MOTOROLA
Semiconductor Products Inc.

AN-846

Application Note

BASIC CONCEPTS OF FIBER OPTICS AND FIBER OPTIC COMMUNICATIONS

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Introduction

This note presents an introduction to the principles of fiber optics. Its purpose is to review some basic concepts from physics that relate to fiber optics and the application of semiconductor devices to the generation and detection of light transmitted by optical fibers. The discussion begins with a description of a fiber optic link and the inherent advantages of fiber optics over wired systems.

A Fiber Optic Link

Webster gives as one definition of a link "something which binds together or connects." In fiber optics, a link is the assembly of hardware which connects a source of a signal with its ultimate destination. The items which comprise the assembly are shown in Figure 1. As the figure indicates, an input signal, for example, a serial digital bit stream, is used to modulate a light source, typically an LED (light emitting diode). A variety of modulation schemes can be used. These will be discussed later. Although the input signal is assumed to be a digital bit stream, it could just as well be an analog signal, perhaps video.

The modulated light must then be coupled into the optical fiber. This is a critical element of the system. Based on the coupling scheme used, the light coupled into the fiber could be two orders of magnitude less than the total power of the source.

Once the light has been coupled into the fiber, it is attenuated as it travels along the fiber. It is also subject to distortion. The degree of distortion limits the maximum data rate that can be transmitted through the fiber.

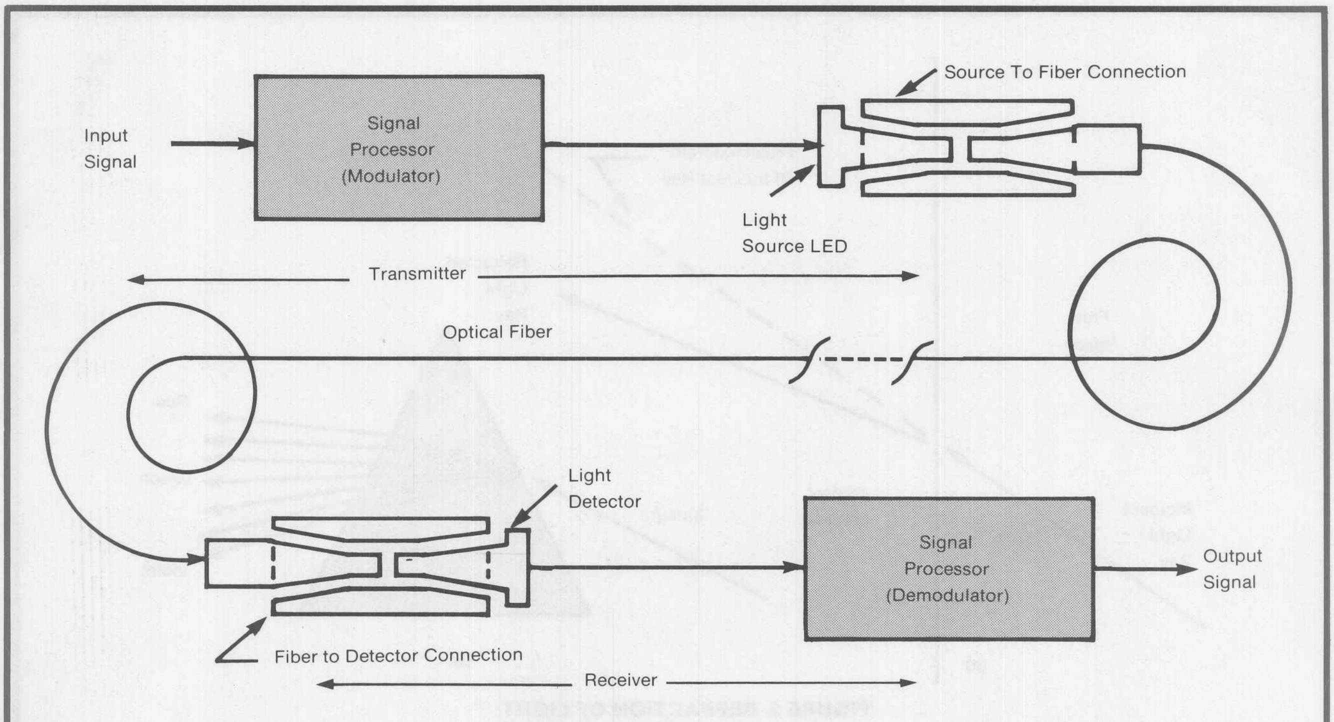


FIGURE 1. A FIBER OPTIC LINK

At the receive end of the fiber, the light is coupled into a detector element (like a photo diode). The coupling problem at this stage, although still of concern, is considerably less severe than at the source end. The detector signal is then reprocessed or decoded to reconstruct the original input signal.

A link like that described in Figure 1 can be fully transparent to the user. That is, everything from the input signal connector to the output signal connector can be prepackaged. Thus, the user need only be concerned with supplying a signal of some standard format and level (like NRZ T^2L) and extracting a similar signal. Such a T^2L in/T^2L out system obviates the need for a designer to understand fiber optics. However, by analyzing the problems and concepts internal to the link, the user is better prepared to apply fiber optics technology to his sytem.

Advantages of Fiber Optics

There are both performance and cost advantages to be realized by using fiber optics over wire.

Greater Bandwidth. The higher the carrier frequency in a communication system, the greater its potential signal bandwidth. Since fiber optics work with carrier frequencies on the order of 10^{13}–10^{14} Hz as compared to radio frequencies of 10^6–10^8 Hz, signal bandwidths are theoretically 10^6 times greater.

Smaller size and weight. A single fiber is capable of replacing a very large bundle of individual copper wire. For example, a typical telephone cable may contain over 1,000 pairs of copper wire and have a cross-sectional diameter of seven to ten centimeters. A single glass fiber cable capable of handling the same amount of signal might be only one-half centimeter in diameter. The actual fiber may be as small as 50 μ-meters. The additional size is the jacket and strength elements. The weight reduction in this example should be obvious.

Lower attenuation. Length for length, optical fiber exhibits less attenuation than does twisted wire or coaxial cable. Also, the attenuation of optical fibers, unlike that of wire, is not signal frequency dependent.

Freedom from EMI. Unlike wire, glass does not pick up nor generate electro-magnetic interference (EMI). Optical fibers do not require expensive shielding techniques to desensitize them to stray fields.

Ruggedness. Glass is 20 times stronger than steel and since glass is relatively inert, corrosive environments are of less concern than with wired systems.

Safety. In many wired systems, the potential hazard of short circuits between wires or from wires to ground, requires special precautionary designs. The dielectric nature of optic fibers eliminates this requirement and the concern for hazardous sparks occurring during interconnects.

Lower Cost. Optical fiber costs are continuing to decline while the cost of wire is increasing. In many applications today, the total system cost for a fiber optic design is lower than for a comparable wired design. As time passes, more and more systems will be decidedly less expensive with optical fibers.

Physics of Light

The performance of optical fibers can be fully analyzed by application of Maxwell's Equations for electromagnetic fields. However, these are necessarily complex and, fortunately, can be bypassed for most users by the application of geometric ray tracing and analysis. When considering LEDs and photo detectors, the particle theory of light is used. The change from ray to particle theory is fortunately a simple step.

Over the years, it has been demonstrated that light (in fact, all electromagnetic energy) travels at approximately 300,000 km/second in free space. It has also been demonstrated that in materials denser than free space, the speed of light is reduced. This reduction in the speed of light as it passes from free space into a denser material results in refraction of the light. Simply

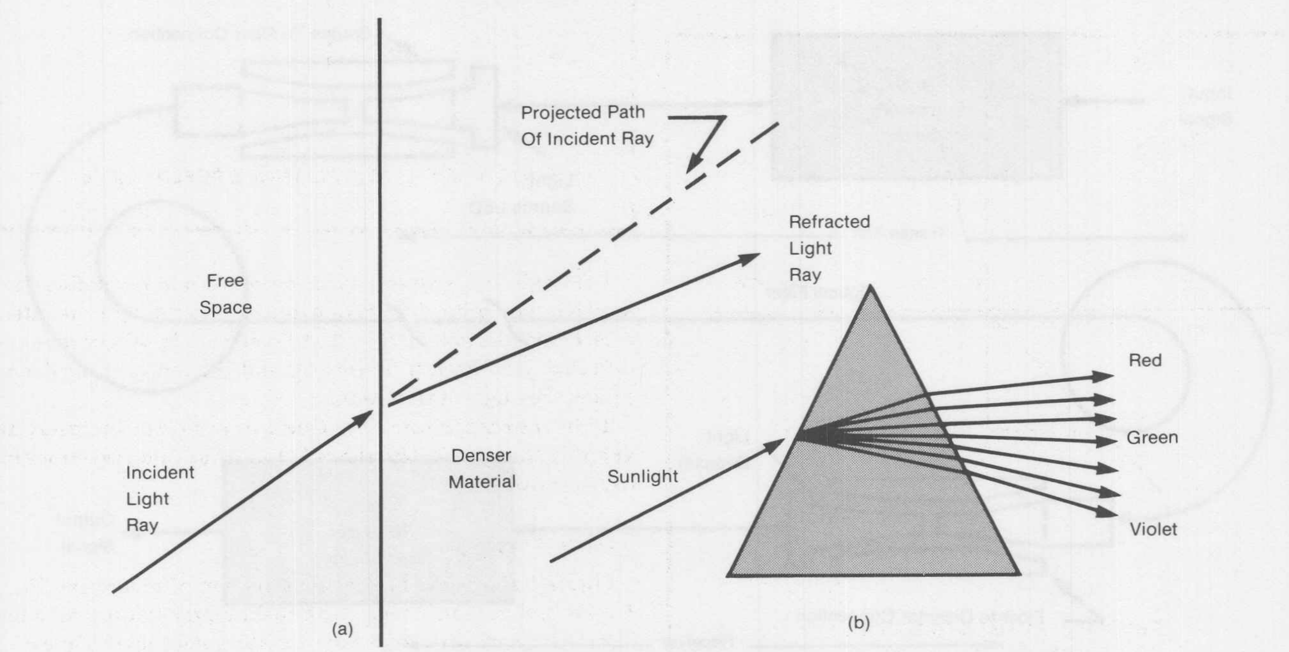


FIGURE 2. REFRACTION OF LIGHT:
a. Light refraction at an interface; b. White light spectral separation by prismatic refraction.

stated, the light ray is bent at the interface. This is shown in Figure 2a. In fact, the reduction of the speed of light is different for different wavelengths; and, therefore, the degree of bending is different for each wavelength. It is this variation in effect for different wavelengths that results in rainbows. Water droplets in the air act like small prisms (Figure 2b) to split white sunlight into the visible sprectrum of colors.

The actual bend angle at an interface is predictable and depends on the **refractive index** of the dense material. The **refractive index**, usually given the symbol n, is the ratio of the speed of light in free space to its speed in the denser material:

$$n = \frac{\text{speed of light in free space}}{\text{speed of light in given material}} \tag{1}$$

Although n is also a function of wavelength, the variation in many applications is small enough to be ignored and a single value is given. Some typical values of n are given in Table 1:

Table 1
Representative Indices of Refraction

Vacuum	1.0
Air	1.0003 (1.0)
Water	1.33
Fused Quartz	1.46
Glass	1.5
Diamond	2.0
Silicon	3.4
Gallium-Arsenide	3.6

It is interesting to consider what happens to a light ray as it meets the interface between two transmissive materials. Figure 3 shows two such materials of refractive indices n_1 and n_2. A light ray is shown in material 1 and incident on the interface at point P. Snell's law states that:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{2}$$

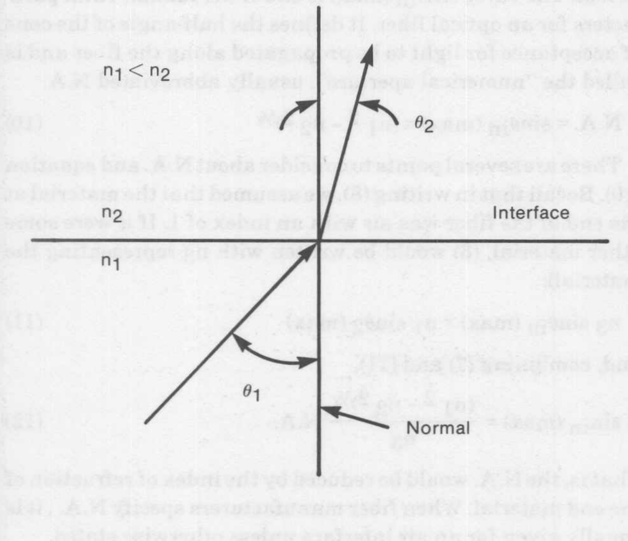


FIGURE 3. REFRACTIVE MODEL FOR SNELL'S LAW

The angle of refraction, θ_2, can be determined:

$$\sin\theta_2 = \frac{n_1}{n_2}\sin\theta_1 \tag{3}$$

If material 1 is air, n_1 has the value of 1; and since n_2 is greater than 1, θ_2 is seen to be less than θ_1; that is, in passing through the interface, the light ray is refracted (bent) toward the normal.

If material 1 is not air but still has an index of refraction less than material 2, the ray will still be bent toward the normal. Note that if n_2 is less than n_1, θ_2 is greater than θ_1, or the ray is refracted away from the normal.

Consider Figure 4 in which an incident ray is shown at an angle such that the refracted ray is along the interface or the angle of refraction is 90°. Note that $n_1 > n_2$. Using Snell's law:

$$\sin\theta_2 = \frac{n_1}{n_2}\sin\theta_1 \tag{4}$$

or, with θ_2 equal to 90°:

$$\sin\theta_1 = \frac{n_2}{n_1} = \sin\theta_c \tag{5}$$

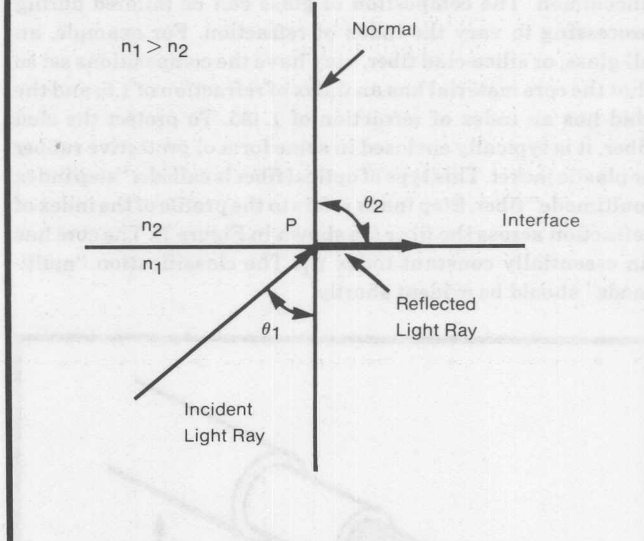


FIGURE 4. CRITICAL ANGLE REFLECTION

The angle, θ_c, is known as the critical angle and defines the angle at which incident rays will not pass through the interface. For angles greater than θ_c, 100 percent of the light rays are reflected (as shown in Figure 5), and the angle of incidence equals the angle of reflection.

