Designer's Guide to FIBER OPTICS

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Designer's Guide to: Fiber optics—Part 1

Fiber selection involves many tradeoffs, and you can choose wisely only when you understand the significance of fiber parameters.

Charles Kleekamp and **Bruce Metcalf**, Mitre Corp

While the principles are the same for the fiber-bundle technology currently employed for short runs, this series will highlight the single-fiber technology that promises much progress in medium- and long-haul applications. Presented from a user's viewpoint, it will answer these questions: What are the important parameters, and how do they affect system design and cost tradeoffs?

Although the task of assembling a fiber-optic link with hair-sized fibers shouldn't be underestimated, it's not as difficult as you might believe. In fiber optic communication-system design, several parameters enter into a designer's cost-vs-performance calculations; they can be grouped into three categories: the light source and associated drive circuitry, optical-fiber and mechanical-cable construction, and photodetector and receiver circuitry characteristics.

A firm understanding of these parameters is mandatory if you hope to select the appropriate components for your system. In this first installment, we'll discuss the parameters relating to optical fibers. While those fibers must be assembled into cable to find use in other than laboratory environments, we'll defer discussion of cable configurations until a later date.

Opposing total component costs are the performance limitations of an optical-fiber system. Bandwidth (dispersion) and optical power, the two constraints that introduce system limitations, define a system's repeater spacing. Because each repeater requires a back-to-back photodetector/transmitter arrangement, it's desirable to maximize repeater spacing (or better yet, eliminate the repeater requirement altogether).

Dispersion and attenuation figures thus govern the bandwidth and power limitations of optical fibers. As a system designer, you control these parameters, since you must pay premium prices for higher bandwidth and/or lower loss fiber cable. Note, however, that from a systems

Material in this series is based on work sponsored by the Electronic Systems Div of the US Air Force Systems Command.

◄ **An explosion of light** from these fiber-optic guides matches the burgeoning range of application possibilities for fiber optics. *(Photo courtesy Dupont Co)*

viewpoint, optical-power and bandwidth limits also depend on the light source (modulation rates, radiance, optical-coupling efficiency) and detector (responsivity, rise time, noise factors).

Dispersion traits vary with fiber type

Because the three basic fiber types (multimode step index, graded index and single mode) emerge naturally from such a discussion, it makes sense to begin with the phenomenon of dispersion in an optical fiber. The ***index of refraction*** (noted as n) is perhaps the best optical parameter to start with. Classically, it's defined (for both glass and plastic) as

$$n = c/v,$$

where c is the speed of light in vacuum (3×10^8 m/sec) and v its speed within the material.

An optical fiber's ***index profile*** refers to how its refractive index varies as a function of radial distance from the fiber's center. In a fiber with a ***step-index*** profile, the refractive index undergoes an abrupt change (step) in value at a radius r_c. The fiber's cross section thus divides into two regions: the circular central ***core*** and a surrounding annular ***cladding.***

Within a step-index fiber, optical-energy propagation occurs through total internal reflection at the core-cladding interface; thus the core index must be greater than the cladding index. Note that air, with an index of 1.00, could serve as the cladding medium. Core support, however, poses a practical problem. Looking ahead, it's important to consider a cladding with an index only slightly less than that of the core. Conventionally, the core and cladding indices are labeled n_1 and n_2 **(Fig 1).**

As you will see, the cladding-to-core-index ratio is a prime factor in determining the dispersion of an optical pulse. Established by the manufacturer's choice of materials and dopants, core and cladding indices are typically $n_1=1.48$ and $n_2=1.46$.

As with a metallic waveguide, a rigorous analysis of energy propagation within an optical fiber involves the electromagnetic field solutions to Maxwell's equations and associated boundary conditions. The analysis is profound; it shows the propagating energy distributed among a discrete set of superposed field solutions called ***modes.*** Differences in the propagation characteristics of these modes give rise to ***modal dispersion,*** which is one factor that limits a fiber's bandwidth.

Why, and why now?

Fiber optics will soon have a major impact on the electronics industry. The technology is far from new, but recent developments in low loss single-fiber cable promise at long last to make fiber optics a viable alternative to copper wire in the telecommunications market.

Witness the telephone experiments underway in various countries (notably England and the US). The size of this and other more specialized market segments of the fiber-optics business is growing exponentially and will soon be a major employer of EE's.

Major stumbling blocks to fiber-optic usage have recently been removed or are in the process of being resolved. The bundle-vs-single-fiber struggle appears to be over, with single fibers emerging as the winner in long-haul communications systems (see **box** elsewhere in this article). According to industry sources, the lack of low cost single-fiber connectors should soon cease to be a problem. Most importantly, an independent industry/user group (Fiber Optic Communication and Information Society—FOCIS) is attacking the problem of standardization of cables and connectors.

For these reasons, EDN launches with this article a major 4-part design tutorial on fiber optics. The authors are industry experts who have taught this material to technical personnel in the military. EDN will build upon the material presented in this series with other product and design articles throughout the year. We welcome your feedback to our efforts. *—WP*

To maintain simplicity, we use a geometrical-ray approach in the following example of how modal dispersion affects fiber bandwidth. The 1-km fiber shown in **Fig 2** has core and cladding indices of $n_1=1.48$ and $n_2=1.46$ and a core diameter of 50 μm. From Snell's law, the minimum angle that supports total internal reflection is

$$\sin\theta_{min} = n_2/n_1$$

$$\theta_{min} = 80.6°.$$

Rays striking the core-cladding interface at angles less than 80.6° will be lost in the cladding. With the geometry of **Fig 2,** calculations yield a total path length of 1014m. Comparing the bouncing ray's path with that of another ray that

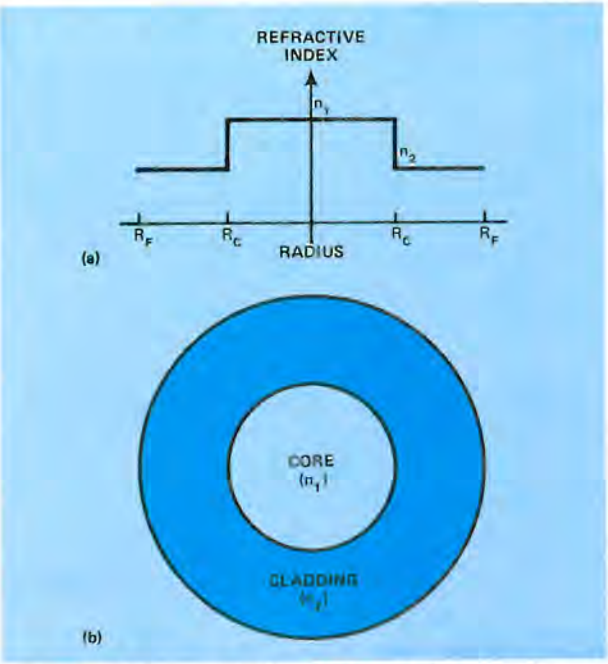

Fig 1—The index profile takes a downward step at the core radius **(a)** in a step-index optical fiber. This step divides the fiber's cross section **(b)** into a central core with index n_1 and a surrounding cladding with index n_2.

propagates straight down the central axis of the fiber produces a path difference of 14m. The speed at which these light rays travel along their paths is

$$v = c/n_1 = \frac{3 \times 10^8 \text{m/sec}}{1.48} = 2.03 \times 10^8 \text{m/sec.}$$

Thus, if both rays start out at the same instant, the bouncing ray reaches the end of the fiber about 69 nsec after the axial ray. The temporal delay (dispersion) in the arrival times of these two rays, as well as those of rays traveling intermediate paths, produces increased bit smearing or intersymbol interference in a pulsed-data system and delay distortion in an analog-modulated system. Regarding the reciprocal of the relative time delay as an order-of-magnitude estimate of the modal dispersion-limited bandwidth yields a figure of 14.5 MHz.

Because of the numerous propagation modes it accommodates, this fiber is properly termed a ***multimode step-index*** type. Field-analysis calculations yield an interesting parameter called the ***normalized frequency*** V, defined as

$$V = \frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2}$$

where d is the fiber core diameter and λ is the wavelength of the optical source. You can use the ***mode volume*** formula ($N=V^2/2$) to estimate the number of propagating modes in a step-index fiber; for the fiber illustrated in **Fig 2,** this number is well over 1000.

There's an alternative solution

Mode volume must be reduced to limit modal dispersion. The normalized-frequency formula suggests three ways to accomplish such a reduction: reduce the core diameter, increase the wavelength or decrease the difference between

TYPICAL FIBER-OPTIC CABLE OFFERINGS

MANUFACTURER	PRODUCT NUMBER	CORE/CLAD MATERIAL	CORE DIA (μm)	FIBER DIA[2] (μm)	ATTENUATION (dB/km)	INDEX PROFILE	CORE INDEX[1,2]	BANDWIDTH/ PULSE DISPERSION[2]	NUMERICAL APERTURE[2]	JACKETING MATERIAL[2]
CORNING	1053 1051	GLASS GLASS	62.5 62.5	125 125	5 @ 0.82 μm 5 @ 0.82 μm	GRADED GRADED	NA NA	400 MHz-km 200 MHz-km	0.21 (12°) 0.24 (14°)	LACQUER LACQUER
duPONT	PFX-S120R	GLASS/ PLASTIC	200	600	50 @ 0.82 μm	STEP	1.456	NA	0.40 (24°)	NA
TIMES FIBER COMMUNICATIONS INC	GA10-90 SINGLE MODE	GLASS GLASS	90 2.5	125 40	15 @ 0.80 μm 250 @ 0.63 μm	GRADED SINGLE MODE (STEP)	1.45 1.45	300 MHz-km NA	0.16 (9°) 0.10-0.12 (6°)	FLUORO-CARBON POLYESTER
FIBEROPTIC CABLE CORP	Q1-1-10	GLASS	250	NA	20 @ 0.82 μm	STEP	1.45	30 nSEC/km	0.25 (14°)	HYTREL
GALILEO	GALITE 4000A (1P)	GLASS/ PLASTIC	100	200	40 @ 0.82 μm	STEP	1.45	NA	0.35 (20°)	PVC
ITT	GS-02-12 GG-02-12	GLASS GLASS	50 50	125 125	12 @ 0.85 μm 12 @ 0.85 μm	STEP GRADED	1.48 1.48	15 nSEC/km 2.5 nSEC/km	0.25 (14°) 0.25 (14°)	HYTREL HYTREL
VALTEC CORP	MS-05 MG-05 SM-10	GLASS GLASS GLASS	65 65 5-15	125 125 100	10 @ 0.82 μm 20 @ 0.82 μm 20 @ 0.82 μm	STEP GRADED SINGLE MODE	NA NA NA	30 nSEC/km 10 nSEC/km 1 nSEC/km	0.20 (11°) 0.20 (11°) NA	NA NA NA
QUARTZ PRODUCTS CORP	QSF-A-200	GLASS/ PLASTIC	200	400	3 @ 0.85 μm	STEP	1.45	30 nSEC/km	0.22 (13°)	TEFZEL

