CHAPTER XI

Fiber Optic Interconnection

Science and religion agree on the primacy of light energy. Light was the first creation, and is also the wave of the future. The overwhelming advantages of fiber optic communication make it a mere matter of time until nearly all information travels by light.

Of the technology's many advantages, most impressive is its enormous information-carrying capacity. The glass optical wave-guide, or optical fiber, is an elegantly simple development which can carry a vast amount of data at ultimate speeds. For example, a single fiber one-fifth the thickness of a human hair can do the work of ten thousand telephone wires, or when used as a TV cable, carry eight thousand channels simultaneously.

Fiber optic systems are also much smaller and lighter than conventional systems (typically reducing mass by a factor of ten), and offer complete electrical isolation and total immunity to noise and interference. Safety is another benefit: the fibers are non-sparking. Security is yet another. Optical signals cannot be tapped without altering transmission characteristics.

Another key advantage: fantastic reliability. Components in existence today offer a projected mean time of one hundred years between failures. Best of all, as volume usage increases there is a strong promise of incredibly low cost. And waiting in the wings are optical microcircuits capable of processing unprecedented mountains of data—gigabits—in a literal flash. Fiber optics is clearly a technological trend of fundamental and monumental significance.

The fiber optical revolution is upon us. Optical fibers have already begun to replace electrical conductors in telecommunications, computers, instrumentation, and television. The overwhelming inherent advantages of fiber optics make it inevitable that this replacement process continue and accelerate.

The major purpose of this chapter is to explain and assess this dynamic new technology. It is written for the prospective first-time user of fiber optic technology, perhaps someone a bit anxious about specifying strange and unfamiliar technological gadgetry. Our goal is to give such engineers enough information to allow them to make some confident and intelligent decisions. In pursuit of this goal we provide:

1/ a basic understanding of fiber optic technology;
2/ a brief history of the technology;
3/ an introduction of principles of fiber optic design, stressing single-fiber, medium- and long-haul applications; and
4/ a guide to practical optical connector use.

We believe that such an approach will convince the engineer that fiber optics are rapidly eliminating conventional electronic systems as a sensible way to process most information. Let us begin to test the truth of this with a brief consideration of fiber optic technology's history.

A Brief History of Light Communication

The technology is new; the idea, old. Light communication is as old as reflective surfaces. Commanders of old used polished shields to send battle commands. Mirrors, signal fires, and lighted steeples mark early attempts to communicate with light. More sophisticated exploitation awaited the scientific developments of the late 19th century.

The famous British physicist, Sir John Tyndall, first showed that light could follow a curved transparent medium. He lighted the interior of a tank, punched a hole in the side of the tank, and an illuminated stream of water flowed into the darkened room.

An Idea Whose Time Had Not Come

Ten years later, in 1880, the first signal-carrying light wave was transmitted. Shortly after his invention of the telephone, Alexander Graham Bell sent a voice message on a beam of light. However, existing technology was too primitive to make his "photophone" practical. No suitable light source existed, nor were there available transmission media which could surmount the limitation of atmospheric transmission. For decades optical devices were to remain laboratory curiosities.

The Fundamental Problem

Early researchers concentrated on atmospheric broadcast. And ran headlong into an immovable stumbling block: diffraction. A basic property of all propagating waves, diffraction is the inevitable tendency of light—and all waves—to deviate from the straight and narrow, deflect from the paths prescribed by geometrical optics. This tendency of a light beam to spread out means increasing signal loss over distance.

Light communication through the atmosphere involves other difficulties: transmission must be line-of-sight, requires extremely precise pointing alignment, and is easily compromised by bad weather. These—and problems such as the lack of a suitable light source—blocked progress.

The Era of Light Foreshadowed

Early in the 20th century great things began to happen. First, a new understanding of the nature of light was achieved when in 1916 a Swiss patent office clerk turned two-hundred years of classical physics upside down and inside out. Among other revolutionary concepts, Albert Einstein introduced the startling idea that light can behave like particles, that energy and mass are interchangeable. A year later he laid down the basic principles of the laser, the first suitable light source for practical fiber-optic communication systems. (Not for a half-century was this theoretical development actually demonstrated.)

Another important early 20th century development was the proposal to surmount diffraction-caused attenuation by channeling light through an optical waveguide. The concept seemed promising. The theoretical feasibility of sending data through dielectric fiber at optical frequencies was unquestioned. But no adequate transmission medium existed. All available optical fibers showed transmission losses of thousands of decibels per kilometer.

By mid-century, fiber optic technology was notable for what it lacked. There was no good way to generate modulated collimated light beams, no effective way to transmit it once produced, and no satisfactory way to receive it once transmitted. A great communications capability lay idle, complete but for components and feasibility.

The Modern Era Commences

Suddenly, change. The firing of the first laser in 1960 ignited new interest in high-speed, multichannel light-beam communication. The 1960's were active and productive years in the field. But progress in active components had limited practical value when all available transmission media showed losses of thousands of dB per kilometer.

An important breakthrough came in 1970 with the introduction of the first low-loss optical fiber. Its 20 dB/km attenuation made practical optical communications possible. This development triggered a new surge of interest and activity in fiber optic communication.

