onto the detector. The stray light competes with the modulated light from the distant transmitter. If the environmental light is sufficiently strong it can interfere with light from the light transmitter. As indicated above, the light striking the detector produces a DC current proportional to the light intensity. But, within the DC signal produced there is also some broadband AC noise components. The noise produces random electrical signal fluctuations. The background static you often hear on an AM radio when tuned between stations is one example of noise. Fortunately, the magnitude of the AC noise seen in an optical receiver is small but it can still be high enough to cause problems. The noise has the effect of reducing the sensitivity of the detector, during high ambient light conditions. As will be discussed in the section on light receiver circuits, some tricks can be employed to lessen the amount of noise that would otherwise be produced at the detector from ambient light. But, as long as there is extra light focused onto a detector there will always be noise.

LIGHT DETECTOR NOISE

$$Id = \sqrt{(3.2 \times 10^{-19})(Bw)(E)(Ia)}$$

Id = RMS NOISE CURRENT FOR DETECTOR IN AMPS
Bw = RECEIVER BANDWIDTH IN HERTZ
E = DETECTOR CONVERSION EFFICIENCY (TYP 0.5)
Ia = DETECTOR DC CURRENT FROM AMBIENT LIGHT IN AMPS

NOTE: TYPICAL PEAK NOISE IS APPROX. 5X THE RMS

Figure 2d

The equation shown in ***Figure 2d*** describes how the detector noise varies with ambient light. The relationship follows a square root function. That means if the ambient light level increases by a factor of four, the noise produced at the detector only doubles. This characteristic both helps and hurts a light receiver circuit, depending on whether the system is being used during the light of day or during the dark of night. The equation predicts that for high ambient daytime conditions, you will have to dramatically reduce the amount of ambient light striking the detector in order to see a significant reduction in the amount of noise produced at the detector circuit.

The above equation also describes that under dark nighttime conditions, the stray light has to dramatically increase in order to produce a sizable elevation in noise. If the system must work during both day and night, it will have to contend with the worst daytime noise conditions. Conversely, some light receivers could take advantage of the low stray light conditions found at night and produce a communications system with a much longer range than would be otherwise possible if it were used during daylight.

Minimum Detectable Light Levels

The weakest modulated light signal that can be detected by a typical PIN diode will be dependent on several factors. The most important factor is the noise produced by the detector. As discussed above, the detector noise is very dependent on the amount of extra light striking the detector. For most medium speed applications, the weakest modulated light signal that can be detected is about 0.1 nanowatts. But, such a sensitivity can only be achieved under very dark conditions, when virtually no stray light is focused onto the detector. In many daytime conditions the ambient light level may become high enough to reduce the minimum detectable signal to about 10 nanowatts. However, to insure a good communications link you should plan on collecting enough light so the signal of interest, coming from the distant transmitter, is at least 10 times higher in amplitude than the noise signal. This rule-of-thumb is often referred to as a minimum 20db signal to noise ratio (SNR).

Optical Heterodyning

Another detector scheme, that has already been demonstrated in the laboratory and may someday be available to the experimenter, is "optical heterodyning". The scheme doesn't actually use a new detector but rather a new way of processing the light with an existing detector. Students of electronics should be familiar with the classical super-heterodyne technique used in most radio receivers. In brief, this method mixes the frequencies from the incoming radio signal with another fixed local oscillator frequency. The result is both a sum and difference family of frequencies that can be more easily amplified and used to separate the desired signal from the background noise and interference. This same principle has now been applied in the realm of optical frequencies.

To make the optical heterodyne concept work, special lasers must be used that have been carefully constructed to emit light of very high purity. The light from these lasers is very nearly one single wavelength of light. When the light from two of these lasers that emit light of slightly different wavelengths, is focused onto a detector, the detector's output frequency corresponds to a sum and difference of the two wavelengths. In practice, the light from a nearby laser produces light with a slightly different wavelength than the distant transmitter laser. As in the radio technique, optical heterodyning should allow very weak signals to be processed more easily and should also permit many more distinct wavelengths of light to be transmitted without interference. A single light detector could then be used in conjunction with multiple laser sources. This technique is often referred to as "wavelength division multiplexing" and could allow a single receiver system to select one color "channel" from among several thousand channels transmitted. But, for the average experimenter, such techniques are just too complicated.