NOTES:

(1) FOR STEP-INDEX FIBERS. AXIAL INDEX FOR GRADED FIBERS

(2) NA = NOT AVAILABLE

SOURCE: AUTHORS

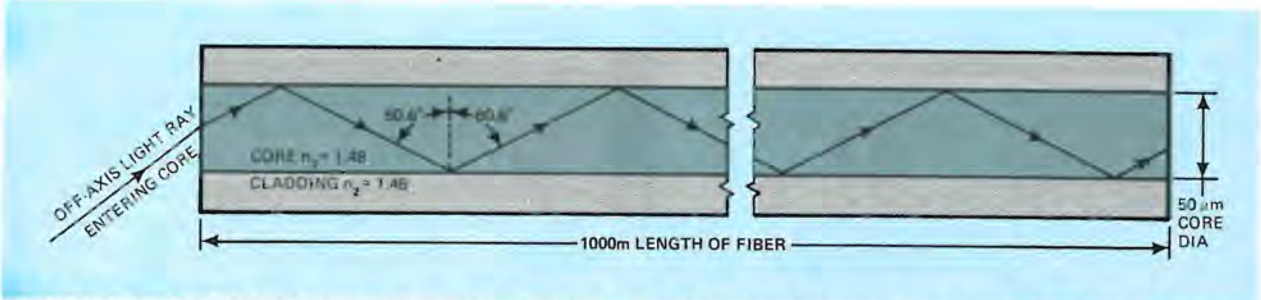

Fig 2—Reflecting back into the core each time it strikes the core-cladding interface, an off-axis light ray follows a zig-zag path 1014m long. Compared with an axial ray, this extra 14m produces an arrival-time difference of 69 nsec.

the core and cladding indices.

Absorption in the glass, which would increase attenuation, limits any increase in wavelength. Decreasing the core diameter is an interesting concept because studies indicate that if V is <2.405, only a single mode (an axial ray) can propagate. Called a ***single-mode*** fiber, such a design exhibits no modal dispersion at all. Maintaining the previous values for the core and cladding indices, and with a source wavelength of 0.82 μm, we see that maximum core diameter equals 2.6 μm for such a fiber.

While this fiber type offers the ultimate in bandwidth, it suffers from the extreme difficulties associated with projecting light into such a small core and the problem of core alignment in making a fiber-to-fiber splice. To relieve this small-core-size constraint, the final alternative is to make n_1/n_2 as small as practical. Of course, the ratio must remain >1 to maintain total internal reflection.

The product is out there waiting

If you would like to get your hands on the fibers described in the nearby **table,** contact the manufacturers listed below. The **table** highlights some (but definitely not all) of their fiber-product offerings.

Corning Glass Works
Telecommunications Dept
Corning, NY 14830
(607) 974-8812
Dupont Co
Plastic Products & Resins Dept
Wilmington, DE 19898
(302) 774-7850
Fiberoptic Cable Corp
Box 1492
Framingham, MA 01701
(617) 875-5530
Galileo Electro-Optics Corp
Galileo Park
Sturbridge, MA 01518
(617) 347-9191
General Cable Corp
500 W Putnam Ave
Greenwich, CT 06830
(203) 661-0100
ITT
Electro-Optical Products Div
Roanoke, VA 24019
(703) 563-0371
Quartz Products Corp
688 Somerset St
Plainfield, NJ 07061
(201) 757-4545
Times Fiber Communications Inc
358 Hall Ave
Wallingford CT 06492
(203) 265-2361
Valtec Corp
Electro Fiberoptics Div
West Boylston, MA 01583
(617) 835-6083

Here's the best solution

The ***graded-index*** fiber, the third available type, satisfies system requirements calling for bandwidths beyond the capability of multimode step-index fibers. At the same time, the graded-index fiber does not impose the coupling problems of the single-mode variety.

In the graded-index design, refractive index decreases continuously with radial distance from the center of the fiber. Light propagation occurs through refraction, a continual bending of the ray toward the fiber's optical axis. As such a fiber's profile illustrates **(Fig 3),** light travels faster in the lower index regions (at the outer extremities of the core), resulting in reduced differences in arrival time and less dispersion.

For minimal modal dispersion, analysis shows that the optimum profile for a graded-index fiber is nearly parabolic, and most available graded fibers have such profiles. Conventionally, the refractive-index value on the central axis is denoted by n_1 and tapers off parabolically with radial distance to the value n_2 at the outer radius.

What goes in doesn't always come out

Impulse response is one measure of dispersion within an optical fiber. With this technique, narrow light pulses are projected into the fiber, and the pulse-width spread is measured as a function of fiber length. Theory shows that the impulse-response width resulting from modal dispersion is a function of the difference between the core and cladding indices.

The modal impulse-response width for a step-index fiber varies linearly with this difference; for a graded-index fiber, the width is proportional to

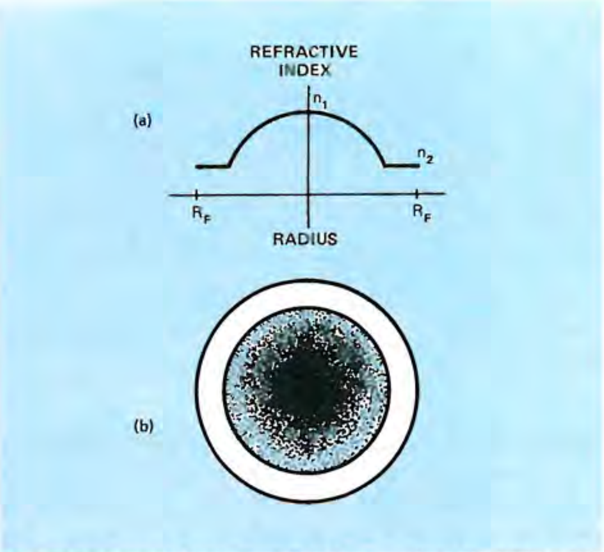

Fig 3—The graded-index profile tapers off parabolically with radius from its central-axis value n_1 to a lower value n_2 at the fiber radius r_f **(a).** The cross section **(b)** shows that light travels slower near the shaded center region than it does away from the center, resulting in more consistent arrival time and less dispersion.

the square of the index difference. Because this difference is generally quite small (typically 0.02), a graded-index profile achieves a considerable reduction in pulse broadening. In practice, approximately an order-of-magnitude improvement has resulted. For example, ITT's GS-02-8 step-index fiber has a 3 dB dispersion spec of 15 nsec/km, while the firm's graded-index GG-02-8 product sports a 2.5-nsec/km dispersion spec.

Specifying dispersion in nanoseconds per kilometer implies that pulse broadening is proportional to fiber length. However, for sufficiently long fibers, this effect is actually proportional to the square root of the fiber length. Theorists have attributed this apparent incongruity to an equilibrium-state energy exchange (or coupling) between the various propagating modes, resulting from index inhomogeneities, diameter nonuniformity or stresses within the cabled fiber.

Thus, pulse broadening varies linearly with fiber length L for lengths less than the ***coupling length*** L_C and is proportional to $\sqrt{LL_C}$ for lengths greater than L_C. Actually, mode coupling tends to improve modal-dispersion effects. However, it does increase attenuation, because some of the propagating energy couples into radiation or cladding modes, which are lossy.

The unique characteristics of the fiber and cable construction define the mode-coupling length. Unfortunately, while its value is usually greater than 1 km, L_C is not usually specified on manufacturers' fiber and cable data sheets. Ironically, because the equilibrium length will increase in future products, this dispersion enhancement

