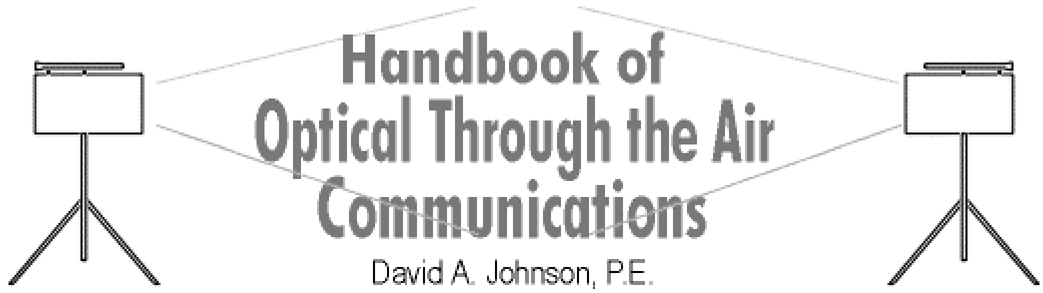

PREFACE

About the author:

David A. Johnson, **P.E**. is consulting electronics engineer with a broad spectrum of experience that includes product research, design and development; electronic circuit design; design, building and testing prototypes; electro-optics; and custom test instruments. Doing business for more than 17 years as David Johnson and Associates, Dave has established himself as an electronics engineer who can provide a variety of services.

His proficiency is based on "hands-on" experience in general engineering, electronics and electro-optics. Mr. Johnson is licensed by the State of Colorado as a Professional Engineer; he is a graduate of University of Idaho and is a member of IEEE. Holds three patents and has four more pending.

He remains well informed of the latest scientific and engineering advancements through independent studies. Dave is a published author with articles and designs in *EDN*, *Electric Design*, *Midnight Engineering* and *Popular Electronics*.

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I became interested in optical through-the-air communications around 1980. At that time I was doing research in high-speed fiber optic computer data networks for a large aerospace company. My research assignment was to produce a report that made recommendations for the best ways of using the latest optical fiber technologies to satisfy the increased demands for fast data transmission in the aerospace industry. My research involved pouring through mountains of technical papers, scientific journals, patents and manufacturer's application notes.

As my research progressed I began to notice that nearly all the optical communications systems described used optical fibers. Little was being written on the subject of through-the-atmosphere communications. It seemed logical to me that many of the techniques being used in fiber optic communications could also be applied in through-the-air communications. I was puzzled by the technical hole that seemed to exist. This lack of information started my personal crusade to learn more about communicating through-the-air using light.

During my studies I reviewed many of the light communications construction projects that were published in some electronics magazines. I was often disappointed with the lack of sophistication they offered and usually found their performance lacking in many ways. Many of the circuits were only able to transmit a signal a few feet. I thought that with a few changes they could go miles. I was determined to see how far the technology could be pushed without becoming impractical. So, I took many of the published circuits and made them work better. I discovered better ways to process the weak light signals and methods to get more light from some common light emitters. I found ways to reduce the influence ambient light had on the sensitive light detector circuits and I developed techniques to increase the practical distance between a light transmitter and receiver. I also experimented with many common light sources such as fluorescent lamps and xenon camera flash tubes to see if they too could be used to send information. To my delight they were indeed found to be very useful.

Today, my crusade continues. I am still discovering ways to apply what I have learned and I'm still making improvements. However, after having devoted some 20 years of work toward advancing the technology I felt it was time to collect what I have learned and pass some of the information on to others. Thus, this book was conceived.

This handbook may be found at http://www.imagineeringezine.com/air-bk2.html.

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INTRODUCTION

Brief History

Communications using light is not a new science. Old Roman records indicate that polished metal plates were sometimes used as mirrors to reflect sunlight for long range signaling. The U.S. military used similar sunlight powered devices to send telegraph information from mountain top to mountain top in the early 1800s. For centuries the navies of the world have been using and still use blinking lights to send messages from one ship to another. Back in 1880, Alexander Graham Bell experimented with his "Photophone" that used sunlight reflected off a vibrating mirror and a selenium photo cell to send telephone like signals over a range of 600 feet. During both world wars some lightwave communications experiments were conducted, but radio and radar had more success and took the spotlight. It wasn't until the invention of the laser, some new semiconductor devices and optical fibers in the 1960s that optical communications finally began getting some real attention.

During the last thirty years great strides have been made in electro-optics. Lightbeam communications devices are now finding their way into many common appliances, telephone equipment and computer systems. On-going defense research programs may lead to some major breakthroughs in long range optical communications. Ground-station to orbiting satellite optical links have already been demonstrated, as well as very long range satellite to satellite communications. Today, with the recent drop in price of some critical components, practical through-the-air communications systems are now within the grasp of the average experimenter. You can now construct a system to transmit and receive audio, television or even high speed computer data over long distances using rather inexpensive components.

Why Optical Communications?

Since the invention of radio more and more of the electro-magnetic frequency spectrum has been gobbled up for business, the military, entertainment broadcasting and telephone communications. Like some of our cities and highways, the airwaves are becoming severely overcrowded. Businesses looking for ways to improve their communications systems and hobbyist wishing to experiment are frustrated by all the restrictions and regulations governing the transmission of information by radio. There is simply little room left in the radio frequency spectrum to add more information transmitting channels. For this reason, many companies and individuals are looking toward light as a way to provide the needed room for communications expansion. By using modulated light as a carrier instead of radio, an almost limitless, and so far unregulated, spectrum becomes available.

Let me give you an example of how much information an optical system could transmit. Imagine a single laser light source. Let's say it is a semiconductor laser that emits a narrow wavelength (color) of light. Such devices have already been developed that can be modulated at a rate in excess of 60 gigahertz (60,000MHz). If modulated at a modest 10GHz rate, such a single laser source could transmit in one second: 900 high density floppy disks, 650,000 pages of text, 1000 novels, two 30-volume encyclopedias, 200 minutes of high quality music or 10,000 TV pictures. In less than 12 hours, a single light source could transmit the entire contents of the library of congress. Such a modulation rate has the capacity to provide virtually all of the typical radio, TV and business communications needs of a large metropolitan area. However, with the addition of more light sources, each at a different wavelength (colors), even more information channels could be added to the communications system without interference. Color channels could be added until they numbered in the thousands. Such an enormous information capacity would be impossible to duplicate with radio.

Why through-the-air communications?

One of the first large scale users for optical communications were the telephone companies. They replaced less efficient copper cables with glass fibers (fiber optics) in some complex long distance systems. A single optical fiber could carry the equivalent information that would require tens of thousands of copper wires. The fibers could also carry the information over much longer distances than the copper cables they replaced. However, complex fiber optic networks that could bring such improvements directly to the small business or home, are still many years away. The phone companies don't want to spend the money to connect each home with optical fibers. Until fiber optic networks become available, through-the-air communications could help bridge the gap. The term “the last mile” is often used to describe the communications bottleneck between the neighborhood telephone switching network and the home or office.

Although light can be efficiently injected into tiny glass fibers (fiber optics) and used like copper cables to route the light information where it might be needed, there are many applications where only the space between the light information transmitter and the receiver is needed. This "freespace" technique requires only a clear line-of-sight path between the transmitter and the distant receiver to form an information link. No cables need to be buried, no complex network of switches and amplifiers are needed and no right-of-way agreements need to be made with landowners. Also, like fiber optic communications, an optical through-the-air technique has a very large information handling capacity. Very high data rates are possible from multiple color light sources. In addition, systems could be designed to provide wide area communications, stretching out to perhaps ten to twenty miles in all directions. Such systems could furnish a city with badly needed information broadcasting systems at a fraction of the cost of microwave or radio systems, and all without any FCC licenses required.

What are some of the limitations of through-the-air communications?

The main factor that can influence the ability of an optical communications system to send information through the air is weather. "Pea soup" fog, heavy rain and snow can be severe enough to block the light path and interrupt communications. Fortunately, our eyes are poor judges of how far a signal can go. Some infrared wavelengths, used by many of the light transmitters in this book, are able to penetrate poor weather much better than visible light. Also, if the distances are not too great (less than 5 miles), systems can be designed with sufficient power to punch through most weather conditions. Unfortunately, little useful information exists on the true effects weather has on long-range optical systems. But, this should not be a hindrance to the development of a through-the-air system, because there are many areas of the world where bad weather seldom occurs. In addition, it would be a shame to completely reject an optical communications system as a viable alternate to radio solely due to a few short interruptions each year. Even with present day systems, TV, radio and cable systems are frequently interrupted by electrical storms. How may times has your cable or TV service been interrupted due to bad weather? I think the advantages that through-the-air communications can provide outweigh the disadvantages from weather.

Another limitation of light beam communications is that since light can't penetrate trees, hills or buildings. A clear line-of-sight path must exist between the light transmitter and the receiver. This means that you will have to position some installations so their light processing hardware would be in more favorable line-of-sight locations.

A third limitation, one that is often overlooked, is the position of the sun relative to the light transmitter and receiver. Some systems may violate a "forbidden alignment" rule that places the light receiver or transmitter in a position that would allow sunlight to be focused directly onto the light detector or emitter during certain times of the year. Such a condition would certainly damage some components and must be avoided. Many installations try to maintain a north/south alignment to lessen the chance for sun blindness.

How can these light-beam techniques be used?

I believe that optical through-the-air or "Freespace" communications will play a significant role in this century. Many of you are already using some of this new technology without even being aware of it. Most remote control devices for TVs, VCRs and stereo systems rely on pulses of light instead of radio. Many commercially available wireless stereo headphones are using optical techniques to send high quality audio within a room, giving the user freedom of movement. In addition, research is on going to test the feasibility of using optical communications in a variety of other applications. Some military research companies are examining ways to send data from one satellite to another using optical approaches. One such experiment sent data between two satellites that were separated by over 18,000 miles. Space agencies are also exploring optical techniques to improve communications to very distant space probes. Some college campuses and large business complexes are experimenting with optical through-the-air techniques for high-speed computer networks that can form communications links between multiple buildings. Some military bases, banks and government centers are using point-to-point optical communications to provide high speed computer data links that are difficult to tap into or interfere with. But, don't become overwhelmed, there are many simple and practical applications for you experimenters. Several such applications will be covered in this handbook. Below are some examples of existing and possible future uses for light-beam communications.

POSSIBLE USES FOR OPTICAL THROUGH-THE-AIR COMMUNICATIONS

Short Range Applications

- Industrial controls and monitors
- Museum audio; walking tours, talking homes
- Garage door openers
- Lighting controls
- Driveway annunciators
- Intrusion alarms
- Weather monitors; fog, snow, rain using light back-scatter
- Traffic counting and monitoring
- Animal controls and monitors; cattle guards, electronic scarecrow
- Medical monitors; remote EKG, blood pressure, respiration

Long Range Applications

- Deep space probe communications; distances measured in light-years
- Building to building computer data links; very high data rates.
- Ship to ship communications; high data rates with complete security.
- Telemetry transmitters from remote monitors; weather, geophysical.
- Electronic distance measurements; hand held units out to 1000 ft.
- Optical radar; shape, speed, direction and range.
- Remote telephone links; cheaper than microwave

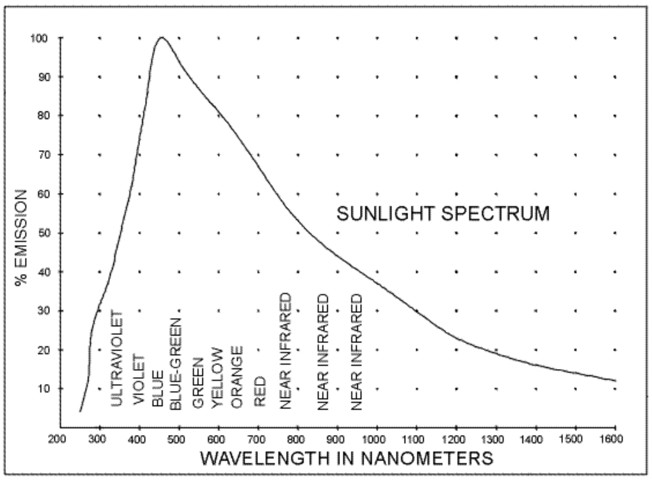
Wide Area Applications

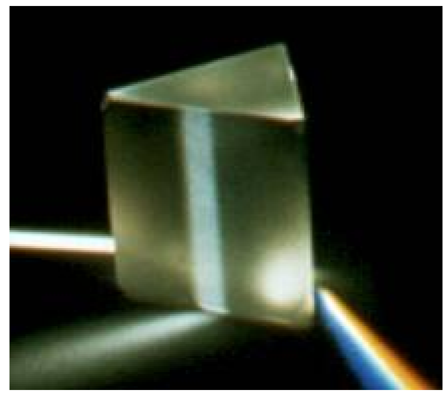
- Campus wide computer networks
- City-wide information broadcasting
- Inter-office data links
- Computer to printer links
- Office or store pagers
- Systems for the hearing impaired; schools, churches, movies
- Cloud bounce broadcasting

Chapter One
LIGHT THEORY

The Spectrum, Human Eye Response

Light is a form of energy. Virtually all the energy you use on a daily basis began as sunlight energy striking the earth. Plants capture and store some the sun's energy and convert it into chemical energy. Later, you use that energy as food or fuel. The rest of the sun's energy heats the earth's surface, air and oceans.





White light disperses color spectrum through a prism

Figure 1a

With the aid of a glass prism you can demonstrate that the white light coming from the sun is actually made up of many different colors as shown in ***Figure 1a***. Some of the light falls into the visible portion of the spectrum while wavelengths, such as the infrared and ultraviolet rays, remain invisible. The human eye responds to light according to the curve shown on ***Figure 1b***. The spectrum that lies just outside the human eye red sensitivity limit is called "near infrared" or simply IR. It is this portion of the spectrum that is used by much of today's light-beam communications systems.

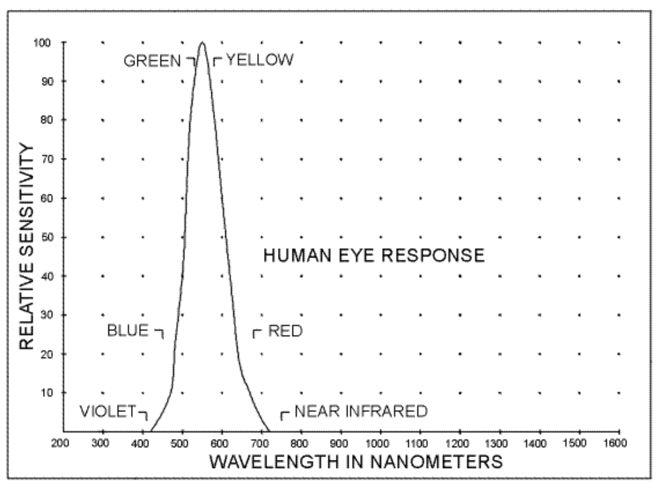


Figure 1b

As can be seen from ***Figure 1a***, sunlight is a very powerful source for this band of light, so are standard incandescent lamps and light from camera photoflash sources. However, many other man-made light emitters, such as fluorescent lamps and the yellow or blue/white street lamps, emit very little infrared light.

Silicon Detector Response

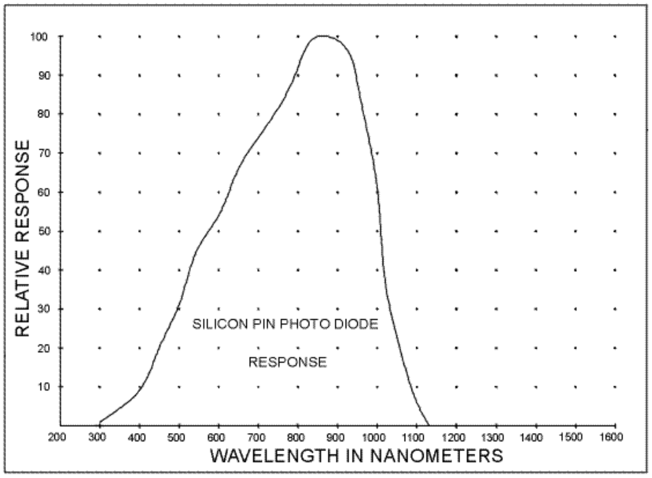


*Figure 1*c

Just as our eyes are more sensitive to certain wavelengths so are some electronic light detectors. As shown in ***Figure 1c*** a typical silicon light detector has a response curve that ranges from the longer mid-infrared wavelengths, through the visible portion of the spectrum and into the shorter and also invisible ultraviolet wavelengths. The most notable feature of the silicon detector's curve is its peak sensitivity at about 900 nanometers. Also note that at 600 nanometers, visible red, the silicon detector response is about one half that of its peak. It should therefore be clear that any light source with a 900 nanometer wavelength would have the best chance of being detected by the silicon detector. Fortunately, as we shall see in the section on light emitters, many of today's infrared light emitting diodes (LEDs) do indeed emit light at or near this 900nm peak.

Units of Light

As shown in ***Figure 1d*** a standard tungsten incandescent light bulb emits a very broad spectrum of light. If you took all the light wavelengths into consideration, including all those that were invisible to the human eye, the light bulb's electrical power to light power conversion efficiency would approach 100%. However, much of the light emitted from such a source takes the form of long infrared heat wavelengths. Although still considered light, heat wavelengths fall well outside the response curve of both our human eye and a silicon detector. If you only considered the visible portion of the spectrum, the light bulb's efficiency would only be about 10%. But, to a detector that was sensitive to heat wavelengths, the bulb's efficiency would appear to be closer to 90%. This takes us to one of the most confusing areas of science. How do you define the brightness or intensity of a light source?

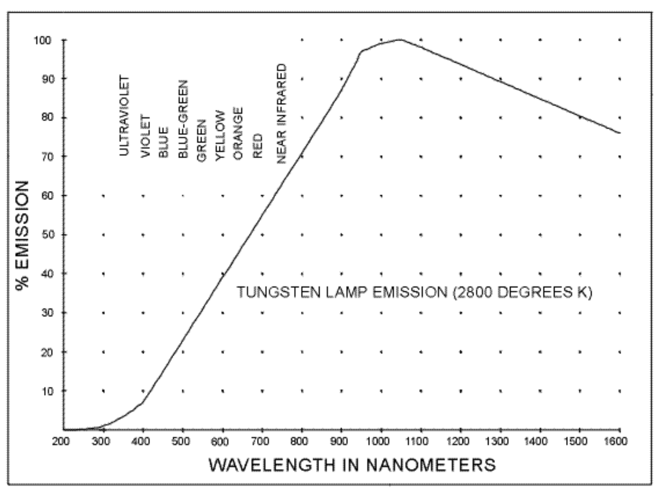


Figure 1d

It isn't enough to say that a standard 100 watt bulb emits more light than a tiny 1 watt bulb. Sure, if you set a big 100 watt bulb next to a small 1 watt flashlight bulb, the 100 watt bulb would appear to emit more light. But there are many factors to consider when defining the brightness of a light source. Some factors refer to the nature of the emitted light and others to the nature of the detector being used to measure the light.

For some light emitting devices, such as a standard tungsten incandescent light bulb, the light is projected outward in all directions (omni-directional). When visually compared to a bare 1 watt bulb, the light emitted from a bare 100 watt bulb would always appear brighter. However, if you were to position the tiny 1 watt bulb in front of a mirror, like a flashlight reflector, the light emerging from the 1 watt light assembly would appear much brighter than the bare 100 watt, if viewed at a distance of perhaps 100 feet. So, the way the light is projected outward from the source can influence the apparent brightness of the source. An extreme example of a highly directional light source is a laser. Some lasers, including many common visible red laser pointers, are so directional that the light beams launched spread out very little. The bright spot of light emitted might remain small even after traveling several hundred feet.

The preferential treatment that a detector gives to some light wavelengths, over others, can also make some sources appear to be brighter than others. As an example, suppose you used a silicon light detector and compared the light from a 100 watt black-light lamp that emits invisible ultraviolet light, with a 100 watt tungsten bulb. At a distance of a few feet, the silicon detector would indicate a sizable amount of light being emitted from the light bulb but would detect very little from the black-light source, even though the ultraviolet light could cause skin burns within minutes. So which is brighter?

In order to define how much light a source emits you first need to specify what wavelengths you wish to be considered. You must also assign a certain value to each of the considered wavelengths, based on the detector being used. In addition, since many light sources launch light in all directions you must also define the geometry of how the light is to be measured. Perhaps you only want to consider the amount of light that can be detected at some distance away. The wavelengths you may want to consider will depend on the instrument used to make the measurements. If the instrument is the human eye then you need to consider the visible wavelengths and you will need to weigh each of the wavelengths according to the human eye sensitivity curve. If the instrument were a silicon detector, then you would use its response curve.

When doing research on light, you will come across many different units being used by various light manufacturers. All the units are trying to describe how much light their devices emit. You will see units such as candle power, foot candles, candelas, foot lamberts, lux, lumens and my favorite: watts per steradian. Some units refer to the energy of the light source and others to the power. Many units take only the human eye sensitivity into account. The light units can be even more confusing when you consider that some light sources, such as a common light bulb, launch light in all directions while others, such as a laser, concentrate the light into narrow beams. Rather than confuse you even more by going into a long discussion of what the various units mean, I'm going to try to simplify the problem. Let's just assume that each light source has a distinctive emission spectrum and a certain emission geometry. You will have to treat each light source differently, according to how it is used with a specific communications system.

