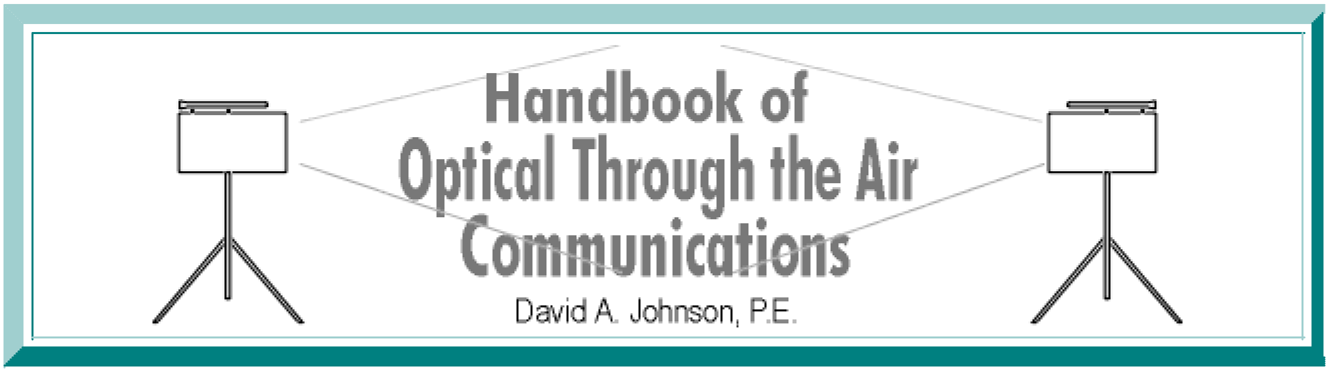

Chapter Five
LIGHT PROCESSING THEORY

Lenses as Antennas

There is a reoccurring analogy between optical communications and radio. Both systems use similar components which, although made from completely different materials, perform similar functions. As an example, a radio system will always use some kind of antenna to capture the diffuse and often weak signals from the air. Optical systems use similar devices in the form of lenses or mirrors to gather the weak light signals for processing. Large antennas or lenses will allow weaker signals to be detected.

In microwave radio communications, such as satellite receivers, the antenna is often a specially dish shaped metal reflector. The microwave signals are bounced off the dish surface and are concentrated at its focal point, where they can be more efficiently amplified. Similarly, mirrors can be used in optical telescopes or some optical communications systems to collect light and focus it onto special light detectors.

In much the same way that the incoming radio or light signals are processed, the outgoing signals can also benefit from specially shaped antennas or lenses. The radio or light source, when positioned at the focal point of a reflector, can shape the outgoing signal into a narrow beam. The larger the antenna or lens, the narrower the beam becomes. A narrow light beam insures that more of the desired signal is directed toward the distant receiver for better efficiency.

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Mirrors and Lenses

Although you can use mirrors in through-the-air communications, lenses are more often used. Lenses are usually much cheaper, readily available and much easier to align than mirrors. Useful lenses can be found in hardware stores, bookstores, office supply stores and even grocery stores. All of the discussions in this book will center on the use of lenses, although some of the techniques used for lenses can also be applied to mirrors.

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Types of Lenses

Most of the lenses used in through-the-air communications have one or two outwardly curved surfaces. Such lenses are called "convex" lenses. Small glass or plastic lenses are great for short range applications. However, glass lenses larger than about 3 inches become too heavy and expensive to be practical. Beyond the 3 inch size it is best to use a flat or "Fresnel" lens. Fresnel lenses can be purchased with diameters ranging from one to more than 36 inches. These lenses are made from molded plastic sheets that have small concentric grooves on one side. When viewed close-up, they look like the grooves in a phonograph record. These lenses are very carefully designed to bend the light just as a convex lens would. When using a Fresnel lens always remember to keep the grooves pointing toward the outside, away from its focal point. Using the lens in reverse will result in lost light and a poor image.

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Divergence Angle

The outgoing light from an optical transmitter forms a cone shaped area of illumination that spreads out from the end of the transmitter. As illustrated in ***Figure 5a*** the specification that mathematically describes the spreading out of the light is called the "divergence angle". It is almost always described as a half angle or the angle from the center axis of the illumination cone. Often the edge of the illumination cone is defined as the 1/2 power point, relative to the center light intensity. To help illustrate the concept, imagine a flashlight whose beam can be adjusted from a broad flood to a bright spot. The bright spot would have a smaller divergence angle than the flood. Likewise, a red laser pointer would be an example of light source with a very narrow divergence angle. If you have ever had a chance to play with as laser pointer, you would have noticed that the beam does not increase appreciably in size as it strikes a wall across a room. Such divergence angles can be so tight, that keeping the spot on a distant target can be nearly impossible. Most optical communications systems therefore purposely allow the beam to diverge a little so optical alignment can be easily maintained.