Brilliant Progress

Frenetic activity in the fiber optic field has piled breakthrough on breakthrough. Some of the recent developments in fiber optic technology which have accelerated its wide range of applications include:

1/ *Improved light sources.* New devices offer an inexpensive, efficient, and long-lived source of coherent carrier waves for encoded signals; e.g., the semiconductor diode laser.

2/ *Superior fibers.* Tremendous progress has been made since the introduction of the first 20 dB/km optical fiber. In less than a decade we have moved from zero practical optical fibers to ultra-thin fibers whose attenuation approaches the theoretical limit. Such fibers make long-range transmission practical.

3/ *New components.* Great progress has been made in optical devices, including the development of a new generation of compact, reliable, high-efficiency optical components.

4/ *New connectors.* For the past several years the lack of efficient, low-cost, low-loss single-fiber connectors has been the major stumbling block in fiber-optics. Innovations within the past year eliminate this as a problem.

These above-described—and other promising developments—make it certain that fiber optics will soon impact electronics in a major way. Fiber optics is already a practical alternative to electrical wire in telecommunications applications. The use of fiber optics in other industry segments is accelerating exponentially.

This completes our brief history of fiber optics. Hopefully this short recital will provide an adequate historical content for a review of basic fiber optic technology. Let us now turn to that subject, seeking to provide a basic understanding of the technology, with emphasis on its relation to interconnection design.

Deutsch Radiant Lens

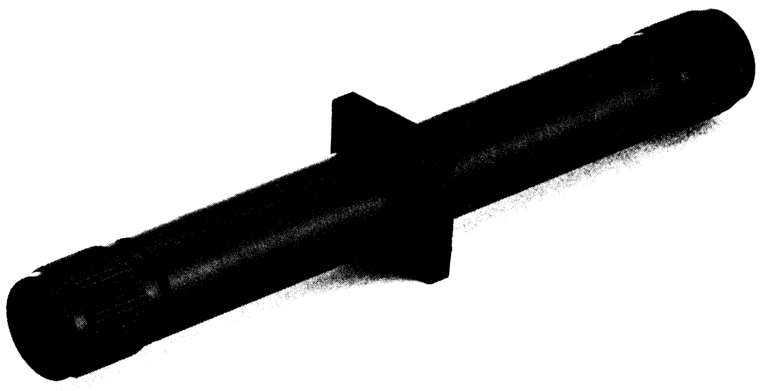


Figure XI-1
Deutsch Radiant Lens—Optical Waveguide Connector.

Optical Theory

The incredible data carrying capacity of the optical fiber is the result of fundamental principles of physics. How much data a propagating wave can carry depends on its frequency. The higher the frequency, the greater the signal carrying capacity of the electromagnetic wave.

Light waves are between 20,000 and 200,000 times higher in frequency than microwaves. Because light waves are so short, a vast number can be sent through an optical fiber simultaneously.

Optical energy propagates just like electromagnetic waves of lower frequency. Its velocity is lower in any transparent medium than it is in a vacuum. The amount a given material slows light down is a characteristic of each material, known as its *index of refraction.* This can be defined as the ratio of the speed of light in a vacuum to that in the transparent medium. (Although basic to each material, this is not a constant, but varies with wavelength.)

When light traveling through a medium strikes a plane interface with another medium of a lower index of refraction, part of the optical energy is reflected back into the first material (see Figure XI-2). The remainder is refracted—transmitted at an angle—into the second material. At a critical angle of incidence, the refracted wave goes skimming along parallel to the interface. At shallower grazing angles than this critical angle, the light wave undergoes *total internal reflection.*

Reflected Optical Energy

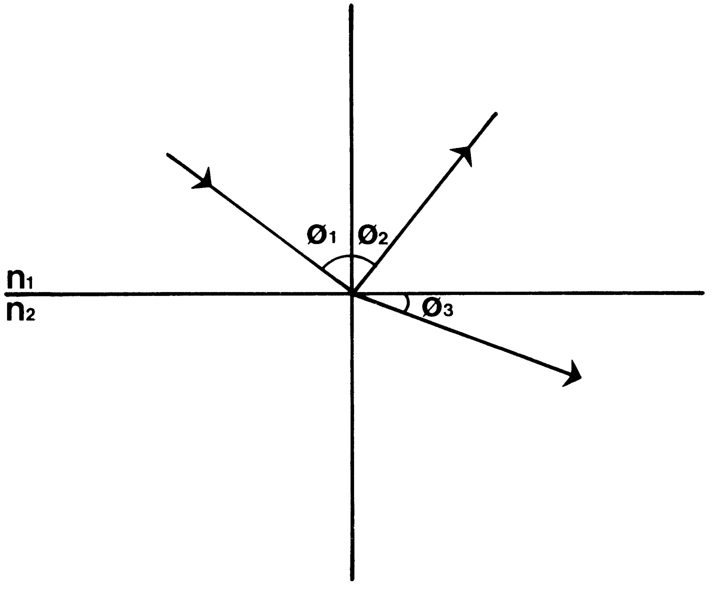


Figure XI-2
When light traveling through a medium strikes a plane interface with another medium of a lower index of refraction, part of the optical energy is reflected back into the first material.