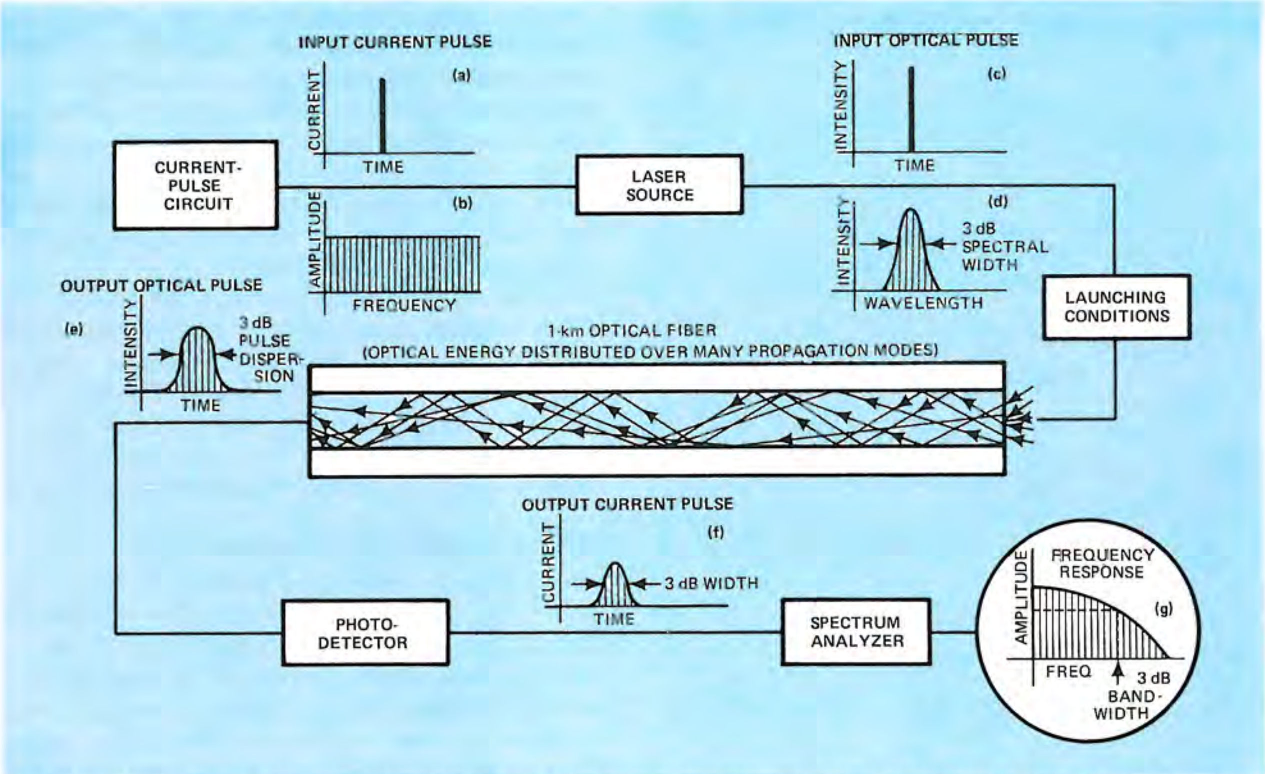

Fig 4—Impulse-response measurements determine the bandwidth of an optical fiber. Narrow time-domain electrical pulses **(a)** with a flat spectrum in the frequency domain **(b)** are converted to light pulses **(c)** with a wavelength distribution characteristic of the laser source **(d).** Depending on the input conditions, light energy propagates through many modes of the fiber under test. Because of modal and material dispersion, the output light pulse spreads with time **(e)** and is photodetected as a widened current pulse **(f).** A frequency-domain analysis then yields the fiber's 3 dB bandwidth **(g).**

will suffer from improved fiber-manufacturing control.

Wavelength is also a factor

Material dispersion, arising from the wavelength dependence of the refractive index, is an additional factor that contributes to the limitation of fiber bandwidth. Practical sources used in today's fiber-optic communication systems emit light over a band of wavelengths—not just one. If the refractive index isn't linear over this wavelength band, material dispersion tends to distort the optical signal. The result? Different optical frequencies travel at varying relative speeds within the fiber.

Material dispersion's effect on the rms impulse response depends nonlinearly on the second derivative of the refractive index with respect to wavelength and also on the wavelength and spectral width of the source. Note that while single-mode fiber is free from modal dispersion, pulse broadening can result from material dispersion. For glass fibers, minimum material dispersion occurs at source wavelengths between 1.2 and 1.3 μm.

Optical fiber's available bandwidth is usually specified by manufacturers as either a bandwidth-length product, with units of megahertz-kilometers, or a pulse dispersion denoted in nanoseconds per kilometer. The basis of this measurement **(Fig 4)** is to send a pulse (or series of pulses) of very short duration into the fiber and observe the output. The ideal impulse consists of a flat frequency spectrum, but after the pulse travels within the fiber, its frequency content changes.

Manufacturers typically identify the 3 dB frequency (fiber bandwidth) by taking the Fourier transform of the fiber output, and sometimes they provide a complete frequency-response curve **(Fig 5).** The two fibers described in **Fig 5** have bandwidths of 200 and 400 MHz for a 1-km length; in a 5-km link, the 3 dB points would be 40 and 80 MHz, respectively, for a monochromatic

A short history of fiber optics

When fabricating decorative glassware, Renaissance Venetian glassblowers could have recognized that light follows a curved transparent medium. However, John Tyndall was the first to rigorously demonstrate this principle in a presentation to the British Royal Society in 1870. He showed that light was conducted in a curved path along an illuminated stream of water flowing from a hole in the side of a tank **(Ref 1).** This experiment illustrated the concept of total internal reflection, wherein light rays propagate by reflection off the boundaries of a medium and escape primarily at the opposite end of the "conductor."

Alexander Graham Bell was another early experimenter; in 1880, he studied the possibility of transmitting speech on a beam of light to a device called a photophone. By 1910, theoretical studies had been completed by Hondros and Debye on dielectric waveguides **(Ref 2).**

While the transmission of optical waves was investigated in the 1920's and '30's, these ideas were not pursued actively until the 1950's, when VanHeel, Hopkins and Kapany developed the flexible fiberscope, now widely used in medicine. During this period, Kapany invented the practical glass-coated glass fiber and coined the term fiber optics **(Ref 3).**

Cladded fiber was then extensively investigated, and K C Kao and G A Hockham, researchers at the Standard Telecommunications Laboratories in England, proposed that this type of waveguide could form the basis of a new communications medium **(Ref 2).** At this time (1967), typical attenuations measured more than 1000 dB/km, and researchers focused attention on reducing these losses.

Just three years later, the breakthrough came when investigators Kapron, Keck and Maurer at Corning Glass Works, Corning, NY announced achievement of losses less than 20 dB/km in fibers hundreds of meters long **(Ref 4).** Currently, practical off-the-shelf fiber cables evidence typical losses of 6 dB/km; at premium prices, you can purchase cables with attenuation as low as 3 dB/km.

Now fiber manufacturers are concentrating their efforts on reducing the dispersion (pulse spreading) characteristics that limit the bandwidth or information capacity of this medium. In practice, you will be interested in determining both the loss-limited and dispersion-limited length of a fiber from specified parameters. The system operating length will then be established by these limitations.

References

1. Kapany, N S, Fiber Optics Principles and Applications, Academic Press, 1967, pg 1.

2. Ramsay, M M, Hockham, K A, Kao, K C, "Propagation in Optical Fiber Waveguides," Electrical Communications, Vol 50, No 5, 1975, pg 162.

3. Ref 1, pg 2.

4. Miller, S E, Marcatil, E A J, Li, T, "Research Toward Optical-Fiber Transmission Systems," Proceedings IEEE, Vol 61, Dec 1973, pg 1703-1751.

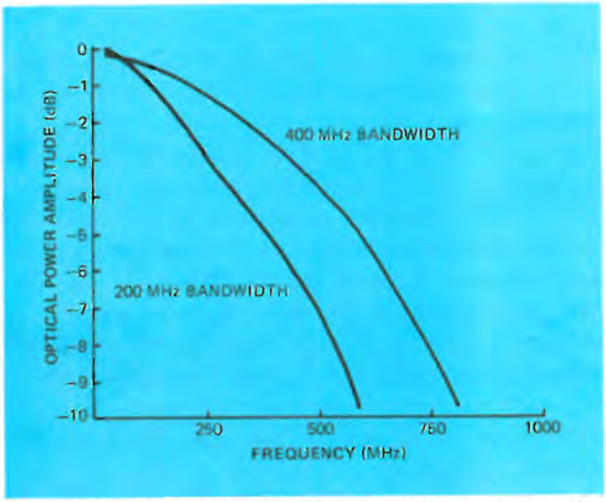

Fig 5—A fiber's 3 dB frequency is identified by taking the Fourier transform of the output signal. Specs are usually quoted for 1-km fiber lengths.

source. Be aware of the type of source used in the impulse-response measurement and the launching conditions used in injecting light into the core.

Shedding some light on system losses

When estimating the total loss budget of a system, you must first determine the optical power needed at the photodetector to ensure an appropriate signal-to-noise ratio (SNR) or bit error rate (BER). Because of various optical losses between the transmitter and receiver, only a fraction of the source's total radiant power reaches the photodetector. You can divide these optical losses into input-coupling losses, connector/splice losses, fiber attenuation and output-coupling losses.

Input-coupling losses occur at the source/fiber interface. Usually, a short length of fiber (called a pigtail) is permanently attached to the source's emitting area in single-fiber communications. Any mismatch between this emitting area and the pigtail's core area results in the first input-coupling loss factor. Additional loss occurs if the core area is smaller than the source-emitting area. A rough value of this fractional loss is simply the ratio of the core area to the emitting area.

Single fibers vs fiber bundles

Several years ago, designers working with fiber-optic cables used bundle designs because they simply had no other practical choice. But developments in single-fiber technology have been so fast and so significant that within the past six months the trend for most applications has clearly swung toward using one channel for each fiber. Because no reversal of this trend is predicted (it can only become more pronounced), the focus of this series lies squarely on single-fiber technology.

Nevertheless, bundle type multiple-fiber cable is not dead and shouldn't be ignored by designers. In particular, bundles are by far the best medium for either collecting or distributing light either at random or in a formatted mode. Scanners, card readers and medical instruments all take advantage of bundles' greater energy (from very economical sources).

Furthermore, bundles and their associated connectors currently have a significant price advantage over their single-fiber counterparts. Thus, telecommunications systems that must become economic realities now must use bundles over even moderate distances (up to 500 ft or so). In five or ten years, however, it's likely that the market for fiber-optic bundles will become a custom-design business. *—WP*

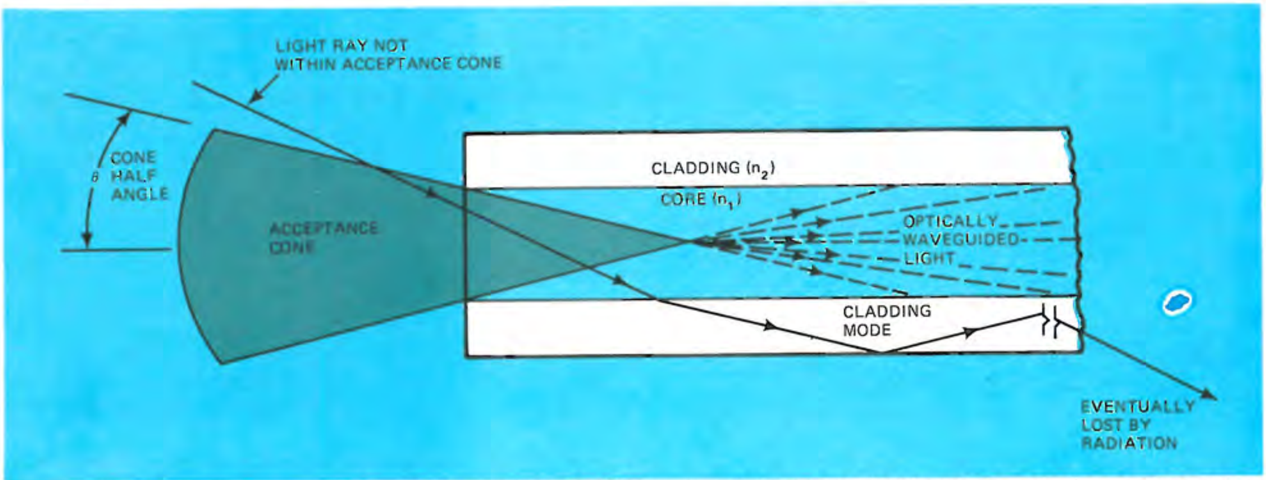

Fig 6—A fiber's acceptance-cone half angle derives from the fiber's numerical aperture. Light projected into the acceptance cone undergoes waveguiding in the core, while rays outside the cone reflect into the cladding and are eventually lost.