Future Detectors

Experimental research in optical computers may lead to some useful light detectors at some time in the future. Most likely, a device will be developed that will amplify light somewhat like a transistor amplifies current. Such a device would use some kind of external light that would be modulated by the incoming light. Perhaps light emitted from a constant source would be sent through the device at one angle and would be modulated by the much weaker light striking the device at another angle. Since these devices would use only light to amplify the incoming light, without an optical to electrical conversion, they should be very fast and might have large active areas. Such detectors may eventually allow individual photons to be detected, even at high modulation rates. If these advanced detectors do become available, then many optical through-the-air communications systems could be designed for much longer ranges than now possible. Perhaps the combination of higher power light sources and more sensitive light detectors will allow a future system to be extended by a factor of 100 over what is now possible.

In addition to the above "all optical" detector there may be other kinds of detectors developed that work on completely different concepts. Some experiments on some special materials suggest that an opto-magnetic device might make a nice detector. Such a device produces a magnetic field change in response to incident light. A coil wrapped around the material might be used to detect the small change in the field and thus might allow small light levels to be detected. As electro-optics science grows I expect many new and useful devices will become available to the experimenter.

Detector Noise

Unlike fiber optic communications, through-the-air systems collect additional light from the environment. Light from the sun, street lights, car head lights and even the moon can all be focused

Photo Multiplier Tube

Photo Multiplier Tub

An older device that is still being used today to detect very weak light levels is the photo multiplier tube (PMT). The photo multiplier is a vacuum tube that operates somewhat like an avalanche photodiode. Light striking a special material called a "photo cathode" forces electrons to be produced. A high voltage bias between the cathode and a nearby anode plate accelerates the electrons toward the anode. The high speed electrons striking the first anode causes another material coated on the anode to produce even more electrons. Those electrons are then accelerated toward a second anode. The process is repeated with perhaps as many as ten stages. By the time the electrons emerge from the last anode, the photo current that results may be 10,000 times greater than the current that might have been produced by a PIN detector.

This high gain makes the PMT the most light sensitive device known. They are also fast. Some will have response times approaching good PIN diodes. However, the PMT has several drawbacks. It is a physically large device. Also, since it is made of glass, it is much more fragile than a solid state detector. Also, the high voltage bias, that is required, makes the supporting circuits much more complicated. In addition, because of the very high gains available, stray light must be kept to very low levels.

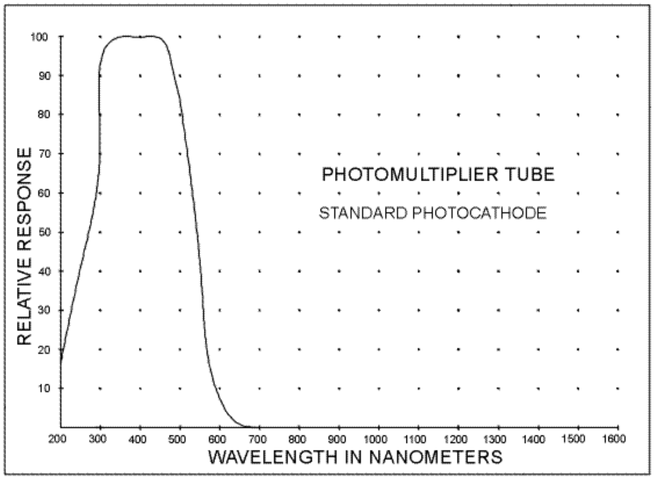


Figure 2c

The ambient light associated with a through-the-air communications system would cause some serious problems. You would have to use a laser light source with very narrow optical band pass filter to take advantage of a PMT. As shown in ***figure 2c***, most PMTs are better suited to detecting visible and ultraviolet light than infrared wavelengths. Only some of the latest devices have useful gains in the near infrared. (see ***Figure 2c-1***.) Finally, PMTs are usually very expensive. Still, PMTs do have rather large active areas. If used with visible wavelength lasers and narrow optical filters, a PMTs large active area could allow a receiver system to use a very large light collecting lens. If optimized, such a system could yield a very long range. But overall, a PMTs disadvantages far outweigh their advantages in most applications.