The optical fiber is designed to exploit this phenomenon: It is composed of a core formed of a light transmitting medium encased in a cladding of lower index of refraction material (see Figure XI-3). Light energy strikes the end of the fiber, and that which is within the *acceptance cone* enters and is transmitted. The acceptance cone's half angle, called the numerical aperture, is a function of the indices of refraction of the core and the surrounding cladding.

Light propagating along the core travels at varied angles of internal reflection. Those reflecting at higher angles must travel farther

The Design of Optical Fiber

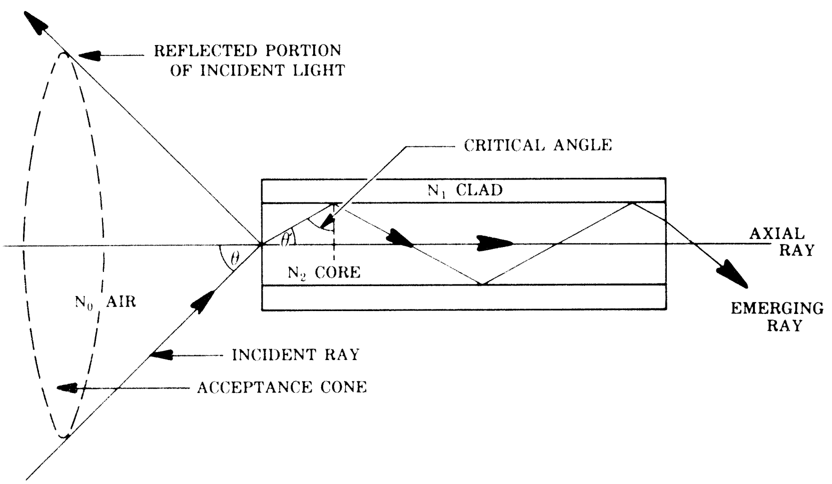


Figure XI-3
The optical fiber is composed of a core formed of a light transmitting medium, encased in a cladding of lower index of refraction material.

than lower angle rays, and this takes more time. Consequently, a light pulse spreads as it travels through the fiber. Such pulse broadening is called *modal dispersion.* Dispersion varies with optical fiber types. Let's consider the subject in that context. First, let's describe the components of a fiber optic communication system, then focus attention on the fiber types themselves.

Fiber Optic Communication System

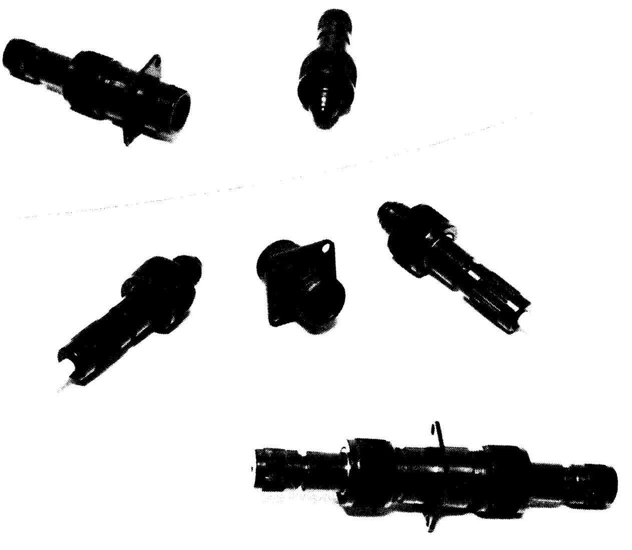


Figure XI-4
Deutsch Optical Waveguide Connector components (first generation).

Components

Like all communication systems, a fiber optic communication system has five basic parts:

1/ an information source which produces a message
2/ a transmitter which produces a signal suitable for transmission
3/ a channel serving as a medium
4/ a receiver performing the inverse operation of the transmitter
5/ a destination for which the message is intended

Figure XI-4 diagrams a typical fiber optic communication system.

Operation

After the information is encoded it modulates an optical signal which is transmitted through the optical fiber. At the receiver end, the signal-encoded wave is reconverted into an electrical signal and sent to the destination.

Optical Source/Transmitter

This component's function is to convert an electrical signal into an optical waveform. Its important parameters are:

power output,
fiber compatibility,
encoding bandwidth,
operational stability,
lifetime, and
cost.

The most widely used optical sources are the light-emitting diode (LED), and the laser diode.

Light-emitting diodes. A typical transmitter comprises such circuits as automatic gain control, oscillator, amplifiers, filters, driver and linearization network, plus a LED. The most commonly used source, the LED must be operated at a wavelength in the optical fiber's low-loss region: near 850 nm and above 1000 nm. LED's are easily modulated as their power output varies linearly with source drive current over a wide range. They offer: low drive voltage, small size, excellent brightness, and fast response time: varying their bias current rapidly varies their optical output. Their design usually optimizes speed or power. They can be configured for either digital or analog electrical input. The two most promising structures are the surface emitting LED and the edge emitting LED, with the latter coupling more power into the optical fiber. Lifetime for both is excellent with lifetimes of 100,000 hours projected.

Laser diodes. Because of their small active region laser diodes can be modulated at gigahertz rates. Their wider bandwidth means faster operation. More costly than LED's, they offer narrower spectral width, less dispersion, and lower coupling loss.