A second input-coupling loss factor relates to the light-gathering ability of the fibers themselves. The ***numerical aperture*** (NA), which defines the ***acceptance-cone*** half angle θ of the fiber, is the important parameter here. Light waves injected at angles within this cone will be waveguided, while rays entering the core at steeper angles will be lost **(Fig 6).** The numerical aperture is related to the acceptance-cone half angle by $NA=\sin\theta$. (For step-index fibers, NA is also equal to $\sqrt{n_1^2 - n_2^2}$.) For example, a numerical aperture of 0.25 gives an acceptance-cone half angle of $\theta=\sin^{-1}(0.25)=14.5°$.

You can't evaluate the NA input-coupling loss without a knowledge of the source's emission profile. We'll discuss this factor further in the next installment of this series.

An additional input-coupling loss, termed the ***packing fraction,*** occurs when you're working with a fiber-bundle cable (many fibers grouped together and illuminated by one light source). This loss is measured by the ratio of the collective core areas of the fibers to the total bundle cross-sectional area; ten times the log of this ratio gives the packing-fraction loss in dB.

The last, and least important, input-coupling loss comes from light reflection from the input end of the fiber. A relatively small loss, it usually equals about 0.2 dB.

At the receiving end of the link, output-coupling losses are generally not as severe as input losses. A conservative estimate pegs total output losses at approximately 1 dB.

Between the system input and output occur fiber-attenuation losses as well as those arising in splices and connectors (to be discussed in a future installment). Light attenuation within the fiber results from scattering and optical absorption. Wavelength dependent, the fiber attenuation is also usually specified in terms of decibels per kilometer.

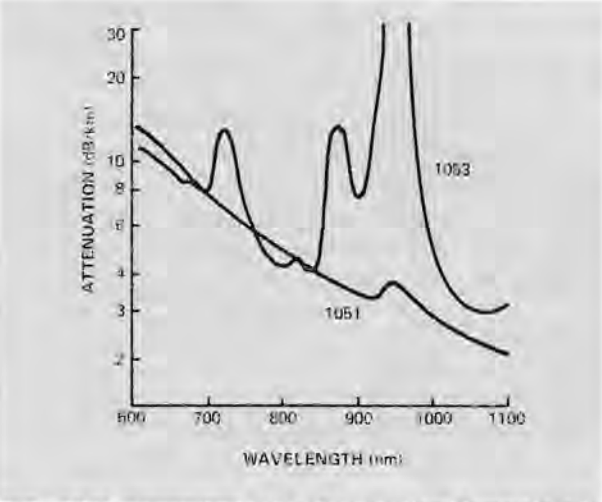

Fig 7—Fiber attenuation varies dramatically with wavelength, so good overall system performance requires a good match between source and fiber characteristics.

To minimize the fiber loss, select a source whose wavelength falls in an area where fiber attenuation is low. An attenuation-vs-wavelength profile for two of Corning's Corguide products **(Fig 7)** illustrates this point; at a typical source wavelength of 820 nm, these fibers exhibit an attenuation of only 5 dB/km, and between 1000 and 1100 nm the losses are even smaller.

There's still a lot of ground to cover

This first part of our series has covered most of the design parameters related to the optical fibers themselves. At this stage, the story of fiber-optic system design is far from complete. If you're wondering how all these parameters fit into the total systems picture, look forward to future installments, which will tie the loose ends together with discussions of source and detector characteristics, circuitry, overall system-design methodology and practical handling hints from our own experience. □

Authors' biographies

Charles Kleekamp, a Technical Staff member at the Mitre Corp, Bedford, MA, has helped to design broadband communication systems and is currently exploring high-payoff applications for fiber-optic systems. He holds Bachelor's degrees in electrical engineering and mathematics and a Master's degree in instrumentation engineering from the University of Michigan. A registered PE, Chuck has extensive experience in designing hybrid computers, minicomputer interface hardware and industrial process-control systems.

Bruce Metcalf is also a member of the Technical Staff at the Mitre Corp; his work focuses on performance and operational limitations of coaxial-cable communication systems. He is currently assigned to the Mitre/ESD Fiber Optic Technology Applications Program. Bruce graduated with distinction from Wayne State University with a BS in mathematics and physics and received his MS and PhD in statistical and thermal physics from Ohio State University.

Designer's Guide to: Fiber optics— Part 2

Proper fiber selection is just the first step in your system design. There remains the matter of choosing the correct source and detector.

Charles Kleekamp and **Bruce Metcalf,** Mitre Corp

In the first installment of this series, we concentrated on the parameters of optical-fiber transmission media. Our purpose was to give you an understanding of communication-link limitations with respect to optical power loss and dispersion in various types of fiber. However, the picture is not complete until we also discuss the characteristics of optical sources and detectors.

Before jumping into the specifics of sources, however, let's consider the parameters that affect input-coupling efficiency and learn something about calculating the losses related to that parameter.

Where does all the light go?

Perhaps second only to fiber attenuation, input coupling contributes most to system loss. When such losses occur, only a fraction of the source's total radiant power is actually coupled into the fiber and waveguided. You can categorize these losses as follows:

- Unintercepted-illumination (UI) loss resulting from an area mismatch between the source's illumination spot (in the plane of the fiber end) and the fiber core area
- Numerical-aperture (NA) loss arising from light rays with angles of incidence not within the fiber's acceptance cone
- Reflection (R) loss from the end of the fiber.

In general, input-coupling-loss magnitude depends on the geometrical and optical characteristics of the source and fiber. Highly significant are parameters such as source emitting area and angular emission profile, fiber core area, refractive index and numerical aperture, and the separation between the emitting surface and the fiber end.

Material in this series is based on work sponsored by the Electronic Systems Div of the US Air Force Systems Command under contract F19628-78-C-0001.

Area mismatch will cause problems

If the source's emitting surface area is larger than the fiber core area, all of the light can't be coupled into the waveguide. This ***unintercepted illumination*** results in very inefficient operation at

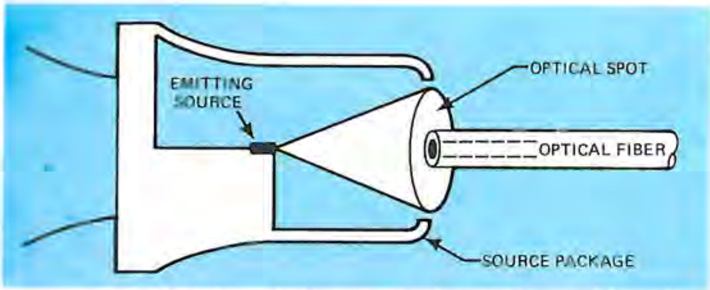

Fig 1—Unintercepted illumination loss can be a problem when the light-emitting surface is separated from the end of the fiber core. You can minimize this loss, however, by using an uncapped source diode or one with a "pigtail" already installed by the manufacturer.

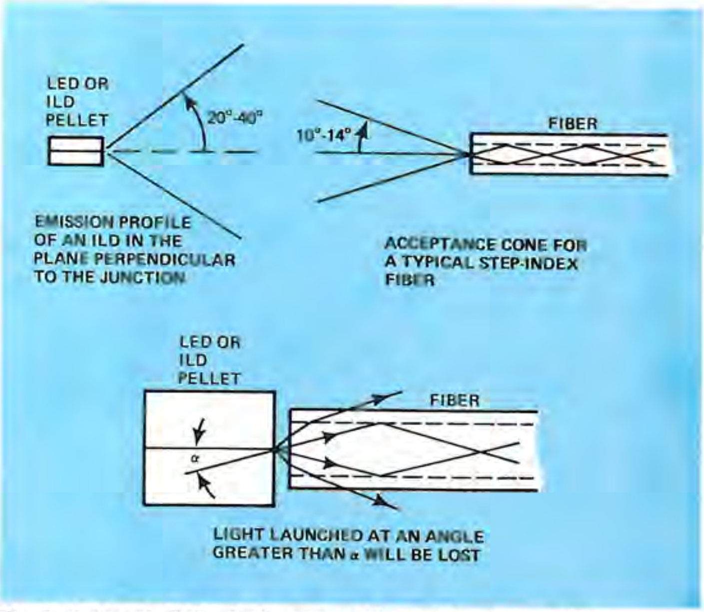

Fig 2—Lots of light isn't necessarily a blessing at the source-fiber interface. Both LED's and ILD's have broadly divergent emission beams, and all light radiated outside of the fiber's acceptance-cone angle contributes to numerical-aperture loss.

best. And unfortunately, you can't use an intermediate lens to ease this situation, because such a lens can't focus all the light into the core. (The brightness of an image can't exceed that of the source, as the law of brightness **(Ref 1)** states. Therefore, choose a source whose emitter is no larger than the core. Fortunately, there are now both LED's and ILD's (injection laser diodes) that qualify.

When the source is smaller than the core, you still might have problems with unintercepted illumination. Any separation between the elements allows emitted light to miss the core **(Fig 1)** and be lost. An approximation of this loss, expressed in dB, is given **(Ref 2)** by

$$\text{UI loss} = 10 \log \frac{A_C}{A_S},$$

where A_C is the fiber core area and A_S the area of the source's projected optical spot in the plane of the fiber end.