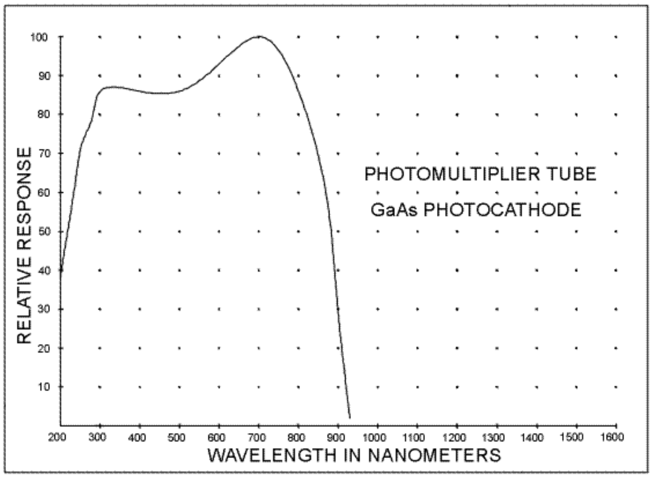


Figure 2c-1

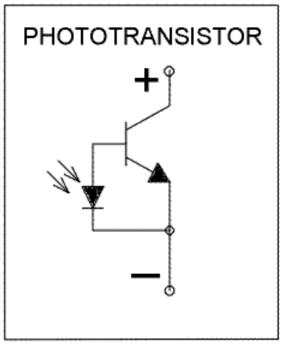


Figure 2b-1

photodiode is still a much better choice if you want systems with better performance. As shown in ***Figure 2b-1***, a phototransistor is a silicon photodiode connected to the base-emitter terminals of a silicon transistor. Since the phototransistor it is made of silicon, it has a similar response curve as a standard silicon PIN photodiode. The photodiode is connected directly to the transistor, it is not reversed biased and operates in a photovoltaic mode. The current produced by the photodiode is routed to the transistor that provides a sizable current gain. This amplification gives the photo transistor much more light sensitivity than a standard PIN diode. But, with the gain comes a price. The photodiode/transistor connection dramatically slows down the otherwise fast response time of the diode inside. Most phototransistors will have response times measured in tens of microseconds, which is some 100 times slower than similar PIN diodes. Such slow speeds reduce the usefulness of the device in most communications systems. They also have the disadvantage of having small active areas and high noise levels. You will often find them being used for simple light reflector and detector applications that do not rely on fast light pulses. But, overall, they are a poor substitute for a good PIN diode when connected to well designed receiver circuit.

Avalanche Photodiode

Although the silicon PIN detector is the most universal device for nearly all optical communications applications, there are a few other devices worth mentioning. Once such device is an "APD" or avalanche photodiode. An APD is a special light detecting diode that is constructed in much the same way as a PIN photodiode. Unlike a PIN diode, that only needs a bias of a few volts to function properly, an APD is biased with voltages up to 150 volts. When light strikes the device it leaks current in much the same way as a typical PIN diode, but at much higher levels. Unlike a PIN diode that may produce only one microamp of current for two microwatts of light, an APD can leak as much as 100 microamps for each microwatt (x100 gain). This gain factor is very dependent on the bias voltage used and the APDs operating temperature. Some systems take advantage of these relationships and vary the bias voltage to produce the desired gain. When used with narrow optical band pass filters and laser light sources APDs could allow a through-the-air system to have a much higher light sensitivities and thus longer ranges than might otherwise be possible with a standard PIN device. However, in systems that use LEDs, the additional noise produced by the ambient light focused onto the device cancels much of the gain advantage the APD might have had over a PIN. Also, most commercial APDs have very small active areas, making them very unpopular for through-the-air applications. They are also typically 20 times more expensive than a good PIN photodiode. Finally, the high bias voltage requirement and the temperature sensitivity of the APD causes the detector circuit to be much more complicated that those needed with a PIN. Still, as the technology improves, low cost APDs with large active areas may become available.