Optical Receiver

A receiver consists of a photo detector—typically a silicon PN junction photodiode—and an amplifier, filter, and demodulation electronics. The most critical parameter is usually noise performance. A PIN diode can provide better performance than a PN junction, and in high bandwidth applications, an avalanche detector yields an improved signal-to-noise ratio.

Cables

Because of their fragile nature, optical fibers must be protected by incorporation into a cable. Optical cable is simply a jacket (usually plastic) containing a buffered fiber (or bundle of fibers), often with a Kevlar (TM) strength member. This strength member is attached to the connector during cable termination in such a way that axial loads are not transmitted to the glass fiber. Except for the special need to avoid losses caused by excessive bending during use (and microbending during manufacturing), mechanical problems are similar to those in conventional cables, and severe testing has demonstrated entirely satisfactory performance.

Optical Fiber

The optical fiber is a core of transparent dielectric material surrounded by a second dielectric material of lower refractive index. For satisfactory optical isolation of the core, the cladding material has a minimum thickness of one or two wavelengths of the light transmitted.

The core may be either plastic or glass, as may the cladding. The properties of the various materials available vary widely; therefore, the type of fiber used must match the system's requirements.

Today's most popular materials are acrylic plastic with a plastic cladding, plastic clad silica (which has a glass core in a silicone plastic cladding) and chemical vapor deposition constructed fiber with a glass core and glass cladding. While the acrylic plastic fiber is by far the lowest cost, it is suitable only for short length systems where high attenuation is allowable.

Glass fibers are manufactured by melting preforms and drawing long lengths of small diameter fibers. It is nearly impossible to draw glass into a small fiber of perfect dimensions. Variations in the core diameter, cladding O.D., and the location of the core within the cladding, all add to losses. Having defined the basic components of a fiber optic communication system, let us return to our discussion of dispersion and different types of optical fibers.

Fiber Types and Dispersion

There are three basic kinds of optical fibers: the multimode step index, single-mode, and multimode graded index.

In the *multimode step-index* type, light travels by total internal reflection at the core-cladding surface. The cladding-to-core change in index of refraction has much to do with dispersion.

An analysis of the way light moves through this optical fiber shows a distribution of field solutions called *modes*. Differences in the way light rays move in these modes causes *modal dispersion*, a key limiting factor in fiber bandwidth.

Obviously, a photon that shoots straight down the center of the core gets there faster than one which ricochets from one interface to another. Because the direct route photon arrives sooner than the bouncing one—and because of time differences among other photons on intermediate paths—light rays starting out at the same instant arrive at different times. The original crisp well-defined light pulse gets smeared on the way. This dispersion means increased intersymbol interference (bit errors) in a pulsed-data (digital) system, and delay distortion in an analog system.

Reducing Dispersion

There are three ways to limit modal dispersion: make the core smaller, increase the wavelength, or cut the difference between the core and cladding indices of refraction. Decreasing the diameter of the core sufficiently produces a *single-mode fiber* which has no modal dispersion at all. With typical core and cladding refraction indices and source wavelength, the maximum diameter of such a core would be 2.6 micrometers. Although such a fiber provides the ultimate in bandwidth, it suffers such constraints that its application seems bound to remain limited. (A major problem: introducing light into such a small fiber.) The alternative is to reduce the differences between the refraction indices of the core and cladding. Of course, their ratio must remain less than one to maintain total internal refraction.

The multimode graded-index fiber provides a greater bandwidth capacity than the multimode step-index fiber. It is also easier to inject light into than the single-mode type. In the graded-index design, refractive index decreases linearly with increasing radius. Light propagates through refraction, a continuous bending of the rays toward the axis of the optical fiber. Light travels faster in the outer parts of the core, so there is less difference in arrival times: reduced dispersion, typically an order-of-magnitude improvement.

For short fibers, light dispersion is proportional to fiber length. But for sufficiently long fibers, the effect drops to the square root of increasing length, apparently because of the existence of harmonic equilibrium states among the different propagating modes.

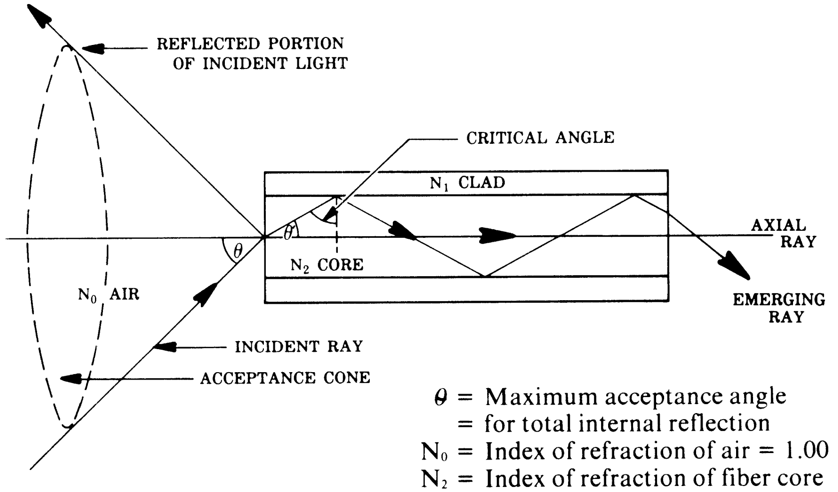
Effects of Wavelength

Material dispersion—caused by the variance in refractive index over the wavelength band—also limits fiber bandwidth. Depending upon their frequency, light waves travel at varying speeds through the fiber.