In summary, the magnitude of UI loss depends on the source's angular emission profile, the distance between the source's emitting surface and the fiber end (a factor determined by source packaging), and the core's diameter.

All small sources have rapidly divergent beams. To avoid intolerable losses, the separation between emitting surface and fiber end can be no more than about 2 to 4× the core diameter (typically 50 μm). Thus you can't use a glass-capped diode, since its source pellet typically lies 1 or 2 mm in back of its window. Instead, buy either an uncapped diode and mount the fiber as closely as possible to the emitting surface, or obtain a source with a "pigtail" already installed by the manufacturer. (There are few standards here—most are made on a custom basis.) Either alternative essentially eliminates UI loss.

Launch profile is also important

Having overcome UI loss, you must next consider reduced performance arising from numerical aperture (NA) loss. In this situation **(Fig 2),** considerable light is lost because of the conflict between the relatively small acceptance-cone angle of a fiber (half angle of approximately 10 to 14°) and the broad divergence of both LED and ILD emission beams.

You can estimate input-coupling efficiency (hence NA loss) rather simply. However, first you must mathematically describe the source-beam profile. Unfortunately, manufacturers don't always give you this information (at least in the form you need it). But it's not that difficult to deduce from the somewhat sketchy specs usually supplied.

Typically, manufacturers plot the source-beam pattern on a polar diagram. They derive the curves by measuring the relative radiant intensity on a small detector that swings through a 180° arc. For example, the intensity of a uniform surface emitter varies with the cosine of the angle between the line perpendicular to it and another line to the observation point **(Fig 3a).** You can express the emission power profile of this ***Lambertian source*** as

$$P = P_0 \cos \phi,$$

where P_0 is the radiant intensity along the line $\phi=0$.

Some sources exhibit narrower beam patterns that you can express to a reasonable approximation by

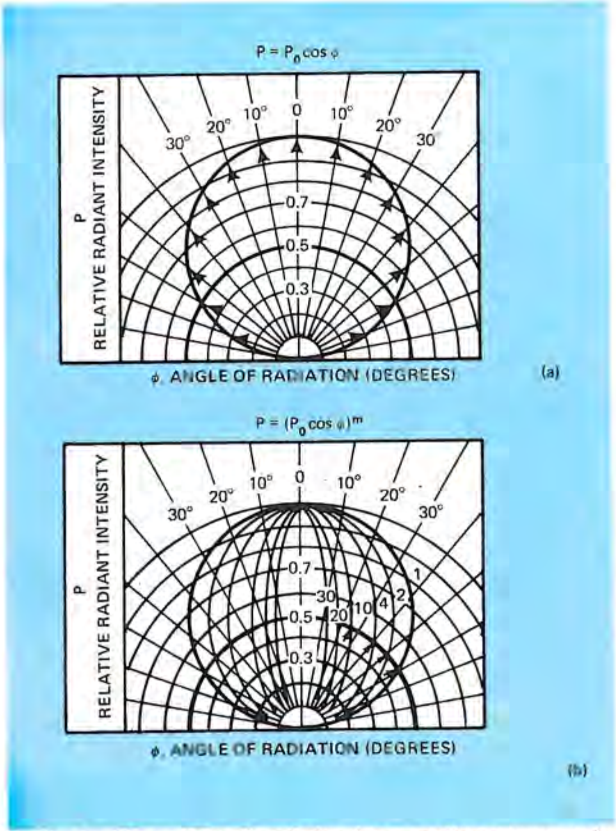

Fig 3—A wide variety of emission-beam patterns appears in sources available today. While uniform surface emitters typically have Lambertian-type profiles **(a)**, some sources **(b)** exhibit much narrower beam profiles.

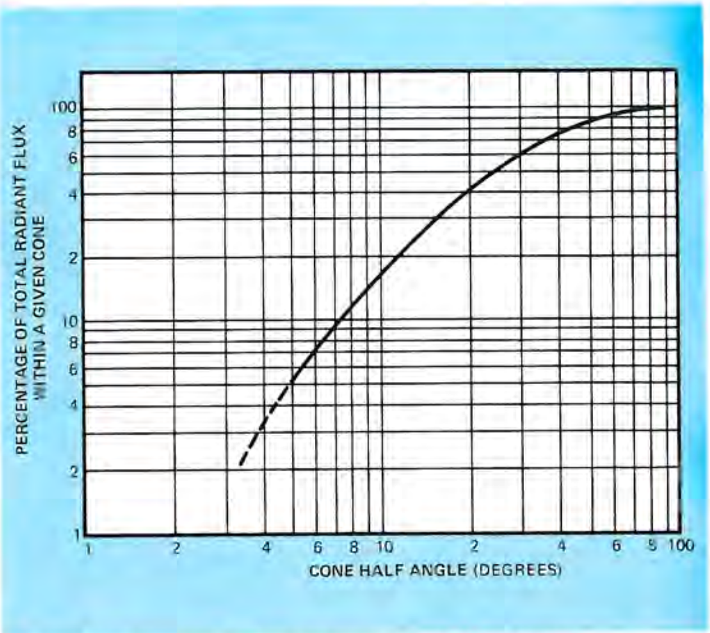

Fig 4—Spec sheets can be useful, as evidenced by this curve occasionally found on source data sheets. By relating cone half angle to the percentage of total radiant flux within a given cone, it allows designers to calculate the amount of light capture at the source-fiber interface.

$$P = P_0 (\cos \phi)^m.$$

A set of curves, plotted for various values of m, appears in **Fig 3b.** From the manufacturers' data sheets, you can match the closest curve here to find the approximate value of m for the particular source under consideration. If the curves don't fit exactly, interpolation yields a more accurate result.

Some manufacturers might specify only the half-angle beam spread at the 50% intensity points. Here you can estimate which curve best fits your device by interpolating where the 0.5 intercept would occur and then using that value of m. For example, if the 50% intensity point were specified as 25°, the value of m would be about 7.

Why do you need m? To calculate the amount of source power (P_C) coupled into a fiber, you must evaluate the expression

$$P_C = P_T[1-(\cos \theta)^{m+1}] ,$$

where P_T is the total source power (usually expressed in mW) and θ is the fiber's acceptance-cone half angle. Note that for a Lambertian emitter, where $m=1$, $P_C=P_T\,(NA)^2$ because $NA=\sin\theta$.

Occasionally, source spec sheets include a curve that relates the cone half angle to the percentage of total radiant flux within a given cone; such a curve (for an RCA C30127 ILD) appears in **Fig 4.** With this particular source, a fiber with an acceptance angle of 14° (NA=0.25) would capture about 28% of the total power.

After determining the ratio of coupled power to total power, you can calculate the NA loss in dB by evaluating the expression

$$\text{NA loss} = 10 \log \frac{P_C}{P_T}.$$

For flat-ended fibers, there's little you can do about this NA loss. However, where the core area is larger than the source area, you can use a lensing technique to reduce it.

You can't get all the light in

Compared with NA loss, reflective (R) loss is almost negligible. However, because of its importance in fiber splices, we'll touch on it briefly.

Because light incident on the fiber core experiences a change in index of refraction at the air/core interface, a portion of it reflects back from the surface and is lost. Reflected/refracted proportioning of the incident rays depends on the core index of refraction. The ***reflection coefficient*** ρ, which gives the fraction of incident light reflected from the core, is approximated by

$$\rho = \left(\frac{n_1 - 1}{n_1 + 1}\right)^2,$$

based on the classical Fresnel formulas for normal incidence. Expressed in dB, the reflection loss is then

$$R = 10 \log (1 - \rho).$$

Typically, a core index equals about 1.5, yielding a 4% reflection or a −0.2 dB loss. Of course, a similar reflection loss occurs at the output end of the fiber.

We'll discuss the role of index-matching media in reducing these losses in a later installment of this series. Note, however, that any attempt to index match at the source coupling would be negated by an increase in the NA loss. Because of this fact, it's fortunate that reflection loss is small enough to be neglected.

Now that we've discussed input-coupling parameters, we can deal with remaining source characteristics that affect system performance.

What constitutes a good source?

Requirements are severe for optical sources that must function with long haul single-fiber transmission media. To maximize link length (or repeater spacing), a source should obviously be as intense as the state of the art allows. As we've noted, the source emitting area should be smaller than the fiber core area to launch optical power effectively into the fiber.

To fit within the fiber's acceptance cone, the emitted beam pattern should be very directional—almost collimated—and nearly monochromatic to avoid material dispersion. Very fast (nanosecond range) rise and fall times are a necessity for high-capacity digital systems, while analog systems require an optical power output linearly related to the drive current (or voltage) over a wide dynamic range.

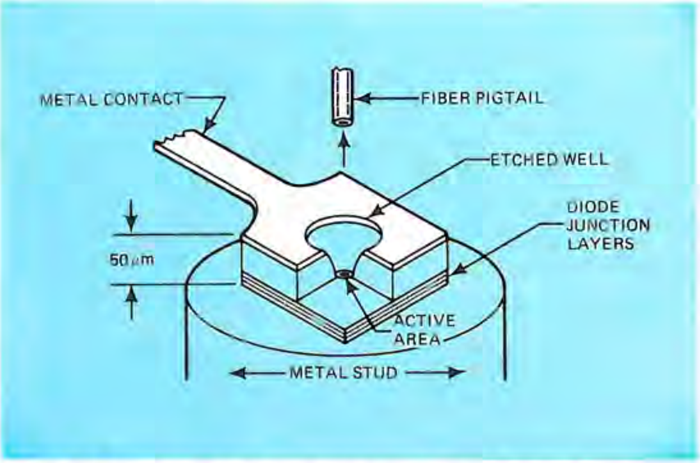

Fig 5—Fiber-source interfacing occurs in the etched well in this Burrus-configured surface emitter. The fiber pigtail, placed in the well in intimate contact with the emitting area, is epoxied into place.

LED's are best suited for analog applications since you can modulate their light output as a nearly linear function of drive current. Used in indicators and electro-optical isolators for many years, these devices can now respond to wideband signals. While "ordinary" LED's suited large-area fiber bundles, some refinements were required to make them compatible with single-fiber applications. Primarily, manufacturers reduced the emitting area to more nearly match that of the fiber.