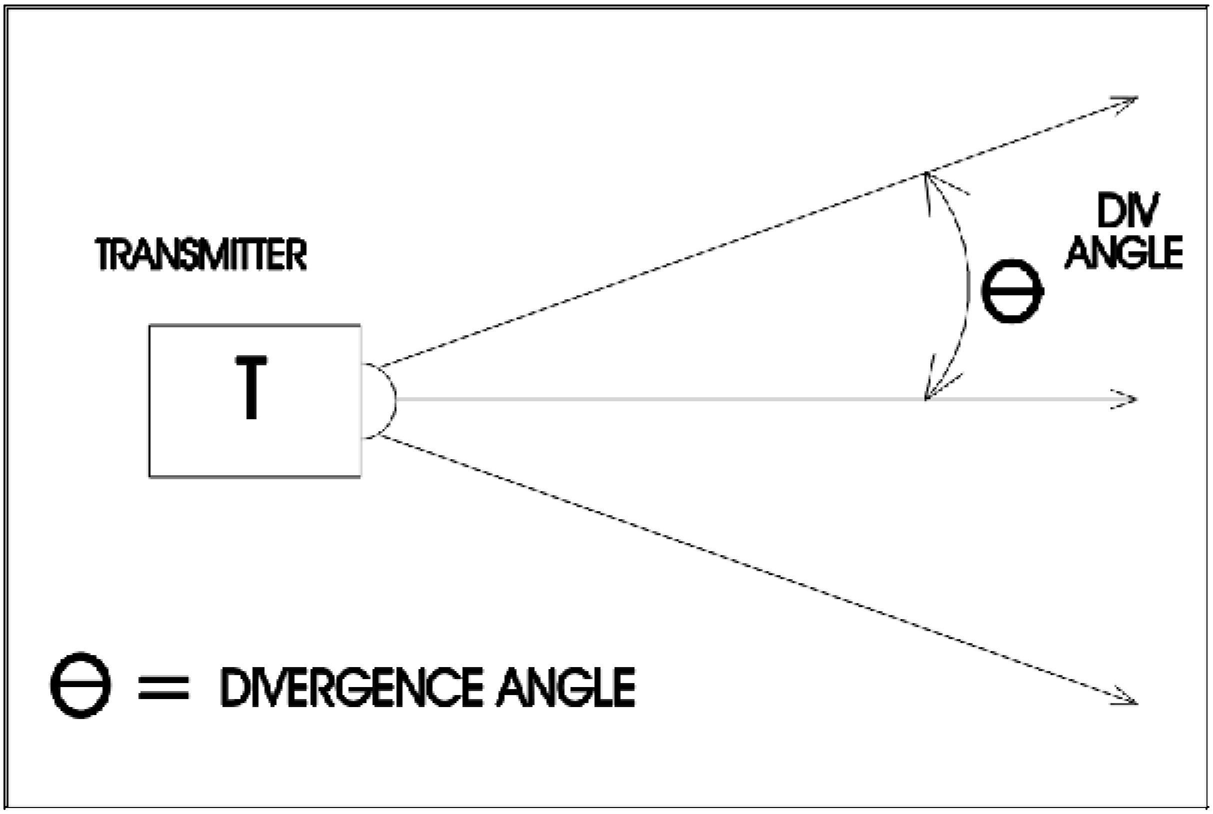

Figure 5a

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Acceptance Angle

The incoming light, focused onto a light detector, also has a restricted cone shaped area of collection. Light striking the lens, outside the cone area, will not be focused onto the detector. As illustrated in ***Figure 5b***, the incoming angle is called the "acceptance angle", which is also defined as a half angle. To help illustrate this concept, imagine looking through a long and a short section of pipe. Even if the two pipes have the same diameter the long pipe will restrict the field of view more than the shorter pipe. Pipes that are specially made to restrict the field of view are often used to help aim an optical system and are referred to as "boresights" (see ***Figure 5c***.) As in divergence angles that are too small, an acceptance angle should also not be too narrow or you will have problems in maintaining alignment with the distant transmitter.