This is a problem because today's sources don't produce a single wavelength, but a broad spectrum of frequencies.

An early task must be to determine how much optical power you need to ensure an adequate signal-to-noise ratio. Because of system losses, only a fraction of the source's radiant power reaches the photodetector.

The Acceptance-Cone Half Angle Formula



θ = Maximum acceptance angle
= for total internal reflection
N_0 = Index of refraction of air = 1.00
N_2 = Index of refraction of fiber core
N_1 = Index of refraction of fiber cladding
NA = Numerical Aperture =

$$N_0 \sin \theta = \sqrt{N_2^2 - N_1^2}$$

Figure XI-5

Types of Optical Losses

Optical losses include: input-coupling losses, connector losses, fiber attenuation, and output coupling losses. Input losses are probably second only to fiber attenuation as a source of lost optical power.

The first input losses appear at the source/fiber interface. These are the result of mismatch between the source emitting area and the pigtail (a short fiber permanently bonded to the emitting area). They also result when the core area is smaller than the emitting area. Another input loss involves the light-accepting ability of the fiber. Only rays within the acceptance cone will be accepted, the remainder lost. The acceptance-cone half angle is defined by the numerical aperture by $N_0 \sin O \quad N_2^2 — N,^2$ (see Figure XI-6).

Total input loss is the sum of three losses: (1) unintercepted illumination (UI), which means inefficient operation caused by an emitter larger than the core. (2) Numerical Aperture loss: light rays whose angle of incidence are not within the fiber's acceptance cone. (3) Reflection: loss from the fiber end.

The important variables in these three kinds of input-coupling losses are:

1/ source emitting area
2/ fiber core area
3/ source angular emission pattern
4/ core/cladding refractive index ratio
5/ lateral and angular misalignment of fiber end
6/ separation of fiber end and emitting surface

The last mentioned form of UI loss is especially significant when the source is small, as such emitters invariably demonstrate highly divergent beam emission. Two good alternatives can essentially do away with such losses: (1) mount the fiber as close as possible to the fiber end*, or (2) buy a source with a pre-installed pigtail.

Having disposed of UI losses, the next input loss to handle is NA loss. Numerical aperture losses result because of the difference between the fiber's narrow acceptance-cone, and the highly divergent beams of both LED's and injection laser diodes.

*Separation of more than two to four times the core diameter (around 50 um) yields intolerable losses.

NA losses are large. A typical fiber with an acceptance angle of 14° (NA = 0.25) captures less than a third of total power. When the source area is smaller than the core area lensing techniques can reduce the loss.

Compared to NA losses, reflective losses are negligible. The amount of light energy reflected off the surface of the core end depends on the core's index of refraction. A 4% loss is typical.

Basics of System Design

The key parameters in designing fiber optic communications systems are bandwidth, length, and fiber attenuation. Connector loss can also be significant if many are required. Transmission dispersion is typically the limiting variable in signal bandwidth.

Length of transmission is determined by the power margin between the source and receiver. The power margin is the difference between transmitter optical output and minimum receiver input, in dB. Long transmission distances mean signal attenuation can degrade optical power to below the level needed to trigger the receiver photodiode.

Attenuation (expressed in dB/km) increases linearly with fiber length. Dispersion (pulse spreading) does too, out to an equilibrium point, but beyond which it increases with the square root of length. Over long transmission lengths time spreading (expressed in MHz/km) can approach that of bit time with consequent error in signal reading. As we have seen, graded index fiber reduces this effect. A fiber material with lower index of refraction does the same, but also reduces the numerical aperture, increasing losses in coupling to the optical source.

Each element in a fiber optical communication system has intrinsic losses. The designer must ensure that these accumulate losses (expressed in dB) do not reduce the optical energy below that of the receiver's sensitivity capability.

Choosing a Source

For maximum repeater spacing the source should be as intense as possible with an emitting area smaller than that of the fiber core area. The beam pattern should be highly directional and nearly monochromatic. Fast rise and fall times are necessary for high-capacity digital systems; linear power output for analog systems.

Solid-state laser diodes are best suited for digital systems. They offer a highly directional beam, very fast rise and fall times, narrow spectral linewidth, and high power output. However, they are more costly, have non-uniform characteristic curves, and are highly temperature dependent.

Light-emitting diodes are better suited for analog applications. Light output is a nearly linear function of drive current, they are inexpensive, and recent refinements—primarily reduction in emitting area—make them compatible with single-fiber systems.

The LED's optical emission wavelength must match the fiber optimum performance. LED's are constructed by combining elements from Columns III and V of the Periodic Chart. By varying these elemental mixtures, optical radiation is created in different wavelengths.

The LED's output radiation pattern must be considered. It must match the acceptance cone or numerical aperture of the fiber if light is to be efficiently sent into the fiber. Coupling efficiency is directly proportional to the square of the numerical aperture, the ratio of the acceptance area to the emission area, and reflection loss. Basically, the LED emitting and fiber receiving areas must be maximized.

Photodiode Specification

The basic problem is selecting a photodiode with sufficient active area to collect all optical energy emanating from the fiber. The principles are the same as in source to fiber coupling. The only loss mechanisms are reflection and angular alignment.

