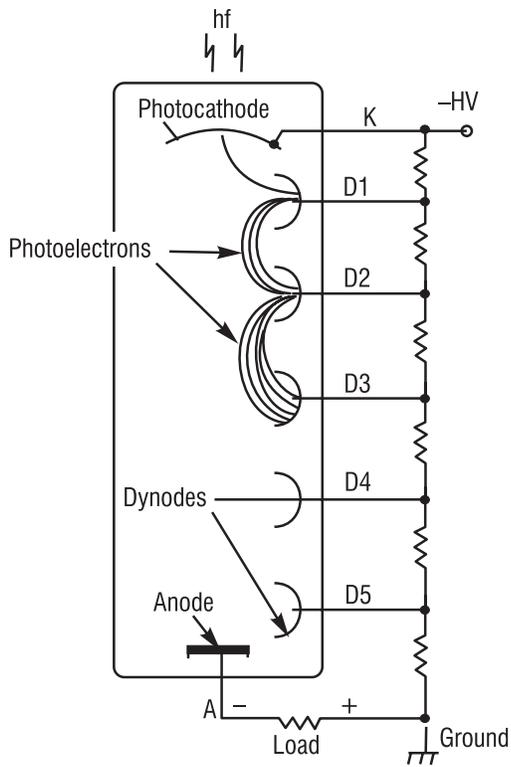


Figure 6-9 Principles of photomultiplier operation. The dynodes are denoted D1, D2, etc.

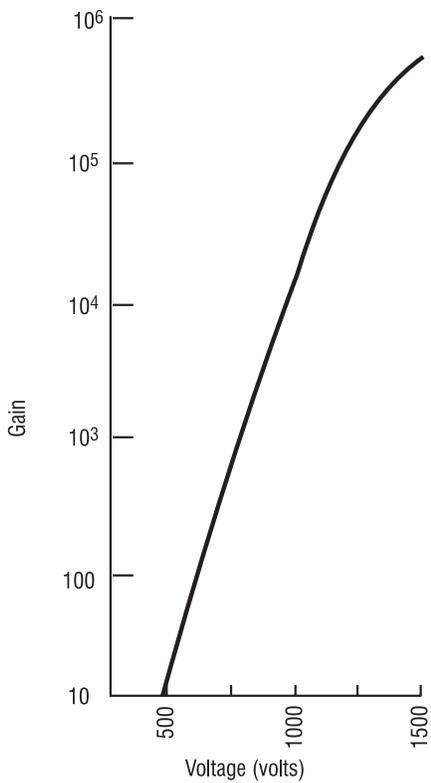


Figure 6-10 Photomultiplier gain as a function of applied voltage

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Photomultiplier tubes are used in many photonics applications, such as air-pollution monitoring, star tracking, photometry, and radiometry.

B. Thermal detectors

The second broad class of optical detectors, thermal detectors, responds to the total energy absorbed, regardless of wavelength. Thus thermal detectors do not have a long-wavelength cutoff in their response, as photon detectors do. The value of D^* for a thermal detector is independent of wavelength. Thermal detectors generally do not have as rapid a response as do photon detectors. For many photonics applications, they are often not used in the wavelength region in which photon detectors are most effective ($\leq 1.55 \mu\text{m}$). They are often used at longer wavelengths.

Bolometers and thermistors

In perhaps the most common manifestation of thermal detectors, the optical energy is absorbed by an element whose properties change with temperature. As the light energy is absorbed, the temperature of the element increases and the change in its properties is sensed. The temperature-measuring elements include *bolometers* and *thermistors*. Bolometers and thermistors respond to the change in electrical resistivity that occurs as temperature rises. Bolometers use metallic elements; thermistors use semiconductor elements. The bolometer or thermistor is in a circuit in series with a voltage source, so that current flows through it and, as the resistance changes, the voltage drop across the element changes, providing a sensing mechanism.

Thermocouples

In another manifestation, light is absorbed by an element to which a thermocouple is attached. The thermocouple is a device formed of two dissimilar metals joined at two points. Thermocouples may be fabricated from wires, but for detector applications they are often fabricated as thin films. The device generates a potential difference, which is a measure of the temperature difference between the points. One point is held at a constant reference temperature. The second point is in contact with the absorber. The light energy heats the absorber and the thermocouple junction in contact with it. This causes the voltage generated by the thermocouple to change, giving a measure of the temperature rise of the absorber and of the incident light energy.

To enhance the performance of the thermocouples, often there are a number of thermocouples in series, perhaps as many as 100. The “hot” junctions are all attached close together. This type of device is called a *thermopile*.

Figure 6-11 shows values of $D^*(\lambda, 1000, 1)$ (see section I.C) for some thermal detectors, including thermistors, bolometers, thermopiles and pyroelectric detectors, which will be described later. The values are independent of wavelength. In the visible and near infrared, the values of D^* for thermal detectors tend to be lower than for good photon detectors, but the response does not decrease at long wavelength.

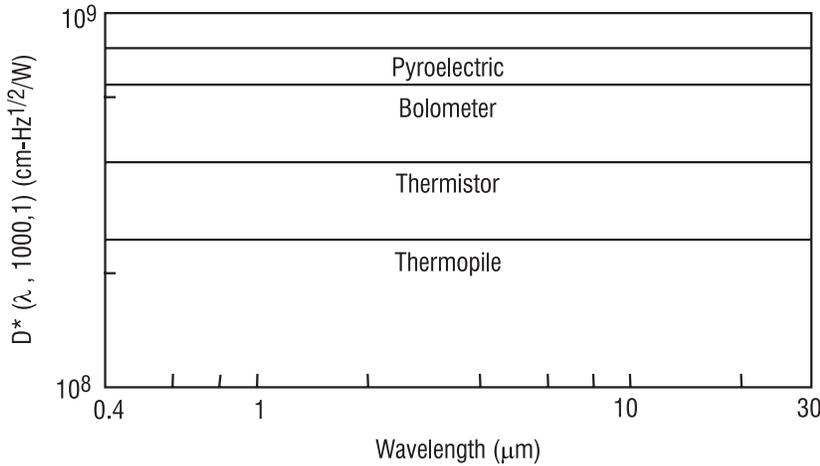


Figure 6-11 Detectivity (D^*) as a function of wavelength for several typical thermal detectors. The temperature of operation is 295 K.