In 1971, C A Burrus of Bell Laboratories configured a high-radiance LED with a small circular surface **(Fig 5)** and an etched well on one side to allow attachment of a single fiber **(Ref 3).** Some manufacturers now offer Burrus-type LED's **(Table 1).** These surface emitters approximate a Lambertian source, suffering high NA loss as a result. However, the power output from an attached pigtail can approach a respectable 1 mW.

When a Burrus surface-emitter diode comes with such an attached pigtail, the fiber's output power will be (or should be) specified. However,

TABLE 1–SUITABLE SOURCES FOR SINGLE FIBER TECHNOLOGY

MANUFACTURER	LASER DIODE LABORATORIES	RCA	RCA	PLESSEY	PLESSEY	BELL NORTHERN	LASER DIODE LABORATORIES	RCA	ITT
MODEL NUMBER	IRE-103	C30123	C30116	HR954F	GAL103	BNR 40-3-30	LCW 10	C30130	901-L
TYPE	LED	LED	LED	LED	LED	LED	ILD	ILD	ILD
CONFIGURATION	STRIPE EDGE EMITTER	STRIPE EDGE EMITTER	–	BURRUS SURFACE EMITTER	BURRUS SURFACE EMITTER	BURRUS SURFACE EMITTER	STRIPE LASER	STRIPE LASER	STRIPE LASER
CW RADIANT POWER (mW) (RADIANCE FOR SURFACE EMITTERS)	1.2	1.0	0.2	35W/SR-CM²	10W/SR-CM²	66W/SR-CM²	10.0	6	7.5
SOURCE SIZE (μm)	1 x 20	25 x 150	–	50 (DIA)	50 (DIA)	75 (DIA)	1 x 13	2 x 13	2 x 20
PEAK WAVELENGTH (nm)	850	830	1060	900	1060	840	850	820	840
SPECTRAL WIDTH (nm)	–	40	60	30	60	40	2.5	2	4
RISETIME (nSEC)	–	8	10	5	2	19	0.1	<1	<2
3 dB INTENSITY ANGLES	–	30°, 42°	23°	–	–	–	2°, 27°	5°, 20°	6°, 26°

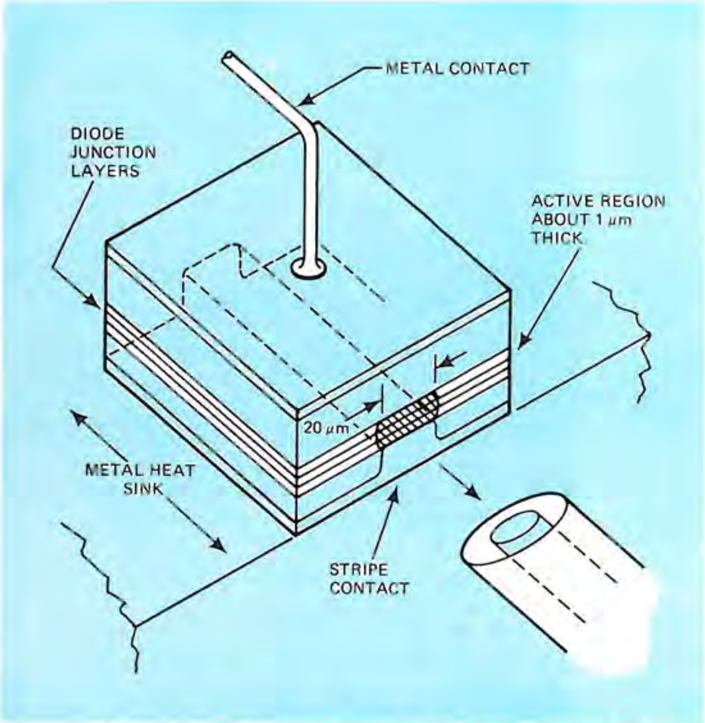

Fig 6—Easy fiber-source coupling occurs in stripe contact edge-emitting sources. However, some broad-area (no stripe) edge emitters suffer from unintercepted-illumination loss.

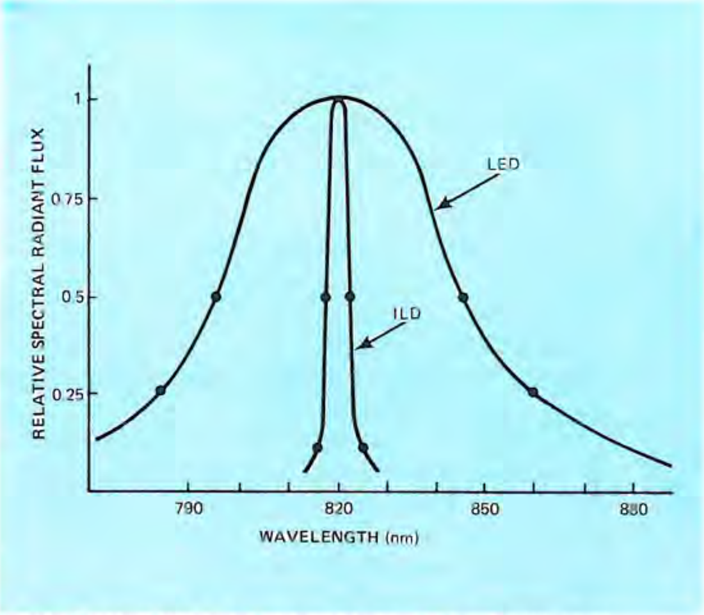

Fig 7—Fiber material dispersion is no problem with laser diodes because their spectral width is so narrow. Compared with LED's, lasers can reduce time spreads by a factor of 40.

if you want a special pigtail to match the physical characteristics of the fiber in your system, you might have to calculate the total power out of the device (and hence the coupling efficiency).

Power output for surface-emitting devices is usually specified in terms of ***radiance,*** the power per unit of solid angle (steradian) per unit area (W/sr-cm^2). For example, radiance can be spec'd as 60 W/sr-cm^2 with an emitting surface area 75 μm in diameter. If the diameter of your fiber core is 50 μm, you would calculate the total power emitted into a solid angle of 2π steradians as

$$(60)(2\pi)(\pi)(25\times10^{-4})^2 = 7.4 \text{ mW}.$$

Next (presuming you're using a Lambertian surface emitter), you would have to calculate the power coupled into the fiber, which butts to the surface:

$$P_C = 7.4[1 - (\cos\theta)^2] \text{ mW}.$$

Here θ is the fiber acceptance-cone half angle. For an angle of 14°, the numbers yield a P_C of 0.43 mW. The NA loss is thus

$$\text{NA loss} = 10 \log \frac{0.43}{7.4} = -12.3 \text{ dB}.$$

Edge- or side-emitting diodes **(Fig 6),** in contrast to the surface (or front) designs we've discussed up to now, are also available. In this configuration, guiding layers channel the light toward the fiber core to produce a narrower beam source with significantly reduced NA losses. Junction-region thickness is typically about 1 or 2 μm, and a stripe contact restricts the width of the active area to 10 or 20 μm.

This process results in a rectangular active source area smaller than the fiber core. A recent paper by Marcuse **(Ref 4)** points out that an edge-emitting diode should be able to output 3 to 7× the power of a surface emitter.

Source/fiber compatibility is important

Peak emission wavelength is another important item on the list of source characteristics; it should be compatible with the fiber's minimum attenuation wavelength. Actually, glass fibers evidence two important minima areas—one around 800 to 850 nm and another around a somewhat lower level of 1050 nm **(Fig 7 in Part 1 of this series).**

Most available LED sources have peak wavelengths of 800 to 850 nm and power outputs of approximately 1 mW. A few sources are available at the lower 1050-nm minima, but their low power output (about 0.1 to 0.2 mW) restricts their widespread use.

A source's ***spectral purity*** is a further consideration. As we discussed in Part 1, pulse spreading arises from both modal and material dispersion. In addition to its fiber-characteristic dependence, material dispersion also depends on the source's ***spectral width,*** which refers to the band of wavelengths the source produces.

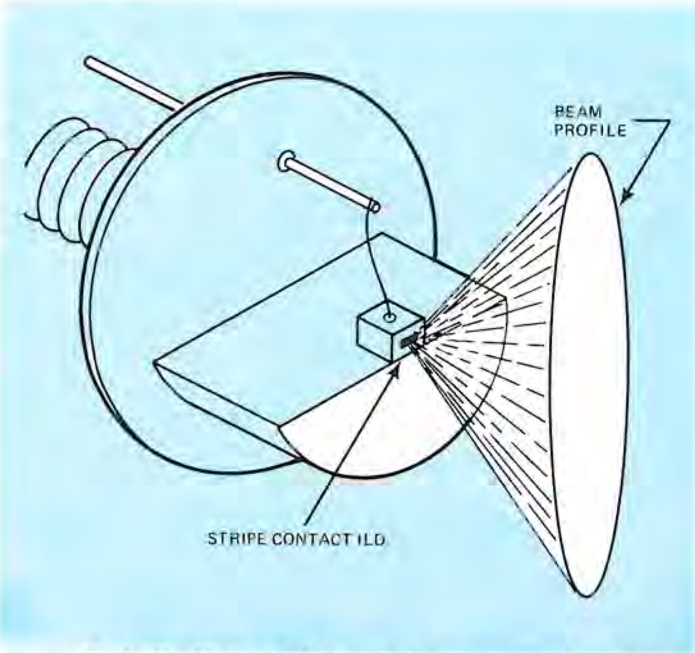

Fig 8—Significant NA-loss reduction results from the narrow beam profile (in the plane parallel to the junction) of stripe-contact-configured laser diodes.

Relative spectral-intensity-vs-wavelength plots for a typical LED and ILD appear in **Fig 7.** The spectral width is usually specified at the half-intensity points. Note that the ILD, with a spectral width of 4 nm, is considerably "purer" than the LED, which has a width of 50 nm.

The exact calculation of material-dispersive impulse response is quite complicated **(Ref 5)** and requires a knowledge of refractive-index wavelength derivatives not usually given on fiber data sheets. However, you can approximate propagation-time spread using the results of Gloge's dispersion analyses **(Ref 6).** His calculations show that the material time spread using a typical LED source measures about 4 nsec/km, while it equals only 0.1 nsec/km for the purer ILD source. Clearly, with a laser source, you can almost always neglect the effects of material dispersion.