In optical communications you only need to consider the light that is sent in the direction of the detector. You also only need to consider the light that falls within the response curve of the detector you use. You should regard all the rest of the light as lost and useless. Since all the light sources discussed in this book rely on electricity to produce light, each source will have an approximate electrical power (watts) to optical power (watts) conversion efficiency, as seen by a silicon detector. You can use the approximate power efficiency and the known geometry of the emitted light to calculate how much light will be emitted, sent in the direction of the light detector and actually collected. Various sections of this book will give you some examples of such calculations.

Light Power and Intensity

The scientific unit for power is the "watt". Since the intensity of a light source can also be described as light power, the watt is perhaps the best unit to use to define light intensity. However, power should not be confused with energy. Energy, is defined as power multiplied by time. The longer a light source remains turned on, the more energy it transmits. But, all of the light detectors discussed in this book are energy independent. They convert light power into electrical power in much the same way as a light source might convert electrical power into light power. The conversion is independent of time. This is a very important concept and is paramount to some of the circuits used for communications. To help illustrate how this effects light detection, imagine two light sources. Let us say that one source emits one watt of light for one second while the other launches a million watts for only one millionth of a second. In both cases the same amount of light energy is launched. However, because light detectors are sensitive to light power, the shorter light pulse will appear to be one million times brighter and will therefore be easier to detect. This peak power sensitivity concept of light processing is a very important concept and is often neglected in many optical communications systems published in various magazines.

Miscellaneous Stuff

Independent on how long the light remains on. The watt is more convenient to use since light detectors, used to convert the light energy into electrical energy, produce an electrical current proportional to the light power, not its energy. Detectors often have conversion factors listed in amps per watt of light shining on the detector. Remember, energy is power multiplied by time.

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

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.

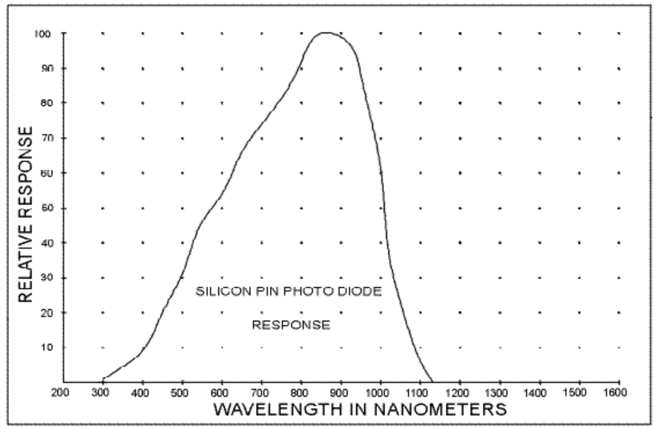
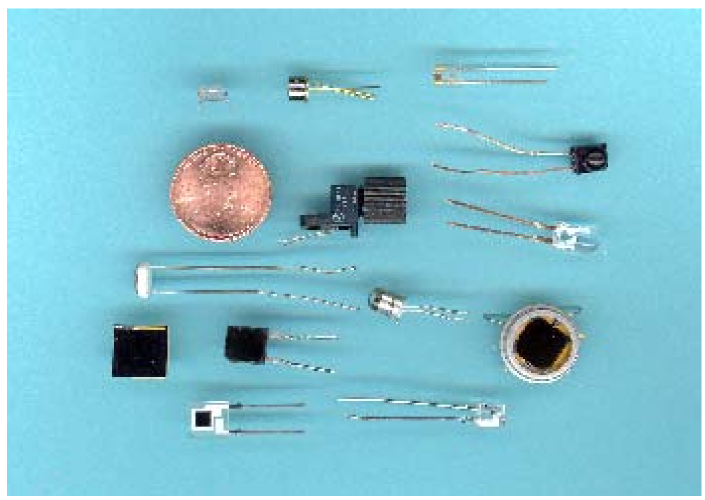


Figure 2a

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.

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.

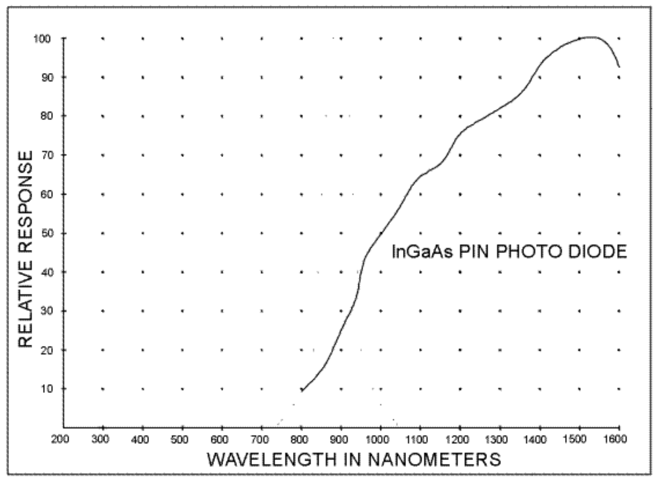


Figure 2a-1

Typical PIN Diode Specifications

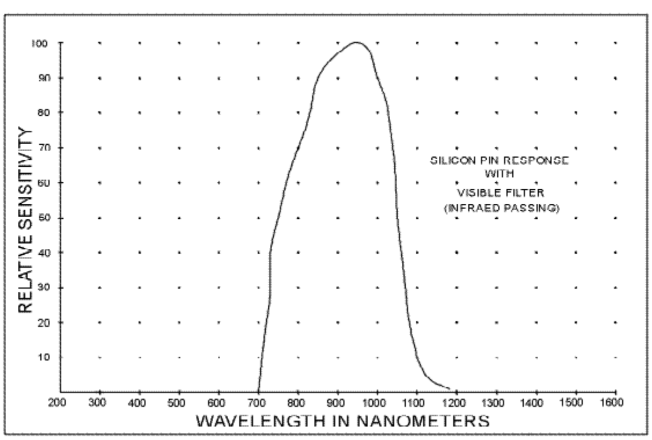


Figure 2b

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 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".

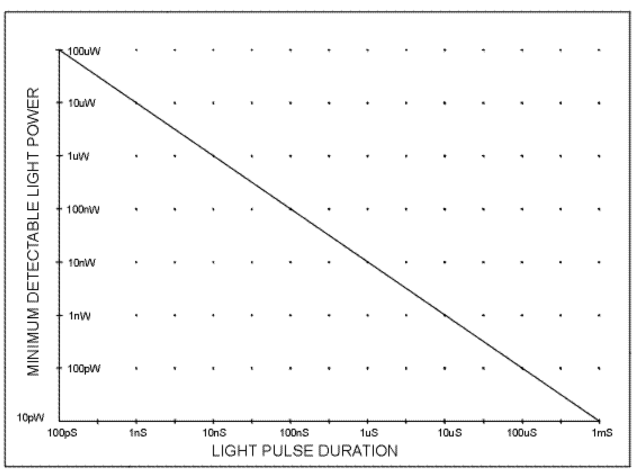


Figure 2b-1

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

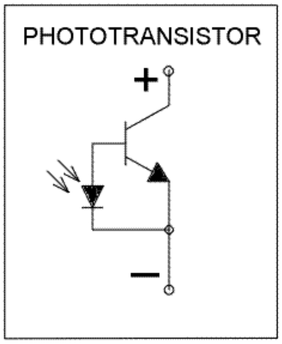


Figure 2b-1

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.

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.

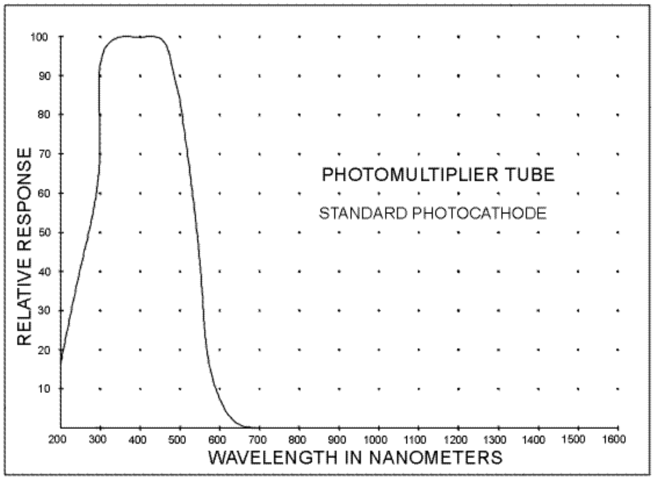


Figure 2c

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.

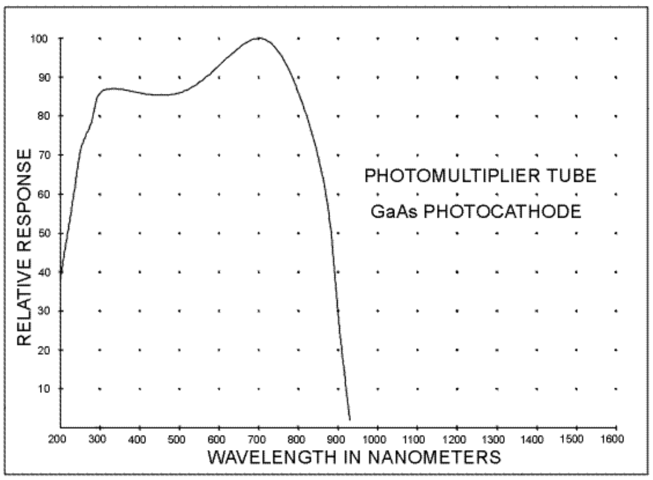


Figure 2c-1

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 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).

Chapter Three
LIGHT EMITTERS

Introduction to Light Emitters

Unlike the limited number of useable light detectors, there is a wide variety of light emitters that you can use for optical through-the-air communications. Your communications system will depend much more on the type of light source used than on the light detector. You should choose the light source based on the type of information that needs to be transmitted and the distance you wish cover to reach the optical receiver. In all cases the light source **must** be modulated (usually turned on and off or varied in intensity) to transmit information.

The modulation rate will determine the maximum rate information can be transmitted. You may have to make some tradeoffs between the modulation rates needed, the distance to be covered and the amount of money you wish to spend.

Samples of Emitters

Many light sources listed below are useful for low to medium speed modulation rates and can have ranges up to several miles. A few others are ideal for low speed telemetry transmission that can reach beyond 50 miles. If you need high speed information transmission, there are only a few choices, and those tend to be expensive. But, as the technology improves the prices should come down. I have also described some of the latest devices that may become available to the experimenter in a few years, but only demonstration devices exist today.

Light Emitting Diodes (LEDS)

For most through-the-air communications applications the infrared light emitting diode (IRLED) is the most common choice. Although visible light emitting devices do exist, the infrared parts are generally chosen for their higher efficiency and more favorable wavelength, especially when used with silicon photodiode light detectors.

GaAlAs IR LED

GaAlAs (gallium, aluminum arsenic) infrared LEDs are the most widely used modulated IR light sources. They have moderate electrical to optical efficiencies, (at low currents 4%), and produce light that matches the common silicon PIN detector response curve (900nm). Most devices can be pulsed at high current levels, as long as the average power does not exceed the manufacturer's maximum power dissipation specification (typically 0.25 watts). Some devices can be pulsed up to 10 amps, if the duty cycle (ratio of on time to the time between pulses) is less than 0.2% (0.002:1 ratio). Some of the faster devices have response times that allow them to be driven with current

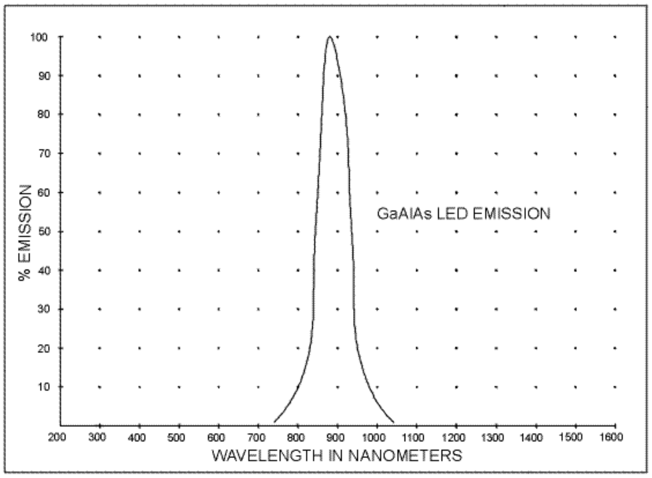


Figure 3a

pulses as short as 100 nanoseconds but most devices require at least 900 nanoseconds. At a current level of about 6 amps a quality device can emit about 0.15 watts of infrared light. However, at higher current levels their efficiency is generally poor, dropping to less than 0.5% (See ***Figures 3a, 3b, 3c and 3d***.) Many resemble the commonly used visible LEDs and will typically be packaged in molded plastic assemblies that have small 3/16" lenses at the end. The position of the actual LED chip within the package will determine the divergence (spreading out) of the exiting light. The typical T-1 3/4 style device will have a half angle divergence ranging from 15 to 40 degrees. They are low cost, medium speed (up to 1 million pulses per second) sources, with long operating lifetimes (typically greater than 100,000 hours).

They are a good choice for short and medium distance control links and general communications applications. When used with a large lens, a single device can be used for a communications system with a multi-mile range. Multi-device arrays can also be constructed to transmit information over wider areas or longer distances. They generally cost between $0.30 to $2.00 each and are available from many manufacturers.

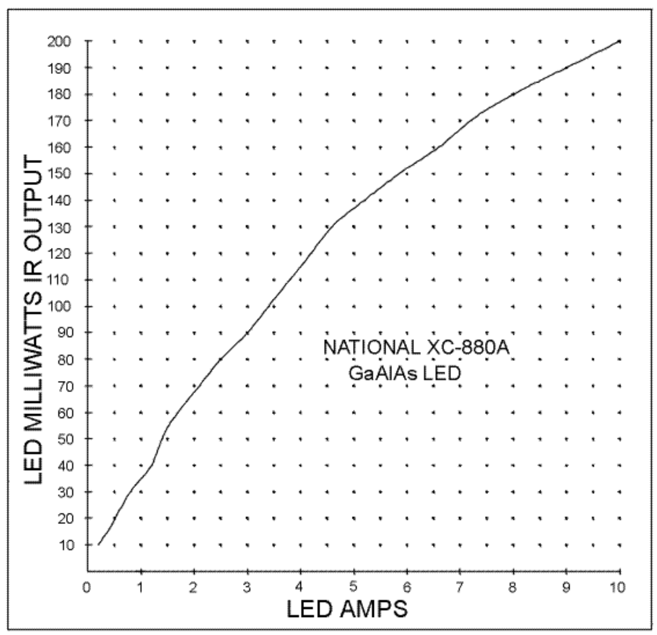


Figure 3b

GaAs IR LED

These devices are the older and less efficient cousin to the GaAlAs devices. They come in all styles and shapes. The more useful devices have smaller emitting surfaces than GaAlAs LED's, permitting narrow divergence angles with small lenses. Also, the small emitting areas make them very useful for fiber optic applications. Some commercial devices have miniature lenses cemented directly to the semiconductor chip to produce a small exiting light angle (divergence angle). In conjunction with a small lens (typically 0.5") such devices can launch light with a narrow divergence angle (0.5 degrees). The most important feature of the GaAs LED is its speed. They are generally 10 times faster than GaAlAs LED's but many only produce 1/6 as much light. They are often picked when medium speed transmission over short distances is required. Their price is typically a little more than the GaAlAs LED's, even though they use an older technology. They will cost between $2.00 to $25.00.

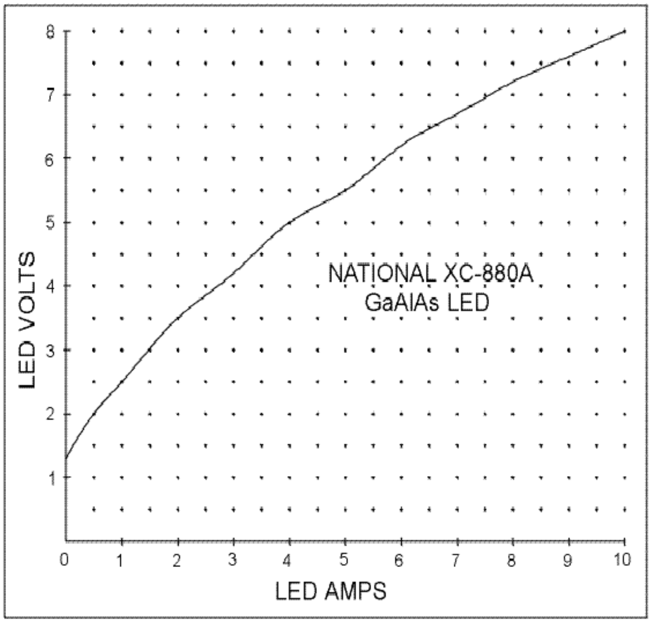


Figure 3c

GaAsP Visible Red LEDs

Although not as efficient as the infrared devices some visible red LEDs (***Figure 3d-1***)are now available, that might find limited use in some short range through-the-air applications. Some so called "super bright" LEDs boast high light output. However, even the brightest components will still produce only 1/3 as much light as a quality infrared part.

Also, since their light is a visible red color, an automatic 2:1 penalty will be paid when the devices are used with a standard silicon detector that has a weaker response to red light. The visible red LEDs are generally faster (up to 2 million pulses per second) than IR components and can therefore be used for medium speed applications. Also, since their light is visible, they are much easier to align than invisible IR devices, especially when the devices are used with lenses.

Solid State Semiconductor Lasers

GaAs (Hetrojunction) Lasers

These devices have been around since the 1960s and can produce very powerful light pulses. Some devices are able to launch light pulses in excess of 20 watts, which is some 200 times more powerful than a typical GaAlAs LED. But, these devices can only be driven with duty cycles, less than 0.1% (off time must be 1000 times longer than on time). Also, their maximum pulse width must be kept short (typically less than 200 nanoseconds) even under low pulse rate applications. However, despite their limitations these devices can be used in some voice transmitter systems if some careful circuit designs are used.

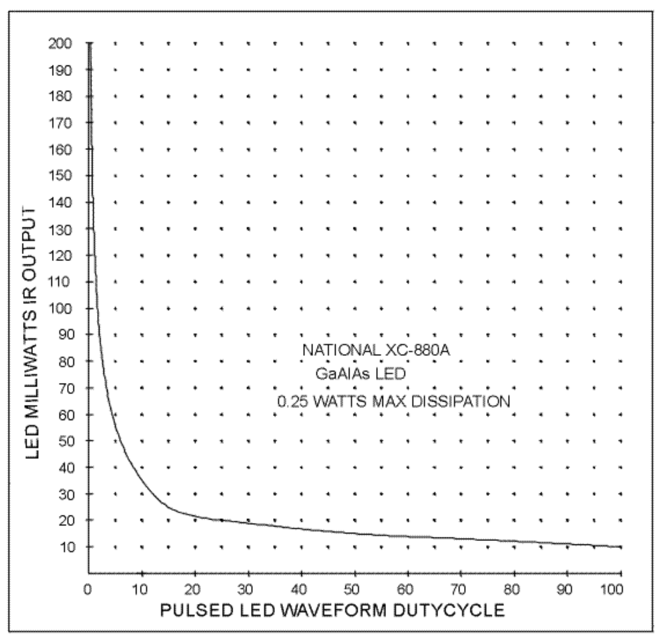


Figure 3d

As in most semiconductor lasers, the GaAs laser does require a minimum current level (typically 10 to 20 amps) before it begins emitting useable light. Such high operating currents demand more complicated drive circuits. Despite a 10:1 sensitivity reduction, caused by the rather narrow emitted pulses (see receiver circuit discussion), the more powerful light pulses available from GaAs lasers can increase the useful range of a communications system by a factor of about 3, over a typical transmitter using a single LED. In

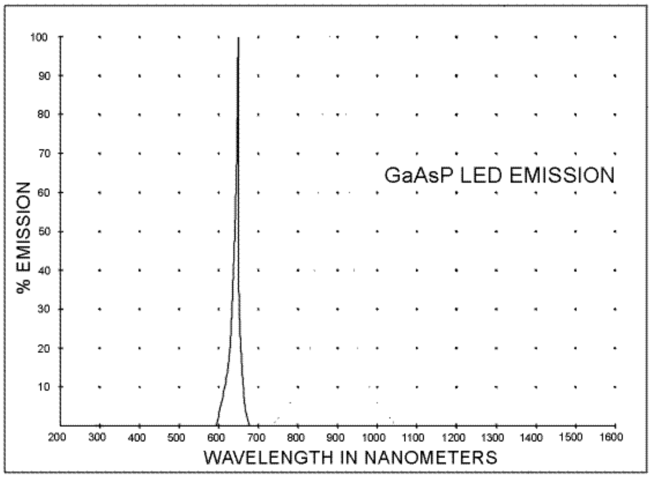


Figure 3d-1

addition, since their emitting spot sizes are very small, they can also be focused into very tight beams using rather small lenses. In addition, since their spectral widths are very narrow the matching light detector circuit can use an optical band pass filter to reduce the noise levels associated with ambient light (see receiver circuit section). For low speed and long distance applications, the GaAs laser should be considered. However, they do have some disadvantages. They typically cost much more than a GaAlAs LED (up to $75). They have shorter lifetimes (may only last a few hundred hours) and are sensitive to temperature. Therefore, they require a carefully designed transmitter circuit that can switch 20 or more amps at high speeds and can compensate for changes in operating temperature.