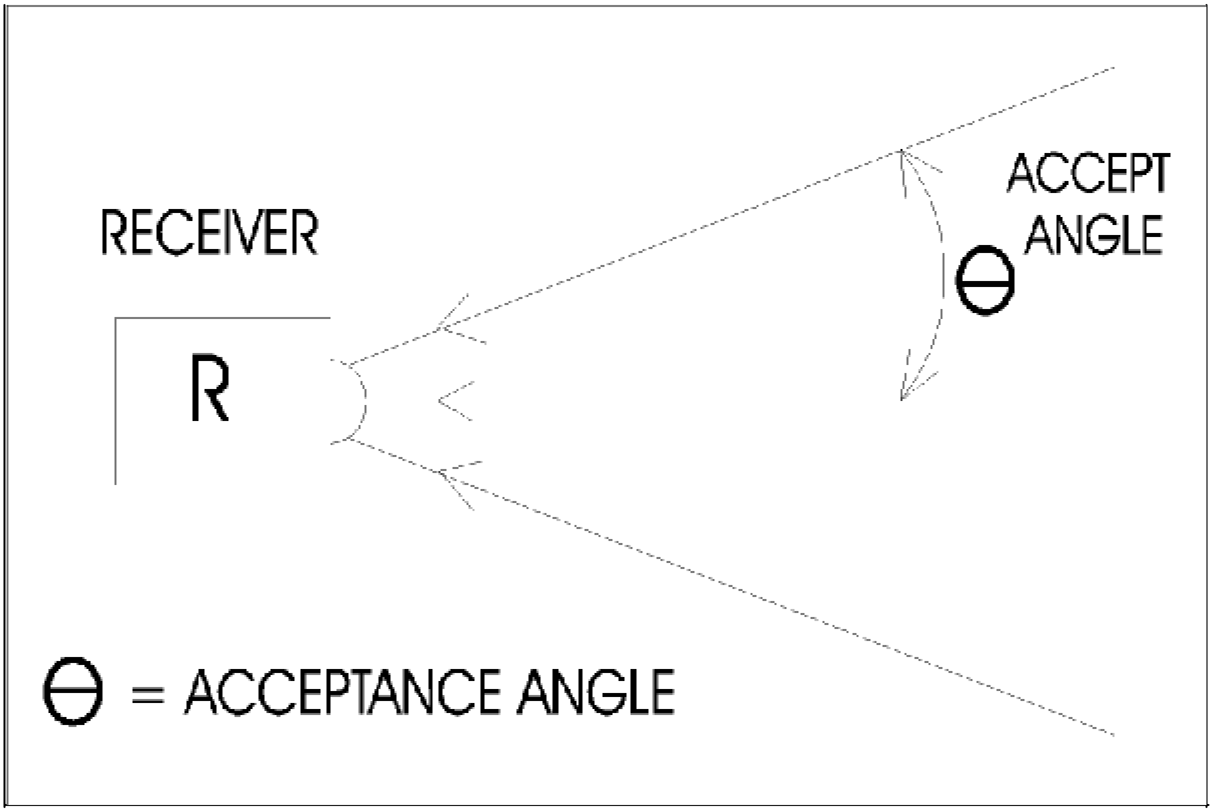

Figure 5b

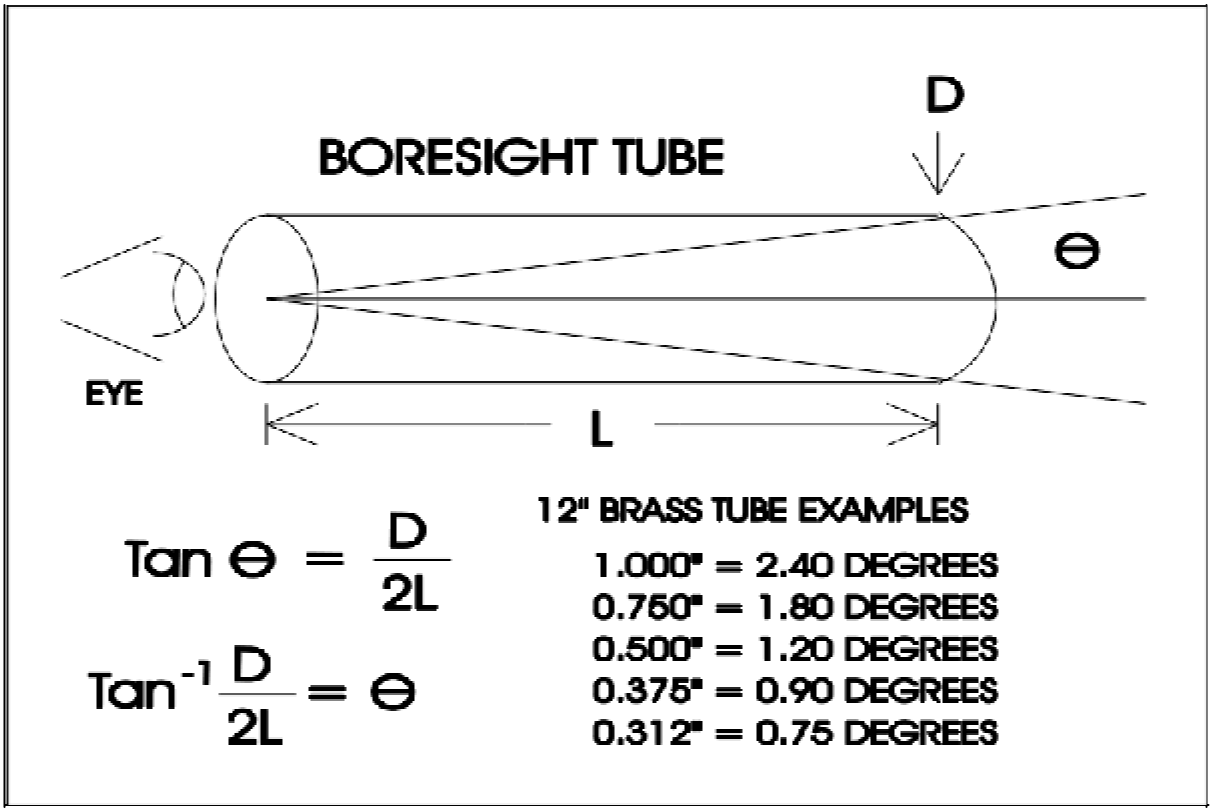

Figure 5c

TOP

Light Collimators and Collectors

The light, bent by a lens as it leaves a transmitter, is said to be "collimated". As illustrated by ***Figure 5d***, lenses used to collimate the emitted light from sources such as LEDs, should be carefully selected for their diameter and focal length. A lens with a focal length that is too long will not capture all of the light being emitted. Conversely, a lens that has a focal length that is too short will only partially use its available diameter and will therefore have a greater overall divergence angle. ***Figure 5e*** illustrates how a lens affects the launched divergence angle from an LED. In a similar way, the size and focal length of the lens used in a light receiver should be selected to insure the light collected is focused properly onto the detector. Fortunately, most light detectors have wide acceptance angles, so you can be use them with a much larger variety of lens shapes, than those required by a light emitter.