Lasers can solve problems

Solid-state laser diodes are exceptionally well suited for use in digital fiber-optic systems. They're made from the same base materials as the LED—gallium-arsenide doped with aluminum—but arranged in somewhat different structures. Like LED's, they are small (typically cubes 10 mils on a side); they're also rugged and have proven lifetimes of well over 10,000 hrs. Stripe-contact versions have active emitter regions measuring about 1×20 μm. While emission through the narrow slit produces a rather broad beam in the plane perpendicular to the junction (20 to 40° half angle), the beam in the plane parallel to this junction is much more narrowly confined **(Fig 8).**

This beam is far more directional than that of an LED, and typical NA losses into flat-ended fibers measure about 6 dB. Current CW lasers have a much higher power output (5 to 10 mW) than LED's and are very fast (rise time of less than 1 nsec). Finally, their spectral linewidth is so small (2 to 4 nm) that material dispersion in fibers becomes negligible.

Unfortunately, ILD's have some disadvantages. First, they are expensive. Currently, low-quantity prices range from $200 to $500/device. However, the history of semiconductor devices suggests that this price will fall when production volume increases and yields improve.

Next, ILD characteristic curves are not uniform. Some have nasty kinks that result in harmonic distortion when you try to use analog modulation. Furthermore, ILD's are notoriously temperature dependent. With respect to injection current, power-output curves are so steep that unless there is some form of feedback (units from Bell Labs incorporate a photodetector for feedback control), a sudden drop in temperature could produce a damaged facet. To avoid this problem, most users now employ a brute-force method of temperature control on the ILD heat sink.

If you do all your homework, you can effect a good source-to-fiber interface. But even then you've only solved half of your problem. You still have to achieve efficient light capture at the other end of the fiber. The device on the receiving end of the link used to transform incoming optical energy to electrical signals must respond to the light wavelength of the source.

Bringing in the light

In fiber-optic systems, the most commonly used receivers utilize photodiodes (either PIN or avalanche types) to convert incident light into electrical energy. So before considering receiver problems, let's look at diode characteristics.

A ***PIN photodiode*** consists of a large intrinsic (very lightly doped) region sandwiched between p- and n-doped semiconducting regions. Photons absorbed in this region create electron-hole pairs that are then separated by an electric field, thus generating an electric current in the load circuit **(Fig 9).**

Efficiency of the optical-photon-to-electron/hole conversion process is specified by the photodiode's ***quantum efficiency,*** η, which measures the average number of electrons released by each incident photon; a number near one indicates a highly efficient diode. In general, quantum efficiency is a function of wavelength

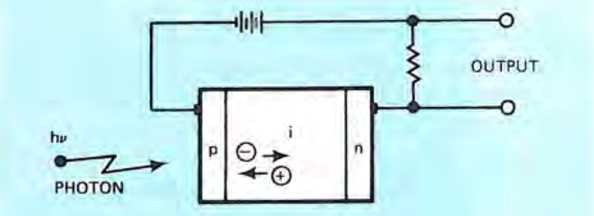

Fig 9—Electron-hole pairs, created by photons absorbed in the intrinsic region of a PIN diode, are separated by the diode's electric field to produce a current in the load circuit.

and temperature.

Responsivity is a diode-performance parameter that's probably more meaningful to you. Related to quantum efficiency by $r=\eta\lambda/1.24$ (λ is the light wavelength), it is the ratio of the output current to the incident optical power, measured in amperes/watt. In other words, the signal current i_s generated when P watts of optical power are incident on a photodiode with responsivity r is

$$i_s = rP.$$

For typical PIN diodes, peak wavelength responsivities are less than 1 A/W **(Fig 10).**

An ***avalanche photodiode*** (APD) is designed for applications requiring greater sensitivity. Because of a strong electric field arising within it as a result of external biasing, the APD exhibits an internal gain mechanism. Primary electrons are accelerated and undergo ionizing collisions with surrounding atoms, thus liberating more electrons.

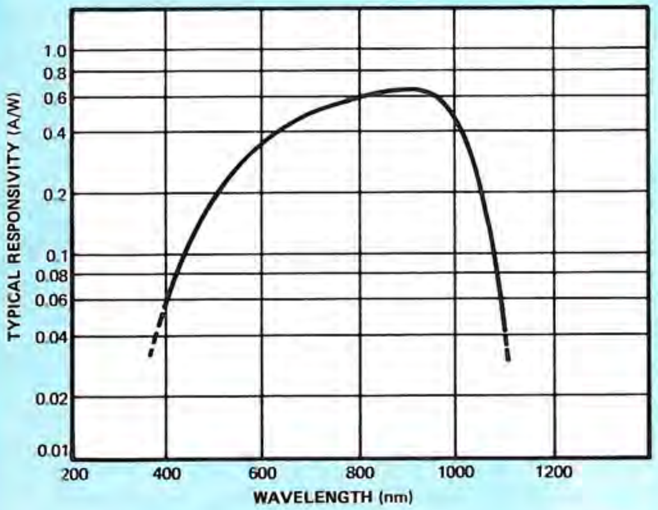

Fig 10—Responsivity is an important parameter because it measures a detector's output current produced by a given amount of incident optical power.

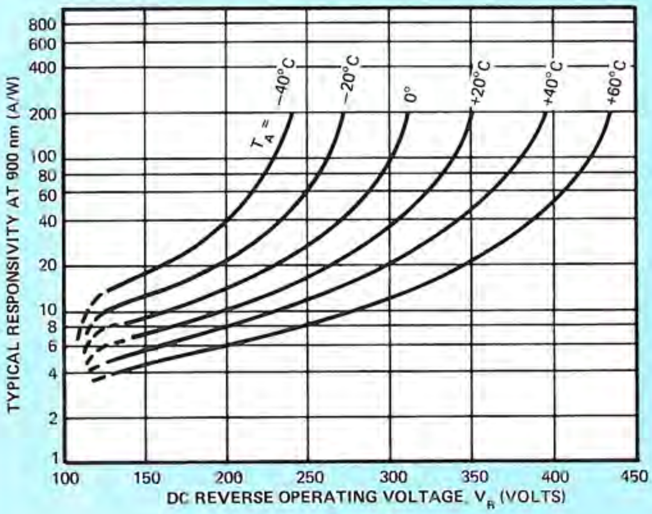

Fig 11—Because they are so temperature sensitive, responsivity is an operational problem with APD's. Some form of gain control is usually employed with APD's used in general-purpose receivers.

As with photoconductive PIN diodes, APD's must be reverse biased in receiver circuits. However, they require a considerably higher bias voltage than PIN diodes (bias voltages on the order of 300V are not uncommon).

Because of their current gain, APD's have a much higher (about an order of magnitude) responsivity than PIN diodes. Nonetheless, the average gain determined by the reverse-bias voltage does not represent the actual gain of individual pulses, which fluctuates about the average to create what is called ***excess noise***—a factor limiting the APD's usable gain. Gain values of about 100-150 are typical. In addition, the temperature dependence of gain, and hence responsivity, is an operational problem with APD's **(Fig 11).** Therefore, for general-purpose use in a receiver, an APD requires some form of automatic gain control.

As we'll see in Part 3, properly designed APD receivers can, under certain conditions, add more than 15 dB extra sensitivity compared with PIN receivers. Thus, if you're using a fiber cable with an attenuation of 10 dB/km, an APD receiver could add an additional 1.5 km to the repeater spacing of your system compared with a PIN type. But for your particular application, you must decide whether the APD's extended operating range justifies its higher cost ($150 to $250 typically, vs $10 to $50 for the PIN).

Reception can be difficult

In the receiver circuit, the signal current must contend with noise currents. In most PIN photo-

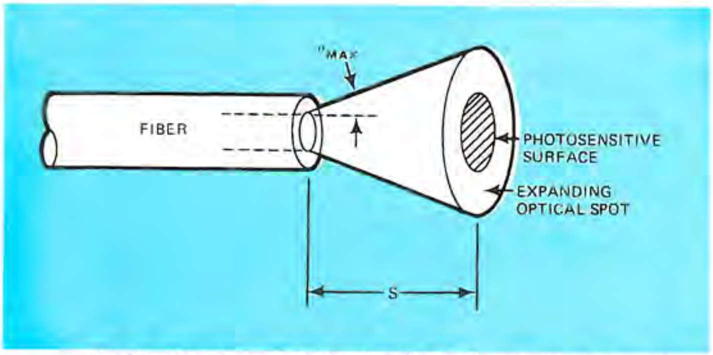

Fig 12—Unintercepted illumination is also a potential problem at the receiving end of a link. Using a photodiode with a large active area keeps this loss down; a better solution involves using an uncapped diode and moving the fiber as close as possible to it.

detectors, the dominant noise component is caused by fluctuations in ***dark current***—the current that flows through the diode-biasing circuit when no light is incident on the photodiode.

Usually, manufacturers specify an average dc value for dark current at a given temperature and bias voltage. Analyses have shown that dark current shot-noise power varies linearly with this average. Dark current increases with temperature; as a general rule, it doubles for every 10°C increase in operating temperature **(Ref 7).**

Noise equivalent power (NEP) is another photodiode figure of merit related to noise performance; it's usually expressed in $W/\sqrt{Hz}$. When you multiply NEP by the square root of the detector-noise bandwidth B, you obtain an absolute power called ***minimum detectable signal*** (MDS) **(Ref 2).**

MDS defines the optical power incident on the photodiode that's required to generate a photocurrent equal to the total photodiode noise current (ie, a 0 dB signal-to-noise ratio). To ensure signal integrity, operate your receiver at a level higher than the MDS.

Additionally, because the current generated by the photodiode is so small, you'll need a preamplifier to boost the signal before further processing. This amplifier (transimpedance or op amp) is also a noise source not included in the photodiode's NEP.

Before discussing coupling problems, we'll mention ***response time.*** In general, it will be limited in the photodiode by the RC time constant associated with the diode's series resistance plus the load resistance into which it operates and by junction capacitance. PIN diodes' 10 to 90% rise times are typically a few nanoseconds; those of APD's are somewhat faster.