If you plot a curve of the minimum detectable light power, using a photodiode, and the light pulse width being detected, you generate the curve shown below. The curve implies that for a very short 100 picoseconds light pulse, you will need at least 100 microwatts of light power to be detectable. But, if the light pulses last longer than 1 millisecond were used, you could detect light pulses down to about 10 picowatts. This is a handy curve to have, when you are designing an optical communications system. It will give you a ballpark idea of how much light you will need based on the light pulse widths being transmitted.

Capacitance

When choosing a suitable light detector from a manufacturer, their data sheets may also list a total capacitance rating for the PIN device. It is usually listed in Picofarads. There is a direct correlation between the active area and the total capacitance, which has an effect on the device's speed. However, the capacitance is not a fixed value. The capacitance will decrease with higher reverse bias voltages. As an example, a typical PIN device with a one square millimeter active area might have a capacitance of 30 Pico farads at bias voltage of zero but will decrease to only 6 Pico farads at 12 volts. Large area devices will always have a larger capacitance and will therefore be slower than small area devices. If you have nothing else to go on, pick a device with the lowest capacitance, if you are detecting short light pulses.

Dark Current

All PIN diodes have dark current ratings. The rating corresponds to the residual leakage current through the device, in the reversed biased mode, when the device is in complete darkness. This leakage current is usually small and is typically measured in nanoamps, even for large area devices. As you would expect, large area devices will have larger dark currents than small devices. However, by using the one of the detector circuit discussed in the section on light receivers, even large leakage levels will have little effect on the detection of weak signals.

Noise Figure

When reviewing PIN diode specifications you may also come across a noise figure listing. The units chosen are usually "watts per square root of hertz". Sometimes the listing will be under the heading of "NEP" that stands for "noise equivalent power". I suggest you ignore the specification. It has little meaning for most through-the-air applications that will always have to contend with some ambient light. Also, many of the detector circuits recommended in this book will reject much of the noise produced by the detector. For a more detailed discussion of detector noise please refer to the section on detector noise below.

Other Light Detectors

Photo Transistor

One of the most popular light detectors is the photo transistor. They are cheap, readily available and have been used in many published communications circuits. But as I have indicated above, the PIN visible light you **must** use an unfiltered PIN device. In the section on light receiver circuits there is a discussion on why the filtered PIN diodes are usually unnecessary when the proper detector circuit is used.

Active Area

There will usually be an active area specification for PIN photodiodes. This corresponds to the size of the actual light sensitive region, independent of the package size. PINs with large active areas will capture more light but will always be slower than smaller devices and will also produce more noise. However, if a small device contains an attached lens it will often collect as much light as a much larger device without a lens. But, the devices with attached lenses will collect light over narrower incident angles (acceptance angle). Flat surface devices are usually used if light must be detected over a wide area. For most applications either style will work. For high speed applications a device with a small active area is always recommended. However, there is a tradeoff between device speed and the active area. For most long-range applications, where a large light collecting lens is needed, a large area device should be used to keep the acceptance angle from being too small. Small acceptance angles can make it nearly impossible to point the receiver in the right direction to collect the light from the distant transmitter.