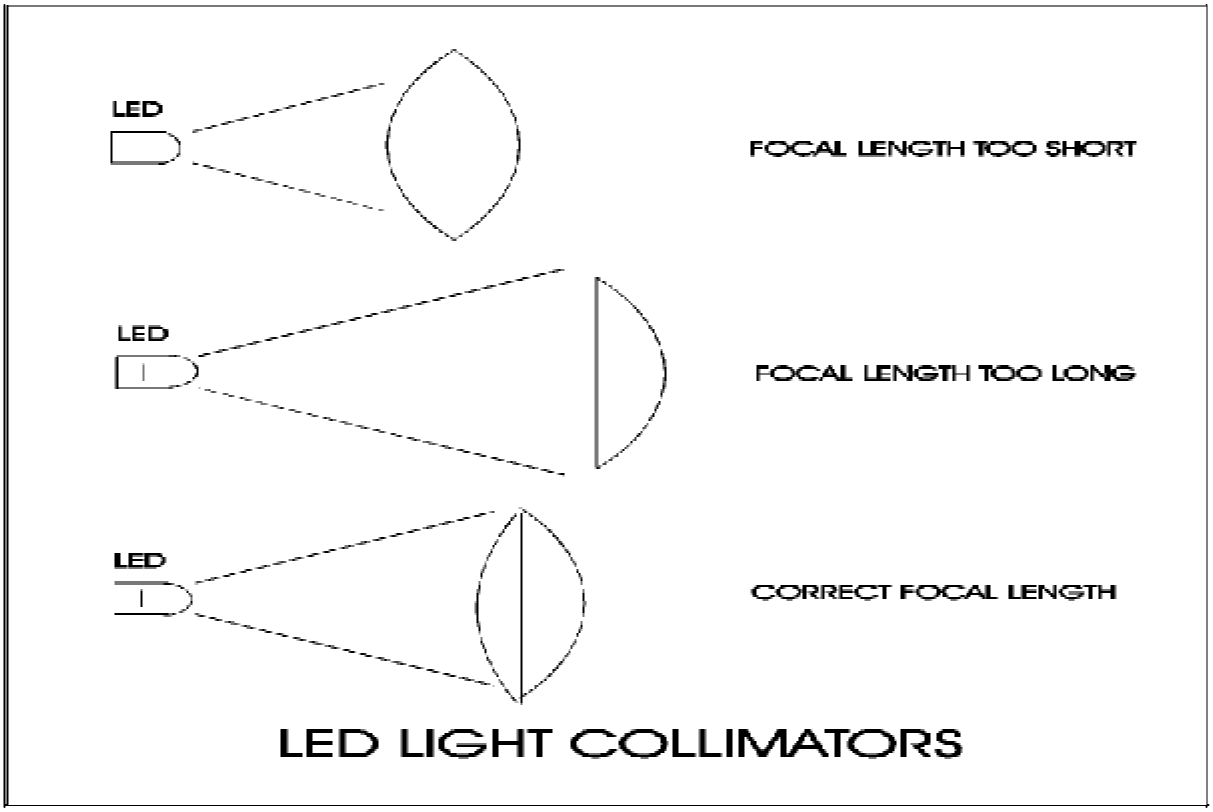
LED
FOCAL LENGTH TOO SHORT
LED
FOCAL LENGTH TOO LONG
LED
CORRECT FOCAL LENGTH
LED LIGHT COLLIMATORS