Calorimeters

Measurements of pulse energy are frequently made using a *calorimeter*, which represents a common thermal detector system. Calorimetric measurements yield a simple determination of the total energy in an optical pulse, but calorimeters usually do not respond rapidly enough to follow the pulse shape. Calorimeters designed for photonics measurements often use blackbody absorbers with low thermal mass and with temperature-measuring devices in contact with the absorber to measure the temperature rise. Knowledge of the thermal mass coupled with measurement of the temperature rise yields the energy in the optical pulse.

A variety of calorimeter designs have been developed for measuring the total energy in an optical pulse or for integrating the output from a continuous optical source. Since the total energy in a pulse is usually not large, the calorimetric techniques are rather delicate. The absorbing medium must be small enough that the absorbed energy may be rapidly distributed throughout the body. It must be thermally isolated from its surroundings so that the energy is not lost.

A commonly encountered calorimeter design, the so-called cone calorimeter, uses a small, hollow carbon cone, shaped so that radiation entering the base of the cone will not be reflected back out of the cone. Such a design is a very efficient absorber. Thermistor beads or thermocouples are placed in contact with the cone. The thermistors form one element of a balanced bridge circuit, the output of which is connected to a display or meter. As the cone is heated by a pulse of energy, the resistance of the bridge changes, leading to an imbalance of the bridge and a voltage pulse that activates the display. The pulse decays as the cone cools to ambient temperature. The magnitude of the voltage pulse gives a measure of the energy in the pulse. Two identical cones may be used to form a conjugate pair in the bridge circuit. This approach allows cancellation of drifts in the ambient temperature.

Pyroelectric detectors

Another type of thermal detector is the *pyroelectric detector*. Pyroelectric detectors respond to the change in electric polarization that occurs in certain classes of crystalline materials (like lithium tantalate) as their temperatures change. The *change in polarization*, called the pyroelectric effect, may be measured as an open-circuit voltage or as a short-circuit current. Because they respond to changes in temperature, pyroelectric devices are useful as detectors for only pulsed or chopped radiation.

The response speed of pyroelectric detectors is fast, faster than that of other thermal detectors like thermistors and thermopiles. Pyroelectric detectors are fast enough to detect very short optical pulses.

The spectral detectivity D^* of pyroelectric detectors was shown in Figure 6-11. It tends to be higher than the detectivity of thermistor or thermopile detectors, and it is independent of wavelength.

III. CALIBRATION

The response of an optical detector in current (or voltage) per unit input of power is often taken as the nominal value specified by the manufacturer. But, for precise work, the detector may have to be calibrated by the user. Accurate absolute measurements of optical power or energy are difficult. A good calibration requires very careful work.

A. Response of detector

One widely used calibration method involves measurement of the total energy in the laser beam (with a calorimetric energy meter) at the same time that the detector response is determined. The temporal history of the energy delivery is known from the shape of the detector output. Since the power integrated over time must equal the total energy, the detector calibration is obtained in terms of laser power per unit of detector response.

In one common approach, you can use a calorimeter to calibrate a detector, which is then used to monitor the laser output from one pulse to another. A small fraction of the laser beam is diverted by a beam splitter to the detector, while the remainder of the laser energy goes to the calorimeter. The total energy arriving at the calorimeter is determined. The temporal history of the detector output gives the pulse shape. Then numerical or graphical integration yields the calibration of the response of the detector relative to the calorimeter. The calibration may be in terms of power or energy in the laser pulse. If you know the fraction of the total beam energy diverted to the detector, you can calibrate the detector response in terms of the energy in the pulse. If the pulse shape is stable from pulse to pulse, you can use the results of the numerical or graphical integration to determine the peak power in the pulse.

If the response of the calorimeter is fast, it can be used for measurement of power from a continuous source. The temperature of the absorber will reach an equilibrium value dependent on the input power. Such units are available commercially as laser power meters. Compared to the power meters based on silicon or other photodiodes, the power meters based on absorbing cones or disks are useful over a wider range of wavelength and do not require use of a compensating factor to adjust for the change in response as the laser wavelength changes.

After the calibration is complete, you can remove the calorimeter and use the main portion of the beam for the desired application. The detector, receiving the small portion of the beam directed to it by the beam splitter, acts as a pulse-to-pulse monitor.

B. Techniques to limit beam power

Filters

Quantitative measurements of laser output involve several troublesome features. The intense laser output tends to overload and saturate the output of detectors if they are exposed to the full power. Thus, absorbing filters may be used to cut down the input to the detector. A suitable filter avoids saturation of the detector, keeps it in the linear region of its operating characteristics, shields it from unwanted background radiation, and protects it from damage. Many types of attenuating filters have been used, including *neutral-density filters*, *semiconductor wafers* (like silicon), and *liquid filters*.

We note that filters also may saturate and become nonlinear when exposed to high irradiance. If a certain attenuation is measured for a filter exposed to low irradiance, the attenuation may be less for a more intense laser beam. Thus, a measurement must be performed at a low enough irradiance so that the filter does not become saturated.

Beam splitters

The use of beam splitters also can provide attenuation of an intense laser beam. If the beam is incident on a transparent dielectric material inserted at an angle to the beam, there will be specular reflection of a portion of the beam. One may measure this reflected beam, which will contain only a small fraction of the incident power. The fraction may be determined using Fresnel's equations. The calculation requires knowledge of the geometry and the index of refraction of the dielectric material.