This characteristic of reflection for light incident at greater than the critical angle is a fundamental concept in fiber optics.

Optical Fibers

Figure 6 shows the typical construction of an optical fiber. The central portion, or core, is the actual propagating path for light. Although the core is occasionally constructed of plastic, it is more typically made of glass. The choice of material will be discussed later. Bonded to the core is a cladding layer — again,

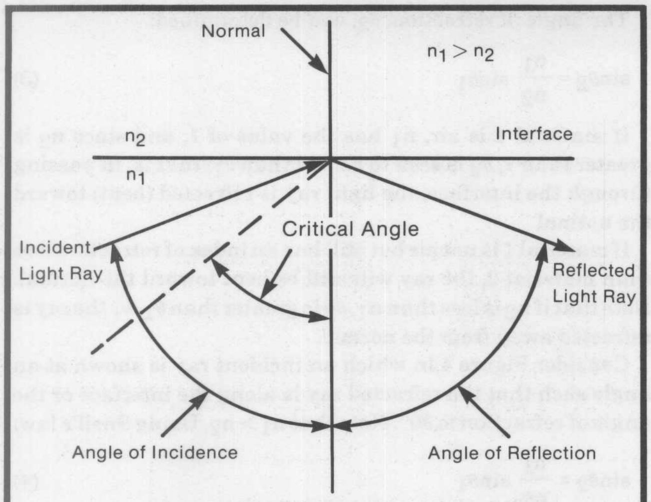


FIGURE 5. LIGHT INCIDENT AT GREATER THAN CRITICAL ANGLE

usually glass, although plastic cladding of glass core is not uncommon. The compositon of glass can be tailored during processing to vary the index of refraction. For example, an all-glass, or silica-clad fiber, may have the compositions set so that the core material has an index of refraction of 1.5; and the clad has an index of refraction of 1.485. To protect the clad fiber, it is typically enclosed in some form of protective rubber or plastic jacket. This type of optical fiber is called a "step index multimode" fiber. Step index refers to the profile of the index of refraction across the fiber (as shown in Figure 7). The core has an essentially constant index n_1. The classification "multimode" should be evident shortly.

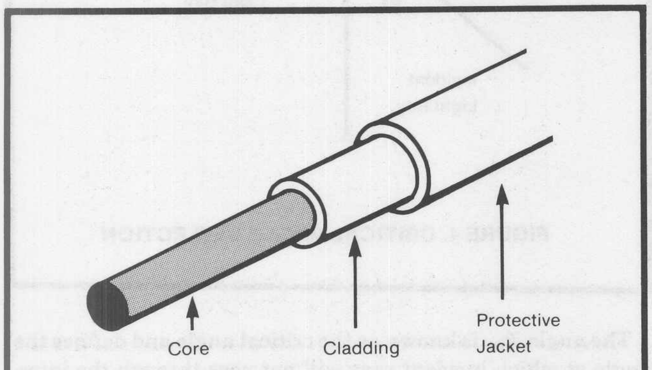


FIGURE 6. SINGLE FIBER CONSTRUCTION

Numerical Aperture

Applying the concept of total internal reflection at the n_1 n_2 interface, we can now demonstrate the propagation of light along the fiber core and the constraint on light incident on the fiber end to ensure propagation. Figure 8 illustrates the analysis. As the figure shows, ray propagation results from the continuous reflection at the core/clad interface such that the ray bounces down the fiber length and ultimately exits at the

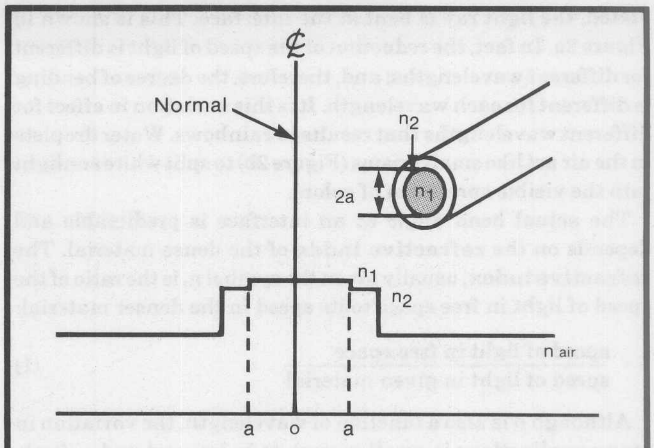


FIGURE 7. INDEX PROFILE FOR A STEP INDEX FIBER

far end. If the principle of total internal reflection is applied at point P, the critical angle value for θ_3 is found by Snell's law:

$$\theta_c = \theta_3\,(\min) = \sin^{-1}\frac{n_2}{n_1} \tag{6}$$

Now, since θ_2 is a complementary angle to θ_3,

$$\theta_2\,(\max) = \sin^{-1}\frac{(n_1{}^2 - n_2{}^2)^{1/2}}{n_1} \tag{7}$$

Again applying Snell's law at the entrance surface (recall $n_{air} = 1$),

$$\sin\theta_{in}\,(\max) = n_1 \sin\theta_2\,(\max) \tag{8}$$

Combining (7) and (8),

$$\sin\theta_{in}\,(\max) = (n_1{}^2 - n_2{}^2)^{1/2} \tag{9}$$

θ_{in} (max) represents the largest angle with the normal to the fiber end for which total internal reflection will occur at the core/clad interface. Light rays entering the fiber end at angles greater than θ_{in} (max) will pass through the interface at P and be lost. The value $\sin\theta_{in}$ (max) is one of the fundamental parameters for an optical fiber. It defines the half-angle of the cone of acceptance for light to be propagated along the fiber and is called the "numerical aperture", usually abbreviated N.A.

$$\text{N.A.} = \sin\theta_{in}\,(\max) = (n_1{}^2 - n_2{}^2)^{1/2} \tag{10}$$

There are several points to consider about N.A. and equation (10). Recall that in writing (8), we assumed that the material at the end of the fiber was air with an index of 1. If it were some other material, (8) would be written with n_3 representing the material):

$$n_3 \sin\theta_{in}\,(\max) = n_1 \sin\theta_2\,(\max) \tag{11}$$

and, combining (7) and (11),

$$\sin_{in}\,(\max) = \frac{(n_1{}^2 - n_2{}^2)^{1/2}}{n_3}\ \text{N.A.} \tag{12}$$

That is, the N.A. would be reduced by the index of refraction of the end material. When fiber manufacturers specify N.A., it is usually given for an air interface unless otherwise stated.

The second point concerns the absoluteness of N.A. The analysis assumed that the light rays entered the fiber, and in propagating along it, they continually passed through the

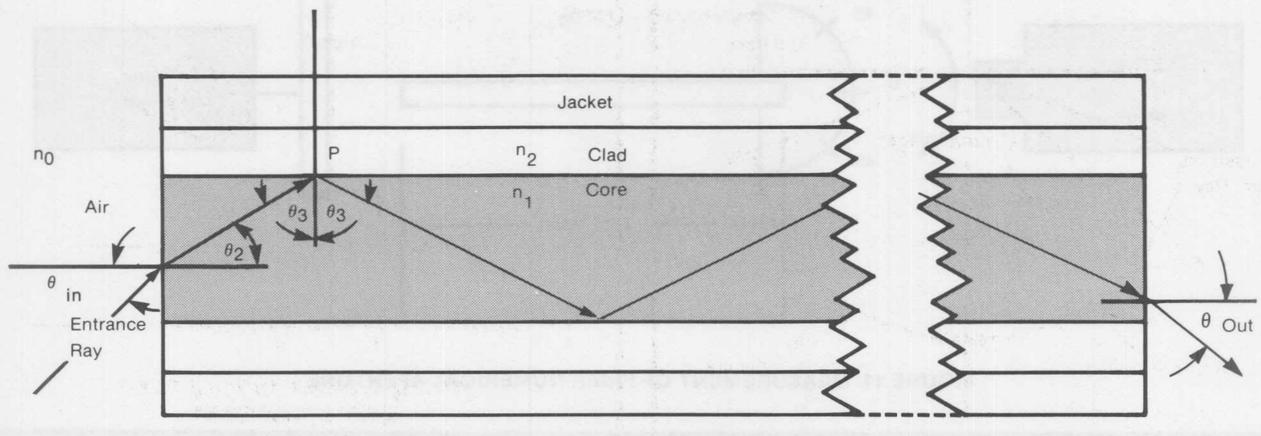


FIGURE 8. RAY PROPAGATION IN A FIBER

central axis of the fiber. Such rays are called "meridional" rays. It is entirely possible that some rays may enter the fiber at such an angle that in passing down the fiber, they never intercept the axis. Such rays are called "skew" rays. An example is shown in both side and end views in Figure 9.

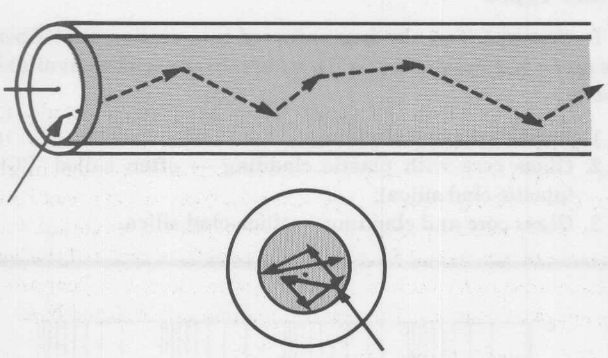


FIGURE 9. SKEW RAY PATH

Also, some rays may enter at angles very close to the critical angle. In bouncing along the fiber, their path length may be considerably longer than rays at shallower angles. Consequently, they are subject to a larger probability of absorption and may, therefore, never be recovered at the output end. However, for very short lengths of fiber, they may not be lost. These two effects, plus the presence of light in the cladding for short lengths, results in the N.A. not cutting off sharply according to equations (10) and (12) and of appearing larger for short lengths. It is advisable to define some criteria for specifying N.A. At Motorola, N.A. is taken as the acceptance angle for which the response is no greater than 10 dB down from the peak value. This is shown in Figure 10. Figure 11 shows a typical method of measuring a fiber's N.A. In the measurement, a sample to be measured (at least 1 meter to allow the attenuation of clad and high order modes[1]) is connected to a high N.A. radiometric sensor, such as a large-area photodiode. The power detected by the sensor is read on a radiometer power meter. The other end

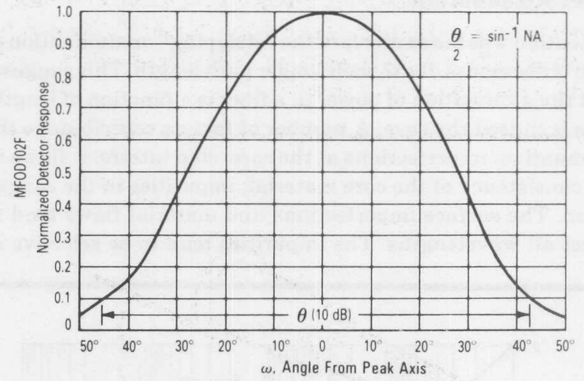


FIGURE 10. GRAPHICAL DEFINITION OF NUMERICAL APERTURE

of the fiber is mounted on a rotatable fixture such that the axis of rotation is the end of the fiber. A collimated light source is directed at the end of the fiber. This can be a laser or other source, such as an LED, at a sufficient distance to allow the rays entering the fiber to be paraxial. The fiber end is adjusted to find the peak response position. Ideally, this will be at zero degrees; but manufacturing variations could result in a peak slightly offset from zero. The received power level is noted at the peak. The fiber end is then rotated until the two points are found at which the received power is one-tenth the peak value. The sine of half the angle between these two points is the N.A.

[1]High order modes refers to steep angle rays.

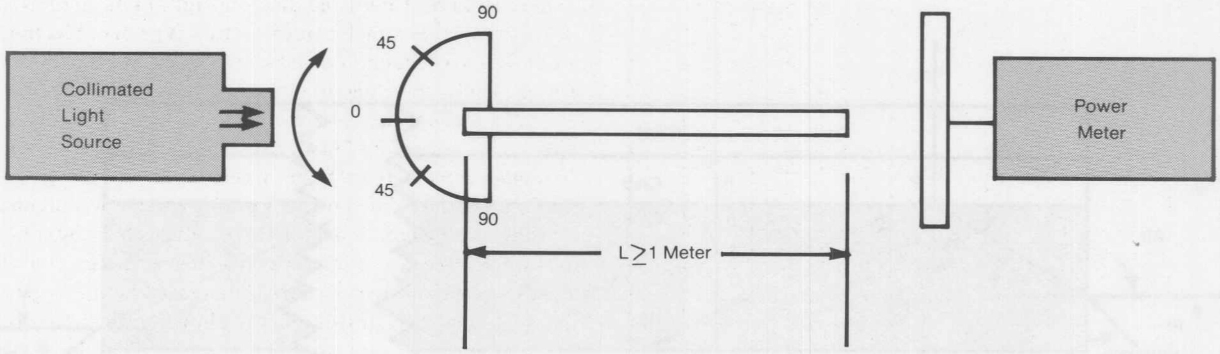


FIGURE 11. MEASUREMENT OF FIBER NUMERICAL APERTURE

The apparent N.A. of a fiber is a function of the N.A. of the source that is driving it. For example, Figures 12a and 12b are plots of N.A. versus length for the same fiber. In (12a) the source has a large N.A. (0.7), while in (12b) the source N.A. is 0.32. Note that in both cases, the N.A. at 100m is about 0.31; but at 1 meter, the apparent N.A. is 0.42 in (12a) but 0.315 in (12b). The high order modes entering the fiber from the 0.7 N.A. source take nearly the full 100 meters to be stripped out by attenuation. Thus, a valid measurement of a fiber's true N.A. requires a collimated, or very low, N.A. source or a very long-length sample.