Figure 5d

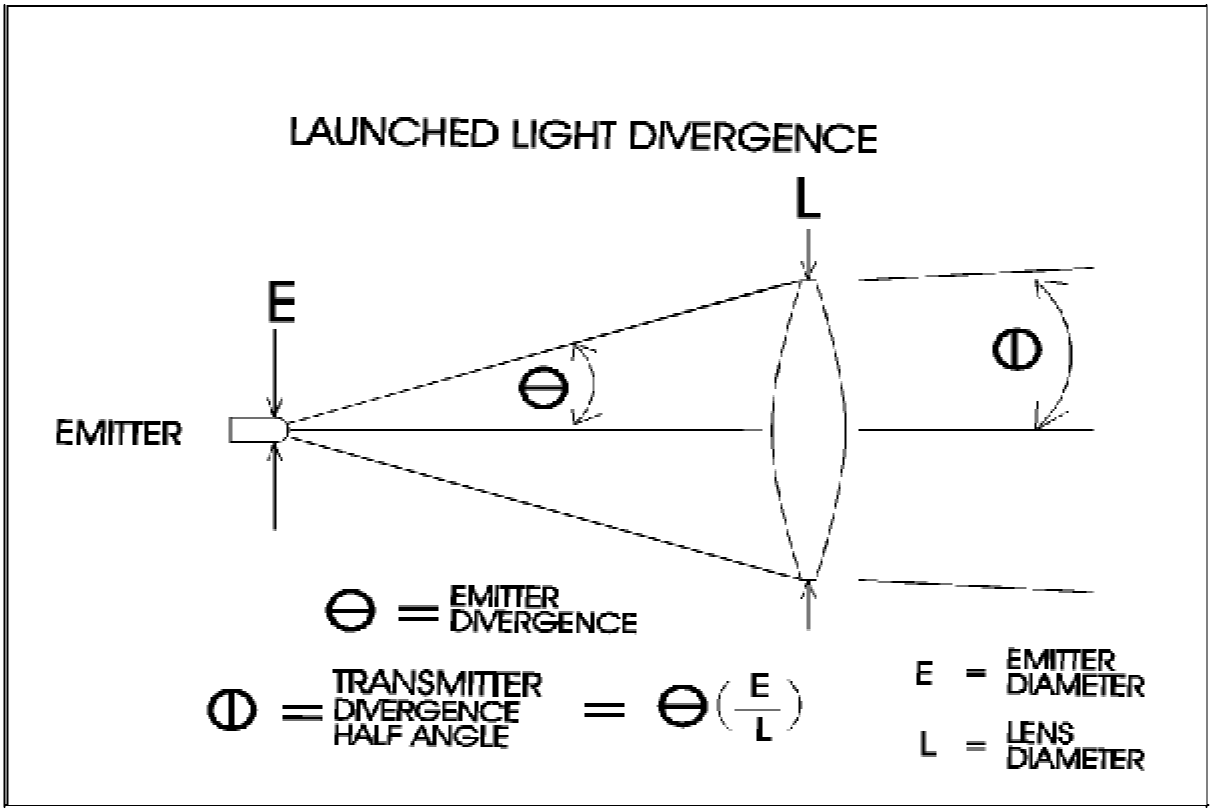

Figure 5e

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Multiple Lenses, Multiple Sources

As illustrated in ***Figures 5f***, there are two methods that you can use to collimate light from multiple emitters. If you place a single lens in front an array of light sources, multiple images of the sources will be directed toward the receiver. The individual images will be widely spaced with large blank areas between them. Only one of the images will be detected by a single receiver. This method may be useful if multiple receivers need to receive the transmitted light, but it is not recommended if only one receiver is used. If you want to increase the effective light intensity sent to a distant receiver, from a transmitter which uses multiple emitters, you will need multiple lenses. As illustrated in ***Figure 5f*** an array of lenses, each with its own light source, will appear as one light source, having a higher intensity than a single emitter. This lens array concept is applied in nature by most insects and can be successfully used to produce more powerful light sources, which will extend the range of a communications system.