Lambertian reflectors

Another method for attenuating the beam before detection is to allow it to fall normally on a diffusely reflecting massive surface, such as a magnesium oxide block. The arrangement is shown in Figure 6-12. The angular distribution of the reflected light is proportional to the angle θ between the normal to the surface and the direction of observation. Thus, the power reflected is maximum along the normal to the surface and decreases to zero at 90 degrees to the surface. This dependency is called *Lambert's cosine law*, and a surface that follows this law is called a *Lambertian surface*. Many practical surfaces follow this relation, at least approximately. The power P_{detector} that reaches the detector after reflection from such a surface is

$$P_{\text{detector}} = P_{\text{tot}} \frac{A_d}{\pi D^2} \cos \theta \quad (6-4)$$

where P_{tot} is the total laser power, A_d is the area of the detector (or its projection on a plane perpendicular to the line from the target to the detector), and D is the distance from the target to the detector. This approximation is valid when D is much larger than the detector dimensions and the transverse dimension of the laser beam.

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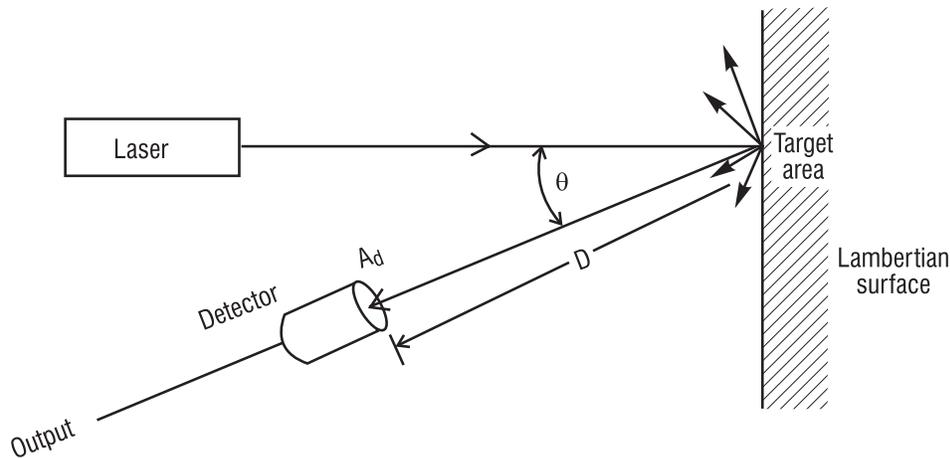


Figure 6-12 Arrangement for measuring laser power using a Lambertian reflector to attenuate the power reaching the detector. D is the distance from the surface target to the detector and A_d is the area of the detector.

With a Lambertian reflector, the power incident on the photosurface can be adjusted in a known way by changing the distance D or the angle θ . The beam may be spread over a large enough area on the Lambertian surface so that the surface is not damaged. The distance D is made large enough to ensure that the detector is not saturated. The measurement of the power received by the detector, plus some easy geometric parameters, gives the fraction of the beam power reaching the detector.

Example 4

A laser beam with total power 10 watts is incident at normal incidence on a Lambertian surface. How much power reaches a detector with an area of 0.5 cm^2 at an angle of 45 degrees if the detector area is 30 cm from where the beam strikes the target reflecting surface?

Solution

According to Equation 6-4, the power reaching the detector is

$$\begin{aligned} P_{\text{detector}} &= 10 \text{ W} \times 0.5 \text{ cm}^2 / \{\pi \times (30 \text{ cm})^2\} \times \cos 45^\circ \\ &= 10 \times 0.5 / (3.1416 \times 900) \times 0.707 \text{ W} \\ P_{\text{det}} &= 0.00125 \text{ W} \end{aligned}$$

C. Electrical calibration

It is also possible to calibrate power meters electrically. It is assumed that the deposition of a given amount of energy in the absorber provides the same response, independent of whether the energy is optical or electrical.

The absorbing element is heated by an electrical resistance heater. The electrical power dissipation is determined from electrical measurements of the current and voltage. The measured response of the instrument to the known electrical input provides the calibration.

Accurate absolute measurement of optical power is difficult. Thus, one must use great care in the calibration of optical detectors.

IV. CIRCUITRY FOR OPTICAL DETECTORS

The basic power supply for an optical detector contains a voltage source and a load resistor in series with the detector. As the irradiance on the detector element changes, the current in the circuit changes and the voltage drop across the load resistor changes. Measurement of the voltage drop provides the basis for the optical power measurement.

A variety of different circuits may be used, depending on the detector type and on the application. A full description of all the types of detector circuits is beyond the scope of this module. We shall describe electrical circuitry used with two representative types of detectors, the photovoltaic detector and the photoconductive detector.

A. Basic circuit for a photovoltaic detector

A photovoltaic detector requires no bias voltage; it is a voltage generator itself. A basic circuit for a photovoltaic detector is shown in Figure 6-13. This shows the conventional symbol for a photodiode at the left. The symbol includes the arrow representing incident light. The incident light generates a voltage from the photodiode, which causes current to flow through the load resistor R_L . The resulting voltage drop across the resistor again is available as a signal to be monitored.