Response Time

All PIN photodiodes will have a response time rating that is usually listed in nanoseconds. The rating defines the time the device needs to react to a short pulse of light. The smaller the number, the faster the device. Sometimes you will see both a rise time and a full-time rating. Usually, the fall-time will be slightly longer than the rise time. Large area devices will always be slower and have longer response times. To be practical for most applications, the device should have a response time less than 500 nanoseconds. However, even devices with response times greater than tens of microseconds may still be useful for some applications that rely on light pulses a few milliseconds long. A slow device will respond to a short light pulse by producing a signal that lasts much longer than the actual light pulse. It will also have an apparent lower conversion efficiency. The detector should have a response time that is smaller than the maximum needed for the detection of the modulated light source (see section on system designs). As an example, if the light pulse to be detected lasts 1 microsecond then the PIN used should have a response time less than ½ microsecond. The response time may also be linked to a specific reverse bias voltage. All devices will respond faster when a higher bias voltage is used. Some device specifications will show a curve of response times as a function of bias voltage. To play it safe, you should use the response time that is associated with a bias voltage of only a few volts on the time vs. voltage curve. If you are interested in measuring a PIN diode's response time, there are some methods described in the section "Component and System Testing".

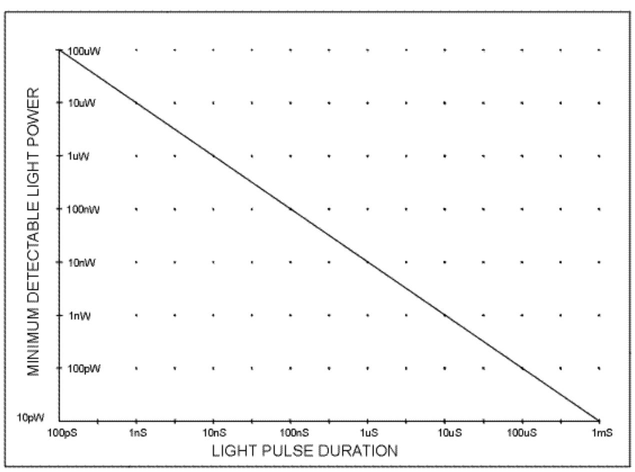


Figure 2b-1

The light power to electrical current relationship also implies that the conversion is independent of the duration of any light pulse. As long as the detector is fast enough, it will produce the same amount of current whether the light pulse lasts one second or one nanosecond. Later, in the section on light transmitter circuits, we will take advantage of this relationship by using short light pulses that don't consume a large amount of electrical power. Also, in the section on light receivers we will use some unique detector circuits that are designed to be sensitive only to the short light pulses being transmitted. Such schemes provide improvements over many existing commercially made systems and enable simple components to produce superior results.

InGaAs PIN Diode

Silicon is not the only material from which to make a solid-state light detector. Other photodiodes made from Gallium and Indium semiconductors work well at longer infrared wavelengths than silicon devices. These devices have been used for many years in optical fiber communications systems, which rely on longer wavelengths. Glass optical fibers operate more efficiently at these longer wavelengths. The curve shown below is the typical response for this device but peak can be shifted slightly as needed. As shown in the curve (***Figure 2a-1***), an InGaAs photodiode's response includes only some of the wavelengths that a silicon photodiode covers. However, most of the devices made are designed for optical fiber communications and therefore have very small active areas. They are also much more expensive. Still, as the technology improves, perhaps these devices will find their way into the hands of experimenters.