GaAlAs (CW) Lasers

These are the latest in infrared light emitting semiconductor devices and are rapidly maturing. The first wide spread application for these devices was in audio compact disk players and CD-ROM computer disk drives. They are also being used in some computer laser printers, bar code readers and FAX machines. They have very small emitting areas, can produce peak power levels in excess of 0.2 watts and have narrow spectral bandwidths (see ***Figure 3e***.) The most important improvement over other light sources is that they can be modulated at frequencies measured in gigahertz.

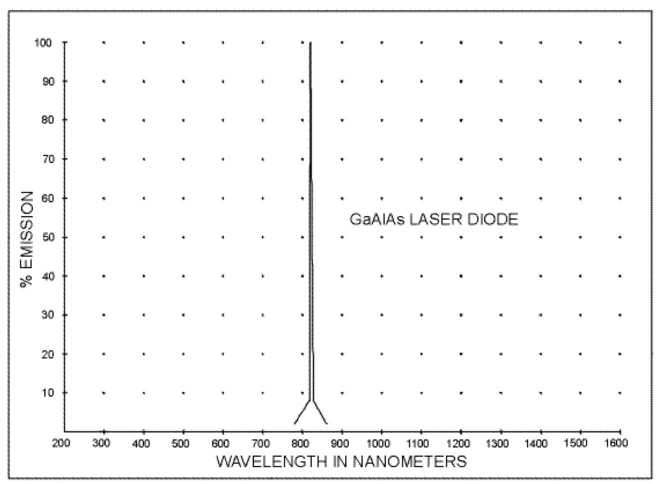


Figure 3e

However, as in any new technology they are still rather expensive. Low power units that emit less than 0.01 watts of 880nm infrared light, sell for about $20.00. Some of the more powerful devices can cost as much as $20,000 each. Although the use of a laser in a communications system might give a project a high tech sound, a much cheaper IR LED will almost always out-perform a low power laser (typical LED will be able to emit 10 times more light at 1/10 the cost) in low to medium speed applications. But, when very high-speed modulation rates (up to 1 billion pulses per second) are needed, these devices would be a good choice.

Although expensive now, these devices should come down in price over the next few years. They will also most likely be available at higher power levels too. But, until then, their advantages do not justify their expense and the more useful high power units are beyond the reach of practical experimental designs. I suggest using these devices only when necessary.

Surface Emitting Lasers (VCSEL)

These devices are just now beginning to appear in some catalogs. Many companies have been experimenting with these latest semiconductor devices since about 1988. Their small size and high efficiency make them very suitable for some applications. They are mostly used in optical fiber communications. Instead of being grown as single chip emitters, these devices are fabricated into large arrays of very small individual laser sources sharing a common substrate. Since the individual laser diode emitters can be as small as one micron (1/10,000cm) as many as 100 million separate devices could be placed into a 1cm X 1cm area.

The output efficiency (electrical power to light power) has been reported to be about 40%, with each tiny device emitting about 0.003 watts. Although each device may emit only a small amount of light, when used as an array, 100 million such devices could launch some 100,000 watts of IR light from about 200,000 watts of electricity. Of course, cooling such a powerful array would be a real challenge, if not impossible. But, perhaps smaller arrays could be placed into common semiconductor packages for easy mounting and cooling. Maybe a 0.1-watt device would be placed into inexpensive LED style packages. Other devices may be mounted in better heat conducting metal packages to allow perhaps 100 watts of light to be emitted. Since their maximum modulation rates have been measured in the multi-billion pulses per second rate, surface-emitting lasers would be ideal for many future through-the-air communications applications. They would especially be useful in broadcasting optical information over a citywide area, where very powerful high-speed light sources are needed. A 10,000-watt source, emitting light in a specially shaped 360-degree pattern, might be able to transmit information over an area covering some 500 square miles. Such a broadcasting system might be used to transmit library type information from large centralized databases.

Externally Excited Solid State Lasers

Some of the very first lasers made were the Ruby and YAG lasers. Most of these lasers are excited externally using large xenon flash tubes that are positioned around the central glass laser rod. A small portion of the light from the xenon flash excites the specially positioned rod material, forming short coherent light pulses. Although these lasers are capable of emitting very power light pulses, with very narrow divergence angles, they are generally much too expensive and too complicated for the average experimenter. They would therefore find very limited use in earth-bound optical communications. However, some scientists believe that the extremely powerful light pulses that these devices are capable of producing, might be useful in transmitting information into very deep space. Since some pulsed lasers have been reported to launch light pulses approaching one terawatt (1000 billion watts), low speed communications might be possible to a range of several light years (one light year = 6 trillion miles). Such a feat would be very difficult to accomplish with microwave techniques.

Gas Lasers

Helium-neon, carbon dioxide and argon are the more common types of gas lasers. The light emitted from a gas arc, inside a glass tube, is bounced back and forth through the excited gas using specially fabricated mirrors. A portion of the light is allowed to escape through one of the mirrors and emerges as very monochromatic (one wavelength) and highly coherent (same phase) light. Such lasers have narrow divergence angles (typically less than 0.1 degrees) but have very low conversion efficiencies (much less than 0.1%). They are also expensive and bulky that makes them impractical for most optical communications applications. Some published designs that did provide experimental optical communications using helium-neon lasers were designed to transmit voice audio information over a range of only a few miles. The modulation technique was to vary the gas arc current that then produced a light intensity modulation. However, the extra cost and relative low power that resulted usually did not warrant the trouble. A properly designed system using a single LED will usually out perform any short-range helium-neon laser communications system at a fraction of the cost.

Although too expensive for the experimenter, some gas lasers have been used by the military for many years. In particular, carbon dioxide lasers, that emit long infrared wavelengths (10,000 nanometers), have been used in some military targeting systems. The long infrared wavelength can penetrate smoke and fog better than visible or near IR lasers. Also, the Navy has been experimenting with some blue-green laser light to attempt to provide communications to submarines deep under water. But, overall gas lasers fall short of the ideal for practical through-the-air communications.

Fluorescent Light Sources

Fluorescent Lamps

Fluorescent lamps work on the principle of "fluorescence" and because of their low cost have many through-the-air applications. An electrical current passed through a mercury vapor inside a glass tube causes the gas discharge to emit ultraviolet "UV" light. The UV light causes a mixture of phosphors, painted on the inside wall of the tube, to glow at a number of visible light wavelengths (see ***Figure 3f***.) The electrical to optical conversion efficiency of these light sources is fairly good, with about 3 watts of electricity required to produce about 1 watt of light. A cathode electrode at each end of the lamp that is heated by the discharge current, aids in maintaining the discharge efficiency, by providing rich electron sources. By turning on and off the electrical discharge current, the light being emitted by the phosphor, can be modulated. Also, by driving the tubes with higher than normal currents and at low duty cycles, a fluorescent lamp can be forced to produce powerful light pulses. However, like the pulse techniques used with LEDs, the fluorescent lamp pulsing techniques must use short pulse widths to avoid destruction of the lamp.

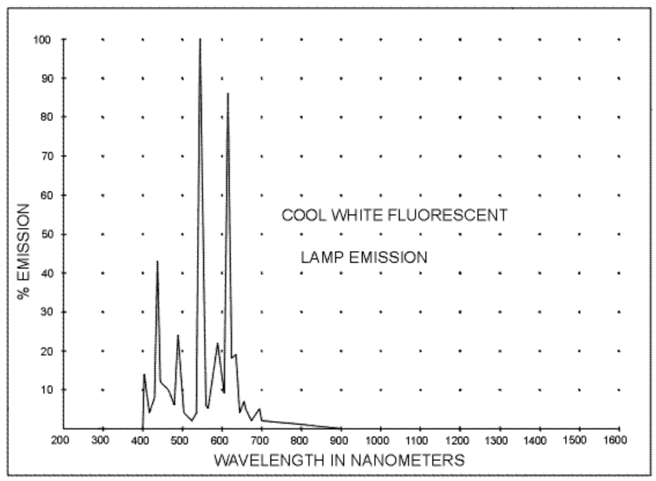


Figure 3f

To modulate a fluorescent lamp to transmit useful information, the negative resistance characteristic of the mercury vapor discharge within the lamp must be dealt with. This requires the drive circuit to limit the current through the tube. The two heated cathode electrodes of most lamps also require the use of alternating polarity current pulses to avoid premature tube darkening. The typical household fluorescent lighting uses an inductive ballast method to limit the lamp current. Although such a method is efficient, the inductive current limiting scheme slows the rise and fall times of the discharge current through the tube and thus produces longer then desired light pulses. To achieve a short light pulse emission, a resistive current limiting scheme seems to work better. In addition, there seems to be a relationship between tube length and the maximum modulation rate. Long tubes do not respond as fast as shorter tubes. As an example, a typical 48" 40 watt lamp can be modulated

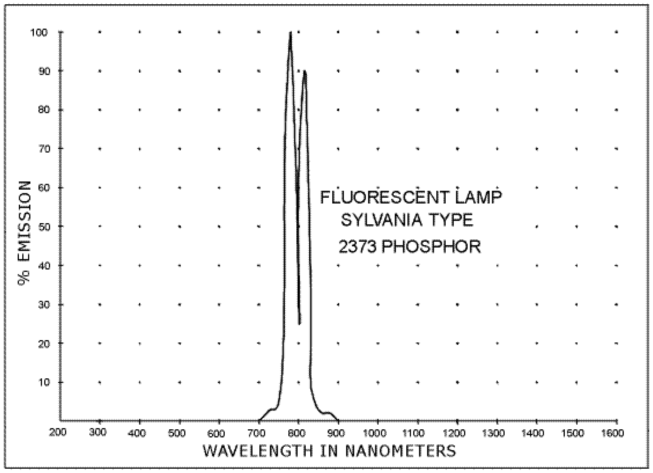


Figure 3g

up to about 10,000 pulses per second, but some miniature 2" tubes can be driven up to 200,000 pulses per second. The main factor that ultimately limits the modulation speed is the response time of the phosphor used inside the lamp. Most visible phosphors will not allow pulsing much faster than about 500,000 pulses per second. The visible light emitted by the typical "cool white" lamp is also not ideal when used with a silicon photodiode. However, some special infrared light emitting phosphors could be used to increase the relative power output from a fluorescent lamp, which may also produce faster response times. (see ***Figure 3g.***)

If a conventional "cool white" lamp is used, a 2:1 power penalty will be paid due to the broad spectrum of visible light being emitted (see ***Figure 3f***.) This results since the visible light does not appear as bright to a silicon light detector as IR light (see section on light detectors). Also, light detectors with built-in visible filters should **not** be used, since they would not be sensitive to the large amount of visible light emitted by the lamps. Although the average fluorescent lamp is not an ideal light source, the relative low cost and the large emitting surface area make it ideal for communications applications requiring light to be broadcasted over a wide area. Experiments indicate that about 20 watts of light can be launched from some small 9-watt lamps at voice frequency pulse rates (10,000/sec). Such power levels would require about 100 IR LEDs to duplicate. But, the large surface emitting areas of fluorescent lamps makes them impractical for long-range applications, since the light could not be easily collected and directed into a tight beam. (For additional information see section on fluorescent lamp transmitter/receiver circuits.)

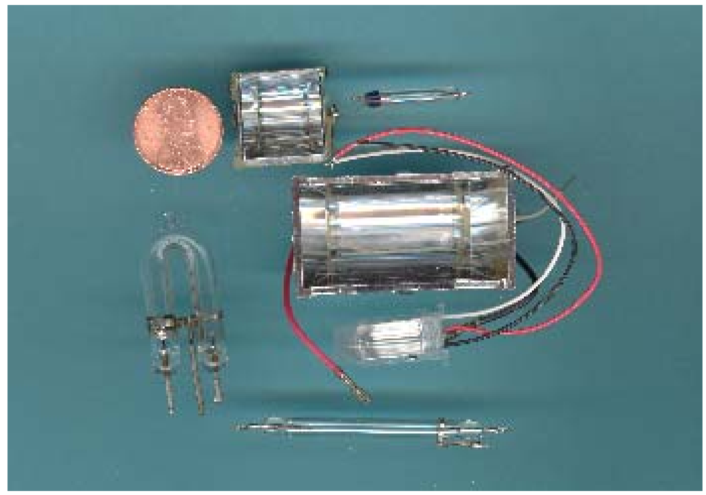
Cathode Ray Tubes (CRT)

CRTs work somewhat like fluorescent lamps, since they too use fluorescence emission techniques. Electrons, emitted from a heated cathode end of the cathode ray vacuum tube, are accelerated toward the anode end by the force of a high voltage applied between the cathode and anode electrodes. Before hitting the anode screen, the electrons are forced to pass through a phosphor painted onto the inside of the screen. In response to the high-speed electrons, the phosphor emits light at various wavelengths. A voltage applied to a special metal grid near the tube's cathode end is used to modulate the electron beam and can thus produce a modulation in the emitted light. This principle is used in most computer and TV screens. Since the electron beam can be modulated at very high rates, the light source modulation rate is limited only by the response time of the phosphor used. Depending on the type of phosphor, the electrical to optical efficiency can be as high as 10%. Some specially made cathode ray tubes produce powerful broad (unfocused) electron beams that illuminate the entire front screen of the CRT instead of a small dot. Such tubes can yield powerful light sources, with large flat emitting areas. A variation on the usual television type CRT design positions a curved phosphor screen at the back of the vacuum tube and places the cathode electrode at the front or side of a clear glass screen (some portable Sony TVs use such CRTs). This technique increases the overall efficiency, since it allows the light from the phosphor to exit from the same side as the electron source. With the aid of external cooling, such techniques could create very powerful light sources that might be able to launch tens of thousands of watts of light, pulsed at rates exceeding tens of millions of light pulses per second. Although the typical experimenter may not be interested in such light power levels it does raise some interesting possibilities for use in city wide optical communications.

Gas Discharge Sources

Xenon Gas Discharge Tubes

The most common form of this class of light source is the electronic camera flash. These devices are some of the most intense light sources available to the experimenter and have many interesting applications. The discharge lamps are typically made from a glass tube with a metal electrode installed at each end. They are filled with xenon gas at about one atmosphere of pressure (14psi). The gas inside the tube can be made to glow with very high intensity when an electrical current is passed through it.



Xenon Lamps

As illustrated in ***Figure 3h***, the xenon arc emits light over a broad spectrum with some large peaks in the near infrared range. The electrical to optical conversion is fairly good. A typical camera flash can produce about 2,000 watts of light from about 10,000 watts of electrical power (20% efficiency). Some specially made discharge tubes can generate flashes that exceed one million watts of light power. As in fluorescent lamps, the minimum flash duration is somewhat dependent on the length of the discharge tube. A typical camera flash tube has an electrode gap of about 15mm (0.6") and will usually produce a flash, which lasts about one millisecond. The energy used to produce the short flash comes from discharging a special capacitor, charged to several hundred volts. By decreasing the size of the capacitor (say to 6 microfarads) and increasing the voltage (say to 300 volts) the camera flash tube can be made to produce flashes as short as 20 microseconds. Shorter discharge flashes are only possible by using specially made discharge tubes with very narrow electrode gaps (0.5mm). These narrow gap lamps can produce flashes as short as one half microsecond. However, the physics of the xenon gas arc prevents flashes much shorter.

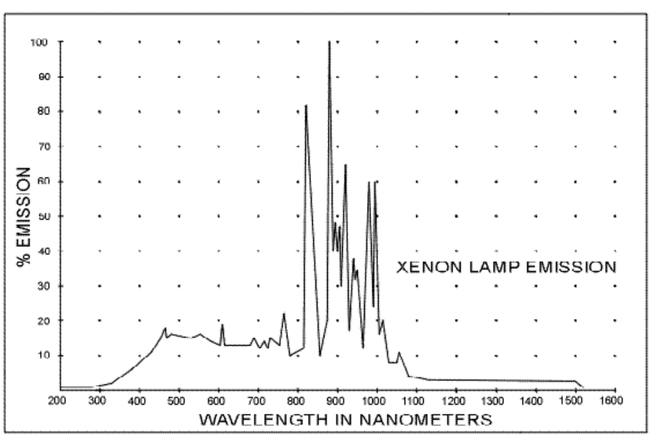


Figure 3h

Flash rates up to 10,000 per second are possible with the short gap lamps, but the typical camera flash tube can't be pulsed much faster than about 100 flashes per second. Since some special high speed lamps can dissipate up to 75 watts of average power, it is possible to design an optical voice information transmitter which could launch as much as 1000 watts of light with a narrow divergence. Such a transmitter would certainly have some long-range possibilities. However, most xenon discharge lamps are more useful for low speed and long-range applications, requiring very powerful light pulses. Many years ago, I constructed a demonstration telemetry system that launched very powerful light pulses at a low data rate that had a useable range of 50 miles. (See discussion on long-range telemetry transmitters using xenon flash sources.)

Nitrogen Gas (air) Sparks

For very powerful and very short light pulse applications, a simple electrical spark in air can be used. Some simple systems use two closely spaced (0.5mm) electrodes (usually made of tungsten) in open air. With sufficient voltage, the air between the electrodes can be made to ionize briefly, forming a small spark. Some gas barbecue grill igniters that use piezoelectric crystals to produce the needed high voltage, can be modified to produce useful sparks for some experiments. Commercially made nitrogen spark sources claim to generate light flashes that pack about 100,000 watts of light power into short 5 nanosecond pulses.

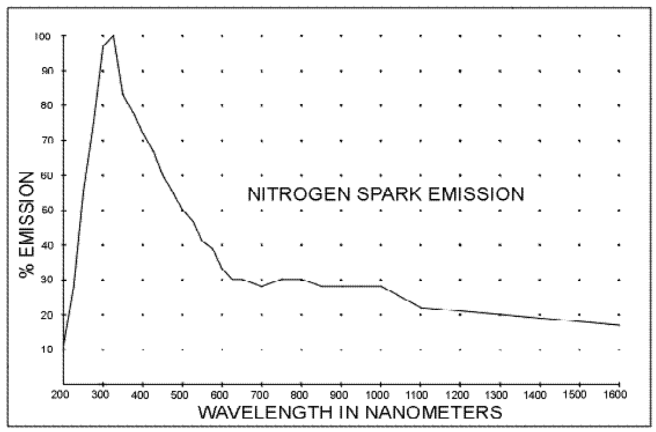


Figure 3i

The nitrogen (air) arc emits a broad spectrum of light with large peaks in the visible blue and invisible ultraviolet (see ***Figure 3i***.) Such a spectrum is not ideal when used with silicon detectors. But the small emission areas of the sparks allow simple lenses or mirrors to be used to form very tight divergence angles. But, the air ionization (sparking) can be become very unstable at high pulse rates, without using specially made discharge tubes and drive circuits. Therefore, the sparks are best used for powerful, very short pulse applications that demand only low pulse rates. Optical radar, electronic distance measurements, air turbulence monitors and wind shear analysis are some possible uses for such a light source. You shouldn't be fooled by the seemingly dim appearance of these light emitters. To our human eyes the tiny flashes may not seem very bright, but to a fast detector they can be very powerful. However, to take advantage of these unique pulses, a fast light detector and an equally fast amplifier must be used. Since few experiments have been conducted with these unique light sources, it is a great area for the experimenter to see what can be done.

Other Gas Discharge Sources

Glass discharge tubes filled with Cesium, Krypton or Rubidium will all produce lots of infrared light. Krypton behaves much like Xenon and has a very similar emission output. Cesium and Rubidium are both semi-liquids at room temperatures and can be operated under high or low pressures in a discharge lamp. Such lamps might be constructed in a similar manner to the more common yellow color sodium vapor street lamp. Cesium, in particular, appears to be a good candidate for some experimentation in developing some powerful light sources with high peak power outputs. Since kilowatt size sodium vapor street lamps are being manufactured, perhaps similar lamps using cesium could be made. Such lamps might be able to produce multi-kilowatts of modulated infrared light using pulse methods.

External Light Modulators

Ferroelectric light valves, modulated mirror arrays, piezoelectric shutters, Kerr cells, Pockels cells, Bragg cells and liquid crystals are all light modulators. They can be used to intensity modulate light being emitted by an external source as it passes through them or reflects off them. The light can originate from incandescent lamps, CW xenon gas arc lamps, light from a gas laser or even focused sunlight. Although usually very expensive, some of the devices can be used to produce powerful modulated light signals at high pulse rates.

Liquid crystal modulators are perhaps the slowest of the group. Most can't be driven much faster than about 100 flashes per second. Ferroelectric light valves and piezoelectric shutters are a little faster and can be pushed to perhaps 10,000 flashes per second. Kerr cells, Bragg cells and Pockel cells, on the other hand, are known to be very fast. However, they work best when used with laser light at a specific wavelength and at narrow angles. Some of these devices can modulate the light from a laser at rates beyond 100 million pulses per second. But, most of these devices are very expensive, are complicated and are therefore impractical for the average experimenter.