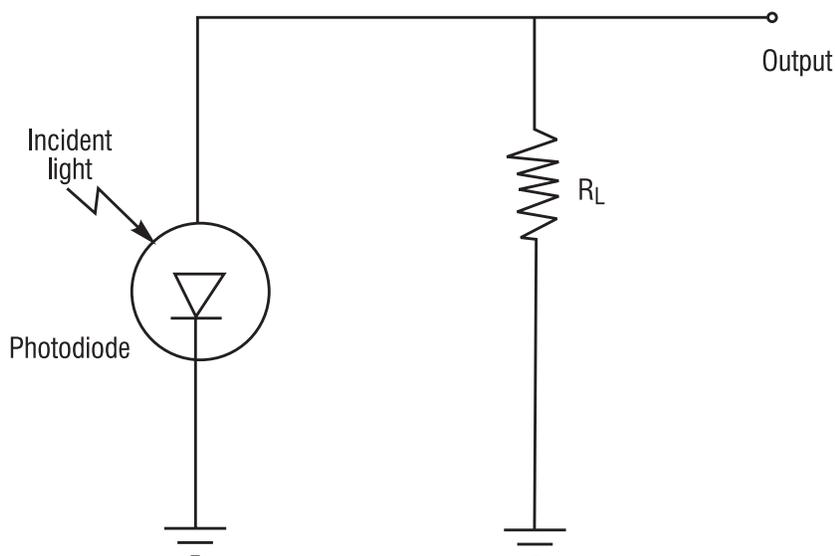


Figure 6-13 Basic circuit for operation of a photovoltaic detector. The symbol for a photodiode is indicated. The load resistor is R_L .

OPTICAL DETECTORS AND HUMAN VISION

In this configuration it is assumed that the value of the load resistor is much larger than the value of the shunt resistance of the detector. The shunt resistance is the resistance of the detector element in parallel with the load resistor in the circuit. The value of the shunt resistance is specified by the manufacturer and for silicon photodiodes may be a few megohms to a few hundred megohms.

Disadvantages of this circuit are that the response is nonlinear (it is logarithmic) and the signal depends on the shunt resistance of the detector, which may vary in different production batches of detectors.

Practical loads that need to be driven are usually much lower than those that can be used with the photovoltaic diode. In order to counter this disadvantage, an amplifier can be used as a buffer between an acceptable high load resistor for the diode and a much lower useful load resistance. Figure 6-14 shows this configuration.

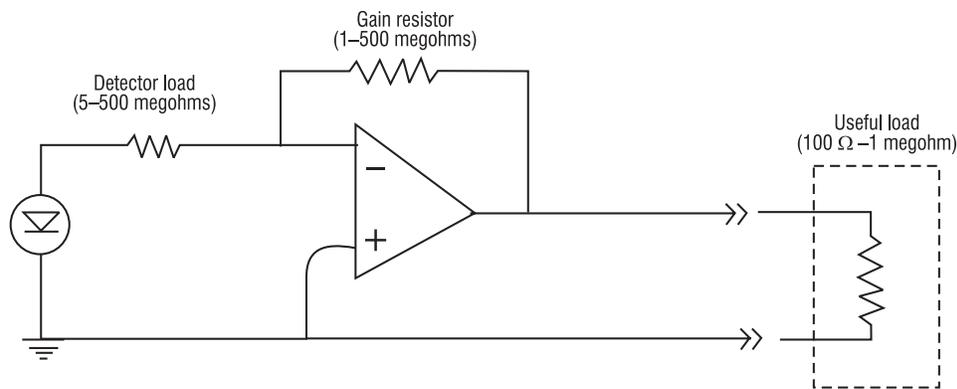


Figure 6-14 *Circuit for photovoltaic detector operation with a high detector load resistance driving a useful load of lower resistance*

This circuit has a linear response to the incident light intensity. It also is a low noise circuit because it has almost no leakage current, so that shot noise is low.

B. Basic circuit for a photoconductive detector

We previously noted that photodiodes may be operated in a photoconductive mode. Figure 6-15 shows a circuit which provides this type of operation. The diode is reverse biased, so that the operation is in the third quadrant of Figure 6-5. The photocurrent produces a voltage across the load resistor which is in parallel with the shunt resistance of the detector. The shunt resistance is nearly constant. One may use large values of load resistance, so as to obtain large values of signal, and still obtain linear variation of the output with the optical power.

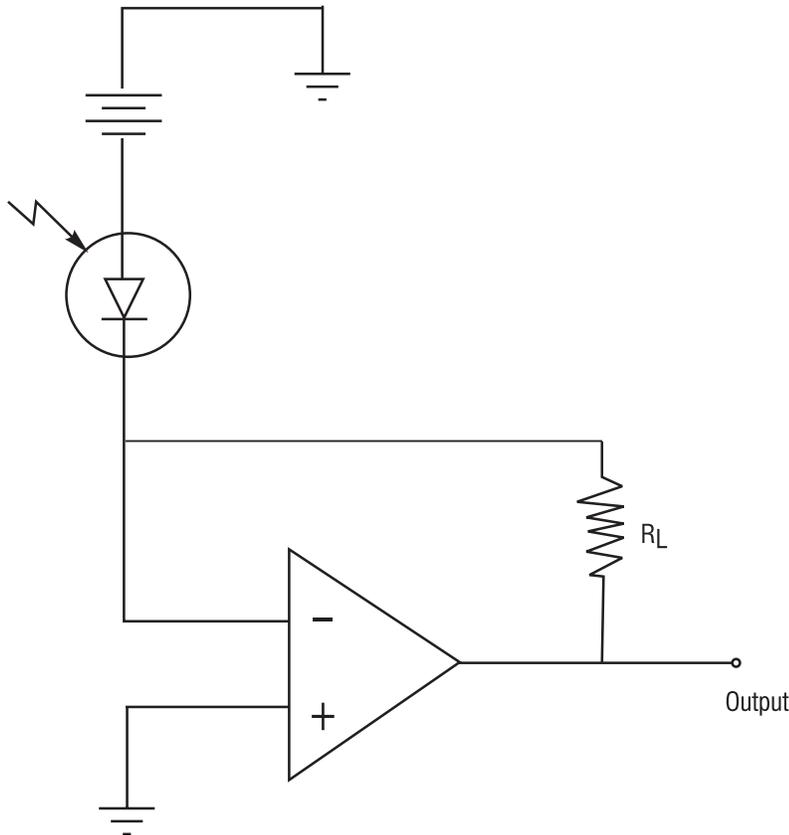


Figure 6-15 Circuit for operation of a photodiode in the photoconductive mode. The load resistor is R_L .