Fiber Attenuation

Mention was made above of the "stripping" or attenuation of high order modes due to their longer path length. This suggests that the attenuation of power in a fiber is a function of length. This is indeed the case. A number of factors contribute to the attenuation: imperfections at the core/clad interface; flaws in the consistency of the core material; impurities in the composition. The surface imperfections and material flaws tend to affect all wavelengths. The impurities tend to be selective in the wavelength they affect. For example, hydroxl molecules (OH^-) are strong absorbers of light at 900 nm. Therefore, if a fiber manufacturer wants to minimize losses at 900 nm, he will have to take exceptional care in his process to eliminate moisture (the source of OH^-). Other impurities are also present in any manufacturing process. The degree to which they are controlled will determine the attenuation characteristic of a fiber. The cumulative effect of the various impurities results in plots of attentuation versus wavelength exhibiting peaks and valleys. Four examples of attenuation (given in dB/km) are shown in Figure 13.

Fiber Types

It was stated at the beginning of this section that fibers be made of glass or plastic. There are three varieties available today:

1. Plastic core and cladding;
2. Glass core with plastic cladding — often called 'PCS' (plastic-clad silica);
3. Glass core and cladding — silica-clad silica.

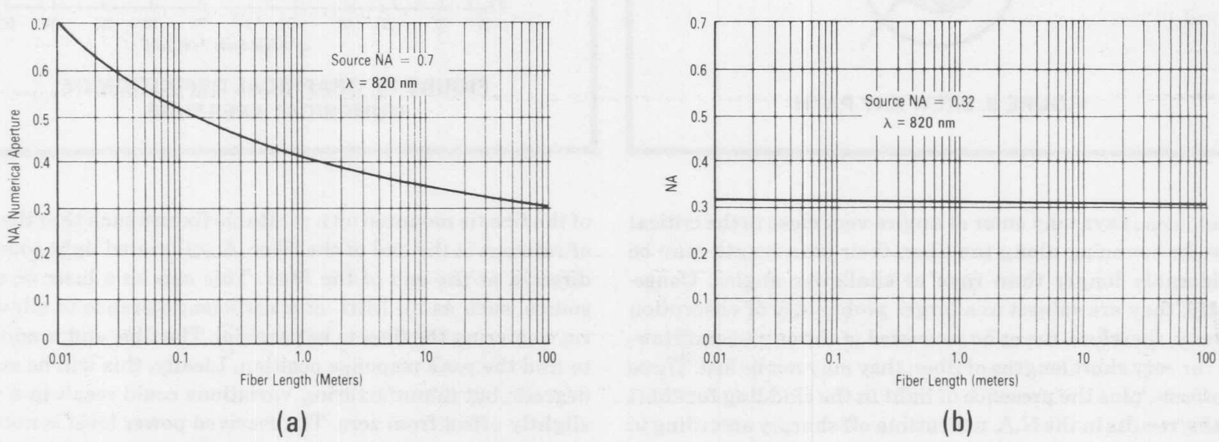


FIGURE 12. FIBER NUMERICAL APERTURE versus LENGTH FOR TWO VALVES OF SOURCE N.A.

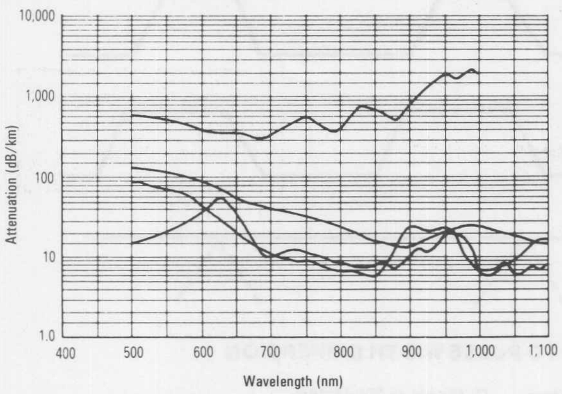


FIGURE 13. FIBER ATTENUATION versus WAVELENGTH

All plastic fibers are extremely rugged and useful for systems where the cable may be subject to rough day-after-day treatment. They are particularly attractive for benchtop interconnects. The disadvantage is their high attenuation characteristic.

PCS cables offer the better attenuation characteristics of glass and are less affected by radiation than all-glass fibers.[2] They see considerable use in military-grade applications.

All glass fibers offer low attenuation performance and good concentricity, even for small-diameter cores. They are generally easy to terminate, relative to PCS. On the down side, they are usually the least rugged, mechanically, and more susceptible to increases in attenuation when exposed to radiation.

The choice of fiber for any given application will be a function of the specific system's requirements and trade-off options.

So far, the discussion has addressed single fibers. Fibers, particularly all-plastic, are frequently grouped in bundles. This is usually restricted to very low-frequency, short-distance applications. The entire bundle would interconnect a single light source and sensor or could be used in a fan-out at either end. Bundles are also available for interconnecting an array of sources with a matched array of detectors. This enables the interconnection of multiple discrete signal channels without the use of multiplex techniques. In this type of cable, the individual fibers are usually separated in individual jackets and, perhaps, each embedded in clusters of strength elements, like Kevlar. In one special case bundle, the fibers are arrayed in a ribbon configuration. This type cable is frequently seen in telephone systems using fiber optics.

In Figure 7, the refractive index profile was shown as constant over the core cross-section with a step reduction at the core/clad interface. The core diameter was also large enough that many modes (low and high order) are propagated along its path. In Figure 14, a section of this fiber is shown with three discrete modes shown propagating down the fiber. The lowest order mode is seen traveling parallel to the axis of the fiber. The middle order mode is seen to bounce several times at the interface. The total path length of this mode is certainly greater than that of the mode along the axis. The high order mode is seen to make many trips across the fiber, resulting in an extremely long path length.

The signal input to this fiber is seen as a step pulse of light. However, since all the light that enters the fiber at a fixed time does not arrive at the end at one time (the higher modes take longer to traverse their longer path), the net effect is to stretch or distort the pulse. This is characteristic of a multimode, step-index fiber and tends to limit the range of frequency for the data being propagated.

Figure 15 shows what this pulse stretching can do. An input pulse train is seen in (15a). At some distance (say 100 meters), the pulses (due to dispersion) are getting close to running together but are still distinquishable and recoverable. However, at some greater distance (say 200 meters), the dispersion has resulted in the pulses running together to the degree that they are indistinquishable. Obviously, this fiber would be unusable at 200 meters for this data rate. Consequently, fiber specifications usually give bandwidth in units of MHz-km — that is, a 200 MHz-km cable can send 200 MHz data up to 1.0 km or 100 MHz data up to 2.0 km etc.

To overcome the distortion due to path length differences, fiber manufacturers have developed graded index fiber. An example of multimode, graded-index fiber is shown in Figure 16.

In the fiber growth process, the profile of the index of refraction is tailored to follow the parabolic profile shown in the

[2]It should be noted that the soft clad material should be removed and replaced by a hard clad material for best fiber core-to connector termination.

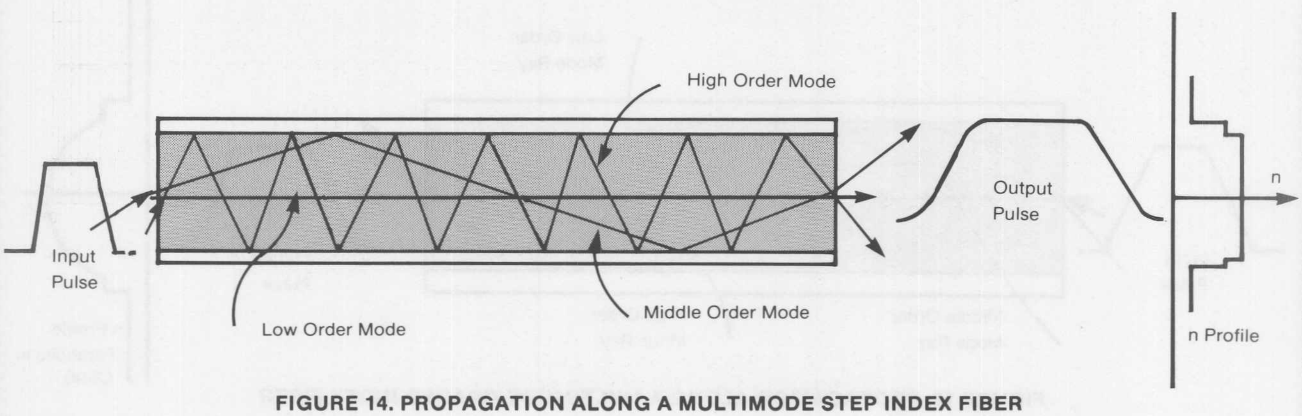


FIGURE 14. PROPAGATION ALONG A MULTIMODE STEP INDEX FIBER

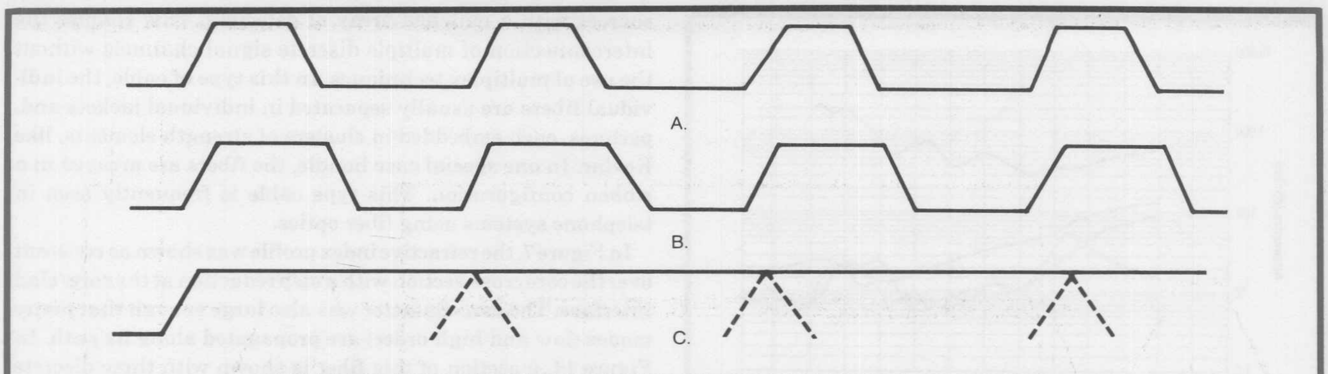


FIGURE 15. LOSS OF PULSE IDENTITY DUE TO PULSE WIDTH DISPERSION

A. Input B. Signal at 100 Meters C. Signal at 200 Meters

figure. This results in low order modes traveling through a constant density material. High order modes see lower density material as they get further away from the axis of the core. Thus, the velocity of propagation increases away from the center. The result is that all modes, although they may travel different distances, tend to cover the length of the fiber in the same amount of time. This yields a fiber with higher bandwidth capability than multimode stepped index.

One more fiber type is also available. This is the single mode, step-index fiber shown in Figure 17. In this fiber, the core is extremely small (on the order of just a few micrometers). This type accepts only the lowest order mode and suffers no modal dispersion. It is an expensive fiber and requires a very high-power, highly-directional source like a laser diode. Consequently, applications for this type of fiber are the very high data rate, long-distance systems.

As a final statement on fiber properties, it is interesting to compare optical fiber with coax cable. Figure 18 shows the loss versus frequency characteristics for a low-loss fiber compared with the characteristics of several common coax cables. Note that the attentuation of optical fiber is independent of frequency (up to the point where modal dispersion comes into play).

Active Components For Fiber Optics

Propagation through fiber optics is in the form of light or, more specifically, electromagnetic radiation in the spectral range of near-infrared or visible light. Since the signal levels to be dealt with are generally electrical in nature (like serial digital logic at standard T^2L levels), it is necessary to convert the source signal into light at the transmitter end and from light back to T^2L at the receive end. There are several components which can accomplish these conversions. This discussion will concentrate on light emitting diodes (LEDs) as souces and PIN photo diodes and Integrated Detector Preamplifiers (IDPs) as sensors.

Light Emitting Diodes

Most people are familiar with LEDs in calculator displays. Just as they are optimized geometrically and visually for the function of displaying characters, some LEDs are specifically designed and processed to satisfy the requirements of generating light, or near infrared for coupling into fibers. There are several criteria of importance for LEDs used with fibers:

1. Output power;
2. Wavelength;
3. Speed;
4. Emission pattern.

Output power. Manufacturers are continually striving to increase the output power or efficiency of LEDs. The more efficient an LED, the lower its drive requirements, or the greater

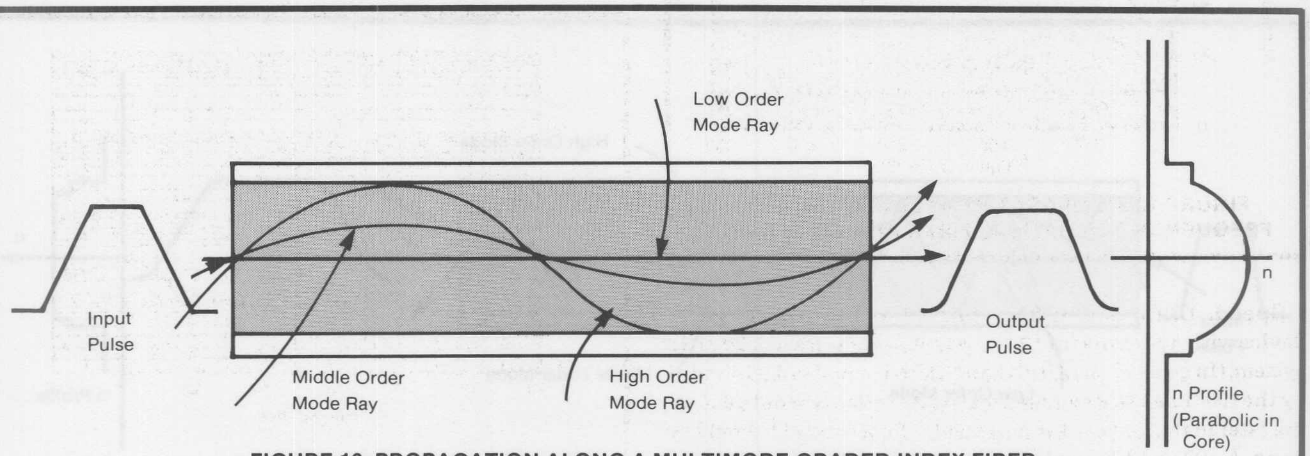


FIGURE 16. PROPAGATION ALONG A MULTIMODE GRADED INDEX FIBER

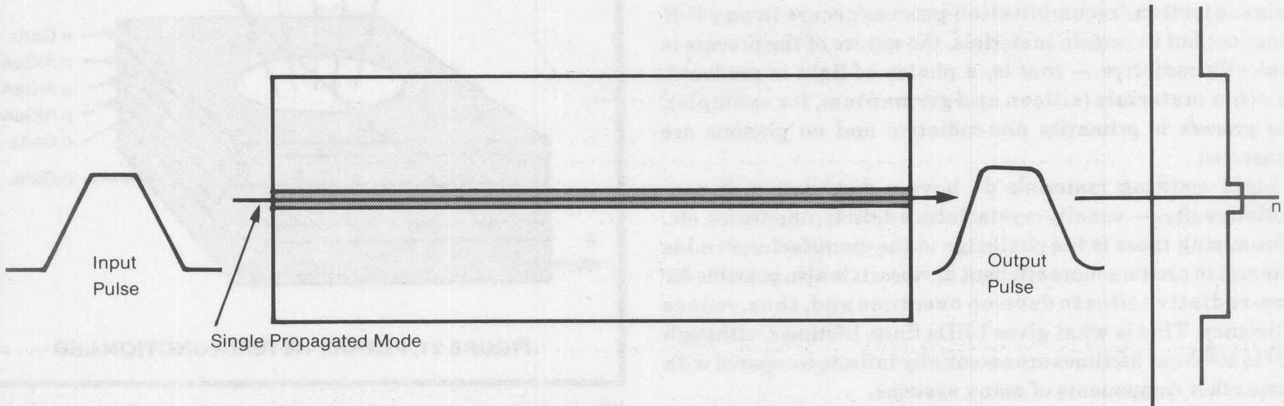


FIGURE 17. PROPAGATION ALONG A SINGLE MODE STEP INDEX FIBER

the losses that can be accomodated elsewhere in the system. However, total power emitted by an LED is not the whole picture (see **Emission Pattern**).