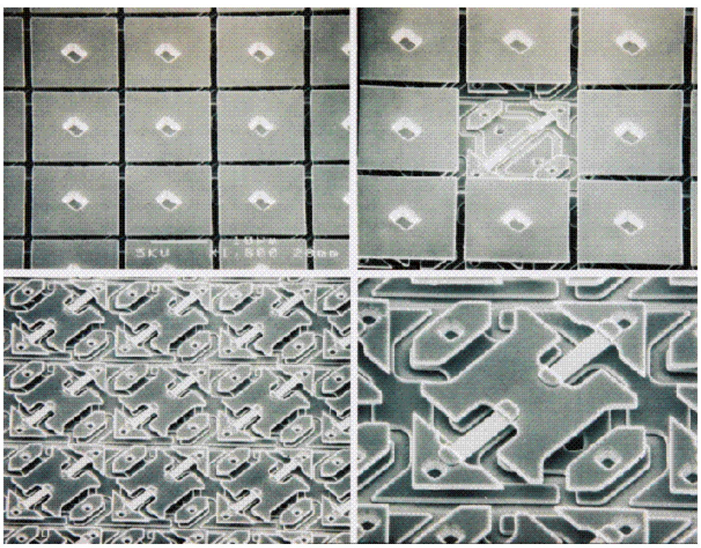


Figure 3j

A new device developed by Texas Instruments (***Figure 3j***) has some interesting possibilities. The technology was originally developed for flat panel computer and TV displays, but the techniques might be useful for optical communications. TI's process fabricates a large array of very small mirrors that can be moved using a voltage difference between the mirror and an area behind the mirror. Like tiny fans, each mirror would wave back and forth in response to the drive voltage. Because the mirrors are very small, the modulation rates might be pushed to perhaps 100,000 activations per second. If the mirrors were used to reflect light from an intense light emitter, a nice source of modulated light could be produced.

Chapter Four
LIGHT SYSTEM CONFIGURATIONS

Whether you are sending a simple on and off signal or high-speed computer data, some kind of light path must be establish between the light transmitter and the distant receiver. The three basic ways the information can be transferred are: "Opposed", "diffused reflective" and "retro reflective". Every communications system will use one or more of these methods.

Opposed Configuration

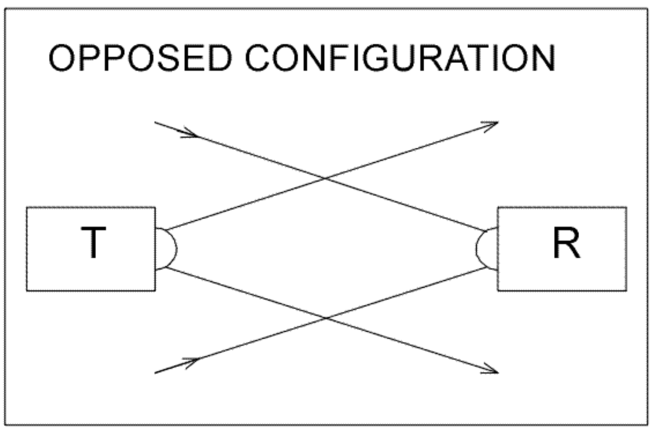


Figure 4a

As illustrated in ***Figure 4a*** an "opposed" or "through beam" configuration points the light transmitter and the receiver directly at each other. Although much of the light launched by the transmitter may never reach the distant receiver assembly, sufficient light is detected to pass information. Since there is only air between the transmitter and receiver, it is the most commonly used configuration to transmit information over long distances. Most optical communications systems rely on this configuration. Remote controllers for televisions, VCRs, audio systems and computers all rely on this direct light link method, since it makes the most efficient use of the transmitted light.

As the light emerges from the end of the transmitter it immediately begins spreading out. The light forms a cone shaped pattern of illumination. The spreading out of the light beam means the area being illuminated at the distant receiver will always exceed the receiver's light collecting area. The light that does not actually strike the receiver assembly is therefore lost. If you tried to design a system so all the launched light hit the receiver, you would soon discover that it would be impossible to maintain proper alignment. Small vibrations, building sway and even air disturbances could bend the light beam enough to miss the receiver assembly altogether. An intentional over-illumination scheme works the best, since it allows for some misalignment without the complete loss of the light signal. When designing a system using an opposed configuration you can use the range equation discussed in the last section as a way of predicting how much light will strike the receiver, how much light power needs to be launched and what kind of divergence angle is needed to establish a communications link over a specified distance.

Diffuse Reflective Configuration

When you look at the stars at night, car headlights or at the sun, your eyes collect the light that is coming directly from the light source. When you look at the moon, a movie screen or when you look at the light reflected off walls from a table lamp, you don't see the source of the light, but the light that happens to reflect off the object being illuminated by the source. Unless the object has a mirrored surface, the light that strikes the object spreads out in all directions. The light that you see is only a very small portion of the total light that actually illuminates the object. This "diffuse reflective" configuration, as shown in ***Figure 4b*** is a technique that is very useful in some communications systems. It is especially good for short distances when multiple reflections allow the light receiver to be aimed, not at the light source directly, but at objects being illuminated by the source. Some cordless stereo headsets use such a method to give a person some freedom of movement as he listens to music. These systems bounce the light off the walls, ceilings and floors with sufficient power that enough light finds its way to a light detector attached to the headset, no matter how the headset detector is oriented.

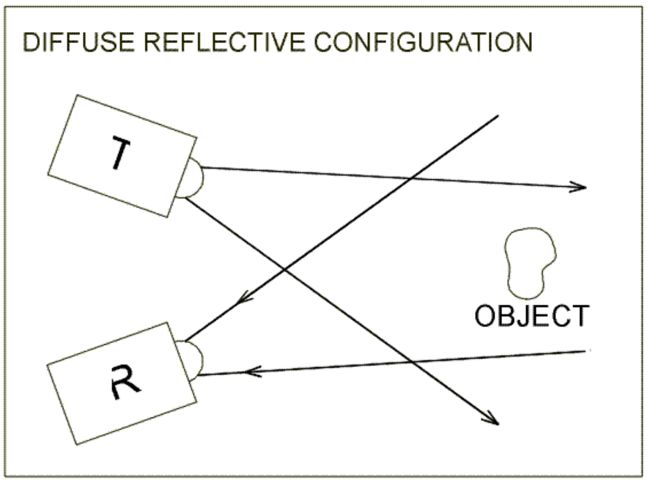


Figure 4b

The amount of light detected by the receiver is very dependent on the nature of object's surface that reflects the light. As an example, walls painted with white paint will reflect more light than those painted with dark paint. Also, rough surfaces will tend to reflect less light than smooth surfaces. Most surfaces reflect the light in a hemispherical pattern with more light being bounced straight back toward the light source then off to the sides. When you are trying to predict the behavior of such reflections it is best to think of the area of illumination as an independent light source that has a 90-degree half-angle divergence pattern. Then, if you know the acceptance angle of the light receiver and its collection area, you can use the range equation to calculate how much of the total light reflected will be collected by the light receiver.

If a single surface reflection is to be used, it is best to try to illuminate the smallest area possible. This concept can be illustrated by imagining how your eyes respond better to a brightly lit spot reflected off a wall than to a broad floodlight. By concentrating most of the light onto a small area more light will be reflected back to a nearby receiver that is aimed at the illuminated area. However, when multiple reflections are desired, such as done with the stereo headsets, a small or large illuminated area will work just about the same. In detecting light from single reflections you should plan to use a large collection area, with a small acceptance angle. The receiver would be aimed directly at the illuminated spot. However, for multiple reflection applications it is best to use a detector with a very wide acceptance angle. Detectors using large lens collectors will have little effect in multiple reflection cases, since they would have narrow acceptance angles.

As food for thought, it may be possible to use fluffy white clouds as diffuse reflectors to link two distant light transceivers. Some preliminary test results indicate that such a scheme may be possible if a transmitter, using a narrow light beam, launches sufficient light power and an equally efficient light receiver with a large light collector is used. Such a method may be very useful in allowing one powerful transmitter to be received by multiple light receivers that do not have a direct line-of-sight path to the transmitter. The imagined scheme might resemble the bright search lights often used to attract people to some gala event. Even the tiny amount of light reflected off dust particles in the air allow you to see the search light beam moving up toward the clouds many miles away. This concept would be a great area for an experimenter to try to see if such a system could actually be made to work.

Retro Reflective Configuration

As illustrated in ***Figure 4c*** if a special mirror reflector, called a "corner cube" reflector, is used to bounce light from a transmitter to a nearby light receiver, the light transmitter and receiver are said to be linked using a "retro reflective" configuration. A corner cube reflector can be made from a specially ground piece of glass, as shown in ***figure 4d*** or from positioning three mirrors at right angles to each other as shown in ***figure 4d-3***. Some plastic reflectors often used on bicycles and roadside indicators are actually large arrays of miniature molded corner cube reflectors (see ***figure 4d-1***). A corner cube has the unique characteristic that will return much of the light striking the assembly directly backs to the light source in a parallel path, independent of the position of the emitter. However, because of the parallel path, the light transmitter and receiver must positioned very close to each other. Some very accurately made corner cube reflectors send the light back in a path that is so parallel that the light receiver must actually be placed inside the light transmitter to properly detect the light being returned.

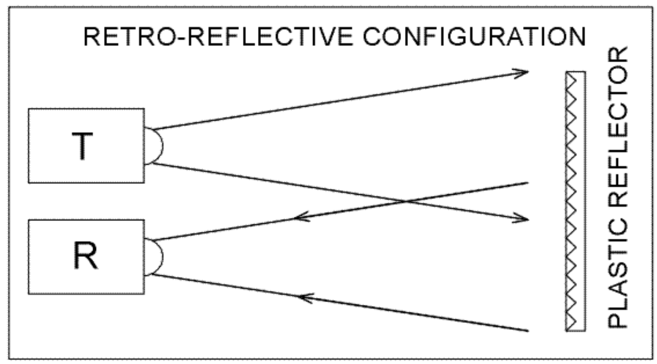


Figure 4c

Corner cube reflectors have a wide variety of applications. Several highly accurate corner cube arrays were left on the moon during some of the Apollo moon missions in the early 1970s. Scientists have been using powerful lasers and specially modified telescopes to bounce light off of the reflectors. By measuring the time the light pulses take to make the round trip from the earth, to the moon and back, the distance can be measured down to inches. Electronic distance measurement devices (EDMs), used by survey crews, also use corner cubes and "time of flight" techniques to measure distances accurate to inches. Some systems have effective ranges of several miles. Remember, light travels about one foot in one nanosecond, so for a round trip of 10,000 feet would cause a pulse delay of 10,000 nanoseconds or 10 microseconds.

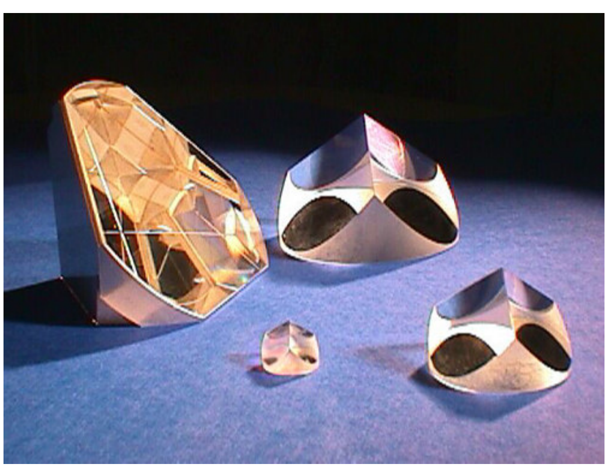


Figure 4d

Some alarm systems also use the retro-reflective technique. Pulsed light is bounced off a distant plastic reflector and is collected by a nearby light receiver. Objects moving between the light transmitter and the reflector break the established light path, setting off the alarm. Some industrial systems also use the technique to monitor products moving down a production line.

Figure 4d-1

You can increase the effective corner cube size by placing a fresnel lens in front of the corner cube as shown in ***figure 4d-2.*** Using the technique, you can make a one inch diameter glass corner cube appear to be several feet in diameter. This technique can dramatically lower the overall cost.

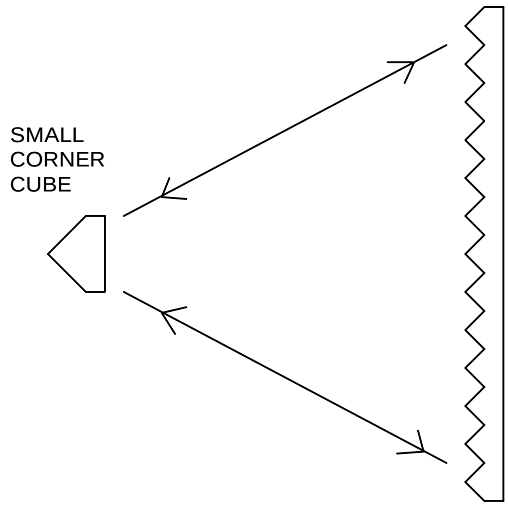


Figure 4d-2

When using the retro reflective technique you have to treat the reflector as a distant light source with its own emitting area and divergence angle. The amount of light sent back by the reflector will depend on the ratio of the illuminated area and the reflector's area. A typical plastic reflector has an equivalent divergence angle of about 0.5 degrees. For long-range applications a large reflector will be needed.

Figure 4d-3 shows a large corner cube reflector you can make yourself. Gluing three glass tile mirrors together makes it. A sturdy cardboard box will help position the mirrors. One mirror is positioned at the bottom of the box and the other two converge at the box sides. You would align such an assembly so the light would enter at a 30-degree angle relative to the bottom. The target for such an assembly would be the point where the three mirrors converge. I have used such a simple mirror for some experiments and was able to detect reflections over a distance of 10 miles. Larger mirror assemblies or even multi-reflector arrays are also possible to increase the effective range. Perhaps you might experiment with your own large reflector to see if a long range distant measuring systems could be devised. Using two such reflectors it might be possible to pinpoint your location using triangulation techniques.

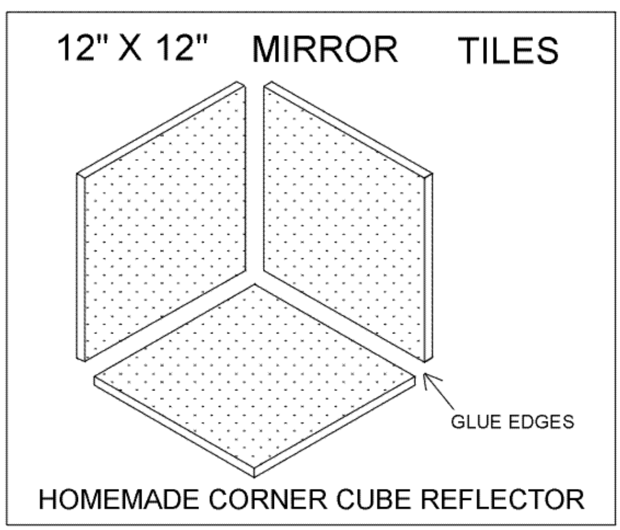


Figure 4d-3

Chapter Five
LIGHT PROCESSING THEORY

Lenses as Antennas

There is a reoccurring analogy between optical communications and radio. Both systems use similar components that, 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.

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.

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.

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.

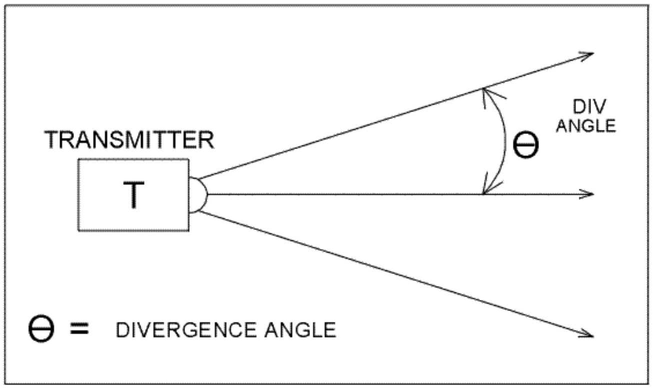


Figure 5a

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" that 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 "bore sights" (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.

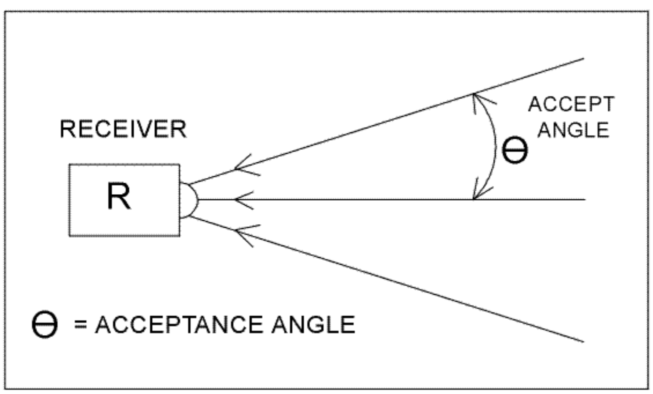


Figure 5b

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.

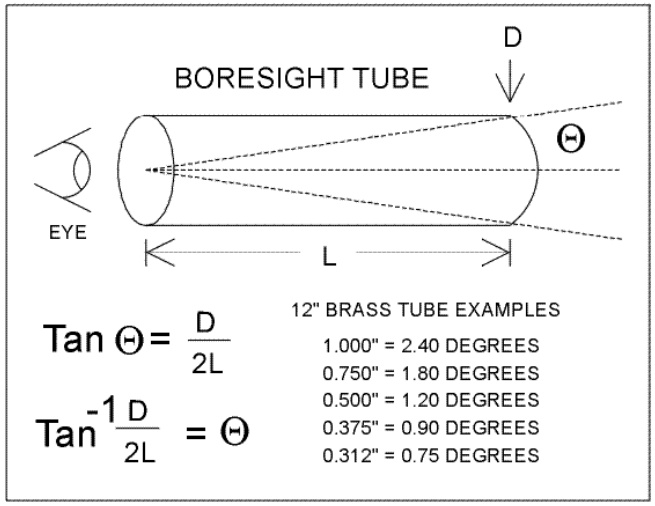


Figure 5c

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. A single receiver will detect only one of the images. 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 that uses multiple emitters, you will need multiple lenses.

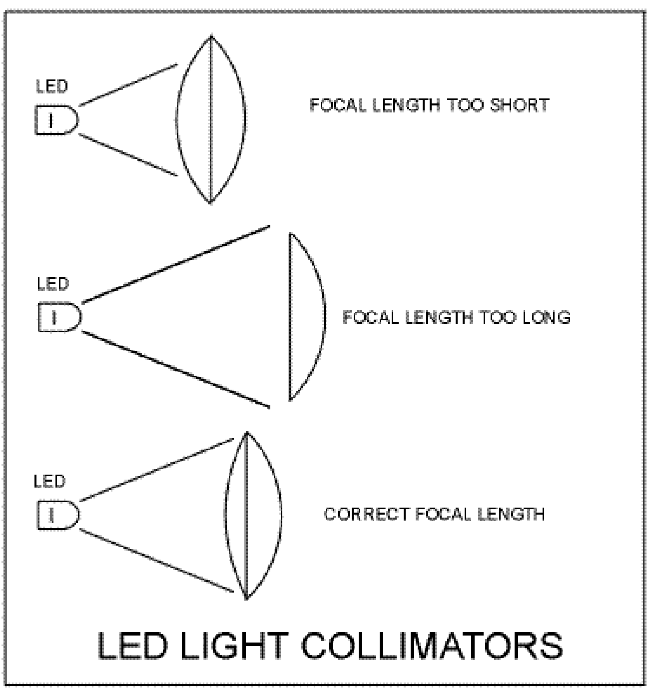


Figure 5d

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 that will extend the range of a communications system.

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 taillights, 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 "band pass" filters and are the most valuable type of filter used in through-the-air communications. Other

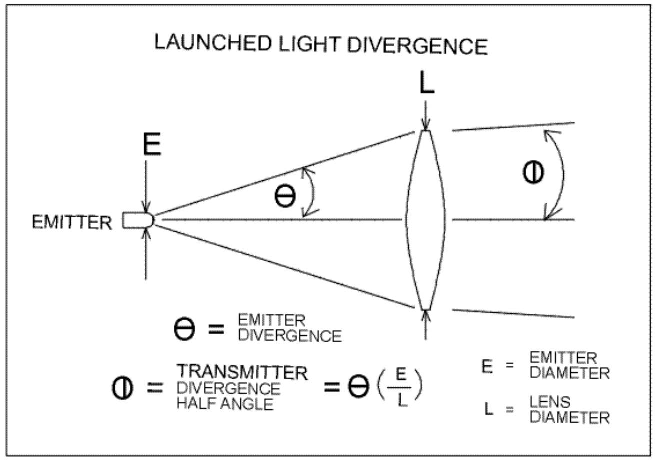


Figure 5e

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.

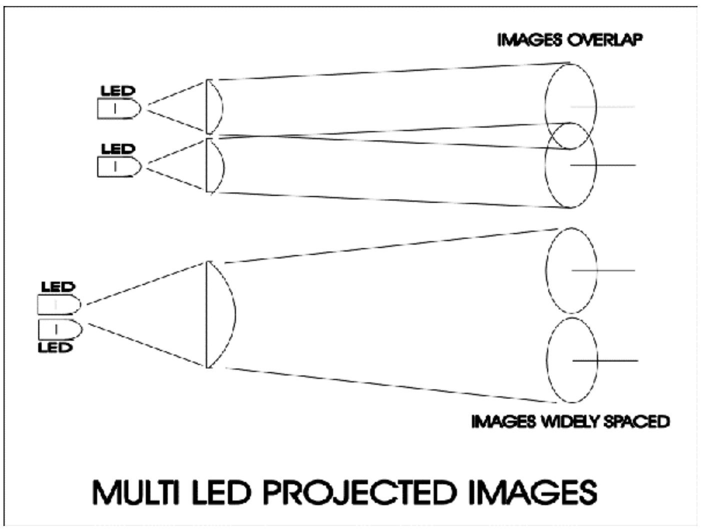


Figure 5f

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, the filter will block much of the stray visible ambient light, which may be collected by a lens. 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 band pass filter is needed. But to take advantage of a band pass filters they must be used with equally narrow spectrum light emitters, such as semiconductor laser diodes.