This circuit can provide very high-speed response. It is possible to obtain rise times of one nanosecond or below with this type of circuit. The biggest disadvantage of this circuit is the fact that the leakage current is relatively large, so that the shot noise is increased.

V. HUMAN VISION

A. The eye as an optical detector

An important optical detector is the human eye. In some respects, the eye can be regarded as a specialized type of detector system, with attributes similar to those of the other detectors that we have considered. In common with other optical detectors, the eye is a *square-law detector*, responding to the incident radiant power, which is proportional to the square of the electric field in the light wave.

The eye has a spectral response that covers the range approximately from 400 to 700 nm, the range that is called the visible spectrum. At longer and shorter wavelengths, the eye is not able to detect incident optical energy.

B. Structure of the eye

The eye can be considered as a complete optical system, including packaging, a variable aperture, a curved corneal surface and a lens that provide for imaging, a variable focus capability, a photosensor, and an output to a computer, the brain. Figure 6-16 shows a simplified diagram of the structure of the eye. The eye is approximately spherical in shape and is contained within a tough, fibrous envelope of tissue called the sclera. The sclera covers all the eyeball except for a portion of its front. At the front of the eyeball is the cornea, which has a refractive index around 1.38. The cornea is a transparent membrane that allows light to enter the eyeball and that contributes significantly to the focusing capability of the eye. Behind the cornea is the iris, an adjustable aperture that expands in dim light and contracts in bright light, controlling the amount of light which enters the eyeball. The pupil of the eye is the opening in the center of the aperture defined by the iris. Light entering the eye passes through the pupil.

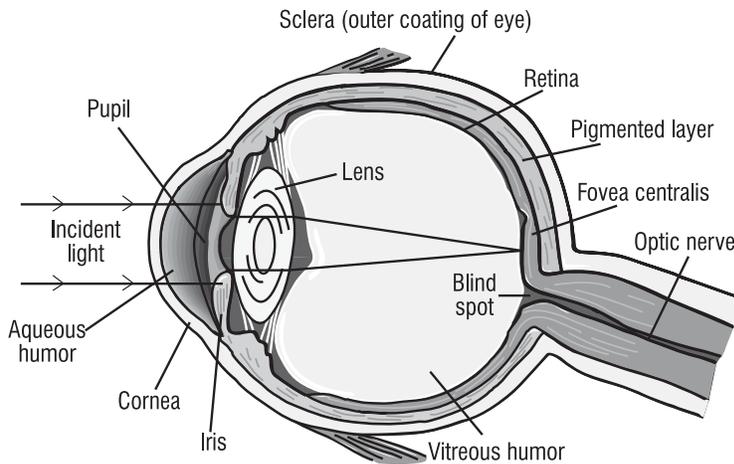


Figure 6-16 *Structure of the human eye*

The region behind the cornea contains a transparent liquid called the aqueous humor with refractive index around 1.34. Then there is the lens of the eye, a capsule of fibrous jelly-like material, with refractive index varying from 1.41 in the center to 1.39 at the periphery. The shape of the lens can be changed by muscles attached to it. This allows for fine focusing of light entering the eye.

After the lens is a transparent thin jelly called the vitreous humor. It has a refractive index around 1.34. Finally, covering most of the back surface of the eyeball is the retina, the photosensitive medium that serves as the actual detector material.

The cells in the retina are of two types, called rods and cones. The rods and cones serve different functions, the cones providing the most sensitive vision near the center of the retina and the rods the peripheral vision farther out in the retina. The rods also are more sensitive in dim light than are the cones, so that the rods tend to dominate night vision.

Near the center of the retina is a slight depression, called the fovea centralis, that contains only cones. This region provides the most acute vision.

The rods and cones are connected through nerve fibers to the optic nerve, which emerges from the back of the eyeball. The rods and cones receive the optical image and transmit it through the

nerve fibers to the brain. At the point where the optic nerve exits the eyeball, there are no rods or cones, so there is a small blind spot at that position.

C. Operation of the eye

The eye is an imaging system. The substantial refraction of incoming light energy by the cornea and the action of the lens combine to form an image of the pattern of incident light on the retina. Because the index of refraction of the lens (about 1.40) is not too different from that of the aqueous and vitreous media (about 1.34), much of the refraction of light entering the eyeball occurs at the cornea, as mentioned earlier.

When a normal eye is relaxed, light from very distant objects is focused on the retina. The light rays from the distant object enter the eye as parallel rays. The eye is said to be focused at infinity.

Fine focusing of light coming from points other than infinity is accomplished by changing the shape of the lens. Muscles attached to the lens and to the eyeball accomplish this. In this way the eye may form a sharp focus of nearby objects. This process is called accommodation. In some cases, where the cornea is too coned, and the length of the eyeball is a bit too long or too short, *corneal sculpting*, performed with lasers, can be carried out to improve visual acuity.

The spectral response of the eye is shown in Figure 6-17. The y -axis is the relative response of the eye, normalized to unity at its peak near 555 nm, as a function of wavelength. This curve is the so-called photopic response, which is characteristic of the cones. It is usually stated to cover the range from 400 to 700 nm, but there is some lower response at longer wavelengths. The peak response is in the green portion of the spectrum, near 555 nm.