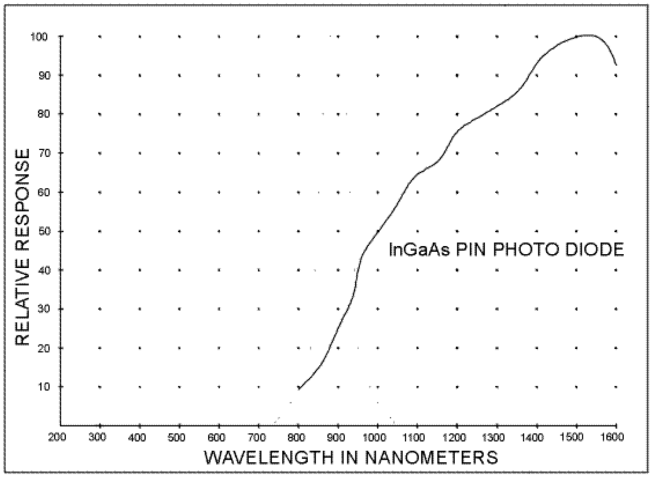


Figure 2a-1

Typical PIN Diode Specifications

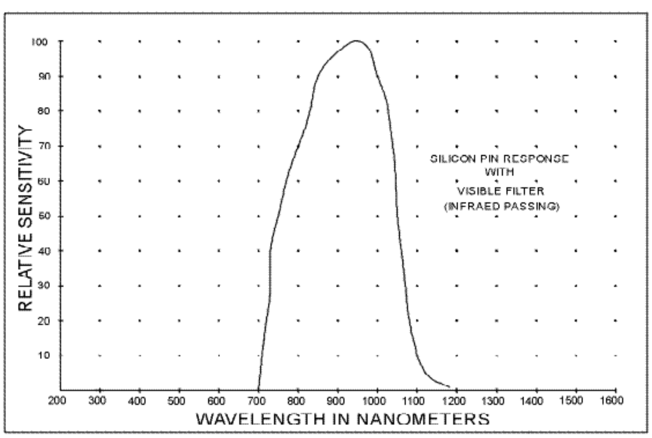


Figure 2b

Package

PIN silicon photodiodes come in all sizes and shapes. Some commercial diodes are packaged in special infrared (IR) transparent plastic. The plastic blocks most of the visible wavelengths while allowing the IR light to pass (see ***Figure 2b***). The plastic appears to be a deep purple color when seen by our eyes but it is nearly crystal clear to infrared light. Some of these packages also place a small plastic lens in front of the detector's active area to collect more light. As long as the modulated light being detected is also IR either the filtered or the unfiltered devices will work. However, if you use a light source that emits

½ its peak at the visible red wavelength (640 nanometers). It should therefore be obvious that if you want to maximize the device's conversion efficiency you should choose an information transmitter light source which closely matches the peak of the silicon PIN photodiode's response. Fortunately, most IR light emitting diodes (LEDs) and infrared lasers do indeed emit light at or near the 900nm peak, making them ideal optical transmitters of information.

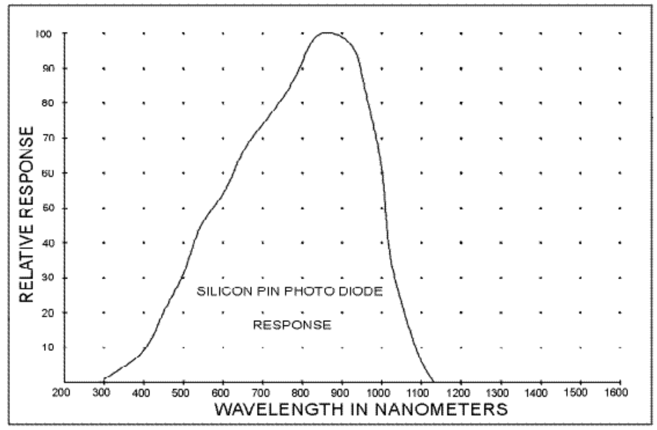
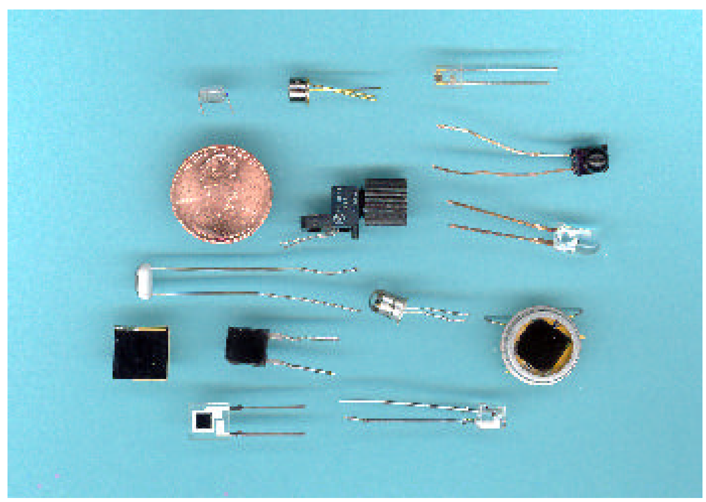