One optical band pass filter, that can be made to closely match a laser diode's emission spectrum, is an "interference" filter. Stacking many very thin layers of special materials onto a glass plate makes interference filters. 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 band pass filters can especially be useful when a single light receiver needs to detect light from only one of many different modulated laser sources. Different band pass 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.

Make Your Own Optical Low Pass Filter

A pretty good optical low pass filter can be made using a photographic film negative. As shown in **Figure 5h-1**, this filter works well at attenuating visible light and is pretty transparent over much of the near infrared wave lengths. However, do note that only light sources with wave lengths longer than 830 nanometers should be used. This filter shouldn't be used for detecting light from many lasers, that operate at 780 nanometers. I found that Kodak Kodacolor film with an ASA of 100 works well. You first remove the unexposed film from the roll and expose it to the light from a cool white fluorescent lamp for about 5 seconds. Then, you wind up the film into roll again and take it to your favorite film developer for processing. Tell them that your not sure if the roll has any images on it and you can usually get them to develop the roll for free. The processed color negatives form the filter material. Keep in mind that the film material is not very robust and should not be used if it can be scratched or exposed to moisture.

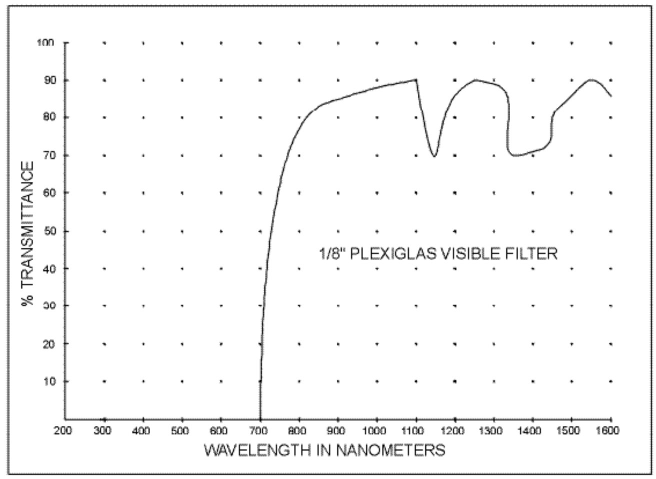


Figure 5g

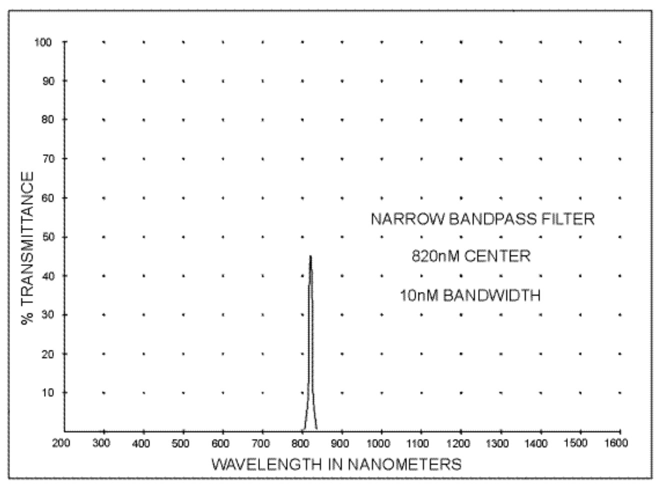


Figure 5h

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 that 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" that combines the inverse square law with some simple trigonometry.

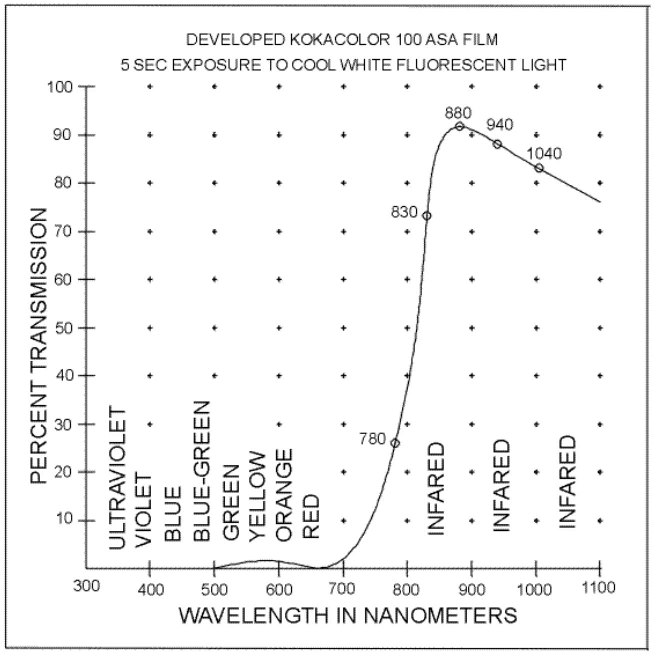


Figure 5h-1

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

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

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.

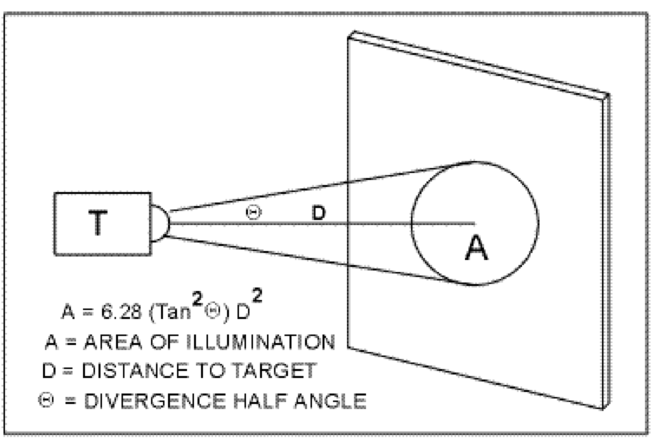


Figure 5j

Chapter Six
OPTICAL RECEIVER CIRCUITS

The overall task of the optical receiver is to extract the information that has been placed on the modulated light carrier by the distant transmitter and restores the information to its original form. The typical through-the-air communications receiver can be broken down into five separate sections. These are: light collector (lens), light detector (PIN), current to voltage converter, signal amplifier and pulse discriminator. There may also be additional circuits depending on the kind of the signal being received. As an example, a receiver that is extracting voice information will need a frequency to voltage converter and an audio amplifier to reproduce the original voice signal. Computer data receivers will also need some decoding circuits that would configure the transmitted serial data bits into 8 bit words. However, this section will concentrate on the circuits needed for processing voice information. Volume II of this book will contain additional circuits for digital data receivers.

Light Collector

For long-range applications it is essential to collect the weak modulated light from the distant transmitter with a glass or plastic lens and focus it onto a silicon PIN photodiode. Although mirrors could also be used to collect the light, glass or plastic lenses are easier to use and cost less. Plastic lenses measuring from a fraction of an inch to six inches are available. For a system that demands a large lens, the flat "Fresnel" lens is much less expensive than a solid lens. Forming special concentric bumps in a clear plastic sheet makes Fresnel lenses. The bumps bend the light just as a conventional thick lens would. Fresnel lenses are available with diameters of several feet.

For certain short-range applications it may also be possible to use a naked light detector without any lens. Distances up to several hundred feet are possible with systems that don't rely on lenses at either the transmitter or the receiver. Lens-less systems are especially useful when very wide acceptance angles are required. Many cordless IR stereo headsets use two or more naked detectors to provide acceptance angles approaching 360 degrees.

The lens chosen should be as large as possible but not too large. A lens that is too large can produce a half angle acceptance angle that is too small. Acceptance angles less than about 0.3 degrees will result in alignment difficulties. Building sway and atmospheric disturbances can cause signal disruption with narrow acceptance angles. A rough rule-of-thumb might be that the lens diameter should not be more than 100 times larger than diameter of the active area of the PIN detector. Also, the receiver should never be positioned so sunlight could be focused onto the light detector. Even a brief instant of focused sunlight will destroy the sensor. A north/south alignment for the transmitter and the receiver will usually prevent an optical system from going blind from focused sunlight.

Light Detector

As discussed in the section on light detectors, the silicon PIN photodiode is the recommended detector for most all through-the-air communications. Such a detector works best when reversed biased. In the reversed biased mode it becomes a diode that leaks current in response to the light striking it. The current is directly proportional to the incident light power level (light intensity).

When detecting light at its peak spectrum response wavelength of 900 nanometers, the silicon PIN photodiode will leak about 0.5 micro amps of current for each microwatt of light striking it. This relationship is independent to the size of the detector. The PIN photodiode size should be chosen based on the required frequency response and the desired acceptance angle with the lens being used. Large PIN photodiodes will have slower response times than smaller devices. For example, 1 cm X 1 cm diodes should not be used for modulation frequencies beyond 200KHz, while 2.5 mm X 2.5 mm diodes will work beyond 50MHz. If a long range is desired, the largest photodiode possible that will handle the modulation frequency should be used.

Stray Light Filters

Some systems can benefit from the placement of an optical filter between the lens and the photodiode. The filter can reduce the effects of sunlight and some stray light from distant street lamps. Filters can be especially effective if the light detector is going to be processing light from a diode laser. Since laser light has a very narrow bandwidth, an optical band pass filter that perfectly matches the laser light can make a light receiver nearly blind to stray sunlight.

If light emitting diode light sources are used, optical filters with a much broader bandwidth are needed. Such a filter may be needed for some situations where man-made light is severe. Many electronically controlled fluorescent and metal vapor lamps can produce unwanted modulated light that could interfere with the light from the distant transmitter.

But, in all but a few rare exceptions, band pass filters produce few overall improvements if the correct detector circuit is used. Since no optical filter is perfectly transparent, the noise reduction benefits of the filter usually do not out weigh the loss of light through the filter. Also, if the detector is going to process mostly visible light, no optical filter should be used.

Current to Voltage Converter Circuits

The current from the PIN detector is usually converted to a voltage before the signal is amplified. The current to voltage converter is perhaps the most important section of any optical receiver circuit. An improperly designed circuit will often suffer from excessive noise associated with ambient light focused onto the detector. Many published magazine circuits and even many commercially made optical communications systems fall short of achievable goals from poorly designed front-end circuits. Many of these circuits are greatly influenced by ambient light and therefore suffer from poor sensitivity and shorter operating ranges when used in bright light conditions. To get the most from your optical through-the-air system you need to use the right front-end circuit.

High Impedance Detector Circuit

One method that is often shown in many published circuits, to convert the leakage current into a voltage, is illustrated in *figure 6a*. This simple "high impedance" technique uses a resistor to develop a voltage proportional to the light detector current. However, the circuit suffers from several weaknesses. If the resistance of the high impedance circuit is too high, the leakage current, caused by ambient light, could saturate the PIN diode, preventing the modulated signal from ever being detected. Saturation occurs when the voltage drop across the resistor, from the photodiode

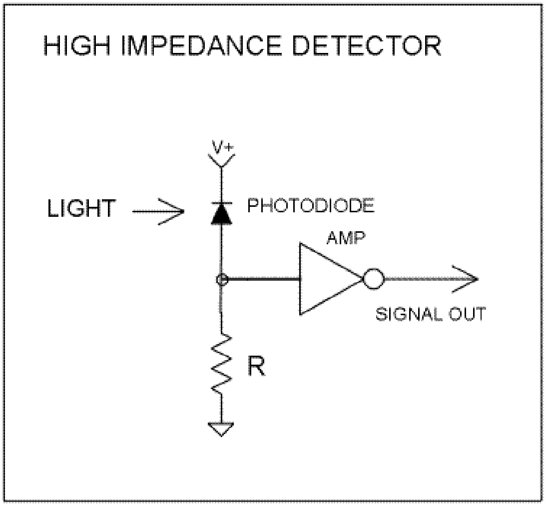


Figure 6a

leakage current, approaches the voltage used to bias the PIN device. To prevent saturation, the PIN must maintain a bias voltage of at least a few volts.

Consider the following example. Under certain bright background conditions a PIN photodiode leakage current of a few milliamps may be possible. If a 12v bias voltage were used, the detector resistance would have to be less than 10,000 ohms to avoid saturation. With a 10K resistor, the conversion would then be about 10 millivolts for each microamp of PIN leakage current. But, to extract the weak signal of interest that may be a million times weaker than the ambient light level, the resistance should to be as high as possible to get the best current to voltage conversion. These two needs conflict with each other in the high impedance technique and will always yield a less than desirable compromise.

In addition to a low current to voltage conversion, there is also a frequency response penalty paid when using a simple high impedance detector circuit. The capacitance of the PIN diode and the circuit wiring capacitance all tend to act as frequency filters and will cause the circuit to have a lower impedance when used with the high frequencies associated with light pulses. Furthermore, the high impedance technique also does not discriminate between low or high frequency light signals. Flickering streetlights, lightning flashes or even reflections off distant car windshields could be picked up along with the weak signal of interest. The high impedance circuit is therefore not recommended for long-range optical communications.

Transimpedance Amplifier Detector Circuit With Resistor Feedback

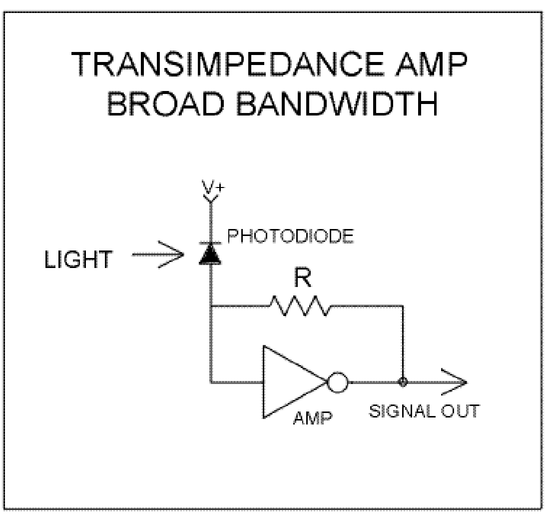


Figure 6b

An improvement over the high impedance method is the "transimpedance amplifier" as shown in **figure *6b*.** The resistor that converts the current to a voltage is connected from the output to the input of an inverting amplifier. The amplifier acts as a buffer and produces an output voltage proportional to the photodiode current. The most important improvement the transimpedance amplifier has over the simple high impedance circuit is its canceling effect of the circuit wiring and diode capacitance. The effective lower capacitance allows the circuit to work at much higher frequencies. However, as in the high impedance method, the circuit still uses a fixed resistor to convert the current to a voltage and is thus prone to saturation and interference from ambient light.

Transimpedance Amplifier Detector Circuit With Inductor Feedback

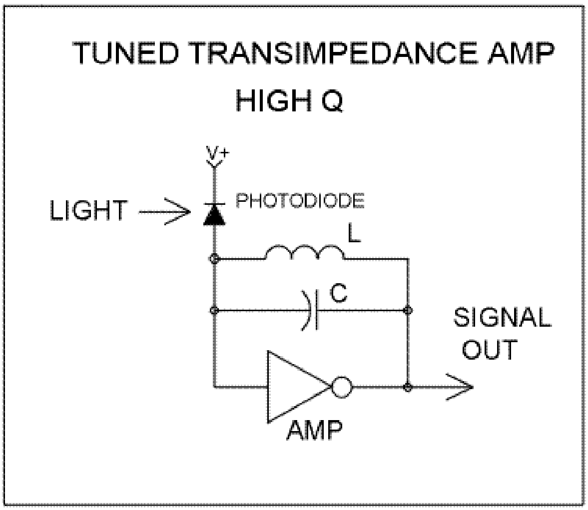


Figure 6c

A dramatic improvement of the transimpedance amplifier with a resistor feedback load is shown in **figure *6c.*** This technique is borrowed from similar circuits used in radio receivers. The circuit replaces the resistor with an inductor. A student in electronics may remember that an inductor will pass DC unaffected but will exhibit a resistance effect or reactance to AC signals. The higher the frequency of the AC signals the higher the reactance. This reactance circuit is exactly what is needed to help extract the sometimes small modulated AC light signal from the large DC component caused by unmodulated ambient light. DC signals from ambient light will yield a low current to voltage conversion while high frequency AC signals will experience a high current to voltage conversion. With the right circuit, an AC vs. DC conversion ratio of several million is possible. Such techniques are used throughout radio receiver circuits to process weak signals.

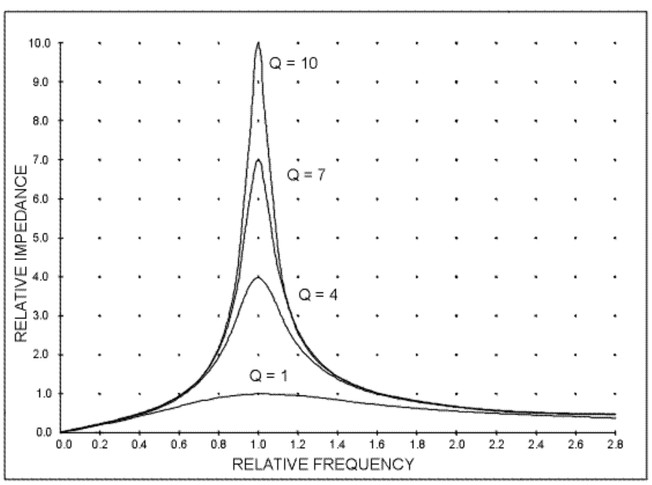


Figure 6d

In addition, as the Q increases so does the impedance of the LC circuit. Such high Q circuits can also be used in a transimpedance amplifier designed for optical communications. To obtain the highest possible overall impedance, the inductance value should be as large as possible and the capacitance should be as small as possible. Since every inductor contains some finite parallel capacitance within its assembly, the highest practical impedance occurs when only the capacitance associated with the inductor assembly is used to form the LC network. In radio, connecting a capacitor in parallel with the inductor often produces high impedances and allowing the LC tuned circuit to resonant at a specific frequency. Such a circuit can be very frequency selective and can yield impedances of several mega ohms. The degree of rejection to frequencies outside the center resonant frequency is defined as the "Q" of the circuit. As **figure *6d*** depicts, a high Q will produce a narrower acceptance band of frequencies than lower Q circuits.

You can calculate the equivalent parallel capacitance of an inductor based on the published "self-resonance" frequency or you can use a simple test circuit to actually measure the resonance frequency **(*see figure 6e on page 54*)** of a coil. ***Figure 6f*** lists the characteristics of some typical coils.

Typical Inductor Self Resonance Frequencies		
Inductance	**Frequency**	**Reactance at Res. Frequency**
4H	200KHz	500K Ohms
100mH	200KHz	100K Ohms
47mH	250KHz	75K Ohms
27mH	300KHz	50K Ohms
15mH	500HKz	50K Ohms
10mH	700KHz	40K Ohms
4.7mH	800KHz	22K Ohms
2.2mH	1MHz	14K Ohms
1mH	2HMz	12K Ohms
470uH	3MHz	9K Ohms
100uH	7MHz	4.4K Ohms

Figure 6f

Transimpedance Amplifier Detector Circuit with Limited Q

The use of a LC tuned circuit in a transimpedance amplifier circuit does improve the current to voltage conversion and does reject much of the signals associated with ambient light. But, high Q circuits are prone to unwanted oscillations. As shown in ***figure 6g***, to keep the circuit from misbehaving, a resistor should be wired in parallel with the inductor. The effect of the resistor is to lower the circuit's Q. For pulse stream applications with low duty cycles (short pulses with lots of time between pulses), it is best to keep the Q near 1. A Q of one exists when the reactance of the coil is equal to the parallel resistance at the desired frequency. If higher Qs were used, with low duty cycle pulse streams, the transimpedance amplifier would produce excessive ringing with each pulse and would be prone to self-oscillation.

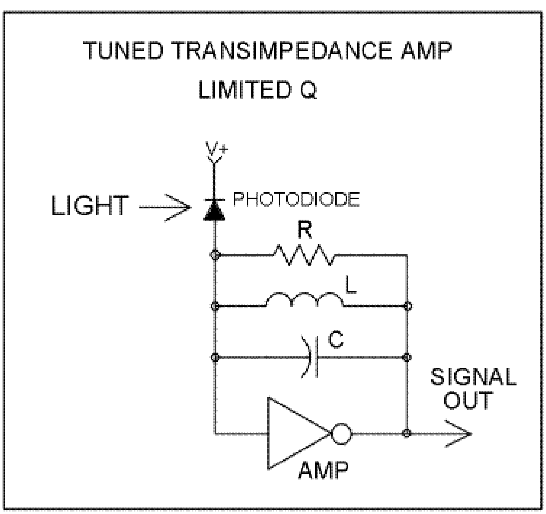


Figure 6g

Figure 6h* and *6i illustrate what happens in a circuit with a low Q and high Q when processing single pulses. If higher duty cycle pulse trains are being transmitted, higher Qs can be used. In near 50% duty cycle transmission systems, Qs in excess of 50 are possible with a careful design. Table *6f* lists the typical self-resonant frequency of some inductors. If you don't know the self-resonant frequency of a coil you can use the schematic shown in ***figure 6e on page 52*** to measure it.