Wavelength. As shown earlier, optical fibers exhibit an attenuation characteristic that varies with wavelength. Figure 19 is a repeat of one of the sample curves from Figure 13. If this fiber were to be used in a system, the desired wavelength of operation would be about 875 nm where the attenuation is down to about 7.0 dB/km. The most undesirable wavelength for use in this fiber's range is 630 nm where the loss is about 600 dB/km. Therefore, all other considerations being satisfied, an LED with a characteristic emission wavelength of 875 nm would be used.

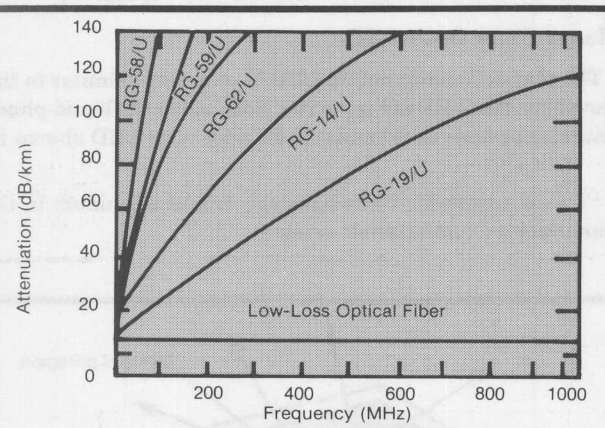


FIGURE 18. COMPARATIVE ATTENUATION versus FREQUENCY FOR OPTICAL FIBER AND COAX CABLE

Speed. LEDs exhibit finite turn-on and turn-off times. A device with a response of 100 ns would never work in a 20 MHz system. (In general, the 3.0 dB bandwidth is equal to 0.35 divided by the risetime.) In a symmetrical RTZ system (see data encoding later in this paper), the pulse width for a single bit would be 25 ns. A 100 ns LED would hardly have begun to turn on when it would be required to turn off. There is often a trade-off between speed and power, so it would not be advisable to select the fastest diode available but rather the fastest required to do the job, with some margin designed in.

Emission Pattern. In typical data communications systems the light from the LED is coupled into a fiber with a core diameter of 100 to 200 μm. If the emission pattern of a particular LED is a collimated beam of 100 μm or less diameter, it might be possible to couple nearly all the power into the fiber. Thus, a 100 μW LED with such an emission pattern might be a better choice than a 5.0 mW LED with a lambertian[3] pattern.

Light Generation

Light is emitted from an LED as a result of the recombining of electrons and holes. Electrically, an LED is just a P-N junction. Under forward bias, minority carriers are injected across

[3]Lambertian: The spatial pattern of reflected light from a sheet of paper, e.g. The intensity of light in any direction from a plane lambertian surface is equal to the intensity in the direction of the normal to the surface times the cosine of the angle between the direction and the normal.

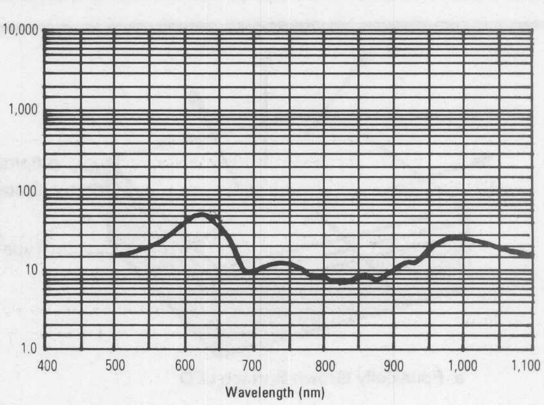


FIGURE 19. ATTENUATION versus WAVELENGTH FOR A SAMPLE FIBER

the junction. Once across, they recombine with majority carriers and give up their energy in the process. The energy given up is approximately equal to the energy gap for the material. The same injection/recombination process occurs in any P-N junction; but in certain materials, the nature of the process is typically radiative — that is, a photon of light is produced. In other materials (silicon and germanium, for example), the process is primarily non-radiative and no photons are generated.

Light emitting materials do have a distribution of non-radiative sites — usually crystal lattice defects, impurities, etc. Minimizing these is the challenge to the manufacturer in his attempt to produce more efficient devices. It is also possible for non-radiative sites to develop over time and, thus, reduce efficiency. This is what gives LEDs finite lifetimes, although 10^5 to 10^6-hour lifetimes are essentially infinite compared with some other components of many systems.

The simplest LED structures are homojunction, epitaxially-grown devices and single-diffused devices. These structures are shown in Figure 20.

The epitaxially-grown LED is generally constructed of silicon-doped gallium-arsenide. A melt of elemental gallium containing arsenic and silicon dopant is brought in contact at high temperature with the surface of an n-type gallium-arsenide wafer. At the initial growth temperature, the silicon atoms in the dopant replace some of the gallium atoms in the crystal lattice. In so doing, they contribute an excess electron to the bond. This results in the grown layer being n-type. During the growth, the temperature is systematically reduced. At a certain critical temperature, the silicon atoms begin to replace some of the arsenic atoms in the crystal. This removes an electron from the bond, resulting in the formation of a p-type layer. As a finished diode, the entire surface, as well as the four sides, radiate light. The characteristic wavelength of this type of device is 940 nm, and it typically radiates a total power of 3.0 mW at 100 mA forward current. It is relatively slow with turn-on and turn-off times on the order of 150 ns. The non-directionality of its emission makes it a poor choice as a light source for use with optical fibers.

The planar diffused LED is formed by controlled diffusions of zinc into a tellurium-doped n-gallium-arsenide wafer. A finished diode has a typical power output of 500 μW at a wavelength of 900 nm. Turn-on and turn-off times are usually around 15–20 ns.

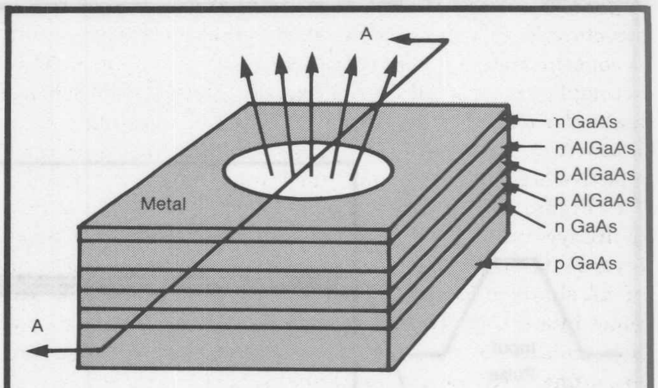


FIGURE 21. PLANAR HETEROJUNCTION LED

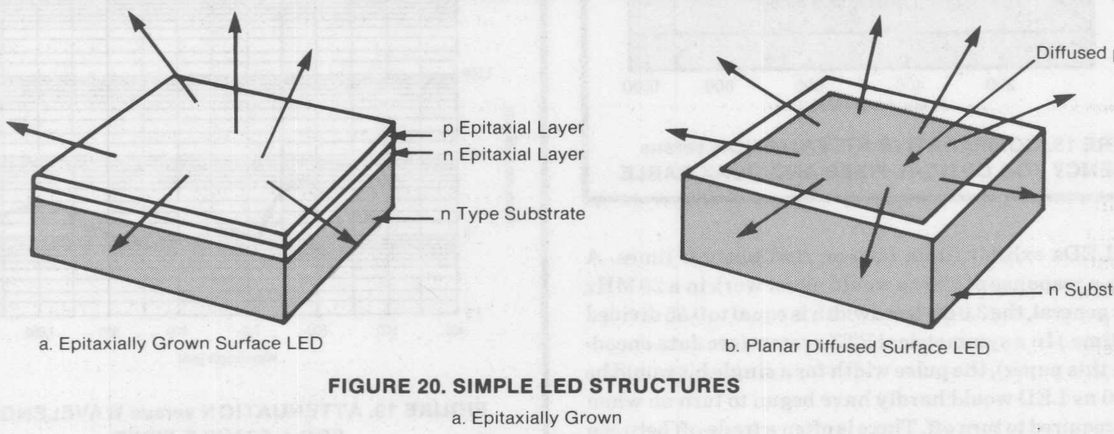
The emission pattern is lambertian, similar to the grown junction LED above.

Both of the above structures, although they can be used in fiber optics, are not optimized for the purpose of coupling into small fibers. Several variations of LED structures are currently used to improve the efficiency of light coupling into fibers. The two basic structures for fiber optic LEDs are surface emitting and edge emitting. Surface-emitting devices are further broken down to planar and etched-well devices. The material used for these devices could be gallium-arsenide or any material which exhibits efficient photon-generating ability. The most common material in use today is the ternary crystal aluminum-gallium-arsenide. It is used extensively because it results in very efficient devices and has a characteristic wavelength around 820 nm[4] at which many fibers give lowest attenuation. (Many fibers are even better around 1300 nm, but the materials technology for LEDs at this wavelength — InGaAsP — is still on the front end of the learning curve; and devices are very expensive.)

Planar Fiber Optic LED

The planar heterojunction LED is somewhat similar to the grown junction LED of Figure 20a. Both utilize the liquid-phase epitaxial process to fabricate the device. The LED shown in

[4]This is adjustable by varying the mix of aluminum in the aluminum-gallium-arsenide crystal.



a. Epitaxially Grown Surface LED

b. Planar Diffused Surface LED

FIGURE 20. SIMPLE LED STRUCTURES
a. Epitaxially Grown
b. Planar Diffused

Figure 21 is a heterojunction aluminum-gallium-arsenide structure. The geometry is designed so that the device current is concentrated in a very small area of the active layer. This accomplishes several things: (1) the increase in current density makes for a brilliant light spot; (2) the small emitting area is well suited to coupling into small core fibers; and (3) the small effective area has a low capacitance and, thus, higher speed.

In Figure 21, the device appears to be nothing more than a multilayer version of the device in Figure 20a with a top metal layer containing a small opening. However, as the section view of AA shows in Figure 22, the internal construction provides some interesting features. To achieve concentration of the light emission in a small area, a method must be incorporated to confine the current to the desired area. Since the individual layers are grown across the entire surface of the wafer, a separate process must be used to confine the current. First an n-type tellurium-doped layer is grown on a zinc-doped p-type substrate. Before any additional layers are grown, a hole is etched through the n-layer and just into the substrate. The diameter of the hole defines the ultimate light-emitting area. Next, a p-type layer of AlGaAs is grown. This layer is doped such that its resistivity is quite high; this impedes carrier flow in a horizontal direction, but vertical flow is not impeded since the layer is so thin. This ensures that current flow from the substrate will be confined to the area of the etched hole. The next layer to be grown is the p-type active layer. The aluminum-gallium mix of this layer gives it an energy gap corresponding to 820 nm wavelength photons. The actual P-N junction is then formed by growth of n-type tellurium-doped aluminum-gallium-arsenide. The doping and aluminum-gallium mix of this layer is set to give it a larger energy gap than the p-layer just below it. This makes it essentially transparent to the 820 nm photons generated below. A final cap layer of gallium-arsenide is grown to enable ohmic contact by the top metal. The end result is an 820 nm planar LED of small emission area. The radiation pattern is still lambertian, however.

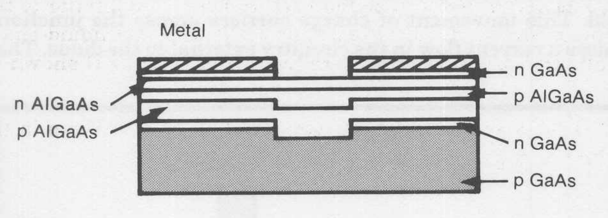


FIGURE 22. SECTION AA OF PLANAR HETEROJUNCTION LED

If a fiber with a core equal in area to the emission area is placed right down on the surface, it might seem that all the emitted light would be collected by the fiber; but since the emission pattern is lambertian, high order mode rays will not be launched into the fiber.

There is a way to increase the amount of light coupled. If a spherical lens is placed over the emitting area, the collimating effect will convert high order modes to low order modes (see Figure 23).