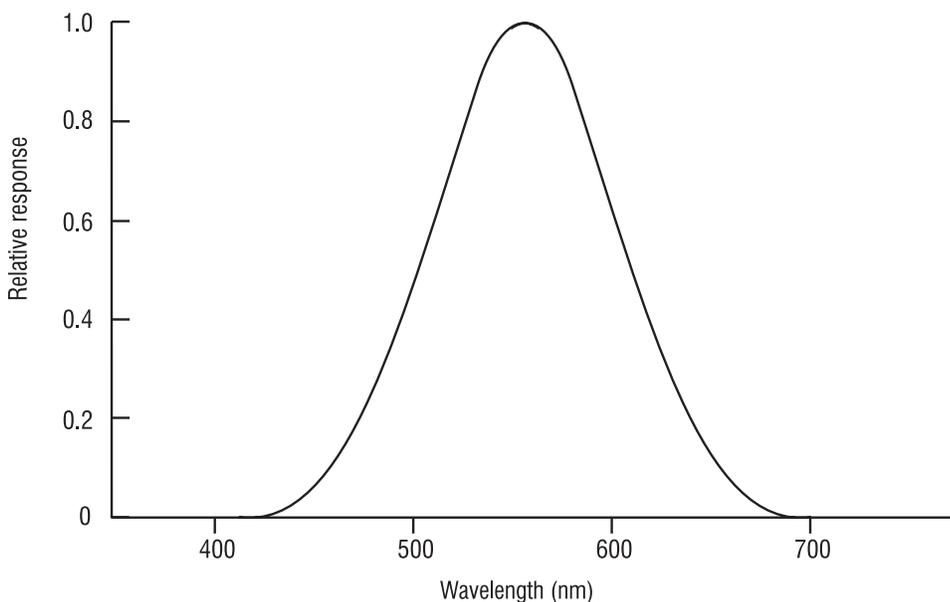


Figure 6-17 *Relative spectral response of the eye (photopic response) as a function of wavelength, normalized to unity at its peak value near 555 nm*

The rods in the eye have a somewhat different response, called the scotopic response. The peak of the scotopic response is shifted toward the blue.

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The interaction of light with the structures of the eye leads to the phenomenon called vision. Vision may be considered to be the sensation in the consciousness of a human observer when the retina of the eye is stimulated by optical energy with appropriate wavelength. The process of vision begins with photochemical changes that occur within the retinal cells when light is absorbed by them. It continues as the complex organic molecules produced in the photochemical processes cause signals to propagate through the nerve fibers to the brain. Finally, in a very important portion of the process, the brain interprets the signals as images corresponding to external objects. This is the process by which the observer becomes aware of optical images through visual sensations that arise because of stimulation of the retina by optical energy.

D. Color

Human vision includes the sensation of color. Color may be considered to be the aspect of things that is caused by differing qualities of the light reflected or emitted by them, other than spatial and temporal inhomogeneities. It is definable in terms of the observer as the appearance of objects or light sources described in terms of the individual's perception of them, involving *brightness*, *saturation* and *hue*.

Taken together, the three attributes of brightness, saturation and hue make up the sensation of color. We will discuss these three attributes one at a time.

Brightness

For *brightness*, consider a series of neutral grays, ranging from white at one end to black at the other. White evokes the greatest sensation of brightness and black the least. Other of the neutral grays are in between. A colored sample may be compared with the series of neutral grays. It will evoke the same sensation of brightness as some member of the group of grays. Brightness is then defined as the attribute of any color that allows it to be considered as equivalent in the sensation produced by some member of the series of neutral grays.

Saturation

The *saturation* is the attribute that describes the extent by which a color departs from a neutral gray and approaches a pure color.

Hue

The attribute of *hue* is the property of color by which it can be perceived as ranging from red through orange, yellow, green, etc. It is related to a property called the dominant wavelength of the light, which will be defined later.

We may clarify these concepts by considering the so-called *chromaticity diagram*. The chromaticity diagram allows us to specify any color in terms of numbers. The chromaticity diagram, usually presented in full color, is shown in Figure 6-18 in black and white. Usually the interior of the diagram is filled in with varying colors.

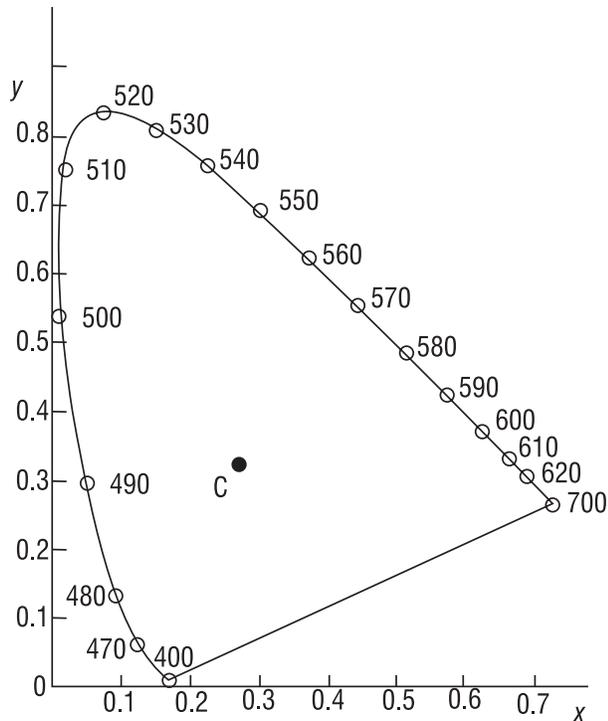


Figure 6-18 Black-and-white version of the chromaticity diagram. The white light point is denoted *C*. The numbers around the edge of the curve denote the wavelengths in nanometers of pure spectral colors.

The wing-like boundary edge of the curve represents pure colors of the visible electromagnetic spectrum. These colors represent monochromatic light of one wavelength and are denoted by the wavelength in nanometers, ranging from 400 to 700 nm. A straight line from 400 to 700 nm completes the closed curve.