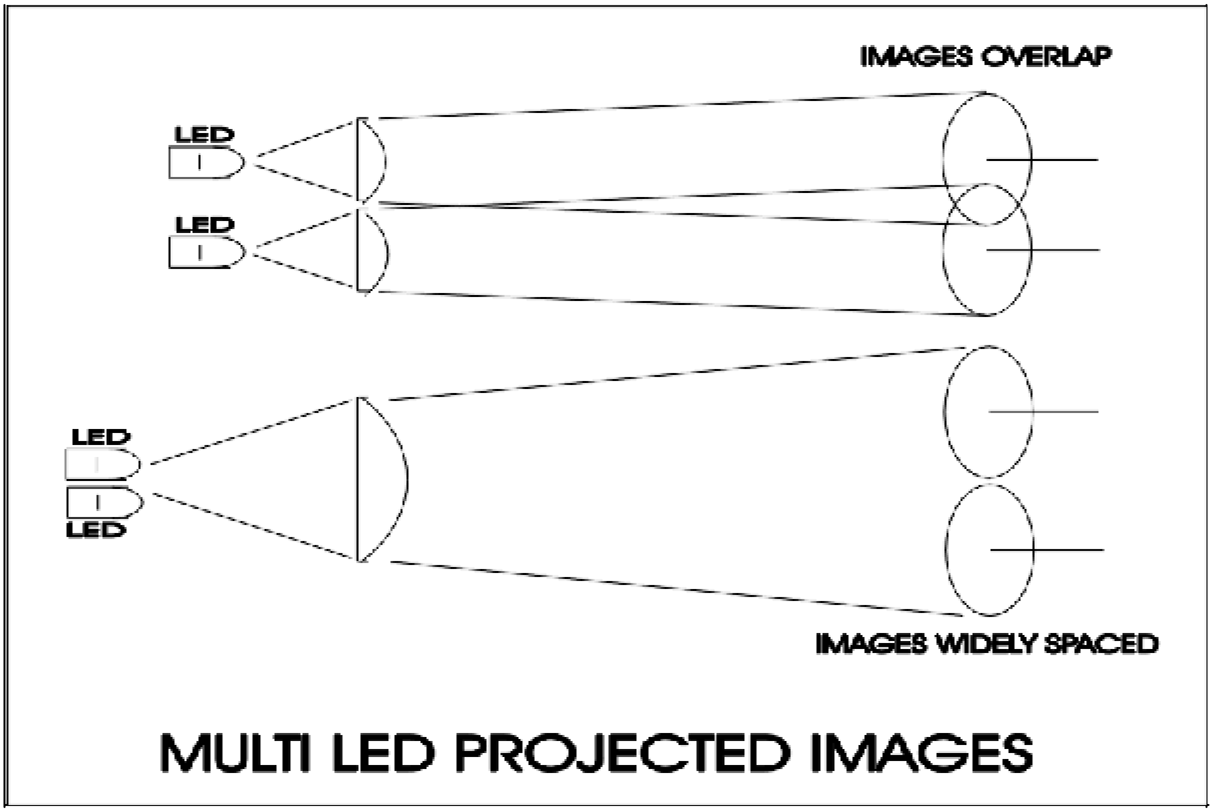

Figure 5f

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Optical Filters

To increase the separation distance between a light transmitter and a receiver, lenses are often used. A light receiver may use a lens to collect the weak light from the transmitter and focus it onto the receiver's detector for processing. But, the lens will always collect extra light from the environment that is not wanted. Stray light will often interfere with the signals of interest. One method to reduce the amount of ambient light that is focused onto a detector is to insert an optical filter between the lens and the detector.

You may see some optical filters every day without realizing it. As an example, the red clear plastic covers, used on most car tail lights, are filters. These filters block most of the unwanted colors emitted by the bulb inside and allow only the red light to pass. These single color band filters are called optical "bandpass" filters and are the most valuable type of filter used in through-the-air communications. Other filters also exist. "High pass" filters are used to block light of long wavelengths and pass shorter wavelengths. Conversely, "low pass" filters block short wavelengths and allow long wavelengths to pass.

Figure 5g shows the transmission spectrum of a low pass filter material. The material has been specifically designed for near infrared use. It is nearly transparent to the near infrared wavelengths but is very dark to most visible light. When placed in front of a silicon detector, much of the stray visible ambient light, that may be collected by a lens, will be blocked by the filter. But as you will see in the section on light detectors, such a filter will have a minimal effect in the reduction of interference with communications systems that use light emitting diodes (LEDs) as light sources. This occurs because the scattered sunlight, picked up by the lens, contains a sizable amount of infrared light as well as visible light. The extra light, not blocked by the filter, will still be enough to cause some interference with the signals from the LED source. Even a filter, perfectly matched to an LEDs spectrum, would still cause problems. To filter out most of the unwanted sunlight, a very narrow bandpass filter is needed. But to take advantage of a bandpass filters they must be used with equally narrow spectrum light emitters, such as semiconductor laser diodes.