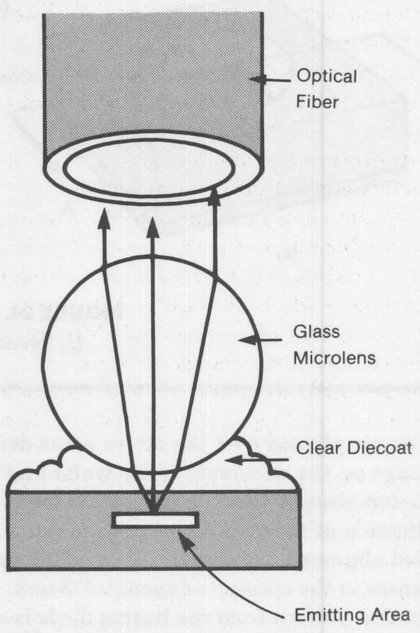


FIGURE 23. INCREASING LIGHT COUPLING WITH A MICROSPHERE

Etched-Well Surface LED

For data rates used in telecommunications (100 MHz), the planar LED becomes impractical. These higher data rates usually call for fibers with cores on the order of 50–62 μm. If a planar LED is used, the broad emission pattern of several hundred micro-meters will only allow a few percent of the power to be launched into the small fiber. Of course, the emission area of the planar device could be reduced; but this can lead to reliability problems. The increase in current density will cause a large temperature rise in the vicinity of the junction, and the thermal path from the junction to the die-attach header (through the confining layer and substrate) is not good enough to help draw the heat away from the junction. Continuous operation at higher temperature would soon increase the non-radiative sites in the LED and the efficiency would drop rapidly. If the chip is mounted upside down, the hot spot would be closer to the die-attach surface; but the light would have to pass through the thick substrate. The photon absorption in the substrate would reduce the output power significantly. A solution to this problem was developed by Burris and Dawson, of Bell Labs. The etched-well, or "Burrus" diode, is shown in Figure 24.

The thick n-type substrate is the starting wafer. Successive layers of aluminum-gallium-arsenide are grown epitaxially on the substrate. The layer functions (confinement, active, window) are essentially the same as in the planar structure. After the final p-type layer (contact) is grown, it is covered with a layer of SiO_2. Small openings are then cut in the SiO_2 to define the active emitting area. Metal is then evaporated over the wafer and contacts the p-layer through the small openings. The final processing consists of etching through the substrate. The

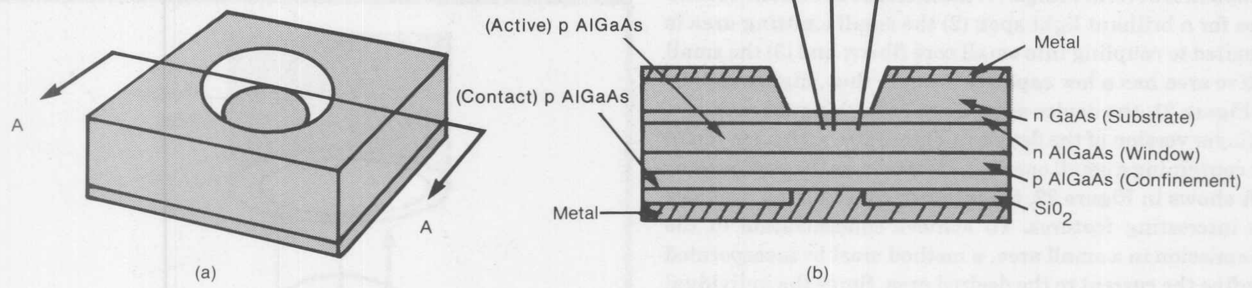


FIGURE 24. BURRUS, OR ETCHED WELL, LED:
(a) Device (b) Crossection at AA

etched wells are aligned over the active areas defined by the SiO_2 openings on the underside of the wafer and remove the heavily-photon-absorptive substrate down to the window layer. As an indication of the delicacy of this operation, it requires double-sided alignment on a wafer about 0.1 mm thick with a final thickness in the opening of about 0.025 mm.

The radiation pattern from the Burrus diode is still lambertian. However, it has a remarkably-small emitting area and enables coupling into very small fibers (down to 50 μm). The close proximity of the hot spot (0.005 mm) to the heat sink at the die attach makes it a reliable structure.

Several methods can be used for launching the emitted power into a fiber. These are shown in Figure 25.

The Burrus structure is superior to the planar for coupling to small fibers (<100 μm) but considerably more expensive due to its delicate structure.

Edge-Emitting LED

The surface structures discussed above are lambertian sources. A variation of the heterojunction family that emits a more directional pattern is the edge-emitting diode. This is shown in Figure 26. The layer structure is similar to the planar and Burrus diodes, but the emitting area is a stripe rather than a confined circular area. The emitted light is taken from the edge of the active stripe and forms an elliptical beam. The edge-emitting diode is quite similar to the diode lasers used for fiber optics. Although the edge emitter provides a more efficient source for coupling into small fibers, its structure calls for significant differences in packaging from the planar or Burrus.

Photo Detectors

PIN Photodiodes. Just as a P-N junction can be used to generate light, it can also be used to detect light. If a P-N junction is reverse-biased and under dark conditions, very little current flows through it. However, when light shines on the device, photon energy is abosorbed and hole-electron pairs are created. If the carriers are created in or near the depletion region at the junction, they are swept across the junction by the electric field. This movement of charge carriers across the junction causes a current flow in the circuitry external to the diode. The

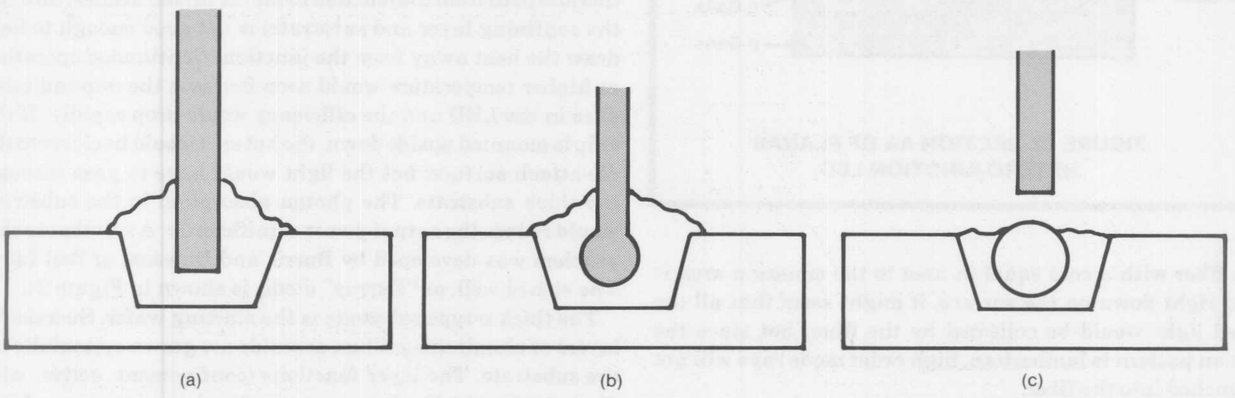


FIGURE 25. FIBER COUPLING TO A BURRUS DIODE
(a) Standard Fiber Epoxied In Well.
(b) Fiber With Balled End Epoxied In Well.
(c) Microlens Epoxied In Well.

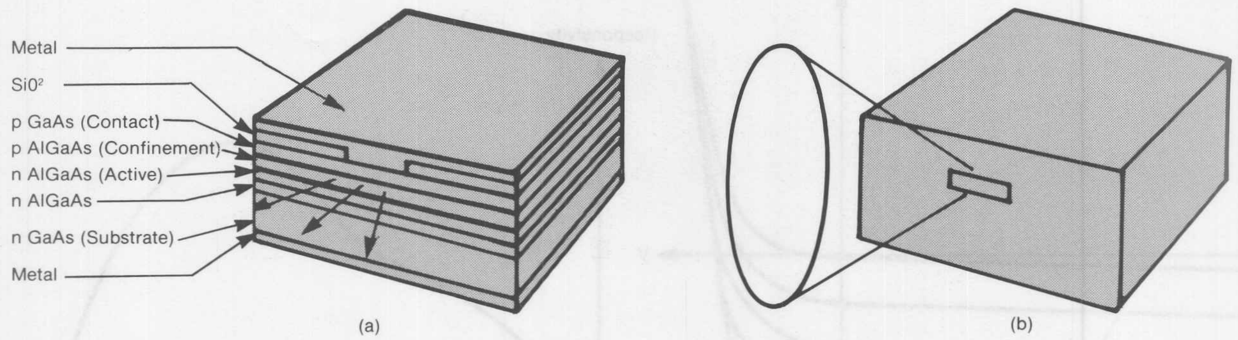


FIGURE 26. EDGE EMITTING LED

(a) Stucture

(b) Beam Pattern

magnitude of this current is proportional to the light power absorbed by the diode and the wavelength. A typical photodiode structure is shown in Figure 27, and the IV characteristic and spectral sensitivity are given in Figure 28.

In Figure 28a, it is seen that under reverse-bias conditions, the current flow is a noticeable function of light power density on the device. Note that in the forward-bias mode, the device eventually acts like an ordinary forward-biased diode with an exponential IV characteristic.

Although this type of P-N photodiode could be used as a fiber optic detector, it exhibits three undesirable features. The noise performance is generally not good enough to allow its use in sensitive systems; it is usually not fast enough for high-speed data applications; and due to the depletion width, it is not sensitive enough. For example, consider Figure 29. The depletion is indicated by the plot of electric field. In a typical device, the p-anode is very heavily doped; and the bulk of the depletion region is on the n-cathode side of the junction. As light shines on the device, it will penetrate through the p-region toward the junction. If all the photon absorption takes place in the depletion region, the generated holes and electrons will be accelerated by the field and will be quickly converted to circuit current. However, hole-electron pair generation occurs from the surface to the back side of the device. Although most of it occurs within the depletion region, enough does occur outside this region to cause a problem in high-speed applications. This problem is illustrated in Figure 30. A step pulse of light is applied to a photodiode. Because of distributed capacitance and bulk resistance, an exponential response by the diode is expected. The photocurrent wave form shows this as a ramp at turn-on. However, there is a distinct tail that occurs starting at point "a." The initial ramp up to "a" is essentially the reponse within the depletion region. Carriers that are generated outside the depletion region are not subject to acceleration by the high electric field. They tend to move through the bulk by the process of diffusion, a much slower travel. Eventually, the carriers reach the depletion region and are sped up. The effect can be eliminated, or at least substantially reduced by using a PIN structure. This is shown in Figure 31, and the electric field distribution is shown in Figure 32. Almost the entire electric

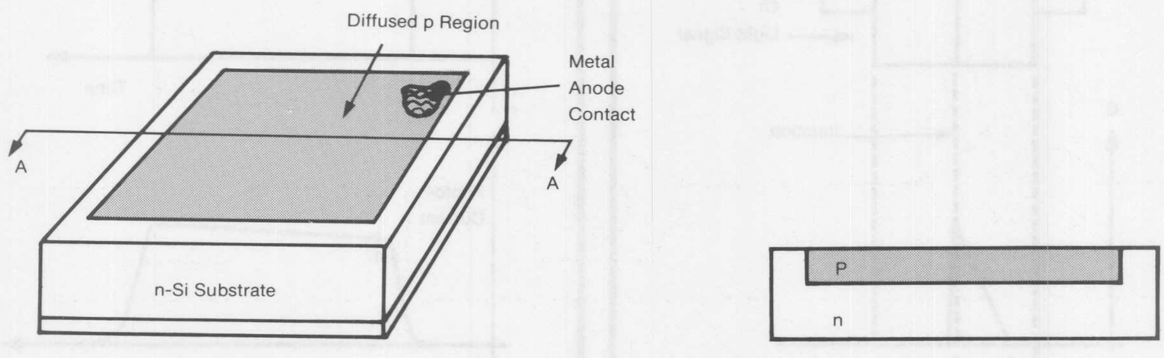


FIGURE 27. PN PHOTODIODE

(a) Device

(b) Section View At AA

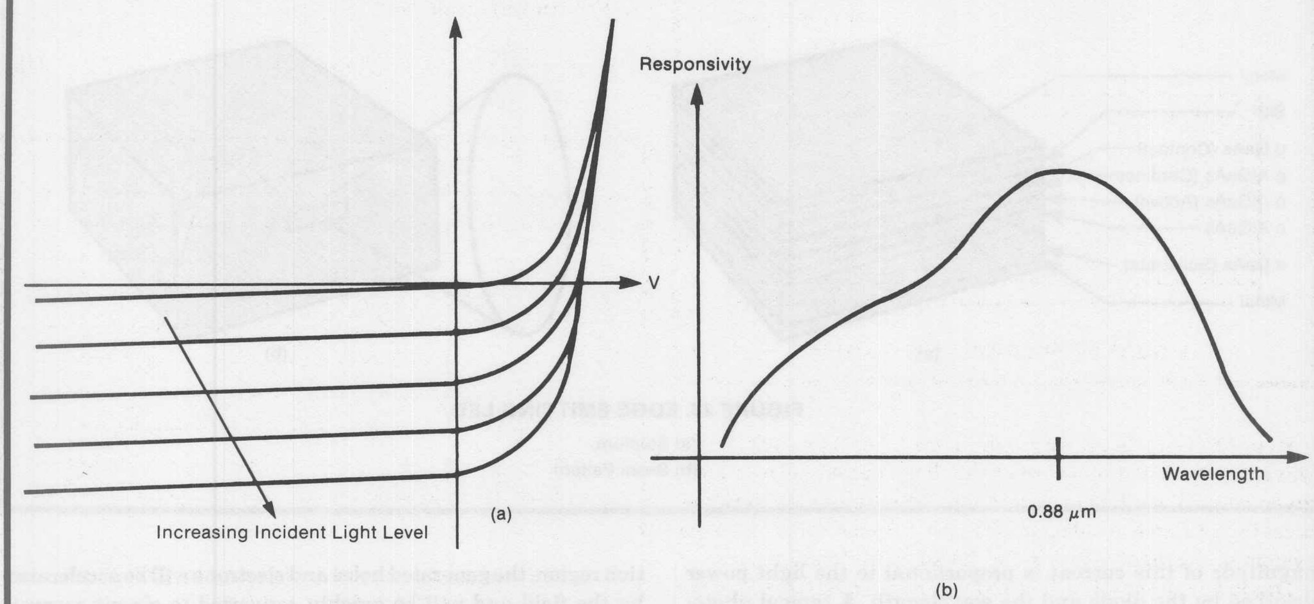


FIGURE 28. CHARACTERISTICS OF A PN PHOTODIODE

(a) I-V Family
(b) Spectral Sensitivity

field is across the intrinsic (I) region and very few photons are absorbed in the p- and n-region. The photocurrent response in such a structure is essentially free of the tailing effect seen in Figure 30.

In addition to the response time improvements, the high resistivity I-region gives the PIN diode lower noise performance.