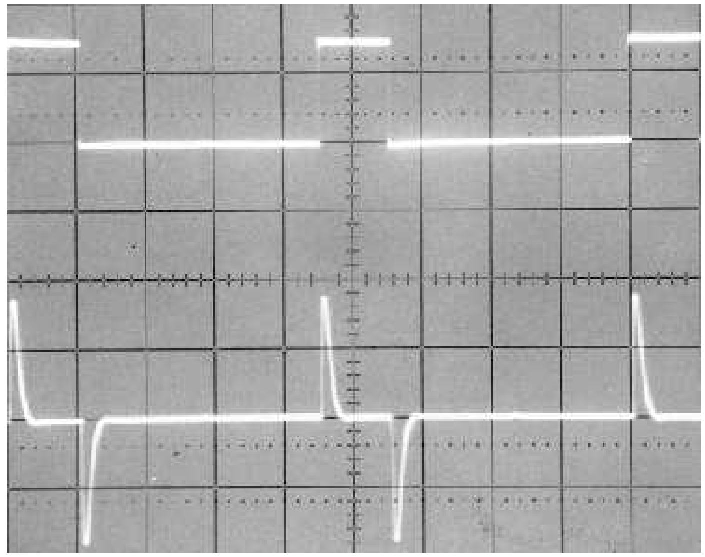


Figure 6h

In low duty cycle light pulse applications, the inductor value should be chosen based on the width of the light pulse being sent by the transmitter. The self-resonant period (1/frequency) of the coil should equal 2W, where W is the width of the light pulse. Since the circuit layout, the amplifier circuit and the PIN diode will all add to the overall circuit capacitance, some experimentation will be necessary to determine the best inductor value for the particular application. The equation 2pFL should be used to calculate the value of the resistor wired in parallel to the inductor to limit the Q to 1.

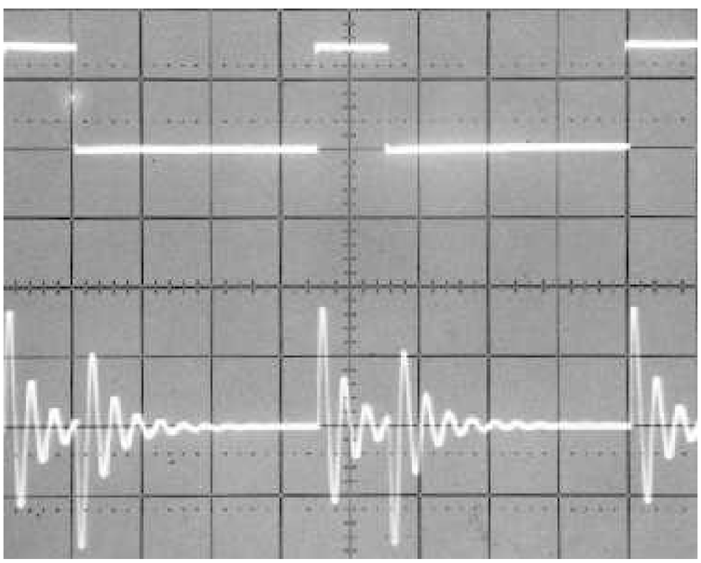


Figure 6i

Figure 6j on page 53 is an example of a complete transimpedance amplifier circuit with inductive feedback. The amplifier circuit shown in ***figure 6j on page 53*** has a light power to voltage conversion of about 23 millivolts per milliwatt (assuming 50% PIN conversion) when used with 1 microsecond light pulses. Such an amplifier should be able to detect light pulses as weak as one nanowatt during dark nighttime conditions.

Post Signal Amplifier

As discussed above, the transimpedance amplifier converts the PIN current to a voltage. However, it may be too much to expect one amplifier stage to boost the signal of interest to a useful level. Typically, one or more voltage amplifier stages after the front end circuit are needed. Often the post amplifiers will include some additional signal filters so only the desired signals are amplified, rejecting more of the undesired noise. A general purpose post amplifier is shown in ***figure 6j on page 53***.

The circuit uses a quality operational amplifier in conjunction with some filter circuits designed to process light pulses lasting about 1 micro second. The circuit boosts the signal by a factor of X20.

Signal Pulse Discriminators

Once the signal has been sufficiently amplified and filtered, it often needs to be separated completely from any background noise. Since most systems use pulse frequency modulation techniques to transmit the information, the most common method to separate the signal from noise is with the use of a voltage comparator. The comparator can produce an output signal that is thousands of times higher in amplitude than the input signal. As an example, a properly designed comparator circuit can produce a 5 volt peak to peak TTL logic output signal from a input of only a few millivolts.

But, to insure that the comparator can faithfully extract the signal of interest, the signal must be greater in amplitude than any noise by a sizeable margin. For most applications, I recommend that the signal to noise ratio exceed a factor of at least 10:1 (20db). Then, with a properly designed comparator circuit, the comparator output would change state (toggle) only when a signal is present and will not be effected by noise.

A complete signal discriminator circuit is shown in ***figure 6k on page 54.*** The circuit is designed so a positive input pulse needs to exceed a threshold voltage before the comparator produces a negative output pulse. A variable resistor network allows the threshold voltage to be adjustable. The adjustment thereby provides a means to set the sensitivity of the circuit. The adjustment should be made under the worst case bright background conditions so the noise produced by the bright background light does not toggle the comparator.

Frequency to Voltage Converters

If the light pulses being transmitted are frequency modulated to carry the information, then the reverse must be done to restore the original information. The pulse frequency must therefore be converted back into the original amplitude changing signal. A simple but very effective frequency to voltage converter circuit is shown in ***figure 6k on page 54***. Each pulse from the pulse discriminator circuit is converted into a well defined logic level pulse that lasts for a specific time. As the frequency increases and decreases, the time between the pulses will change. The changing frequency will therefore cause the average voltage level of the signal produced by the converter to change by the same proportion. To remove the unwanted carrier frequency from the desired modulation frequency, the output of the converter must be filtered.

Modulation Frequency Filters

A complete filter circuit is shown in ***figure 6l on page 55.*** The circuit uses a switched capacitor filter (SCF) integrated circuit from National Semiconductor. With the values chosen, the circuit removes the majority of a 10KHz carrier signal, leaving the wanted voice audio frequencies. The filter's cutoff frequency is set at about 3KHz that is the minimum upper frequency needed for voice audio.

Audio Power Amplifiers

The final circuit needed to complete a voice grade light pulse receiver is an audio power amplifier. The circuit shown in ***figure 6l on page 55*** uses a single inexpensive LM386 IC. The circuit is designed to drive a pair of audio headphones. The variable resistor shown is used to adjust the audio volume. Since the voice audio system described above does not transmit stereo audio, the left and right headphones are wired in parallel so both ears receive the same audio signal.

Light Receiver Noise Considerations

One of the most difficult problems to overcome in an optical through the air communications system is ambient light. Any stray sunlight or bright background light that is collected by the receiver optics and focused onto the light detector will produce a large steady state DC level through the detector circuit. Although much of the DC is ignored with the use of an inductive feedback amplifier method in the front-end circuit, the large DC component in the light detector will produce some unwanted broadband noise. The noise is very much like the background static you may hear on an AM radio when tuning the dial between stations. As discussed in the section on light detectors, the amount of noise produced by the detector is predictable.

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 6m

The equation shown in ***figure 6m*** 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 an significant reduction in the amount of noise produced at the detector circuit. The 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.

As mentioned above, inserting an optical filter between the lens and the light detector can reduce the effects of ambient light. But, as shown by the noise equation, the amount of light hitting the detector needs to be dramatically reduced to produce a sizable reduction in the induced noise. Since most sunlight contains a sizable amount of infrared light, such filters do not reduce the noise level very much. However, very narrow band filters that can be selected to match the wavelength of a laser diode light source, are effective in reducing ambient light and therefore noise.

Other Receiver Circuits

The circuits described above were designed for a voice audio communications system that received narrow 1uS light pulses. An experimenter may wish to use other modulation frequencies. In addition, untuned broad band receiver circuits are handy when monitoring modulated light signals where the frequency is not known. I have included some additional circuits below that you may find helpful.

A very simple and inexpensive broad band light receiver circuit is shown in ***figure 6n on page 56***. The circuit uses a CD4069UB C-MOS logic integrated circuit. Make sure to use the unbuffered UB version of this popular device. The first section of the circuit performs the current to voltage conversion. The other section provides voltage gain. The overall conversion is about 2 volts per microwatt. With the values shown, the circuit will work with light modulation frequencies between 1KHz and 200KHz.

A similar circuit is shown in ***figure 6o on page 57***. It uses a much faster 74HCU04 device instead of the CD4069UB. The circuit should be operated from a 3v supply. For real flexibility, I have shown how a Motorola MFOD-71 optical fiber photodiode module can be used. The circuit's 2MHz bandwidth is great when monitoring light pulses with fast edges. A section of inexpensive plastic optical fiber can be attached to the detector and used as a light probe to inspect the output from various modulated light sources. Keep in mind, that since both broad band circuits do not use an inductor in the feedback circuit, they should only be operated in low ambient light conditions.

A very sensitive light receiver circuit, designed for detecting the 40KHz signal used by many optical remote control devices, is shown in ***figure 6p on page 58.*** The circuit shown uses a one inch plastic lens in conjunction with a large 10mm X 10mm photodiode. With the values chosen, the circuit will detect light from a typical optical remote from several hundred feet away. If the remote control circuit also used a small lens the separation distance could extend to several miles.

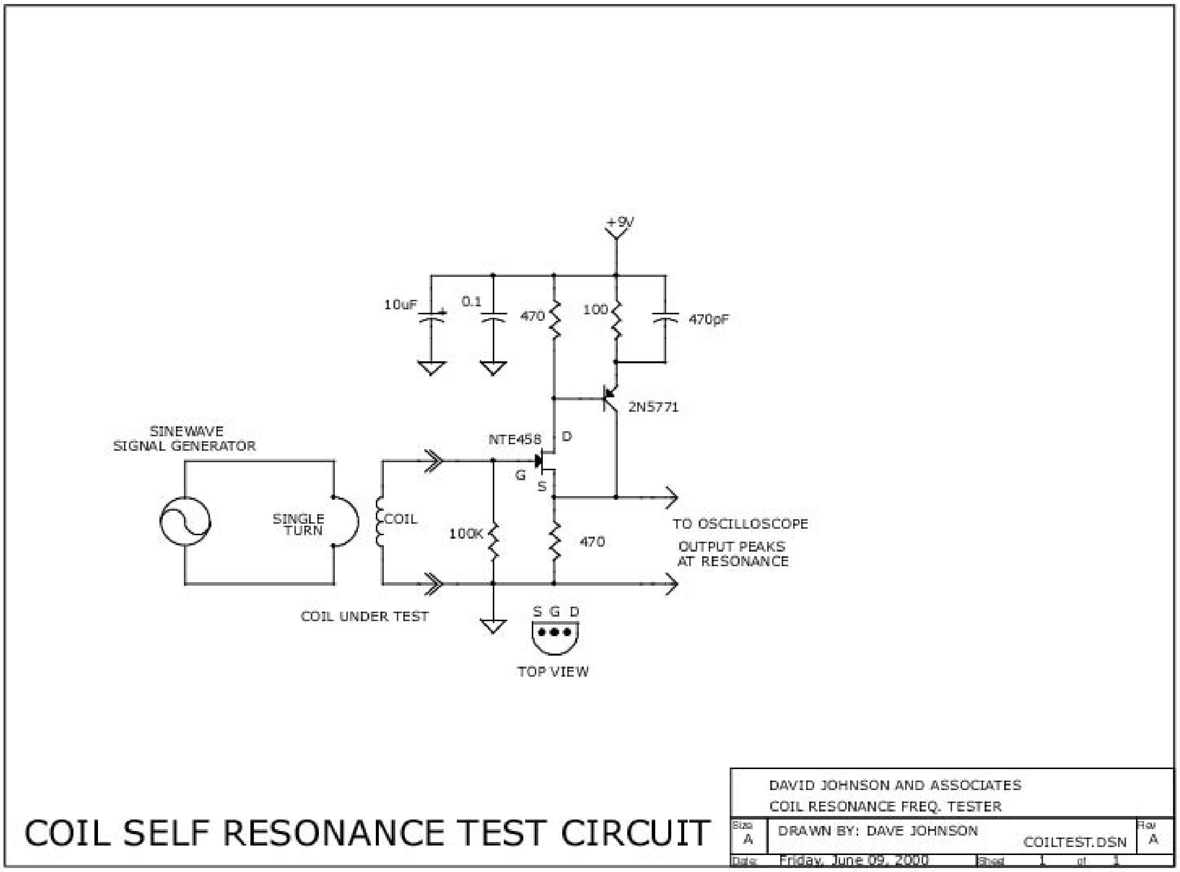

+9V
10uF
0.1
470
100
470pF
2N5771
SINEWAVE
SIGNAL GENERATOR
NTE458
D
G
S
SINGLE
TURN
COIL
100K
470
TO OSCILLOSCOPE
OUTPUT PEAKS
AT RESONANCE
COIL UNDER TEST
S G D
TOP VIEW
DAVID JOHNSON AND ASSOCIATES
COIL RESONANCE FREQ. TESTER
COIL SELF RESONANCE TEST CIRCUIT
Size A
DRAWN BY: DAVE JOHNSON
COILTEST.DSN
Rev A
Date Friday, June 09, 2000
Sheet 1 of 1

Figure 6e

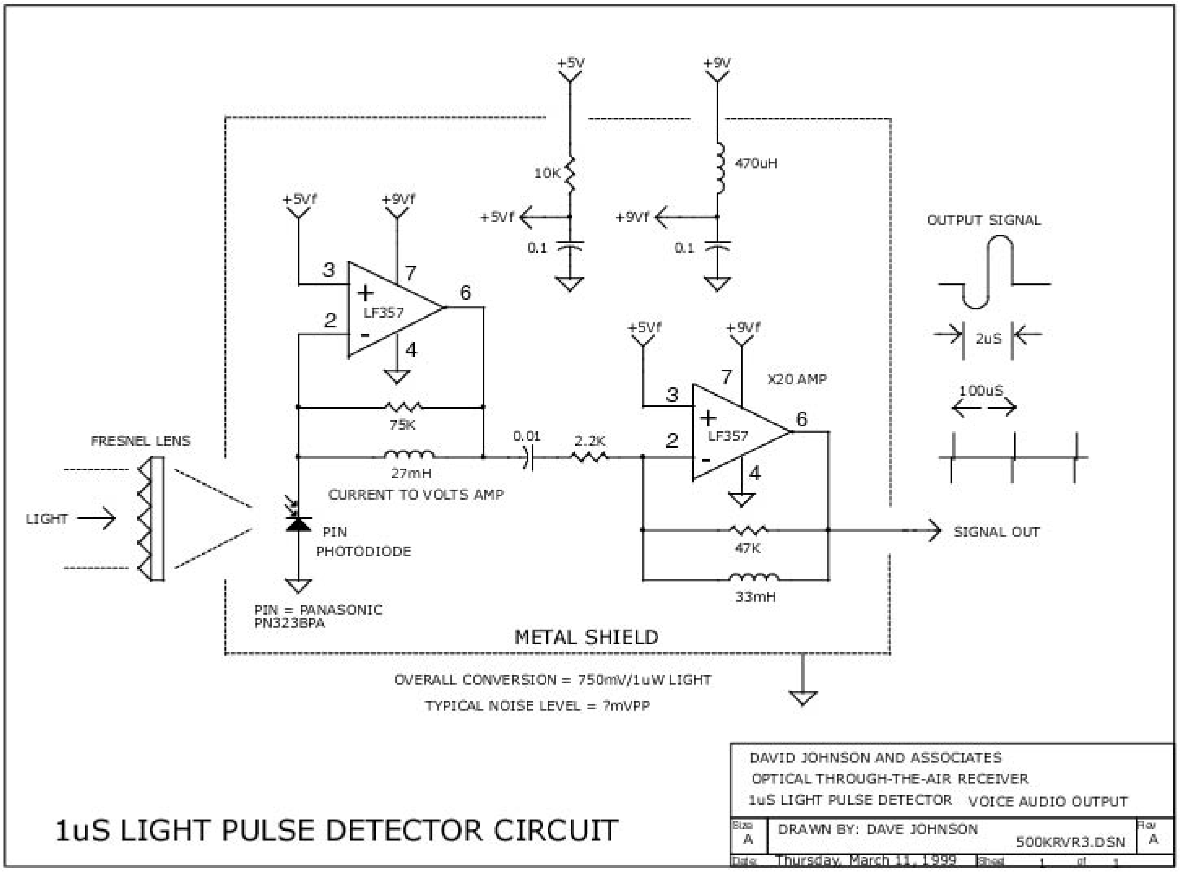

+5V
+9V
10K
470uH
+5Vf
+9Vf
0.1
0.1
OUTPUT SIGNAL
2uS
100uS
LF357
X20 AMP
75K
27mH
CURRENT TO VOLTS AMP
0.01
2.2K
47K
33mH
FRESNEL LENS
LIGHT
PIN
PHOTODIODE
PIN = PANASONIC
PN323BPA
SIGNAL OUT
METAL SHIELD
OVERALL CONVERSION = 750mV/1uW LIGHT
TYPICAL NOISE LEVEL = ?mVPP
DAVID JOHNSON AND ASSOCIATES
OPTICAL THROUGH-THE-AIR RECEIVER
1uS LIGHT PULSE DETECTOR VOICE AUDIO OUTPUT
DRAWN BY: DAVE JOHNSON
500KRVR3.DSN
Thursday, March 11, 1999
1uS LIGHT PULSE DETECTOR CIRCUIT

Figure 6j

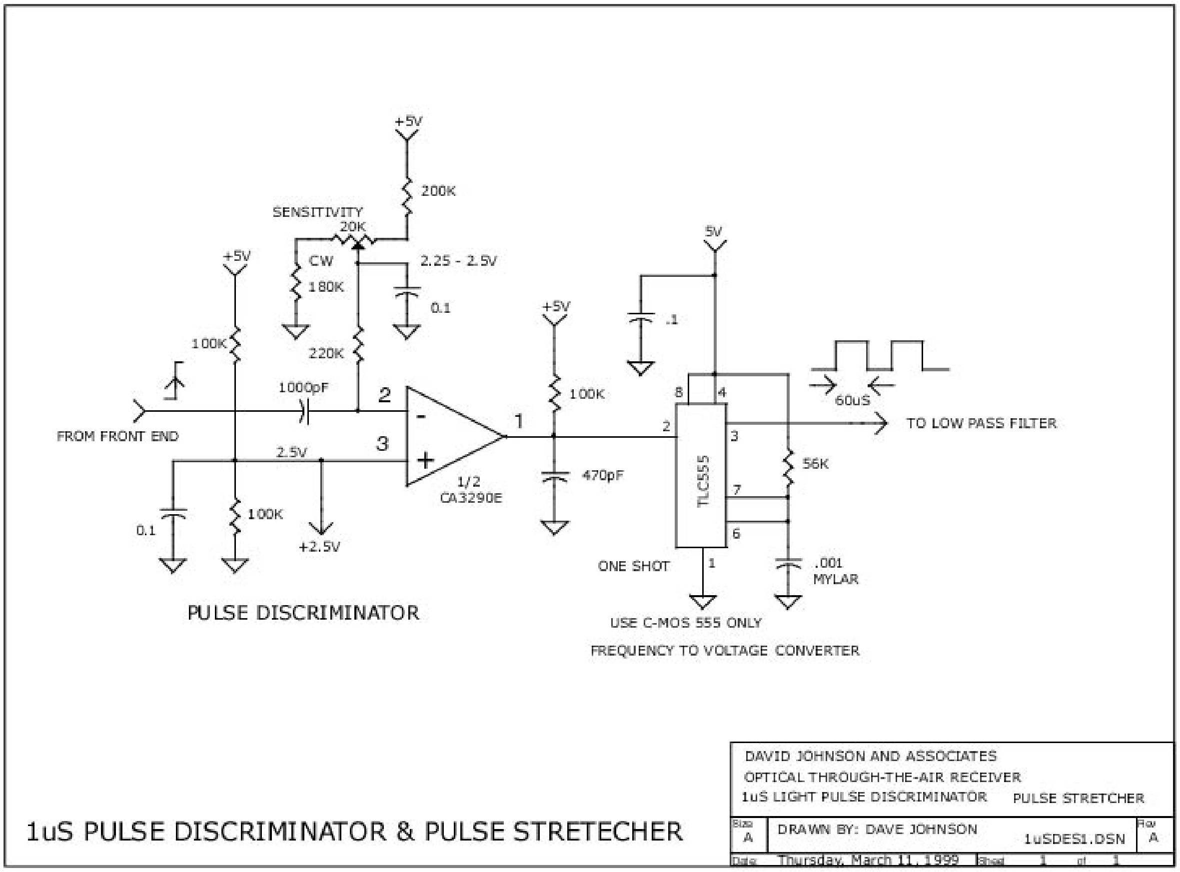

+5V
200K
SENSITIVITY
20K
CW
180K
2.25 - 2.5V
0.1
+5V
100K
220K
1000pF
2
FROM FRONT END
2.5V
3
1/2
CA3290E
1
0.1
100K
+2.5V
PULSE DISCRIMINATOR
+5V
100K
470pF
5V
.1
8
4
2
3
TLC555
7
6
1
56K
.001
MYLAR
ONE SHOT
60uS
TO LOW PASS FILTER
USE C-MOS 555 ONLY
FREQUENCY TO VOLTAGE CONVERTER
DAVID JOHNSON AND ASSOCIATES
OPTICAL THROUGH-THE-AIR RECEIVER
1uS LIGHT PULSE DISCRIMINATOR
PULSE STRETCHER
DRAWN BY: DAVE JOHNSON
1uSDES1.DSN
Thursday, March 11, 1999
1uS PULSE DISCRIMINATOR & PULSE STRETECHER