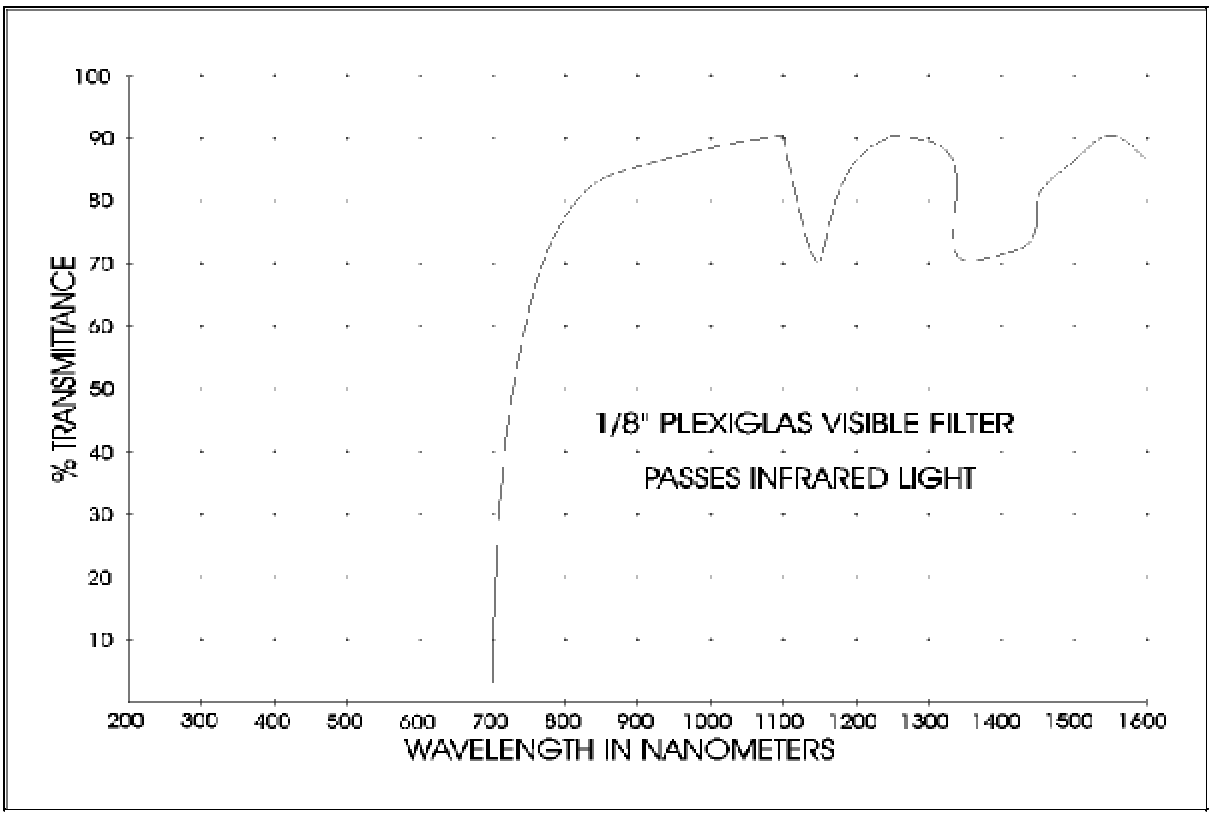

Figure 5g

One optical bandpass filter, that can be made to closely match a laser diode's emission spectrum, is an "interference" filter. Interference filters are made by stacking many very thin layers of special materials onto a glass plate. By varying the thickness and the kind of materials deposited, the width of the pass band and the center wavelength can be controlled. ***Figure 5h*** is an example of such a filter. As can be seen, its bandwidth is very narrow and happens to match the emission spectrum of a typical infrared laser diode. If such a filter were used in a communications system, almost all the laser light collected would be allowed to reach the detector, but it would allow only a tiny amount of stray sunlight to pass. Narrow bandpass filters can especially be useful when a single light receiver needs to detect light from only one of many different modulated laser sources. Different bandpass filters can be moved in front of the detector to reject all sources except one. Such techniques make it possible to have perhaps 10,000 different light receiver bands without interference.