Most fiber optic systems use either PIN or avalanche photodiodes as receivers. When greater sensitivity is required, avalanche photodiodes are often used. Because of their internal gain mechanism, they offer a responsivity about an order of magnitude greater than PIN diodes. However, for most applications, they require some kind of automatic gain control, as gain is highly temperature dependent.

Connectors

The key road back to widespread use of single-fiber systems has been the lack of inexpensive, fast, efficient connectors. Only recently have affordable instruments become available which can provide the precision and speed necessary for practical high-performance interconnection.

Fiber Optic Interconnection

Cable strength members must be terminated within the connector so that any axial load is borne by the connector hardware and its mounting, and not transferred to the fiber.

Alignment considerations are the fundamental starting points in fiber optic connector design. For the mating of opposing fibers, each degree of freedom in alignment is responsible for an additive loss. These are: (1) lateral (coaxial) alignment, (2) gap (space between fiber ends), and (3) angular (angular difference between fiber axis).

Figure XI-6 displays the coupling loss in dB as a function of these three kinds of misalignments.

Most components are manufactured with a short optical fiber permanently attached, so the usual coupling problem is the interconnection of two fiber optic cables. Although distribution systems involve sending optical energy to or from a remote terminal, these are usually permanent connections, hence splicing problems. The purpose of an optical coupler is to bus the signals together, distribute the optical signal into multiple branches of a data transmission system. Today's couplers are custom items, either a "T" type, or a distributive star. By one of several construction methods, the inputs from numerous branches are mixed together and distributed to the output branches.

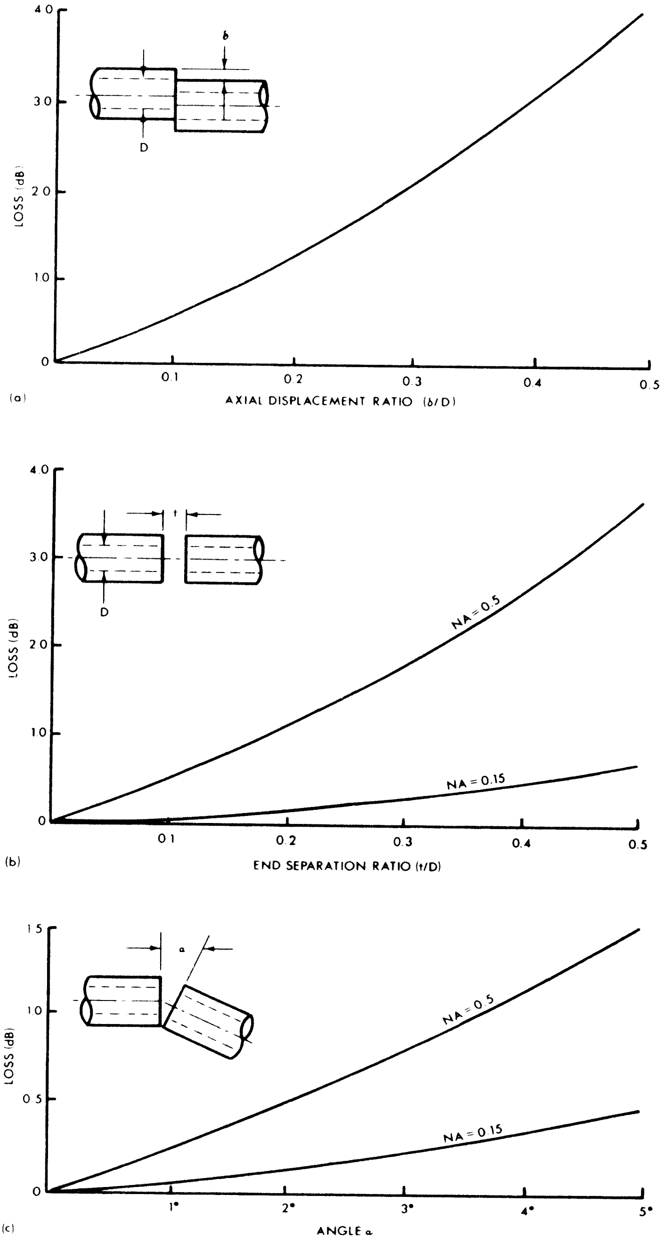
The real challenge in fiber optic interconnection is the need for repeated disconnection and reconnection. The difficulties are appreciable. Most connectors show relatively high coupling loss. This problem has been approached in five different ways.

Connector Types

In one plug-in connector the fiber end is bonded inside a tube of precise concentricity which is then cemented to a connector shell. This demonstrates adequately low losses (under 1.0 dB), but the demand for precise lateral and angular alignment is great, fiber ends must be polished, and time-consuming heat-curing of epoxies is required.

Figure XI-6

Misalignment Coupling Loss



A second approach uses three precision rods within a cylinder for precise alignment. However, this mechanical approach involves great difficulties in angular and lateral alignment, and even more serious ones in maintaining fiber end separation under a few microns—necessary for low connector loss.

A third technique uses a V-groove design to align the fiber within the connector jack. By using a deformable material for the V-groove and its cover good lateral and angular alignment is attained. Unlike the three-rod method, end-loading can be used to keep end separation losses low. A critical problem is material selection: it must be soft enough to accommodate a range of fiber diameters, but not so soft as to be easily scratched or subject to cold flow.