The critical parameters for a PIN diode in a fiber optic application are:

1. Responsivity;
2. Dark current;
3. Response speed;
4. Spectral response.

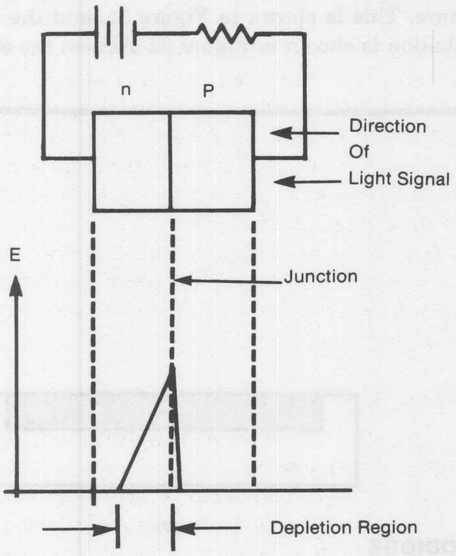


FIGURE 29. ELECTRIC FIELD IN A REVERSE-BIASED PN PHOTODIODE

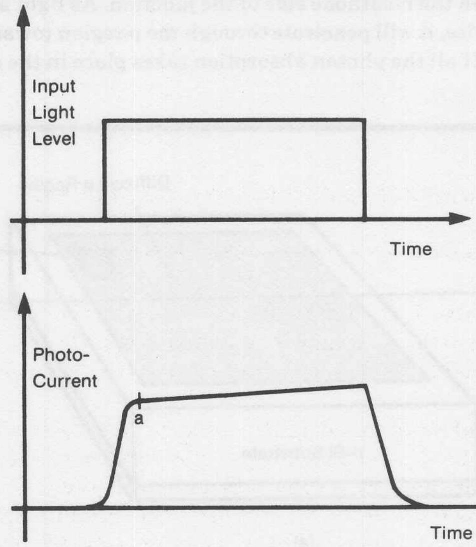


FIGURE 30. PULSE RESPONSE OF A PHOTODIODE

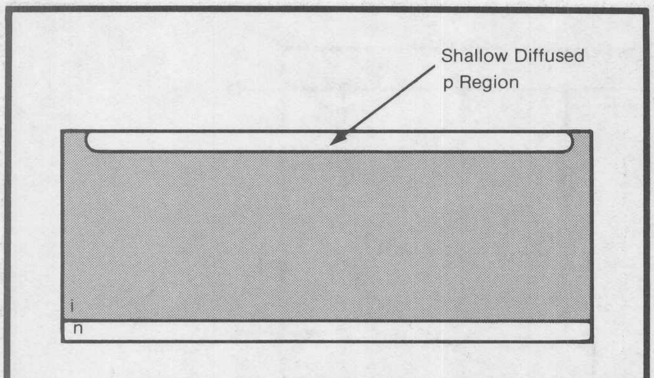


FIGURE 31. PIN DIODE STRUCTURE

Responsivity is usally given in amps/watt at a particular wavelength. It is a measure of the diode output current for a given power launched into the diode. In a system, the designer must then be able to calculate the power level coupled from the system to the diode (see AN-804, listed in Bibliography).

Dark current is the thermally-generated reverse leakage current in the diode. In conjunction with the signal current calculated from the responsivity and incident power, it gives the designer the on-off ratio to be expected in a system.

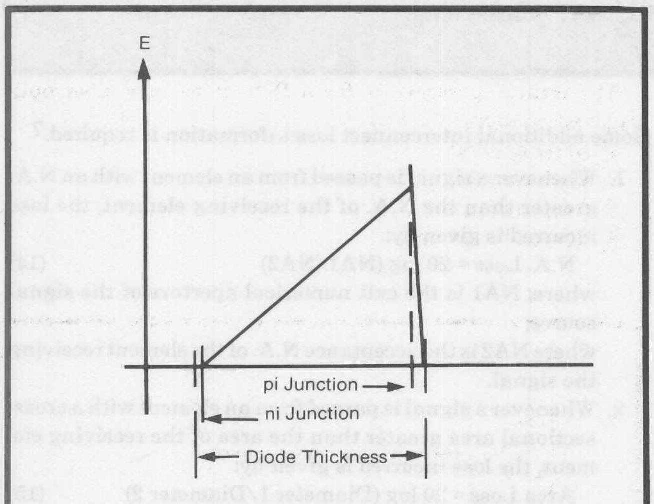


FIGURE 32. ELECTRIC FIELD DISTRIBUTION IN A PIN PHOTODIODE

Response Speed determines the maximum data rate capability of the diode; and in conjunction with the response of other elements of the system, it sets the maximum system data rate.[5]

Spectral Response determines the range, or system length, that can be achieved relative to the wavelength at which responsivity is characterized. For example, consider Figure 33. The responsivity of the MFOD102F is given as 0.15 A/W at 900 nm. As the curve indicates, the response at 900 nm is 78 percent of the peak response. If the diode is to be used in a system with an LED operating at 820 nm, the response (or system length) would be:

$$R_{(820)} = \frac{0.98}{0.78} R_{(900)} = 1.26 R_{(900)} = 0.19 \text{ A/W} \quad (13)$$

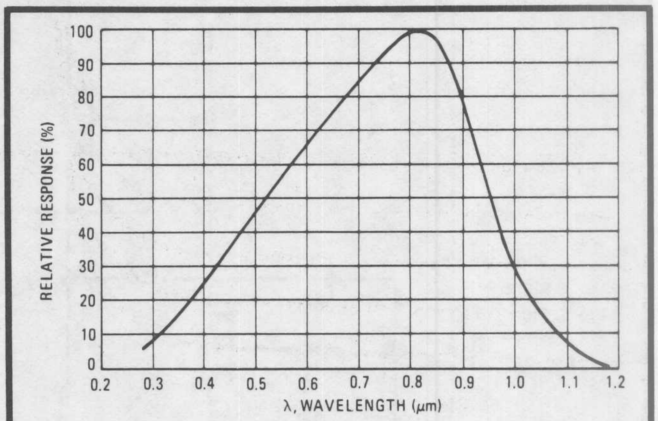


FIGURE 33. RELATIVE SPECTRAL RESPONSE MFOD102F PIN PHOTODIODE

Integrated Detector Preamplifiers. The PIN photodiode mentioned above is a high output impedance current source. The signal levels are usually on the order of tens of nanoamps to tens of microamps. The signal requires amplification to provide data at a usable level like T^2L. In noisy environments, the noise-insensitive benefits of fiber optics can all be lost at the receiver connection between diode and amplifier. Proper shielding can prevent this. An alternative solution is to integrate the follow-up amplifier into the same package as the photo diode. This device is called an integrated detector preamplifier (IDP). An example of this is given in Figure 34.

Incorporating an intrinsic layer into the monolithic structure is not practical with present technology, so a P-N junction photodiode is used. The first two transistors form a transimpedance amplifier. A third stage emitter follower is used to provide resistive negative feedback. The amplifier gives a low impedance voltage output which is then fed to a phase splitter. The two outputs are coupled through emitter followers.

The MFOD404F IDP has a responsivity greater than 230 mV/μW at 820 nm. The response rise and fall times are 50 ns maximum, and the input light power can go as high as 30 μW before noticeable pulse distortion occurs. Both outputs offer a typical impedance of 200 Ω.

The IDP can be used directly with a voltage comparator or, for more sophisticated systems, could be used to drive any normal voltage amplifier. Direct drive of a comparator is shown in Figure 35.

A Fiber Optics Communication System

Now that the basic concepts and advantages of fiber optics and the active components used with them have been discussed, it is of interest to go through the design of a system. The system will be a simple point-to-point application operating in the simplex[6] mode. The system will be analyzed for three aspects:

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[5]Device capacitance also impacts this. See "Designer's Guide to Fiber-Optic Data Links" listed in Bibliography.

[6]In a simplex system, a single transmitter is connected to a single receiver by a single fiber. In a half duplex system, a single

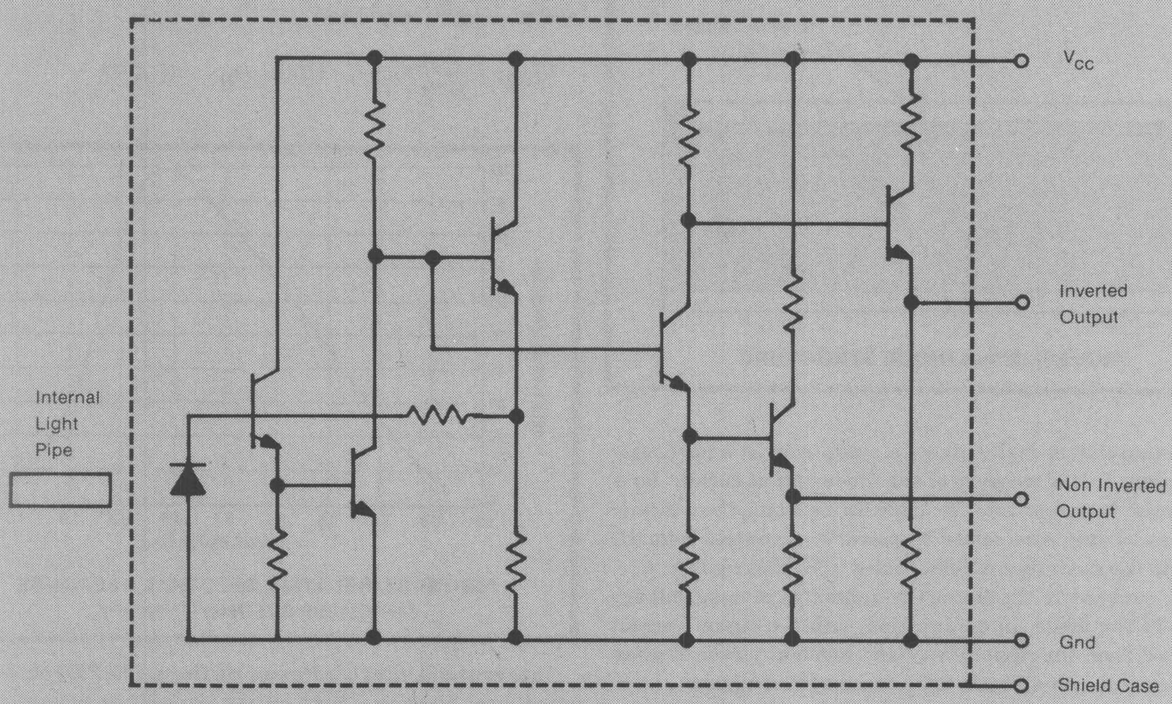


FIGURE 34. INTEGRATED DETECTOR PREAMPLIFIER

1. Loss budget;
2. Rise time budget;
3. Data encoding format.

Loss Budget. If no in-line repeaters are used, every element of the system between the LED and the detector introduces some loss into the system. By identifying and quantifying each loss, the designer can calculate the required transmitter power to ensure a given signal power at the receiver, or conversely, what signal power will be received for a given transmitter power. The process is referred to as calculating the system loss budget.

This sample system will be based on the following individual characteristics:

Transmitter:	MFOE107F/108F, characteristics as in Figure 36.
Fiber:	Silica-clad silica fiber with a core diameter of 200 μm; step index multimode; 20 dB/km attenuation at 820 nm; N.A. of 0.35, and a 3.0 dB bandwidth of 5.0 MHz-km.
Receiver:	MFOD404F, characteristics as in Figure 37.

The system will link a transmitter and receiver over a distance of 1000 meters and will use a single section of fiber (no splices).

[6]cont.

fiber provides a bidirectional alternate signal flow between a transmitter/receiver pair at each end. A full duplex system would consist of a transmitter and receiver at each end and a pair of fibers connecting them.

Some additional interconnect loss information is required.[7]

1. Whenever a signal is passed from an element with an N.A. greater than the N.A. of the receiving element, the loss incurred is given by:
   N.A. Loss = 20 log (NA1/NA2) (14)
   where; NA1 is the exit numerical aperture of the signal source;
   where NA2 is the acceptance N.A. of the element receiving the signal.
2. Whenever a signal is passed from an element with a cross-sectional area greater than the area of the receiving element, the loss incurred is given by:
   Area Loss = 20 log (Diameter 1/Diameter 2) (15)
   where: Diameter 1 is the diameter of the signal source (assumes a circular fiber port);
   where: Diameter 2 is the diameter of the element receiving the signal.
3. If there is any space between the sending and receiving elements, a loss is incurred. For example: an LED with an exit N.A. of 0.5 will result in a gap loss of 1.5 dB if it couples into a fiber over a gap of 0.15 mm.
4. If the source and receiving elements have their axes offset, there is an additional loss. This loss is also dependent on the separation gap. For an LED with an exit N.A. of 0.5, a gap with its receiving fiber of 0.15 mm, and an axial misalignment of 0.035 mm, there will be a combined loss of 1.8 dB.

[7]For a detailed discussion of all these loss mechanisms, see AN-804.