The interior of the curve represents all colors. Shades of blue would be found inside the curve near the number 480, shades of yellow near 575, etc. The point marked *C* represents “white light,” or average daylight. Any color within the diagram can be expressed quantitatively by the two coordinates x and y .

With the aid of the chromaticity diagram, the hue of a color can be expressed in terms of its principal wavelength. For a given color, with coordinates x and y in the diagram, a line is drawn from the point *C* through the point given by x and y and extended to the edge of the diagram, where it intersects the edge at some pure spectral color. That wavelength of that color is the principal wavelength for the given color.

The purity, related to the saturation, may be found in the same way. On the line from *C* through the coordinates x and y to the edge of the diagram, the purity of the color expressed by x and y is the distance from *C* to the point represented by x and y , expressed as a percentage of the distance from *C* to the edge of the diagram. Thus, the purity of white light is 0% and the purity of a spectral color at the edge of the diagram is 100%.

E. Defects of vision

Vision can be imperfect in a number of ways. Some imperfections arise because there is an incorrect relation between the positions of various parts of the eye. In a normal, relaxed eye, parallel light rays entering the eye will be focused on the retina, as shown in Figure 6-16. For very distant objects, the light rays coming from the object will be nearly parallel and the image of the object will be focused on the retina of the relaxed eye.

If the eyeball is too long, parallel light rays will come to a focus in front of the retina. For this eyeball, the most distant object that will be in focus on the retina of the relaxed eye will be at a distance less than infinity. In this case, the eye is said to be nearsighted. The condition is called *myopia*.

If the eyeball is too short, the focus of parallel light rays will be behind the retina. The eye is then said to be farsighted. This condition is called *hyperopia*.

Another defect arises when the surface of the cornea is not spherical. It may be more sharply curved along one great circle than along another. This leads to a condition called *astigmatism*. Astigmatism makes it impossible to focus clearly on horizontal and vertical lines at the same time.

The conditions of myopia, hyperopia, and astigmatism may all be alleviated by the use of corrective lenses.

Another defect of vision, which does not arise from improper relation of the different parts of the eye is *color blindness*. Color blindness, also called color vision deficiency, involves abnormalities that cause a person to be unable to distinguish certain colors, or to perceive colors differently than most people. Color blindness arises from inherited defects in the pigment in cone cells in the retina. It may take on a wide range of degrees of severity, from very mild to a situation in which the eye sees only shades of gray. Color blindness is a lifelong condition. It may disqualify people from certain occupations.

Laboratory

In this laboratory, you will set up and operate circuitry for a silicon PIN photodiode and will use the circuitry to measure chopped HeNe laser light and argon laser light and will determine the relative response of the detector system at several wavelengths.

Materials

Photodiode (Centronic OSD100-5T or equivalent)

Operational amplifier (National Semiconductor LF356 or equivalent)

Electric motor with toothed chopper wheel (Laser Precision CTX-534 Variable Speed Optical Chopper or equivalent)

Helium-neon laser (few milliwatt output)

Resistors (selection of values, kilohms to megohms)

Neutral-density filters (selection of different values, with total neutral density at least 4)

Oscilloscope

Power meter (Spectra-Physics model 405 or equivalent)

Argon ion laser (line tunable, with at least 4 visible wavelengths available)

DC voltage source

PROCEDURE

The first part of the *Procedure* will involve fabrication of a circuit to operate a photodiode as a photovoltaic detector. You will use the circuit to measure chopped laser light and to measure the responsivity of the photodiode.

First, you will set up circuitry for using the photodiode in the photovoltaic mode. Figure 6-19 shows the experimental arrangement. In this arrangement, the photodiode operates as a photovoltaic detector.

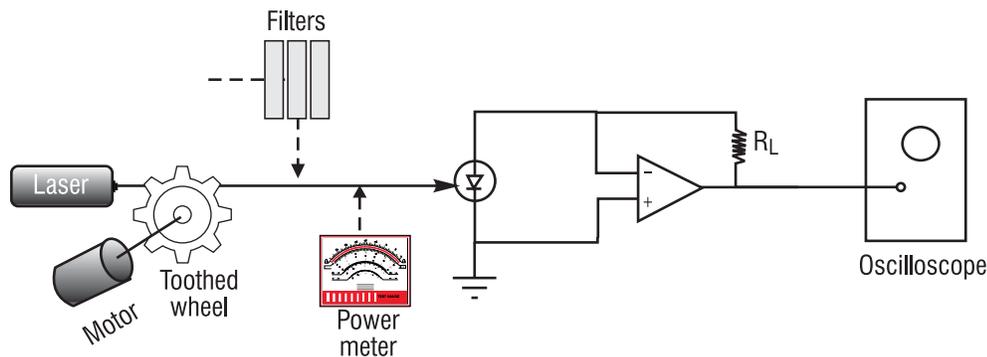


Figure 6-19 *Experimental arrangement for measurements with photodiode operated in a photovoltaic mode*

The toothed wheel is mounted on the electric motor. When it rotates, it chops the light. That is, it periodically blocks the HeNe laser light from reaching the detector. The speed of the motor should be adjusted so that the light is blocked 1000 times per second. This is a standard measurement condition. If the wheel has 10 teeth, for example, the motor should rotate at 100 revolutions per second.

Assemble the circuit as shown in Figure 6-19. The load resistor should be much smaller than the value of the shunt resistance of the photodiode, which is specified by the manufacturer. The output of the circuit will be hooked to the input of the oscilloscope.

The oscilloscope screen should show a square wave with a frequency of 1000 Hertz. Use the voltage calibration of the oscilloscope to measure the peak voltage of the signal. Then insert the power meter into the laser beam in front of the photodiode and measure the power in the beam. Calculate the responsivity of the detector and compare it to the manufacturer's specification. Remove the power meter.