Figure 6k

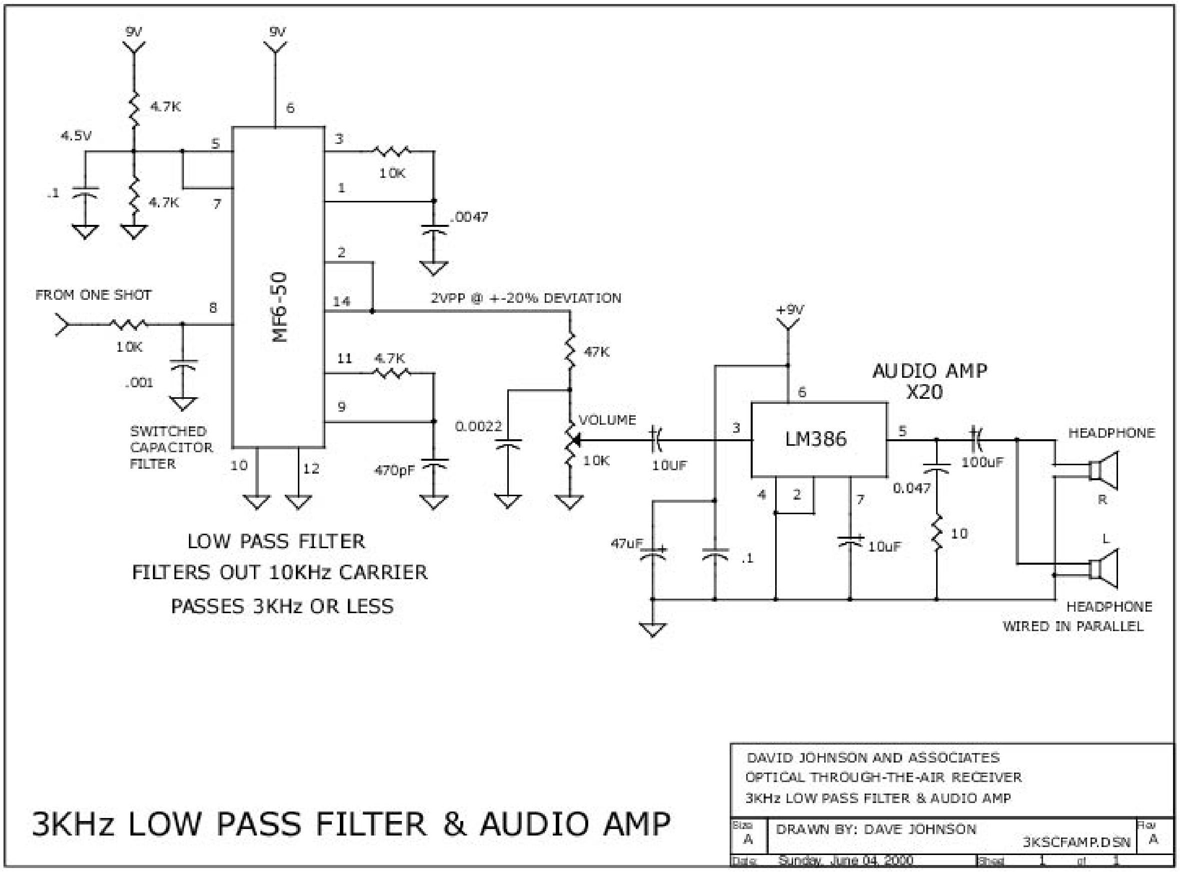

9V
9V
4.7K
4.5V
.1
4.7K
MF6-50
10K
.0047
FROM ONE SHOT
10K
.001
SWITCHED
CAPACITOR
FILTER
2VPP @ +-20% DEVIATION
47K
4.7K
0.0022
VOLUME
10K
470pF
10UF
+9V
AUDIO AMP
X20
LM386
0.047
100uF
HEADPHONE
R
L
47uF
.1
10uF
10
HEADPHONE
WIRED IN PARALLEL
LOW PASS FILTER
FILTERS OUT 10KHz CARRIER
PASSES 3KHz OR LESS
DAVID JOHNSON AND ASSOCIATES
OPTICAL THROUGH-THE-AIR RECEIVER
3KHz LOW PASS FILTER & AUDIO AMP
3KHz LOW PASS FILTER & AUDIO AMP
DRAWN BY: DAVE JOHNSON
3KSCFAMP.DSN
Sunday, June 04, 2000

Figure 6l

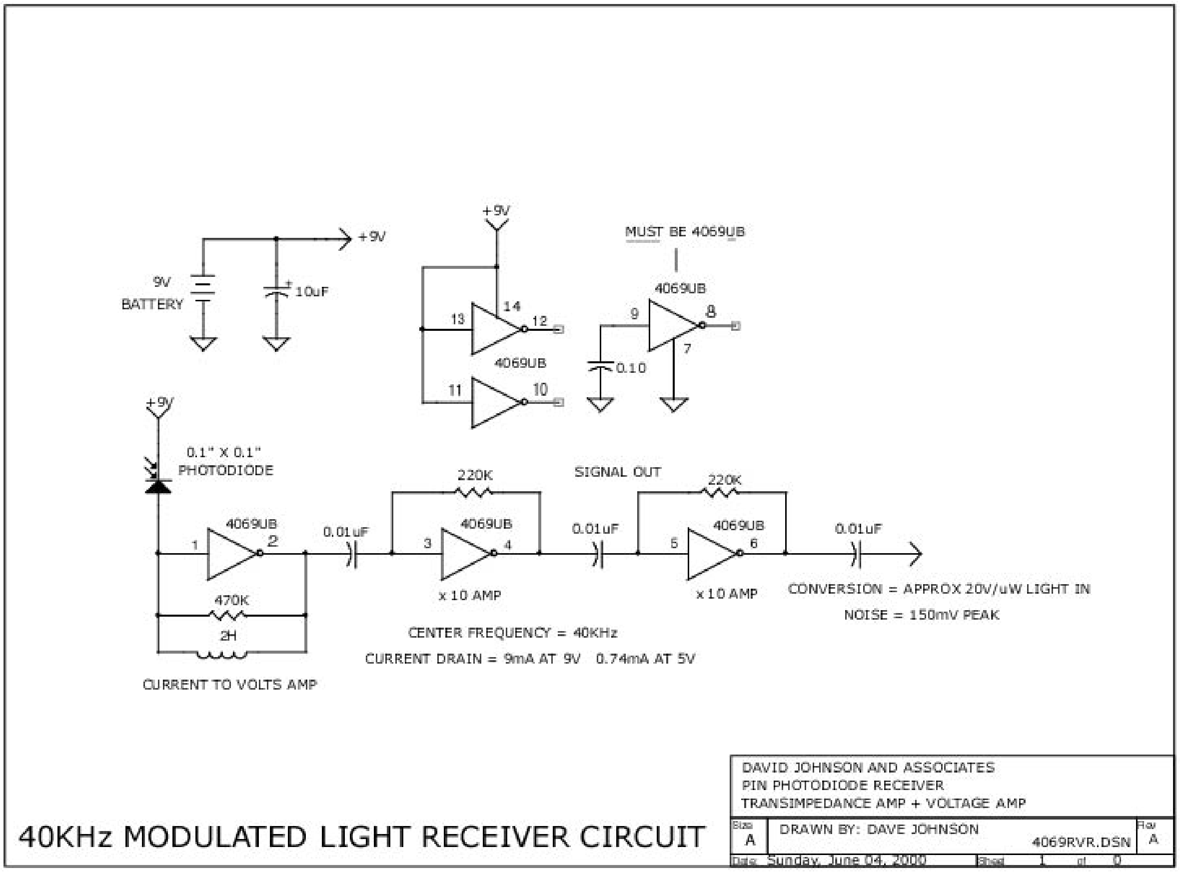

+9V
9V
BATTERY
10uF
+9V
MUST BE 4069UB
4069UB
14
13
12
9
8
7
0.10
4069UB
11
10
+9V
0.1" X 0.1"
PHOTODIODE
220K
SIGNAL OUT
220K
4069UB
1
2
0.01uF
4069UB
3
4
0.01uF
4069UB
5
6
0.01uF
x 10 AMP
x 10 AMP
470K
2H
CONVERSION = APPROX 20V/uW LIGHT IN
NOISE = 150mV PEAK
CENTER FREQUENCY = 40KHz
CURRENT DRAIN = 9mA AT 9V 0.74mA AT 5V
CURRENT TO VOLTS AMP
DAVID JOHNSON AND ASSOCIATES
PIN PHOTODIODE RECEIVER
TRANSIMPEDANCE AMP + VOLTAGE AMP
40KHz MODULATED LIGHT RECEIVER CIRCUIT
A
DRAWN BY: DAVE JOHNSON
4069RVR.DSN
A
Sunday, June 04, 2000

Figure 6n

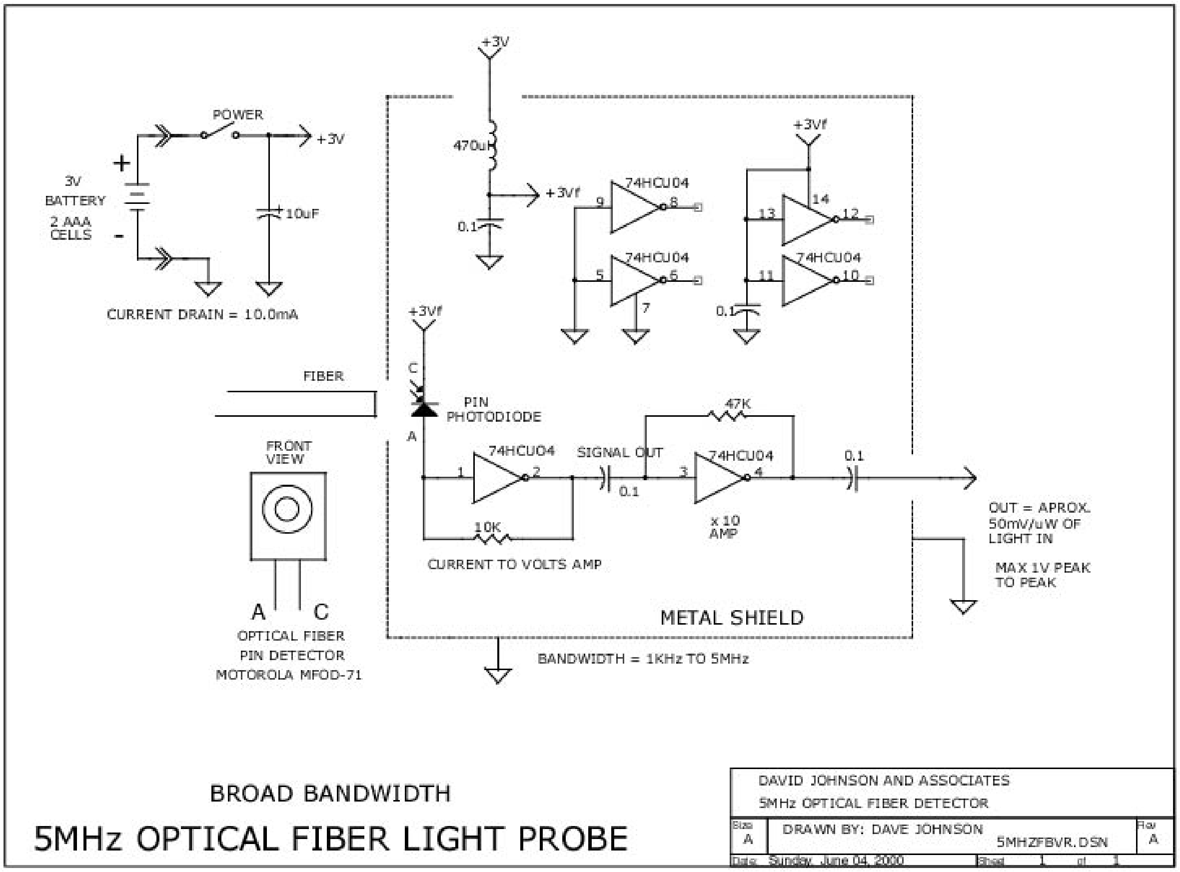

+3V
POWER
+3V
3V BATTERY 2 AAA CELLS
10uF
CURRENT DRAIN = 10.0mA
470uH
+3Vf
0.1
74HCU04
+3Vf
74HCU04
74HCU04
74HCU04
0.1
+3Vf
FIBER
C
PIN PHOTODIODE
A
47K
FRONT VIEW
74HCU04
SIGNAL OUT
74HCU04
0.1
0.1
10K
x 10 AMP
OUT = APROX. 50mV/uW OF LIGHT IN
MAX 1V PEAK TO PEAK
CURRENT TO VOLTS AMP
A
C
METAL SHIELD
OPTICAL FIBER PIN DETECTOR MOTOROLA MFOD-71
BANDWIDTH = 1KHz TO 5MHz
BROAD BANDWIDTH
5MHz OPTICAL FIBER LIGHT PROBE
DAVID JOHNSON AND ASSOCIATES
5MHz OPTICAL FIBER DETECTOR
DRAWN BY: DAVE JOHNSON
5MHZFBVR.DSN
Sunday, June 04, 2000

Figure 6o

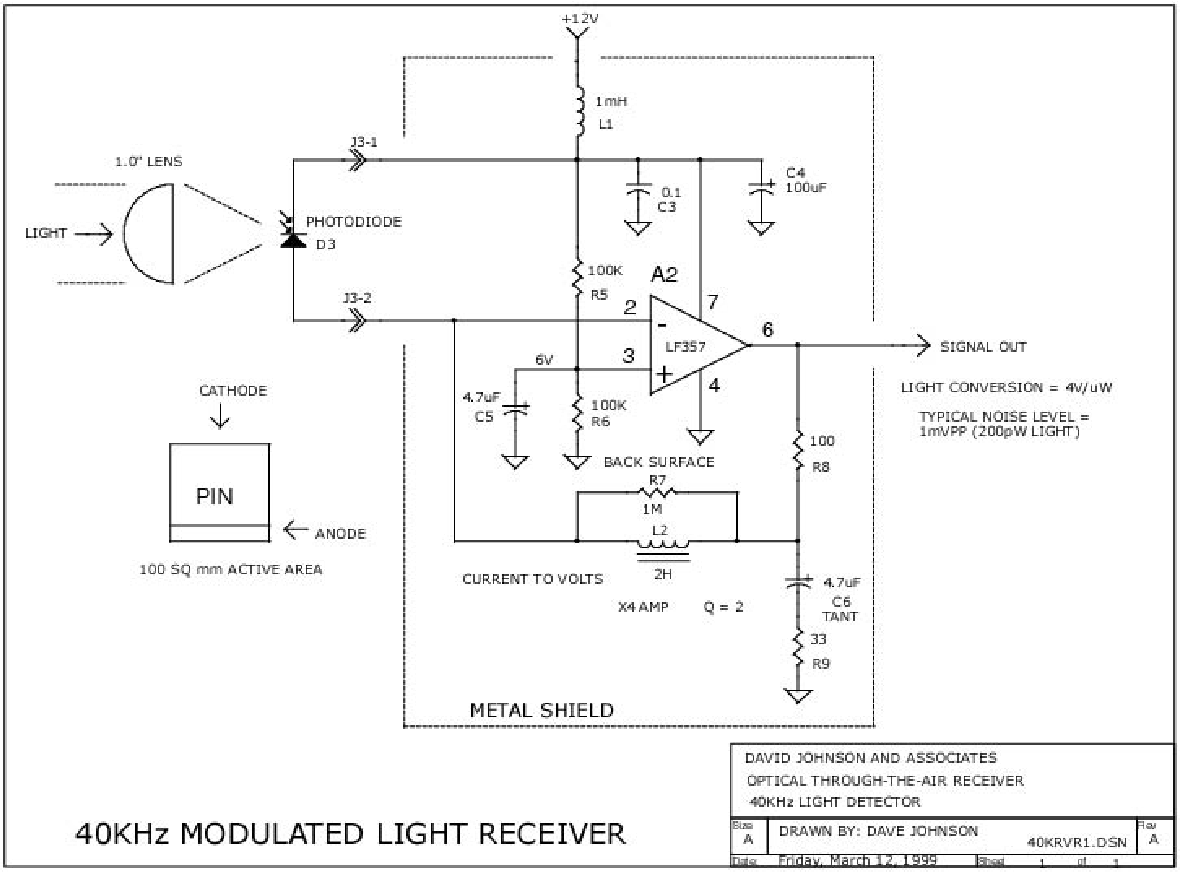

+12V
1mH
L1
J3-1
1.0" LENS
LIGHT
PHOTODIODE
D3
C4
100uF
0.1
C3
100K
R5
A2
2
7
6
J3-2
LF357
3
6V
4
SIGNAL OUT
LIGHT CONVERSION = 4V/uW
TYPICAL NOISE LEVEL =
1mVPP (200pW LIGHT)
CATHODE
4.7uF
C5
100K
R6
100
R8
BACK SURFACE
R7
1M
PIN
L2
ANODE
100 SQ mm ACTIVE AREA
CURRENT TO VOLTS
2H
4.7uF
C6
TANT
X4 AMP
Q = 2
33
R9
METAL SHIELD
DAVID JOHNSON AND ASSOCIATES
OPTICAL THROUGH-THE-AIR RECEIVER
40KHz LIGHT DETECTOR
40KHz MODULATED LIGHT RECEIVER
A
DRAWN BY: DAVE JOHNSON
40KRVR1.DSN
A
Friday, March 12, 1999
1
of
1

Figure 6p

Chapter Seven
OPTICAL TRANSMITTER CIRCUITS

As in radio transmitters, optical through-the-air transmitters must rely on some type of carrier modulation technique to transmit information. The method most often chosen for optical systems is a simple on/off light pulse stream. The position or frequency of the light pulses carries the information. Flashing roadside warning lights and blinking radio tower lights are examples of low speed optical transmitters. To transmit human voice information you will need to increase the light flashing rate to at least 7,000 flashes per second. For television you will need about 10 million flashes per second. Although much of the discussion in this book will focus on voice audio transmitters, you can apply many of the same techniques for video and computer data transmission.

An audio signal optical transmitter can be broken down into 6 sections: an audio amplifier, a voice frequency filter, a voltage to frequency converter, a pulse generator, a light emitter and a light collimator. However, if you are sending only an on/off control signal you won't require an audio amplifier or a voltage to frequency converter. Transmitters used for television or high speed computer data will use variations of the same methods used for voice but would require much higher modulation rates.

Audio Amplifier with Filter

An electret microphone is commonly used to detect the speech sound. These devices are quite small in size but are very sensitive. Unlike passive microphones, an electret microphone contains an internal FET transistor buffer amplifier and therefore requires an external DC voltage source to supply some power to the assembly. Another benefit of the electret microphone is that it produces an output signal that has sufficient drive to go straight into an audio amplifier without any impedance matching circuitry as some other microphones require.

Since the development of the telephone, extensive testing has concluded that frequencies beyond 3.5KHz are not needed for voice audio communications. Therefore, most telephone systems reject frequencies higher than 3.5 KHz. An optical system designed for voice audio transmission can therefore get by with a fairly low pulse rate. Usually a 10,000 pulse per second signal will be sufficient.

Figure 7a on page 65 shows a simple operational amplifier circuit that not only amplifies (gain of x30) the speech signal from an electret microphone but also removes the high frequency components not needed when transmitting voice information. The "low pass" filter rejects signals above 3.5KHz with a 18db/octave slope. A low pass filter is recommended to prevent erratic operation from audio frequencies higher than the modulation frequency.

Voltage to Frequency Converter

Although many kinds of pulse modulation schemes are possible, the most efficient method for transmitting voice audio is pulse frequency modulation. The frequency modulated pulse stream carries the voice information. The voice audio, whose upper frequency is restricted to less than

3.5KHz, is connected to a voltage to frequency converter. The converter is essentially an oscillator whose frequency is shifted up and down according to the amplitude and frequency of the audio signal. A shift of +-20% is usually sufficient for voice signals. As discussed above, a voice audio optical transmitter only requires a pulse rate of about 10,000 pulses per second. The most important requirement of the conversion is that it must be linear in order to reproduce the audio accurately. Circuits using a non-linear VCO or voltage to controlled oscillator will always lead to an abnormal sounding voice signal when the signal is later detected by an optical receiver.