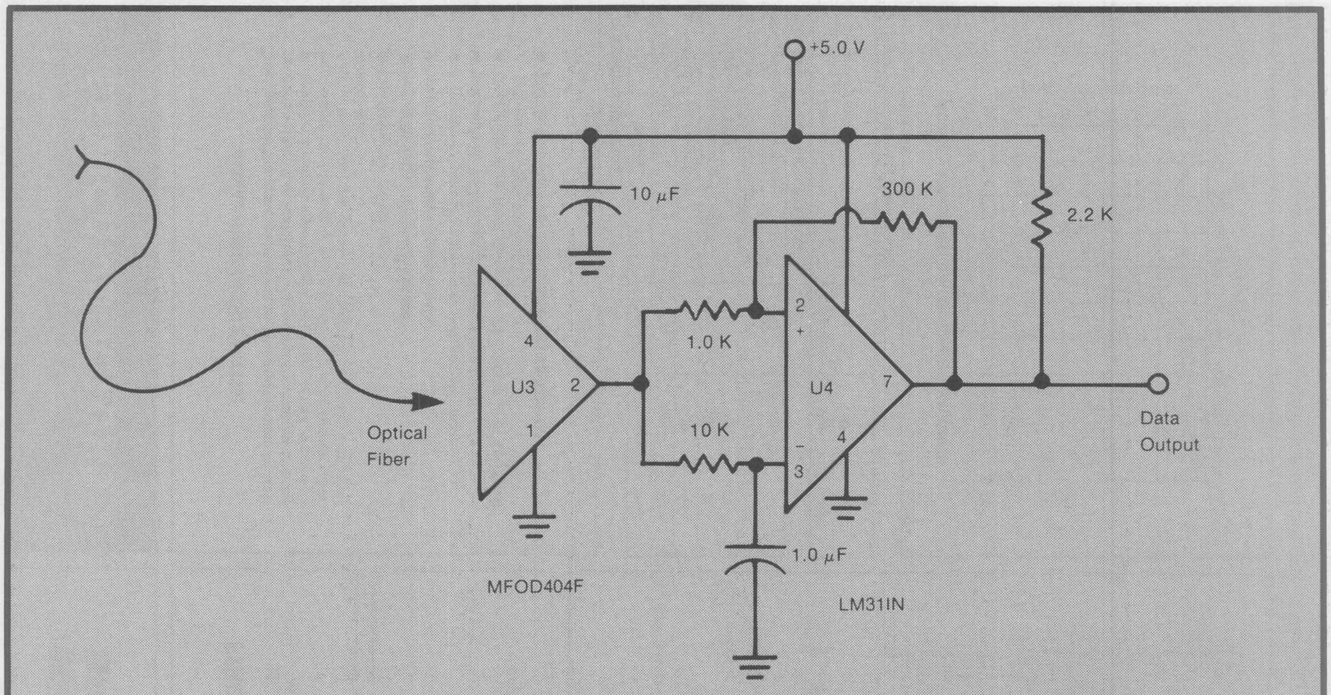


FIGURE 35. SIMPLE F/O DATA RECEIVER USING IDP AND A VOLTAGE COMPARATOR

5. If the end surfaces of the two elements are not parallel, an additional loss can be incurred. If the non-parallelism is held below 2-3 degrees, this loss is minimal and can generally be ignored.
6. As light passes through any interface. some of it is reflected. This loss, called Fresnel loss, is a function of the indices of refraction of the materials involved. For the devices in this example, this loss is typically 0.2 dB/ interface.

The system loss budget is now ready to be calculated. Figure 38 shows the system configuration. Table II presents the individual loss contribuiton of each element in the link.

TABLE II
Fiber Optic Link Loss Budget

	Loss Contribution
MFOE107F to Fiber N.A. Loss	3.10 dB
MFOE107F to Fiber Area Loss	0
Transmitter Gap and Misalignment Loss (see text)	1.80 dB
Fiber Entry Fresnel Loss	0.20 dB
Fiber Attenuation (1.0 km)	20.00 dB
Fiber Exit Fresnel Loss	0.20 dB
Receiver Gap and Misalignment Loss	1.20 dB
Detector Fresnel Loss	0.20 dB
Fiber to Detector N.A. Loss	0
Fiber to Detector Area Loss	0
Total Path Loss	26.70 dB

Note that in Table II no Fresnel loss was considered for the LED. This loss, although present, is included in specifying the output power in the data sheet.

In this system, the LED is operated at 100 mA. Figure 36 shows that at this current the instantaneous output power is typically 1100 μW. This assumes that the junction temperature is maintained at 25°C. The output power from the LED is then converted to a reference level relative to 1.0 mW:

$$P_o = 10 \log \frac{1.1 \text{ mW}}{1.0 \text{ mW}} \tag{16}$$

$$P_o = 0.41 \text{ dBm} \tag{17}$$

The power received by the MFOD404F is then calculated:

$$P_R = P_o - \text{loss} \tag{18}$$

$$\begin{aligned} &= 0.41 - 26.70 \\ &= -26.29 \text{ dBm} \end{aligned} \tag{19}$$

This reference level is now converted back to absolute power:

$$P_R = 10(-26.29)\text{mW} = 0.0024 \text{ mW} \tag{20}$$

Based on the typical responsivity of the MFOD404F from Figure 37, the expected output signal will be:

$$V_o = 35 \text{ mV}/\mu\text{W})\ (2.4\ \mu\text{W}) = 84 \text{ mV} \tag{21}$$

As shown in Figure 37, the output signal will be typically two hundred times above the noise level.

In many cases, a typical calculation is insufficient. To perform a worst-case analysis, assume that the signal-to-noise ratio at the MFOD404F output must be 20 dB. Figure 37 shows the maximum noise output voltage is 1.0 mV. Therefore, the output signal must be 10 mV. With a worst-case responsivity of 20 mV/μW, the received power must be:

$$P_R = \frac{V_o}{R} = \frac{10 \text{ mV}}{23 \text{ mV}/\mu\text{W}} = 0.43\ \mu\text{W} \tag{22}$$

MOTOROLA

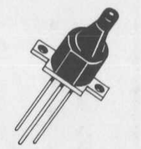
SEMICONDUCTORS

P.O. BOX 20912 • PHOENIX, ARIZONA 85036

MFOE107F
MFOE108F

FIBER OPTICS

HIGH-POWER AlGaAs LED



AlGaAs FIBER OPTIC EMITTER

...designed for fiber optic applications requiring high-power and fast response time. It is a AlGaAs LED spectrally matched to the minimum attenuation region of most fiber optic cables. Motorola's ferrule package fits directly into a metal fiber optic system cable. Applications include industrial controls, military and other applications.

- Fast Response - 15 ns Typ
- Ferrule Package - Small and Rugged
- Integral Heatsink Improves Reliability
- Prepolished Optical Port Enhances Coupling Efficiency
- Complements All Motorola Fiber Optic Detectors
- Compatible With AMP Connector #227240-3 and Amphenol Connector #905-135-5000
- 200 μm Diameter Fiber Core Optical Port With 0.5 NA

MAXIMUM RATINGS

Rating	Symbol	Value	Unit
Reverse Voltage	V_R	3.0	Volts
Forward Current-Continuous	I_F	200	mA
Total Device Dissipation @ T_A = 25°C Derate above 25°C	P_D	400 4.0	mW mW/°C
Operating Temperature Range	T_A	-30 to+85	°C
Storage Temperature Range	T_{stg}	-30 to+100	°C

THERMAL CHARACTERISTICS

Characteristics	Symbol	Max	Unit
Thermal Resistance, Junction to Ambient	θ_{JA}	250 175*	°C/W

*Installed in compatible metal connector housing.

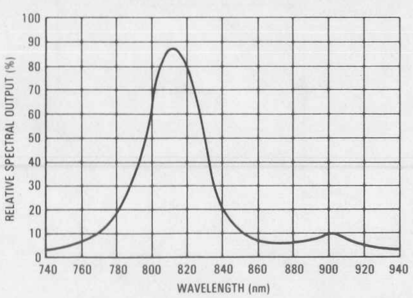
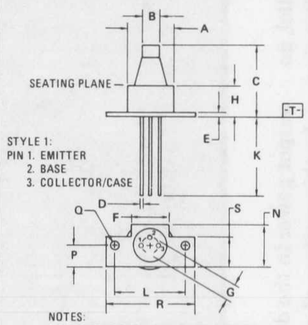


FIGURE 1 — SPECTRAL OUTPUT versus WAVELENGTH



NOTES:
1. DIMENSIONS N AND R ARE DATUMS.
2. [-T-] IS GAUGE PLANE.
3. POSITIONAL TOLERANCE LEADS AND MOUNTING HOLES
   ⌀ | Ø 0.36 (0.014) Ⓜ | T | N Ⓜ | R Ⓜ
4. DIMENSIONING AND TOLERANCING PER ANSI Y14.5, 1973.

DIM	MILLIMETERS MIN	MILLIMETERS MAX	INCHES MIN	INCHES MAX
A	6.86	7.11	0.270	0.280
B	2.54	2.64	0.100	0.104
C	10.93	11.55	0.430	0.455
D	0.41	0.48	0.016	0.019
E	0.64	0.89	0.025	0.035
F	5.72	5.96	0.225	0.235
G	2.54 BSC		0.100 BSC	
H	3.94	4.44	0.155	0.175
K	12.70	—	0.500	—
L	10.41 BSC		0.410 BSC	
N	5.97	6.22	0.235	0.245
P	3.05 BSC		0.120 BSC	
Q	1.15	1.29	0.045	0.051
R	12.83	13.08	0.505	0.515
S	4.32	4.57	0.170	0.180

CASE 338D-01

ELECTRICAL CHARACTERISTICS (T_A = 25°C)

Characteristic	Symbol	Min	Typ	Max	Unit
Reverse Leakage Current (V_R = 3.0 V, R_L = 1.0 Megohm)	I_R	—	5.0	—	μA
Reverse Breakdown Voltage (I_R = 100 μA)	$V_{(BR)R}$	2.0	—	—	Volts
Forward Voltage (I_F = 100 mA)	V_F	—	1.5	2.0	Volts
Total Capacitance (V_R = 0 V, f = 1.0 MHz)	C_T	—	450	—	pF

OPTICAL CHARACTERISTICS (T_A = 25°C)

Characteristic		Symbol	Min	Typ	Max	Unit
Total Power Output From Optical Port (I_F = 100 mA, λ ≈ 820 nm)	MFOE107F MFOE108F	P_o	700 1100	1100 1500	1400 2200	μW
Total Power Output in dBm (I_F = 100 mA, λ ≈ 820 nm)	MFOE107F MFOE108F	P_o	-1.55 0.41	0.41 1.76	1.46 3.42	dBm
Numerical Aperture of Output Port (200 μm [8 mil] diameter core)		NA	—	0.50	—	—
Wavelength of Peak Emission		—	—	812	—	nm
Spectral Line Half Width		—	—	35	—	nm
Optical Turn-On or Turn-Off Time		t_r, t_f	—	15	20	ns

TYPICAL CHARACTERISTICS

FIGURE 2 — POWER OUTPUT versus JUNCTION TEMPERATURE

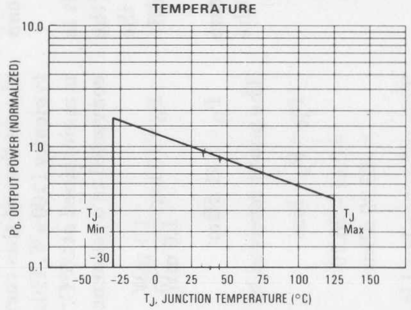


FIGURE 3 — POWER OUTPUT versus FORWARD CURRENT

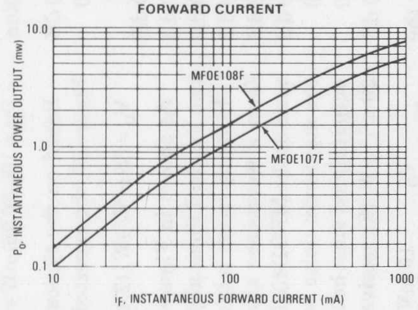
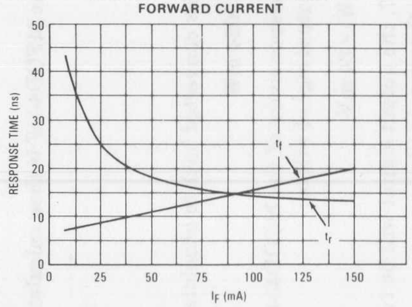


FIGURE 4 — RESPONSE TIME versus FORWARD CURRENT



DS2553

MOTOROLA *Semiconductor Products Inc.*

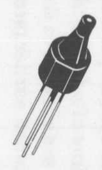
FIGURE 36. MFOE107F/MFOE108F DATA SHEET

MOTOROLA
SEMICONDUCTORS
P.O. BOX 20912 • PHOENIX, ARIZONA 85036

MFOD404F

FIBER OPTICS

INTEGRATED DETECTOR PREAMPLIFIER



INTEGRATED DETECTOR/PREAMPLIFIER FOR FIBER OPTIC SYSTEMS

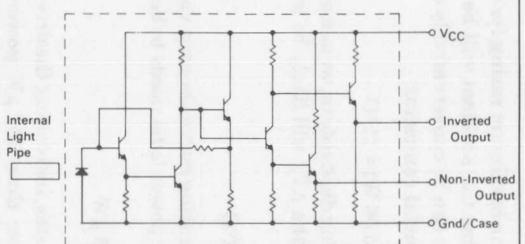
. . . designed as a monolithic integrated circuit containing both detector and preamplifier for use in medium bandwidth, medium distance systems. It joins Motorola family of Straight Shooter devices packaged in the Fiber Optic Ferrule case. The device fits directly into AMP Incorporated fiber optic connectors which also provide excellent RFI immunity. The output of the device is low impedance to provide even less sensitivity to stray interference. The MFOD404F has a 200 μm (8 mil) fiber input with a high numerical aperture.

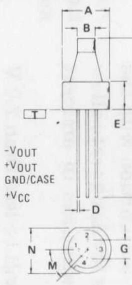
- Usable for Data Systems up to 10 Megabaud
- Dynamic Range Greater than 100:1
- RFI Shielded in AMP Connector #227240-1
- May be Used with MFOExxx Emitters
- Ferrule Package — Small and Rugged
- Fiber Input Port Greatly Enhances Coupling Efficiency
- Prepolished Optical Port

MAXIMUM RATINGS (T_A = 25°C unless otherwise noted)

Rating	Symbol	Value	Unit
Supply Voltage	V_{CC}	7.5	Volts
Operating Temperature Range	T_A	-30 to +85	°C
Storage Temperature Range	T_{stg}	-30 to +100	°C

FIGURE 1 — EQUIVALENT SCHEMATIC





STYLE 1:
PIN 1. $-V_{OUT}$
2. $+V_{OUT}$
3. GND/CASE
4. $+V_{CC}$

NOTES:
1. T IS SEATING PLANE.
2. POSITIONAL TOLERANCE FOR LEADS:
| ⌖ | Ø 0.36 (0.014) Ⓜ | T |
3. DIMENSIONING AND TOLERANCING PER Y14.5, 1973.