Next, check the linearity of the detector response by inserting neutral-density filters into the path of the beam as indicated. Gradually increase the number of neutral-density filters and

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record the total neutral density and the peak voltage at each step. Increase the neutral density to at least 4, increasing the sensitivity of the oscilloscope display as necessary. Plot the peak voltage as a function of neutral density on semilogarithmic paper. The plot should be a straight line.

Next, you will operate the photodiode in the photoconductive mode. The experimental arrangement is shown in Figure 6-20. Note that a DC voltage source is added in this figure.

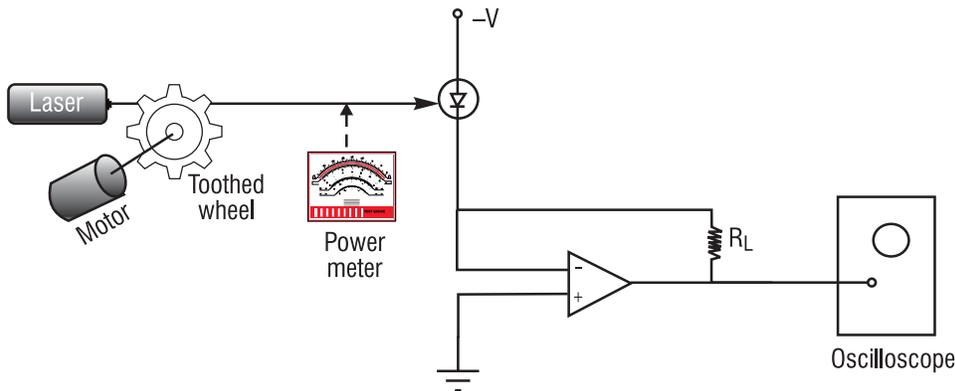


Figure 6-20 *Experimental arrangement for measurements with photodiode operated in a photoconductive mode*

Hook up the circuit as shown in Figure 6-20. The load resistor should be relatively large, in the megohm regime. The output of the circuit is used as the input of the oscilloscope.

The output on the oscilloscope screen should be a 1000-Hz square wave. Use the voltage calibration of the oscilloscope to measure the peak voltage of the signal. Then insert the power meter into the laser beam in front of the photodiode and measure the power in the beam. Calculate the responsivity of the detector and compare it to the manufacturer's specification.

Next, you will investigate the effect of varying the load resistor. Remove the power meter and change the value of the load resistor. Use several different values of load resistor, and for each one record the value of the peak signal. Plot the peak signal as a function of the value of the load resistor. How does the signal vary with load resistance?

Now you will measure the responsivity as a function of wavelength. One measurement is already available, at 633 nm. Use the line-tunable argon laser to obtain values for at least four different visible wavelengths.

Replace the helium-neon laser in Figure 6-20 with the argon laser. Replace the load resistor with the same value that was used for the responsivity measurement at 633 nm. For each of four different argon laser wavelengths, measure the peak voltage on the oscilloscope and the laser power reading with the power meter in the same way that you measured them at 633 nm. If the argon laser power is too high, insert neutral-density filters in front of the photodiode and the power meter to reduce it to an appropriate value. Record the results and calculate the responsivity for each wavelength. Plot the responsivity as a function of wavelength and compare the result to the manufacturer's specification.

DATA TABLE

Detector responsivity measurement (photovoltaic mode)

Voltage measurement _____
 Laser power _____
 Calculated detector responsivity _____
 Manufacturer's quoted responsivity _____

Linearity measurement

Measurement number	Neutral density	Voltage
1.	_____	_____
2.	_____	_____
3.	_____	_____
4.	_____	_____

(Plot the results on semilog paper.)

Detector responsivity measurement (photoconductive mode)

Voltage measurement _____
 Laser power _____
 Calculated detector responsivity _____
 Manufacturer's quoted responsivity _____

Effect of load resistor

Measurement number	Load resistor	Signal voltage
1.	_____	_____
2.	_____	_____
3.	_____	_____
4.	_____	_____

(Plot the results.)

Responsivity vs wavelength

Measurement number	Voltage	Power	Calculated responsivity	Manufacturer's responsivity
1.	_____	_____	_____	_____
2.	_____	_____	_____	_____
3.	_____	_____	_____	_____
4.	_____	_____	_____	_____

(Plot the results, including the value for 633 nm obtained earlier.)

Problems

1. Define detector responsivity, noise equivalent power, quantum efficiency, detectivity, and rise time.
2. Define sources of detector noise, including shot noise, Johnson noise, $1/f$ noise, and photon noise. Explain methods employed to reduce these noise sources in the detection of optical radiation.
3. Describe and explain important types of photodetectors, including photon detectors, thermal detectors, photoemissive detectors, photoconductive detectors, photovoltaic detectors, and photomultiplier detectors. Describe the spectral response of each type.
4. Draw and explain a typical circuit used with a photovoltaic detector.
5. Draw and explain a typical circuit used with a photoconductive detector.
6. Describe concepts related to human vision, including structure of the eye, the formation of images by the eye, and common defects of vision.
7. With an irradiance of 0.001 W/cm^2 incident on a detector of area 0.5 cm^2 and with a bandwidth of 2 Hz, the ratio of the noise voltage to the signal voltage is 10. What is the noise equivalent power of the detector?
8. A detector has a noise equivalent power of $5 \times 10^{-10} \text{ watts/(Hz)}^{1/2}$ and an area of 0.2 cm^2 . What is its value of D^* (detectivity)?
9. A detector has a responsivity of 0.12 ampere per watt at a wavelength of $1.06 \mu\text{m}$. What is the quantum efficiency of the detector?
10. A laser beam with total power of 22 watts is incident at normal incidence on a Lambertian surface. How much power reaches a detector with an area of 0.1 cm^2 at an angle of 22 degrees located at a distance of 50 cm from where the beam strikes the surface?

References

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