Figure 2a

The PIN photo detector behaves very much like a small solar cell or solar battery that converts light energy into electrical energy. Like solar cells, the PIN photodiode will produce a voltage (about 0.5v) in response to light and will also generate a current proportional to the intensity of the light striking it. However, this unbiased current sourcing mode, or "photovoltaic" mode, is seldom used in through-the-air communications since it is less efficient and is slow in responding to short light flashes. The most common configuration is the "reversed biased" or "photoconductive" scheme.

In the reversed biased mode, the PIN detector is biased by an external direct current power supply ranging from a few volts to as high as 50 volts. When biased, the device behaves as a leaky diode whose leakage current is dependent on the intensity of the light striking the device's active area. It is important to note that the intensity of a light source is defined in terms of power, not energy. When detecting infrared light at its 900 nanometer peak response point, a typical PIN diode will leak about one milliamp of current for every two milliwatts of light power striking it (50% efficiency).



Samples of Detectors

For most devices this relationship is linear over a 120db (1 million to one) span, ranging from tens of milliwatts to nanowatts. Of course wavelengths other than the ideal 900 nanometer peak will not be converted with the same 50% efficiency. If a visible red light source were used the light to current efficiency would drop to only 25%.

The current output for light power input relationship is the most important characteristic of the PIN photodiode. The relationship helps to define the needs of a communications system that requires a signal to be transmitted over a certain distance. By knowing how much light power a detector circuit requires, a communications system can be designed with the correct optical components.

Chapter Two
LIGHT DETECTORS

What Does a Light Detector Do?

In radio, the information that is to be transmitted to a distant receiver is placed on a high frequency alternating current that acts as a carrier for the information. To convey the information, the carrier signal must be modulated in some fashion. Most radio systems either vary the amplitude (amplitude modulation, AM) or the frequency (frequency modulation, FM) of the carrier. To extract the information from the carrier at the receiver end, some kind of detector circuit must be used.

In optical communications a light source forms the carrier and must also be modulated to transmit information. Virtually all present optical communications systems modulate the intensity of the light source. Usually the transmitter simply turns the light source on and off. To decode the information from the light pulses, some type of light detector must be employed. The detector's job is to convert the light signals, collected at the receiver, into electrical signals. The electrical signals produced by the detector's optical energy to electrical energy conversion are much easier to demodulate than pure light signals.

As discussed in the section on light theory, although light is a form of energy, it is the intensity or power of the light that determines its strength. Therefore, the real job of the light detector is to convert light power into electrical power, independent of the energy of the transmitted light pulses. This relationship also implies that the conversion is independent of the duration of the light pulses used. This is an important concept and is taken advantaged of in many of the systems that follow.

The Silicon PIN Photodiode

Although you may be aware of many kinds of light detectors, such as a "photo transistor", "photo cells" and "photo resistors", there are only a few devices that are practical for through-the-air optical communications. Many circuits that have been published in various magazines, have specified "photo transistors" as the main light detector. Although these circuits worked after a fashion, they could have functioned much better if the design had used a different detector. From the list of likely detectors, only the silicon "PIN" photodiode has the speed, sensitivity and low cost to be a practical detector. For this reason virtually all of the detector circuits described in this book will call for a PIN photodiode.

As the letters PNP and NPN designate the kind of semiconductor materials used to form transistors, the "I" in the "PIN" photodiode indicates that the device is made from "P" and "N" semiconductor layers with a middle intrinsic or insulator layer.

Most PIN photodiodes are made from silicon and as shown on ***Figure 2a***, have specific response curves. Look carefully at the curve. Note that the device is most sensitive to the near infrared wavelengths at about 900 nanometers. Also notice that the device's response falls off sharply beyond 1000 nanometers, but has a more gradual slope toward the shorter wavelengths, including the entire visible portion of the spectrum. In addition, note that the device's response drops to about