DIM	MILLIMETERS MIN	MILLIMETERS MAX	INCHES MIN	INCHES MAX
A	6.86	7.11	0.270	0.280
B	2.54	2.64	0.100	0.104
C	10.16	10.80	0.400	0.425
D	0.40	0.48	0.016	0.019
E	3.94	4.44	0.155	0.175
G	2.54 BSC		0.100 BSC	
K	12.70	–	0.500	–
M	45° BSC		45° BSC	
N	6.22	6.73	0.245	0.265

CASE 338B-01

ELECTRICAL CHARACTERISTICS (V_{CC} = 5.0 V, T_A = 25°C)

Characteristics	Symbol	Conditions	Min	Typ	Max	Units
Power Supply Current	I_{CC}	Circuit A	3.0	3.5	5.0	mA
Quiescent dc Output Voltage (Non-Inverting Output)	V_q	Circuit A	0.5	0.6	0.7	Volts
Quiescent dc Output Voltage (Inverting Output)	V_q	Circuit A	2.7	3.0	3.3	Volts
Output Impedance	z_o		—	200	—	Ohms
RMS Noise Output	V_{NO}	Circuit A	—	0.4	1.0	mV

OPTICAL CHARACTERISTICS (T_A = 25°C)

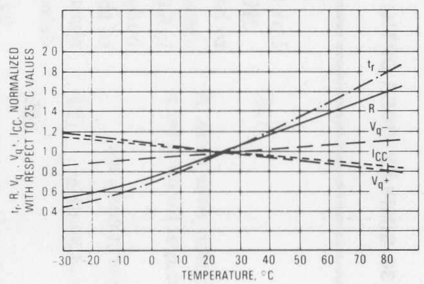
Characteristics	Symbol	Conditions	Min	Typ	Max	Units
Responsivity (V_{CC} = 5.0 V, P = 2.0 μW*) λ = 900 nm λ = 820 nm	R	Circuit B	20 —	30 35	50 —	mV/μW
Pulse Response	t_r, t_f	Circuit B	—	35	50	ns
Numerical Aperture of Input Core (200 μm [8 mil] diameter core)	NA		—	0.70	—	—
Signal-to-Noise Ratio @ P_{in} = 1.0 μW peak*	S/N		—	35	—	dB
Maximum Input Power for Negligible Distortion in Output Pulse*			—	—	30	μW

RECOMMENDED OPERATING CONDITIONS

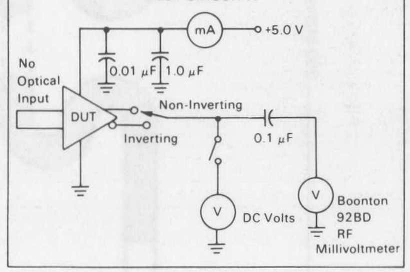
Characteristics	Symbol	Conditions	Min	Typ	Max	Units
Supply Voltage	V_{CC}		4.0	5.0	6.0	Volts
Capacitive Load	C_L		—	—	100	pF
Input Wavelength	λ		—	900	—	nm

*Power launched into Optical Input Port. The designer must account for interface coupling losses.

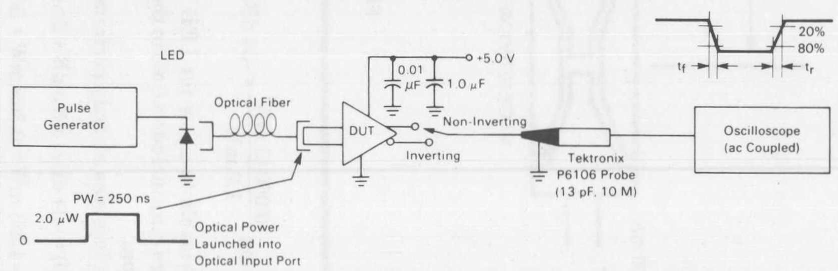
FIGURE 2 — TYPICAL PERFORMANCE OVER OPERATING TEMPERATURE RANGE



TEST CIRCUIT A



TEST CIRCUIT B



Patent applied for.
Straight Shooter is a trademark of Motorola Inc.

DS2544

MOTOROLA Semiconductor Products Inc.

FIGURE 37. MFOD404F DATA SHEET

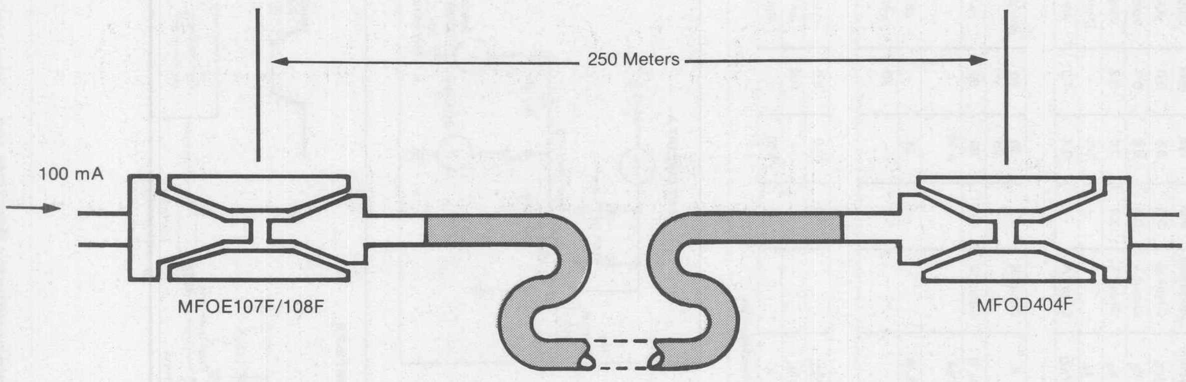


FIGURE 38. SIMPLEX FIBER OPTIC POINT TO POINT LINK

$$P_R = 10 \log \frac{0.00043 \text{ mW}}{1.0 \text{ mW}} = -34 \text{ dBm} \quad (23)$$

It is advisable to allow for LED degradation over time. A good design may include 3.0 dB in the loss budget for long-term degradation.

The link loss was already performed as worst case, so:

$$P_o \text{ (LED)} = -34 \text{ dBm} + 3.0 \text{ dB} + 20.62 \text{ dB} = -4.38 \text{ dBm} \quad (24)$$

$$P_o = 10(-4.38) \text{ mW} = 0.365 \text{ mW} = 365\ \mu\text{W} \quad (25)$$

Based on the Power Output versus Forward Current curve in Figure 36, it can be seen that the drive current (instantaneous forward current) necessary for 365 μW of power is about 30 mA.

Figure 36 also includes a Power Output versus Junction Temperature curve which, when used in conjunction with the thermal resistance of the package enables the designer to allow for higher drive currents as well as variations in ambient temperatures.

At 30 mA drive, the forward voltage will be less than 2.0 V worst case. Using 2.0 V will give a conservative analysis:

$$P_D = (30 \text{ mA})\ (2.0 \text{ V}) = 60 \text{ mW} \quad (26)$$

This is well within the maximum rating for operation at 25°C ambient. If we assume the ambient will be 25°C or less, the junction temperature can be conservatively calculated. Installed in a compatible metal connector:

$$\Delta T_J = (175°\text{C/W})\ (0.06 \text{ W}) = 11°\text{C} \quad (27)$$

If we are transmitting digital data, we can assume an average duty cycle of 50% so the ΔT_J will likely be less than 6°C. This gives:

$$T_J = T_A + \Delta T_J = 32°\text{C} \quad (28)$$

The power output derating curve shows a value of 0.9 at 32°C. Thus the required dc power level needs to be:

$$P_o \text{ (dc)} = \frac{365}{0.9} = 406\ \mu\text{W} \quad (29)$$

As Figure 36 indicates, increasing the drive current to 40 mA would provide greater than 500 μW power output and only increase the junction temperature 1°C. This analysis shows the link to be more than adequate under the worst case conditions.

Rise Time Budget. The cable for this system was specified to have a bandwidth of 5.0 MHz-km. Since the length of the system is 1.0 km, the system bandwidth, if limited by the cable, is 5.0 MHz. Data links are usually rated in terms of a rise time budget. The system rise time is found by taking the square root of the sum of the squares of the individual elements. In this system the only two elements to consider are the LED and the detector. Thus:

$$t_{R_S} = \sqrt{(t_{R\text{-LED}})^2 + (t_{R\text{-detector}})^2} \quad (30)$$

Using the typical values from Figures 36 and 37:

$$t_{R_s} = \sqrt{(15)^2 + (35)^2} = 38 \text{ ns} \quad (31)$$

Total system performance may be impacted by including the rise time of additional circuit elements. Additional considerations are covered in detail in AN-794 and the Designer's Guide mentioned earlier (see Bibliography).

Data Encoding Format. In a typical digital system, the coding format is usually NRZ, or non-return to zero. In this format, a string of ones would be encoded as a continuous high level. Only when there is a change of state to a "0" would the signal level drop to zero. In RTZ (return to zero) encoding, the first half of a clock cycle would be high for a "1" and low for a "0." The second half would be low in either case. Figure 39 shows an NRZ and RTZ waveform for a binary data stream. Note between a-b the RTZ pulse rate repetition rate is at its highest. The highest bit rate requirement for an RTZ system is a string of "1's". The highest bit rate for an NRZ system is for alternating "1's" and "0's," as shown from b-c. Note that the highest NRZ bit rate is half the highest RTZ bit rate, or an RTZ system would require twice the bandwidth of an NRZ system for the same data rate.

However, to minimize drift in a receiver, it will probably be ac coupled; but if NRZ encoding is used and a long string of "1's" is transmitted, the ac coupling will result in lost data in the receiver. With RTZ data, data is not lost with ac coupling since only a string of "0's" results in a constant signal level; but that level is itself zero. However, in the case of both NRZ and RTZ, any continuous string of either "1's" or "0's" for NRZ or

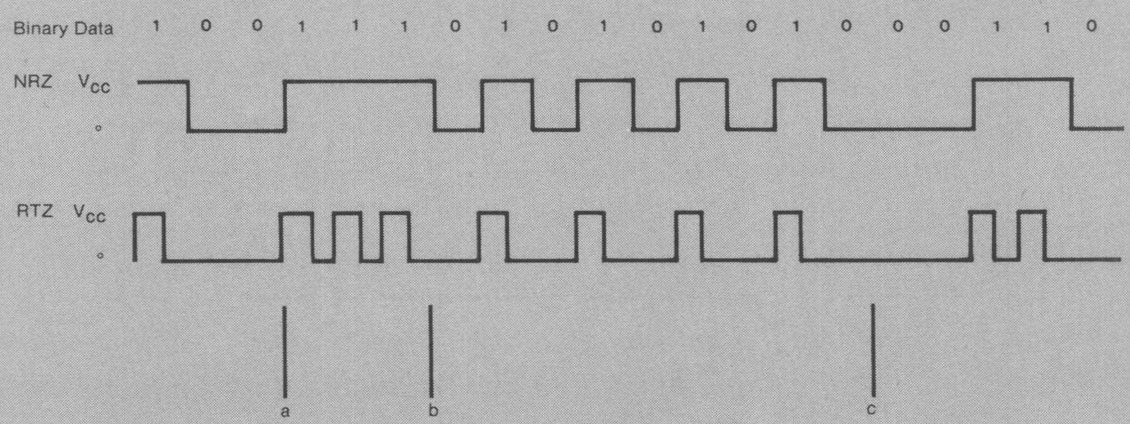


FIGURE 39. NRZ AND RTZ ENCODED DATA

or "0's" for RTZ will prevent the receiver from recovering any clock signal.

Another format, called Manchester encoding, solves this problem, by definition, in Manchester, the polarity reverses once each bit period regardless of the data. This is shown in Figure 40. The large number of level transitions enables the receiver to derive a clock signal even if all "1's" or all "0's" are being received.

In many cases, clock recovery is not required. It might appear that RTZ would be a good encoding scheme for these applications. However, many receivers include automatic gain control (AGC). During a long stream of "0's", the AGC could crank the receiver gain up; and when "1's" data begin to appear, the receiver may saturate. A good encoding scheme for these applications is pulse bipolar encoding. This is shown in Figure 41. The transmitter runs at a quiescent level and is turned on

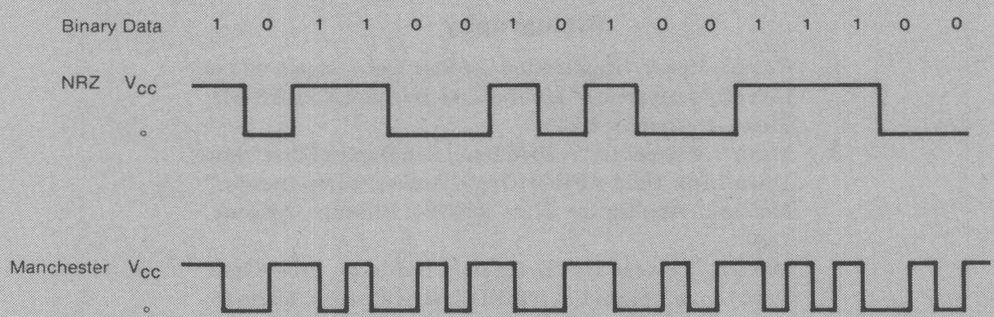


FIGURE 40. MANCHESTER DATA ENCODING

harder for a short duration during a data "0" and is turned off for a short duration during a data "1."

Additional details on encoding schemes can be obtained from recent texts on data communications or pulse code modulation.

Summary

This note has presented the basic principles that govern the coupling and transmission of light over optical fibers and the design considerations and advantages of using optical fibers for communication information in the form of modulated light.

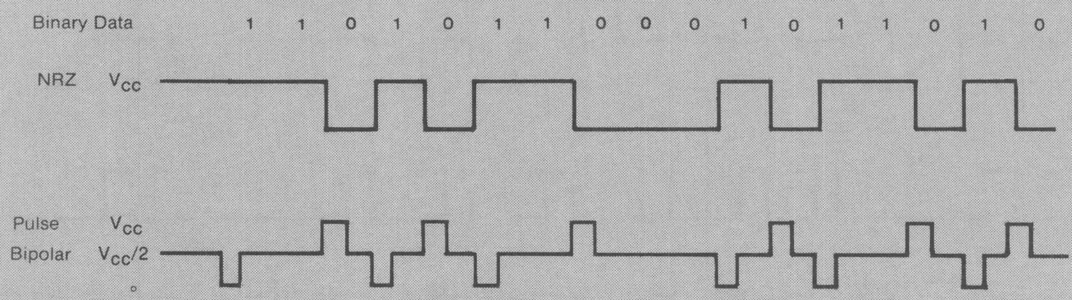


FIGURE 41. PULSE BIPOLAR ENCODING

Biblography

1. Gempe, Horst: "Applications of Ferruled Components to Fiber Optic Systems," Motorola Application Note AN-804; Phoenix, Arizona; 1980.
2. Mirtich, Vincent L.; "A 20-M Baud Full Duplex Fiber Optic Data Link Using Fiber Optic Active Components." Motorola Application Note AN-794; Phoenix, Arizona, 1980.
3. Mirtich, Vincent L.; "Designer's Guide to: Fiber-Optic Data Links." Parts 1, 2, & 3; EDN June 20, 1980; August 5, 1980; and August 20, 1980.