Figure 7b on page 66 is an example of a linear VCO whose center frequency can be adjusted from about 8Khz to about 12KHz. It is made from two separate circuits. An operational amplifier and a transistor form a current source which charges a 0.,001uF capacitor at a very linear rate. The upward ramping voltage across the capacitor is connected to a C-MOS version of the popular 555 timer whose internal voltage thresholds control the amplitude of the saw tooth waveform that results. The capacitor is thus charged by the current source producing a linear ramp waveform and is quickly discharged though the timer, producing a pulse. With the values shown, the 555 produces an output pulse width that can be adjusted from about 800 nanoseconds to about 1.2 microseconds. As the audio signal that is AC coupled to the current source, swings up and down, the capacitor charging current is increased and decreased from a nominal level. The modulated current source thus produces a frequency modulation of the output pulse stream from the 555 timer. With the values shown, the circuit only requires an audio amplitude of about +-0.1 volts to produce a +-20% frequency shift.

Other linear VCO circuits are also possible using the C-MOS phase locked loop IC (CD4046), the LM766 or the National Semiconductor LM331. Sometime in the future I will include some VCO circuits using these parts.

Pulsed Light Emitter

Whether the through-the-air light transmitter is used to send high-speed computer data or a simple on/off control message, the light source must be intensity modulated in some unique fashion so the matching light receiver can distinguish the transmitted light signal from the ever present ambient light. As discussed in the section on light detectors, silicon PIN light detectors convert light power into current. Therefore, to aid the distant light receiver in detecting the transmitted signal, the light source should be pulsed at the highest possible power level. In addition, as discussed in the section on light emitters, an LED can be very effectively used to transmit voice information. To produce the highest possible light pulse intensity without burning up the LED, a low duty cycle drive must be employed. This can be accomplished by driving the LED with high peak currents with the shortest possible pulse widths and with the lowest practical pulse repetition rate. For standard voice systems, the transmitter circuit can be pulsed at the rate of about 10,000 pulses per second as long as the LED pulse width is less than about 1 microsecond. Such a driving scheme yields a duty cycle (pulse width vs. time between pulses) of less than 1%. However, if the optical transmitter is to be used to deliver only an on/off control signal, then a much lower pulse rate frequency can be used. If a pulse repetition rate of only 50 pps were used, it would be possible to transmit the control message with duty cycle of only 0.005%. Thus, with a 0.005% duty cycle, even if the LED is pulsed to 7 amps the average current would only be about 300ua. Even lower average current levels are possible with simple on/off control transmitters, if short multi-pulse bursts are used. Such a method might find uses in garage door openers, lighting controls or telemetry transmitters.

To obtain the maximum practical efficiency, the LED should be driven with low loss transistors. Power field effect transistors (FET) are ideal. These devices can efficiently switch the required high current pulses as long as their gates are driven with pulses with amplitudes greater than about 7 volts. ***Figure 7b on page 66*** illustrates a FET driver that is used to power a LED directly without any current limiting resistor. The circuit takes advantage of the rather high voltage drop of the LED at high current levels to self limit the LED current. With the components selected, the LED current will be about 5 amps peak when used with a 9v supply. The inductor capacitor network between the LED and the power supply acts as a filter and helps keep the high current signals from interfering with other parts of the transmitter circuit sharing the 9v supply.

Light Collimator

For long range applications, the light emitted by the LED must be bent into a tight light beam to insure that a detectable amount of light will reach the distant light receiver. For most LED applications a simple plastic or glass lens will do. As discussed in the section on light emitters, the placement of the lens in front of the light source has the effect of reducing the exiting light divergence angle. Selecting the right lens for the application is dependent on the type of LED used. As illustrated in ***figure 7c***, the lens's focal length should be picked so it can capture most of the emitted light. LEDs with wide divergence angles will require lenses with short focal lengths and LEDs with narrow divergence angles can use lenses with long focal lengths. Keep in mind that the LED divergence angle is usually defined at the 1/2 power points. Therefore, to capture most of the emitted light, a wider LED divergence angle specification should be used when making calculations.

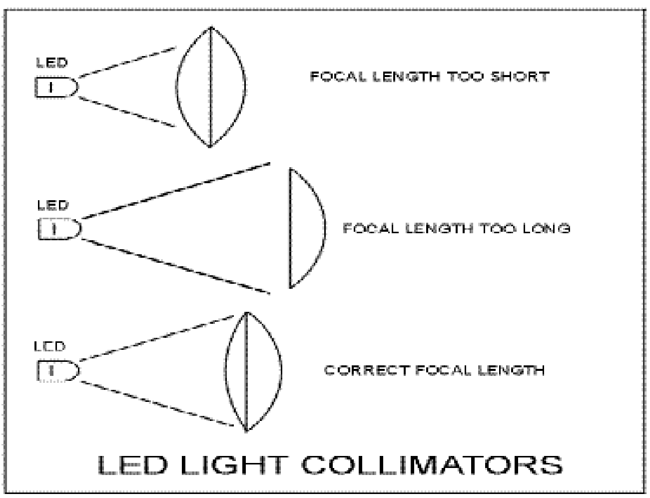


Figure 7c

The divergence angle of light launched using a lens is: (LED div. angle) x (LED dia/ lense dia)

As an example, a 1.9" lens and a 0.187" LED would reduce the naked LED divergence by a factor of 10. A LED with a naked divergence half-angle of 15 degrees would have an overall divergence angle of 1.5 degrees, if a small 1.9" lens were used. A 6" lens would yield a divergence angle of less than 0.5 degrees that is about the practical limit for most long range systems. Divergence angles less than 0.5 degrees will cause alignment problems. Very narrow light beams will be next to impossible to maintain proper alignment. Building sway and atmospheric distortion will result in forcing the light beam to miss the distant target. It is much better to waste some of the light to insure enough hits the receiver to maintain communications.

Multiple Light Sources for Extended Range

For some very long range communications systems, the light from one LED many not be enough to cover the desired distance. As discussed above, a large lens used in conjunction with a single light source may result in a light beam that is too narrow to be practical. The divergence angle may be so small, that keeping the transmitted light aimed at the distant receiver may become impossible. To launch more light at the distant receiver, multiple light sources will be needed. However, as illustrated in ***figure 7d***, a single lens should not be used with multiple light sources. As shown in the illustration, two light sources placed side by in front of a single lens will launch two spots of light, spaced widely apart. Only one of the spots would hit the distant receiver. This mode may be desirable in very rare situations, but for most long range systems, only one spot of light needs to be launched. Adding more light sources in front and a single lens would not increase the amount of light sent to a light receiver.

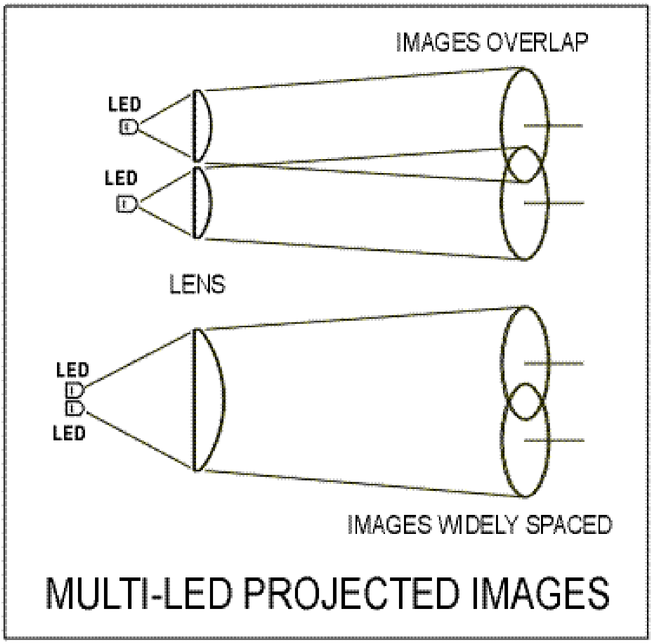


Figure 7d

As illustrated in ***figure 7d,*** a much more efficient method to send more light to a distant receiver is to use multiple LEDs, each with its own lens. The multi-source array will appear as a single light source with an intensity of XP where X is the number of lenses in the array and P is the light power launched by a single LED/lens section. A picture of an actual working unit using such a method is shown in ***figure 7e*** below. The unit uses 20 separate LEDs and 20 Fresnel lenses.

The system demonstrated a range of six miles when transmitting voice audio information. Transmitter systems should consider making some compromises between a large number of smaller LED/lenses that will be easier to aim at a distant transmitter and a system that has fewer lenses but is harder to point at a distant receiver. If power consumption is a concern, the system with fewer LEDs should be used. Consider the examples below.

Figure 7e

Let's consider two transmitter enclosures. Each enclosure has the same surface area on which to install lenses. One system used a single large lens and the second used multiple lenses. Suppose one system uses 4 LEDs with 3.5" lenses (49 sq. inches) that when combined formed a 0.4 watt source with a divergence angle of 1.0 degrees.

Now let's suppose the second system uses a single LED with a 7" lens (also 49 square inches) which yields a combined power level of 0.1 watts but a divergence angle of 0.5 degrees. As seen from the vantage point of a distant light receiver, the two systems would appear to have the same intensity Figure 7e.

One system launches more power but spreads the light over a wider area while the other launches less power but points more of it at the target. The effect is the same. From a power consumption standpoint, the single LED system would be obviously much more efficient. But, the unit with multiple light sources and lenses would be easier to aim at the distant receiver.

Wide Area Light Transmitters

In some applications the challenge is not to send the modulated light to some distant receiver, whose position is fixed, but to send the light in a wide pattern, so either multiple receivers or a receiver whose position changes, can receive the information. Cordless audio headsets, VCR and TV remote controllers and some cordless keyboards all rely on either a direct link or in a indirect diffuse reflective link between the light transmitter and the receiver. The indirect paths would rely on reflections off of walls. Many of the light receiver and transmitter techniques discussed above could be used for wide area communications. However, keep in mind that to cover a wider area the distance between the light transmitter and the receiver would have to be shorter than a narrow beam link. Since the light being transmitted is spread out, less of it would make its way to the receiver. But, it would be possible to use large arrays of light emitting diodes or some other light sources so a large area can be bathed with lots of modulated light. If only short ranges are needed, one light source can be used in conjunction with a light detector as long as the detector had a wide acceptance angle. To achieve the widest acceptance angle, a naked silicon PIN photodiode works fine. Some large 1cm x 1cm detectors work great for receiving the 40KHz signals from optical TV remote control devices. When these large area detectors are used with a quality receiver circuit, as was discussed in the receiver circuit section, a receiver can be designed to be at least a hundred times more sensitive than conventional light receiver circuits often used in VCRs. The increased sensitivity means, when used in a direct link mode, the normal operating distance can be increased by a factor of ten. If your typical VCR remote normally has a 50 foot range, with the receiver changes, the distance could be increased to 500 feet.

Wide Area Information Broadcasting

If you increase the scale of the above methods, some interesting concepts emerge. For many years I attempted to get some communications companies interested in the idea of optical information broadcast stations. The idea was to transmit high speed digital data (up to 1Gigabit per second) from many transmitting towers scattered around a large metropolitan area. Each tower might have an effective radius of 5 miles in all directions. Such a wide area would mean only 4 towers would be needed to cover an area of 400 square miles. Since an optical broadcasting system and a radio broadcasting system could coexist on the same tower, many new towers would not have to be erected. Preexisting radio towers could be used. The light transmitters would also not require any FCC licenses. So far, no federal agency has been assigned the task of regulating optical communications.

The light being transmitted from the towers could originate from arrays of powerful lasers. Optical fiber cables could carry the light from the ground based light emitters to the top of the towers. Since the laser sources would emit light with very narrow wave lengths, the matching light receivers could use equally narrow optical filters to select only certain laser colors or wavelengths. This technique is called wavelength division multiplexing and has been used for many years in communications systems using optical fibers. The technique could be so selective that the number of different light channels that could be transmitted and received could number in the hundreds. Using such an optical approach, the data rate from each optical transmitter could exceed 100 billion bits per second. Such a data rate is far more than possible with communications systems using transmission cables.

The main objection potential investors had for my idea were the communications interruptions from bad weather. It is true that during some heavy snow storms and thick fog conditions the reception of the transmitted light signals could be blocked. But, overall I felt that people subscribing to such a service could tolerate a few interruptions each year. In spite of my arguments, I was not able to find any investors. So, It is hoped that someone reading this might someday consider the idea and make it a commercial success.

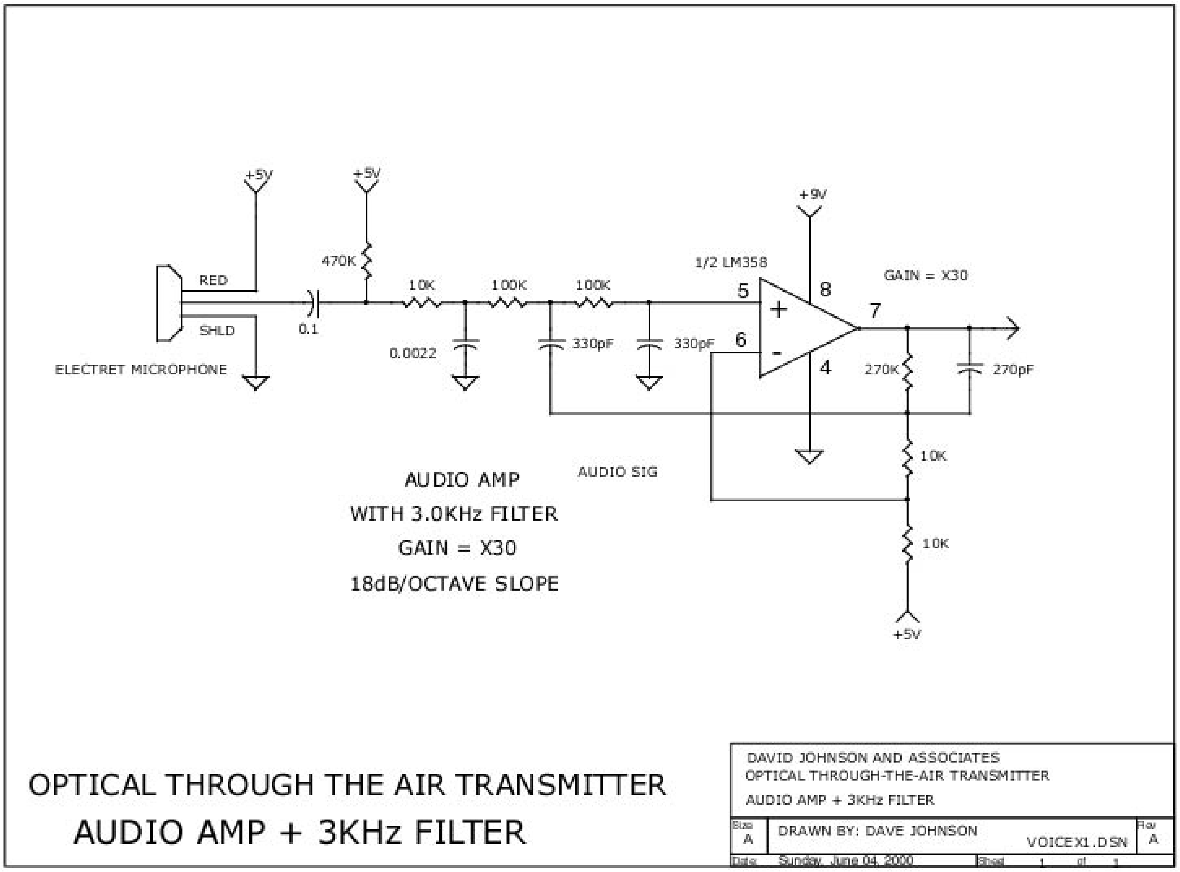
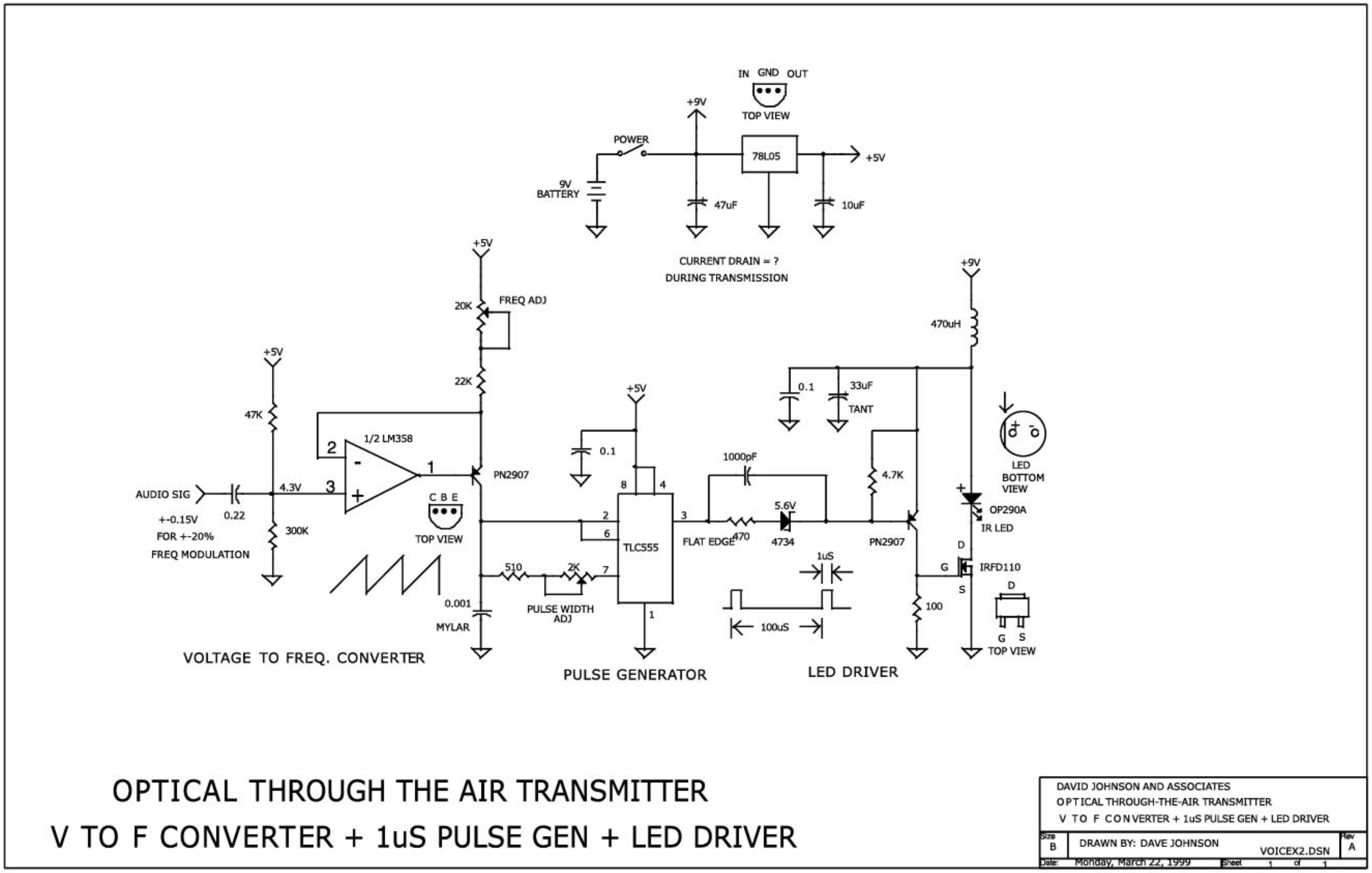

+5V
+5V
+9V
470K
1/2 LM358
RED
10K
100K
100K
5
8
GAIN = X30
7
SHLD
0.1
0.0022
330pF
330pF
6
ELECTRET MICROPHONE
4
270K
270pF
10K
AUDIO AMP
WITH 3.0KHz FILTER
GAIN = X30
18dB/OCTAVE SLOPE
AUDIO SIG
10K
+5V
OPTICAL THROUGH THE AIR TRANSMITTER
AUDIO AMP + 3KHz FILTER
DAVID JOHNSON AND ASSOCIATES
OPTICAL THROUGH-THE-AIR TRANSMITTER
AUDIO AMP + 3KHz FILTER
DRAWN BY: DAVE JOHNSON
VOICEX1.DSN
Sunday, June 04, 2000

Figure 7a

Fig


IN GND OUT
TOP VIEW
+9V
POWER
78L05
+5V
9V BATTERY
47uF
10uF
CURRENT DRAIN = ?
DURING TRANSMISSION
+5V
FREQ ADJ
20K
22K
+5V
47K
1/2 LM358
PN2907
AUDIO SIG
4.3V
+-0.15V
FOR +-20%
FREQ MODULATION
0.22
300K
C B E
TOP VIEW
510
2K
PULSE WIDTH ADJ
0.001
MYLAR
+5V
0.1
TLC555
FLAT EDGE
470
1000pF
5.6V
4734
1uS
100uS
+9V
470uH
0.1
33uF
TANT
4.7K
PN2907
100
LED BOTTOM VIEW
OP290A
IR LED
IRFD110
G
D
S
TOP VIEW
VOLTAGE TO FREQ. CONVERTER
PULSE GENERATOR
LED DRIVER
OPTICAL THROUGH THE AIR TRANSMITTER
V TO F CONVERTER + 1uS PULSE GEN + LED DRIVER
DAVID JOHNSON AND ASSOCIATES
OPTICAL THROUGH-THE-AIR TRANSMITTER
V TO F CONVERTER + 1uS PULSE GEN + LED DRIVER
Size B
DRAWN BY: DAVE JOHNSON
VOICEX2.DSN
Rev A
Date: Monday, March 22, 1999
Sheet 1 of 1