A fourth technique mates two eccentric plugs in a V-groove. The plugs are then rotated to achieve maximum light transfer. Its disadvantages are the need to polish the fiber ends and to tune each connector for low loss.

Perhaps the most promising approach—considered in detail in the following section—provides an optical solution for what is essentially an optical problem. Light is coupled between fibers by a compound lens formed of two fluid-filled conical cavities in a solid transparent medium. Fiber ends are inserted into the cavities, resting at the spherical apexes. The half-domes of fluid in front of each fiber end, along with the medium of selected refractive index, form a three-element compound lens which efficiently couples light from one fiber to the other. As losses in this type of connector are very sensitive to lateral offset of cone's apexes, the lens must be precision-molded in one self-aligned piece, with tolerances of a few micrometers. However, this reduces the usual need for extremely tight tolerances on other connector parts. Mismatched fiber outer diameters—a significant cause of loss in other connectors—is not a problem: the cone transforms a variation in fiber diameter into a longitudinal displacement of the fibers (see Figure XI-7).

Performance Parameters and the Optical Approach

The ideal optical connector:

1/ can be manufactured at low cost

2/ can be efficiently field applied without special techniques or training

3/ is durable, and environment-resistant
4/ provides less than 1.0 dB coupling loss

Longitudinal Displacement of Fibers

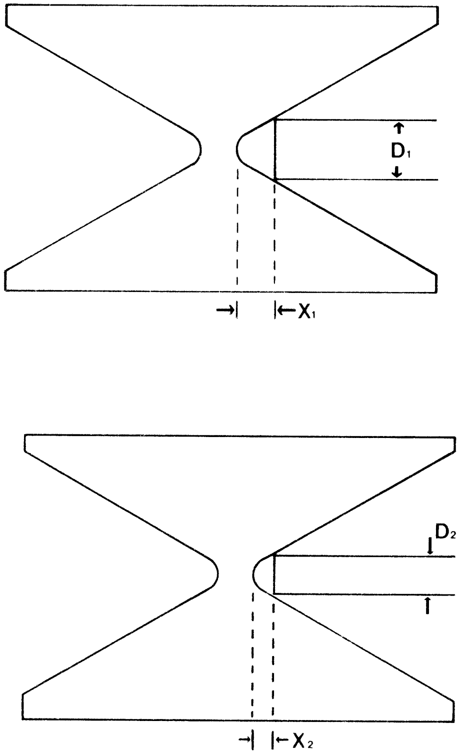


Figure XI-7
Cone transforming fiber diameter variation into longitudinal fiber displacement.

To meet such formidable design criteria it has been necessary to go beyond the mere mechanical mating of fiber ends. The design of the connection is viewed as an optical problem. In such an approach (briefly described above) a concave lens transfers light from fiber to fiber, surmounting the typical problems in mechanically mated devices. The optical approach has produced a detachable connector which:

1/ is field terminable in less than 10 minutes
2/ involves no grinding or polishing
3/ uses no chemical processing or epoxy
4/ accommodates fibers of varying physical and optical properties
5/ maintains integrity of fiber ends in connect-disconnect process
6/ requires no special fixtures
7/ provides less than 1.0 dB repeatable coupling losses
8/ is largely immune to the effects of minute sized particles
9/ makes displacement and angular alignment non-critical
10/ uses interchangeable plugs and receptacles
11/ meets environmental requirements of MIL-C-81511
12/ can be manufactured at reasonable cost in high volume

These numerous and important performance features are offered by what is essentially a simple connector. It consists of three pieces: two male connector plugs (which hold the fibers) and a central receptacle which houses the lens.

The Concave Lens Concept

The concave lens is provided by opposed conical cavities in a transparent medium (see Figure XI-8). The cavities' conical surfaces automatically align the fibers during insertion. The apexes of the conical cavities are spherical with diameters near that of the fiber. Each cavity contains a viscous index-of-refraction fluid. When the fiber is properly seated this fluid is sealed into the half-dome space in front of each fiber.

The result is a three-element compound lens. Such lens parameters as apex separation, surface radii, and fluid and molded lens indices-of-refraction are selected for optimal coupling. Thus, the compound lens is unique to each specific fiber type.

The Fluid Lens

Besides optical advantages, the system offers a number of mechanical advantages. The fluid provides hydraulic cushioning as well as

Concave Lens

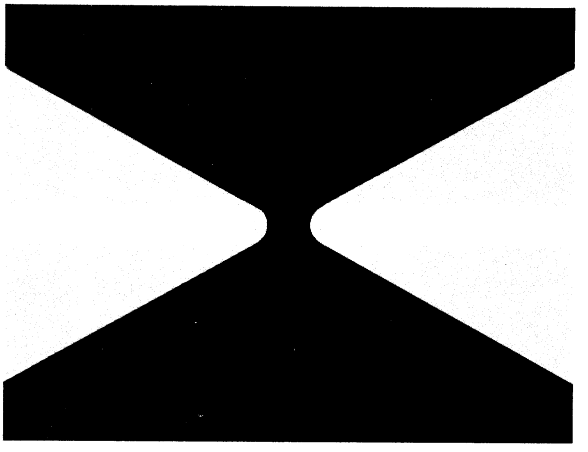


Figure XI-8
The concave lens is provided by opposed conical cavities in a transparent medium. The cavities' conical surfaces automatically align the fibers during insertion.

lubrication during fiber insertion, preventing damage to the fiber end during mating. Dust particles tend to float on the surface of the fluid minimizing abrasive damage. (Although glass has high tensile strength—up to 10^5 psi—its surface is easily abraded.)