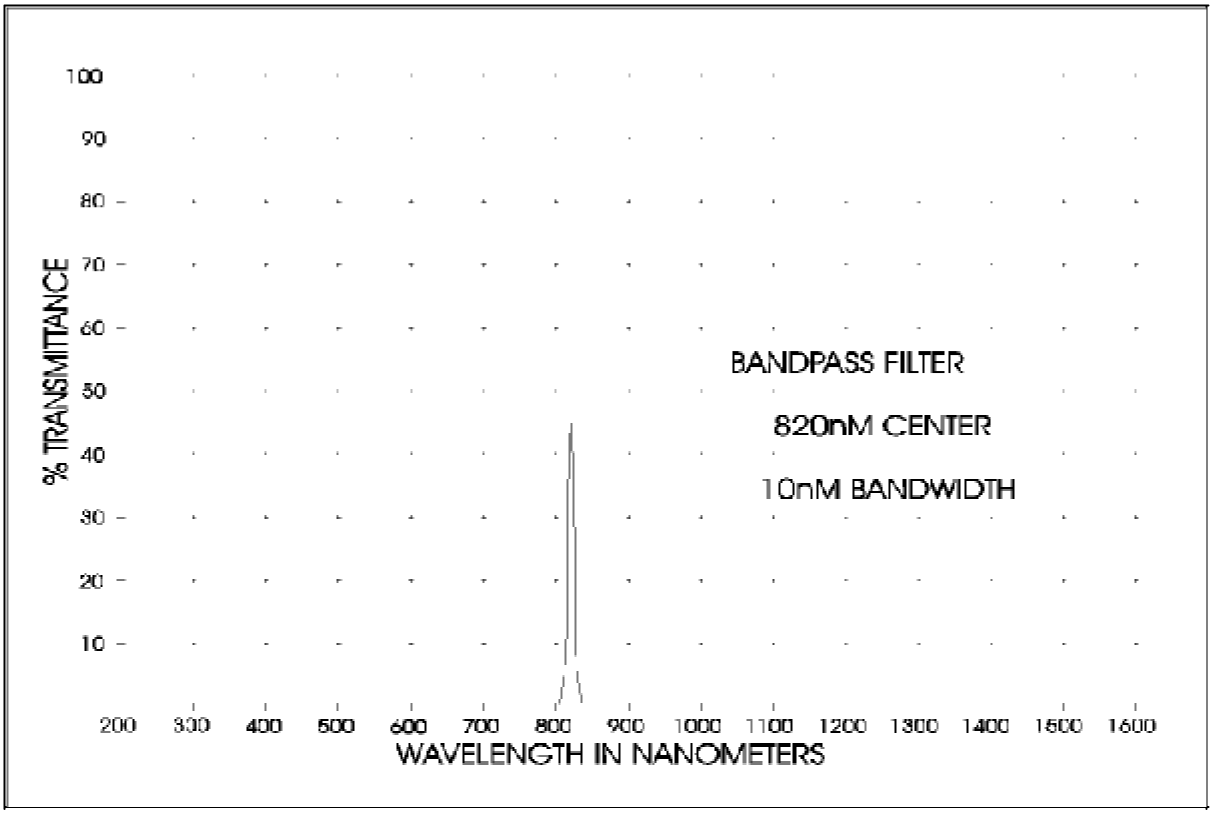

Figure 5h

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Inverse Square Law

One of the most important principles you will discover in optics is the inverse square law. The law defines how a light receiver's ability to collect light from a distant emitter will decrease as the receiver is moved away from the source. To help illustrate the concept, let's use a water analogy. Imagine light from a transmitter as a fine spray of water from a small nozzle which produces a cone shaped pattern of water droplets. Also imagine our water source to be in the vacuum of space so that the spray is not effected by air or gravity and will continue to spread out evenly, forever. The gallon per minute rate of water flowing through the nozzle would then represent the intensity of the light source. Now, imagine moving a bucket through the spray at various distances from the nozzle, the bucket representing a light receiver's collection area. When the bucket is near the nozzle it would fill much faster than when it is positioned farther away. The inverse square law predicts that if the distance between the bucket and the nozzle is doubled, the bucket will fill 4 times slower. If it is moved 4 times farther away it will fill 16 times slower. Such a reduction rate would continue as the bucket is moved away from the nozzle. Conversely, if the bucket is moved, so it halved the distance, it would fill four times faster. By knowing the flow of water from the nozzle (light intensity) and the spray pattern (divergence angle) you can predict how fast the bucket would be filled (light collected) at any position (range) within the spray. Such a prediction is described by the "optical range equation", which combines the inverse square law with some simple trigonometry.

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Range Equation

The equation shown in ***Figure 5i*** combines the inverse square law with some other known information. You can use the equation to calculate a number of factors for a typical through-the-air communications system. As in any algebraic equation, you can solve for any unknown factor if the other factors are known. As an example, the equation can tell you how large a light collector you will need at the receiver or the maximum distance you can position the light receiver from the transmitter. Of course, the equation does not take into account any other losses that may exist within the link, such as poor air quality. ***Figure 5j*** illustrates how the divergence angle effects the illumination area from a light source.

RANGE EQUATIONS

$$D = \sqrt{\frac{(P)(A)(E)}{(\mathrm{Tan}^2 \Theta)(32N)}}$$

$$P = \frac{(32N)(D^2)(\mathrm{Tan}^2 \Theta)}{(A)(E)}$$

D = MAXIMUM RANGE IN FEET
P = TRANSMITTER POWER IN WATTS
A = RECEIVER LENS AREA IN SQ FEET
Θ = TRANSMITTER DIVERGENCE HALF ANGLE
N = PIN DETECTOR NOISE FLOOR IN WATTS
E = PIN CONVERSION EFFICIENCY (TYP 0.5)

Figure 5i

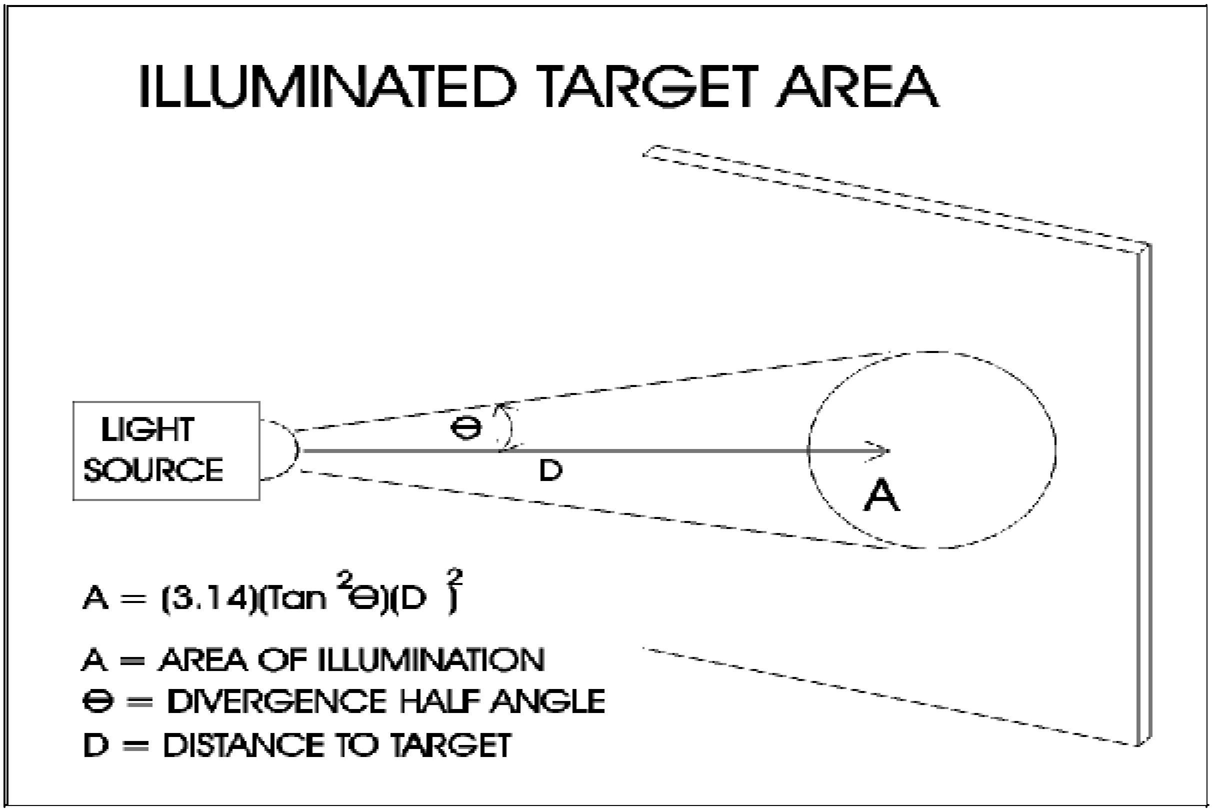

Figure 5j

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