The fluid is an integral part of the lens, introduced during production, not by the user. Contained by surface tension, the fluid will not flow out, even during severe shock and other forms of stress.

Unavoidable variation in fiber outside diameter is a significant source of loss in mechanically mated devices. Such variation in this case is transformed into a longitudinal displacement by the lens cones. Such displacement has negligible effect on coupling efficiency.

Figure XI-9 displays the losses caused by mechanical misalignments. Note the severe effect of lateral offset. This loss is controlled in this connector by the precision molding of the single self-aligning compound lens element. Such an insertion mechanism reduces the problem of mechanical alignment to one of angular control. Angular insertion need be accurate to only less than a half degree in order to produce an expected loss of less than 0.6 dB. Such angular control is easily accomplished.

Mechanical Misalignment Loss

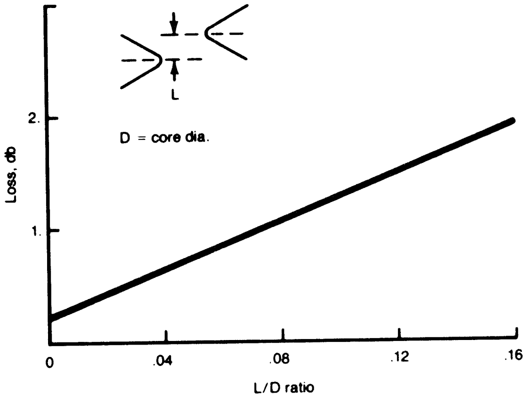


Figure XI-9
This loss is controlled in the connector by the precision molding of the single cell self-aligning compound lens element. Note the severe effect of lateral offset.

The Connector

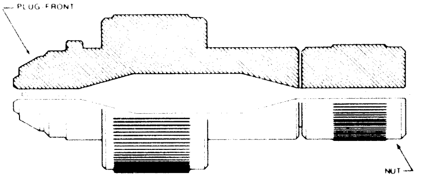
The connector plugs are a feed-thru type illustrated in Figure XI-10. The fiber feeds through the back of the plug, protruding through the front enough to allow the fiber ends to be prepared with a scribe-and-break process. Tightening a nut on the rear of the plug clamps the fiber with enough pressure to hold it firmly yet with negligible microbending loss.

In the scribe-and-break process, the connector is held in a tool which places the fiber under proper tension over a curved surface, scribes the fiber and breaks it, providing an optical quality fiber endface. Removing the plug from the tool allows the fiber to retract inside the plug and protrude only when the rear section of the plug is compressed during mating.

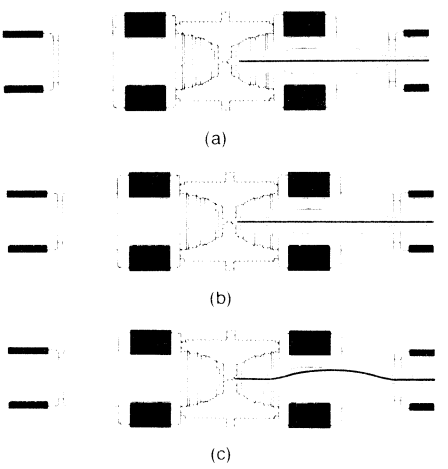
When the plugs are inserted into the receptacle, the plug tips align the floating lens (see Figure XI-11). As the coupling rings are tightened, the compression of the plugs' telescoping inserts causes the fibers to protrude from the plug tip and enter the lens cavity (see Figure XI-12). When the coupling rings are fully tightened, the fiber reaches bottom in the lens cavity. Excess fiber length accumulates in the chamber between the plug tip and the clamp on the plug's rear (see Figure XI-13). This provides forward pressure on the fiber for positive retention in the cavity, and allows the connector mechanism to be insensitive to longitudinal positioning of the fiber in the plugs.

Figure XI-10

Feed Thru Plug



XI-11, 12, 13



References

This chapter introduced you to the nomenclature and principles of fiber optic communication systems. The following materials are of use in actual system design:

1/ "Designer's Guide to Fiber Optics," 1978, Cahners Publishing Company, 221 Columbus Avenue, Boston, Ma. 02116.

2/ "Fiber Optics—From Devices to Systems," *Electronic Design,* October 25, 1978, Hayden Publishing Co., 50 Essex Street, Rochelle Park, NJ 07662.

3/ "Estimating When Fiber Optics Will Offer Greater 'Value in Use,' " *Electronics,* November 9, 1978.

4/ "Progress Report on Fibre-Optic Connectors," *Electronic Engineering,* Mid-October 1978.

5/ Fiber-Optics Communication: "1978 Handbook and Market Guide," Information Gatekeepers, Inc., 167 Corey Road, Brookline, Ma. 02146.