Getting it all together

As light exits from the end of an optical fiber, it spreads out with a divergence approximately equal to the acceptance-cone angle θ (determined by the NA of the fiber). Photodiodes are packaged with their photosensitive surfaces located some distance S behind a protective glass window **(Fig 12).** Because only the light striking a diode's active area is converted to current, all light in the output beam that expands beyond the active area represents a coupling loss.

Consider coupling a fiber with a characteristic exit angle $\theta=14°$ (corresponding to an NA of 0.24) and a core diameter of 0.05 mm to a photodiode whose circular sensitive surface has an area of 5 mm^2 located at S=2.5 mm behind the glass window. If the fiber butts against the window, the light beam diverges over the separation S and forms a circular spot of area

$$A = \pi\left(S\tan\theta + \frac{d}{2}\right)^2,$$

which equals 1.3 mm^2 in our example. Because this figure is smaller than the 5-mm^2 detector area, the only loss evidenced will be the minute reflection loss.

As a second example, consider the case where a large-NA fiber is used to gather more light at the input end. An NA of 0.6 gives an exit angle of $\theta=37°$. With all parameters the same as in the first example, the output light-beam

Getting to the sources

Because many readers will want to gain hands-on experience with fiber optics, we include this partial listing of detector and source manufacturers. A few of the available PIN and avalanche photodiodes are listed in **Table 2,** along with some of the parameters discussed in this article.

Detectors
Bell & Howell
Control Products Div
706 Bostwick Ave
Bridgeport, CT 06605
(203) 368-6751
EG&G
Electro Optics Div
35 Congress St
Salem, MA 01970
(617) 745-3200
Meret Inc
1815 24th Street
Santa Monica, CA 90404
(213) 828-7496
RCA
Electro-Optics and Devices
New Holland Ave
Lancaster, PA 17604
(717) 397-7661
Spectronics Inc
830 E Arapaho Rd
Richardson, TX 75080
(214) 234-4271
Texas Instruments Inc
Box 5012
Dallas, TX 75222
(214) 238-3333

Sources
Bell Northern Research
Box 3511, Station C
Ottawa, Canada K1Y 4H7
(613) 596-2305
ITT
Fiber Optic Systems
7635 Plantation Rd
Roanoke, VA 24019
(703) 563-0371
Laser Diode Laboratories Inc
205 Forrest St
Metuchen, NJ 08840
(201) 549-7700
Plessey
Wood Burcote Way
Towcester
Northamptonshire, England
(0327) 50312
RCA
Electro-Optics and Devices
New Holland Ave
Lancaster, PA 17604
(717) 397-7661

TABLE 2—SOME TYPICAL PHOTODIODE DETECTOR PARAMETERS

MANUFACTURER	EG&G	RCA	SPECTRONICS	MERET	TEXAS INSTRUMENTS		RCA	
MODEL NUMBER	SGD–100A	C30831	SD 5426	MD31	TIXL98	TIXL59	C30817	C30895
TYPE	PIN	PIN	PIN	PIN	PIN	APD	APD	APD
ACTIVE AREA (mm^2)	5.1	0.2	1.27	0.8	0.8	0.45	0.5	0.5
RESPONSIVITY (A/W)	0.5 @ 0.82 μm	0.6 @ 0.82 μm	0.64 @ 0.907 μm	0.65 @ 0.905 μm	0.52 @ 0.82 μm	33 @ 0.82 μm	65 @ 0.82 μm	30 @ 1.06 μm
DARK CURRENT (nA)	10 @ 100V	10 @ 100V	1 @ 100V	–	2 @ 25V	8 @ 160V	106 @ 325V	112 @ 320V
NEP (W/Hz)	10^{-13}	10^{-14}	–	–	–	2×10^{-13}	1.5×10^{-14}	4×10^{-14}
JUNCTION CAPACITANCE (pF)	4	1	2.7	–	1.6	8.5	2	2
RISE TIME (50Ω LOAD) (nSEC)	4	3	1.5	3	45	1	2	2

area becomes 11.5 mm^2. Because the area ratio here is 5/11.5=0.435, the resulting coupling loss is −3.6 dB. To reduce this loss, you might consider removing the diode's glass window and moving the fiber closer to the detector. Alternatively, you could use a photodiode with a larger active area. □

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Designer's Guide to: Fiber optics—Part 3

To this point, our coverage has focused on components. Now it's time to broaden our horizons and look at the overall systems picture.

Bruce Metcalf and **Charles Kleekamp,** Mitre Corp

In Parts 1 and 2 of this series, we dealt with fiber-optic communications characteristics of individual components such as fibers, sources and detectors. In this installment, we'll examine some general system considerations.

These issues include tradeoffs in such factors as component selection, component compatibility, system configuration, multiplexing methods, forms of modulation and system performance.

Weigh those tradeoffs

Initial system considerations call for evaluation of the pros and cons of individual component alternatives. The optical source—LED or ILD—is the first area where you must make tradeoffs.

Because it outputs more radiant power and has a narrower beam profile, an ILD allows longer optical links (or greater repeater spacing). For all practical purposes, its narrower spectral width lets you ignore fiber-material dispersion. And the ILD's faster response time permits higher modulation rates than those of LED's.

However, there are some negative aspects. With regard to linear analog-intensity modulation, output-power nonlinearities at and above the lasing-current threshold embarrass the ILD. Here, the LED's linear power-vs-drive-current characteristic is preferable.

Wide temperature variations in the ILD's power-current characteristic require some form of feedback control, which complicates the circuitry; an LED does not impose this need. In addition, it enjoys a longer lifetime and costs less than the ILD.

Next, consider the three available types of fiber—multimode step, graded index and single mode. The latter offers the ultimate in bandwidth capacity, but its extremely small core diameter makes input coupling and fiber splicing very difficult. It has a very poor numerical aperture (NA) and costs much more than other types.

Step-index fiber generally has a higher NA than the graded-index variety and therefore provides better input-coupling efficiencies. However, with regard to bandwidth, graded index has the edge. It is also more expensive, but price differences between step- and graded-index fibers have recently begun to diminish.

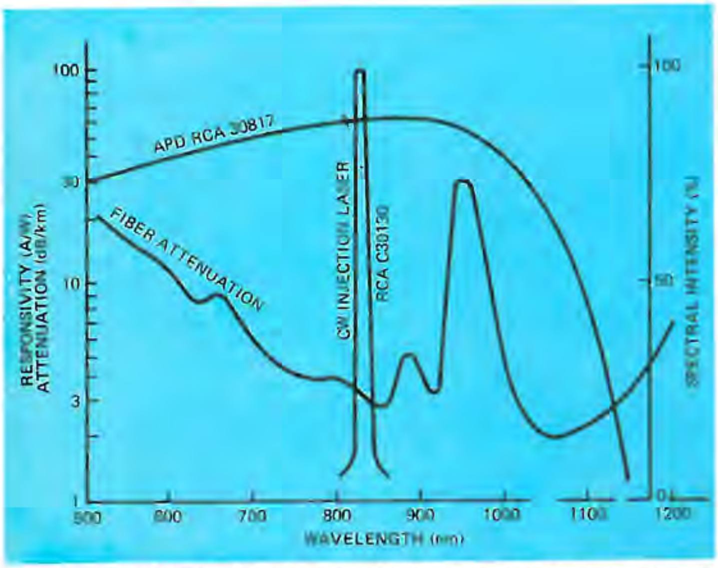

Fig 1—Wavelength compatibility is necessary for optimum system performance. Fortunately, today's fiber-optic components provide this necessary compatibility.

For your receiver, you can choose between a PIN photodiode and an avalanche photodiode (APD). Because of its high responsivity, the costlier APD better suits applications where high signal bandwidth and low power-level detection are critical. However, high cost isn't the only penalty. An APD requires a large bias voltage and a bias control to prevent avalanche gain from varying with temperature changes. For moderately long links, a PIN photodiode could prove your best choice.

When choosing components for a system, you must ensure that your selections are wavelength compatible. For optimum system performance, the source's emission-peak wavelength should match the valleys in the fiber's attenuation-wavelength characteristics. Additionally, the detector must be responsive in this wavelength range. Fortunately, Mother Nature has been kind to us **(Fig 1).** These devices operate harmoniously and are wavelength compatible. Seemingly, fiber-optic system designers are spared the vagaries of Murphy's Law.

Add system architecture to the puzzle

For a fiber-optic system, the simplest architecture is a point-to-point configuration with an access point at each end. For bidirectional communication, you could use a 2-fiber cable in such a layout. Or, depending on the type and degree of multiplexing you choose for your system, several fibers could be involved.

Unfortunately, this simple architecture does not suit some applications. Quite often, systems require communication between several geographically distributed terminals. In these cases, a multiple-access configuration (often termed a bus structure or a multiterminal system) is appropriate. As you might anticipate, this architecture calls for an additional fiber-optic component—a coupler. There are two coupler options—the T and the star.

The generic ***T coupler*** design (or in-line data bus; **Ref 1**) is illustrated in **Fig 2a;** subscribers can tap off or inject optical energy onto the main trunk at each coupler. Single-fiber couplers are still in the experimental stage. In one approach **(Fig 2b)** the tap fiber is fused to the main trunk fiber, bringing the cores closely enough together to provide transfer of evanescent energy between the fibers. You control the amount of light coupling by adjusting the core-to-core spacing and interaction length.

The ***star*** configuration **(Fig 3)** offers designers an alternative coupling solution for multiterminal applications. Operation is straightforward: A subscriber transmits a signal on a dedicated fiber toward the coupler. Entering the coupler at port 1, the light spreads out and is reflected by the dielectric mirror into all ports. Spectronics has put this star coupler to use with bundle technology **(Ref 1),** and the coupler also adapts to single-fiber technology.

How do the two types of coupler compare? With the in-line configuration shown in **Fig 2,** the optical signal suffers a loss at each T coupler in the bus. Worst-case system loss (in decibels) increases linearly with the number of terminals. On the other hand, the star configuration introduces only one coupler loss. Furthermore, as the number of ports, n, increases, the star coupler's power-splitting loss increases only as 10log(n).

When you use units with a constant tap loss, T couplers can also create dynamic-range prob-

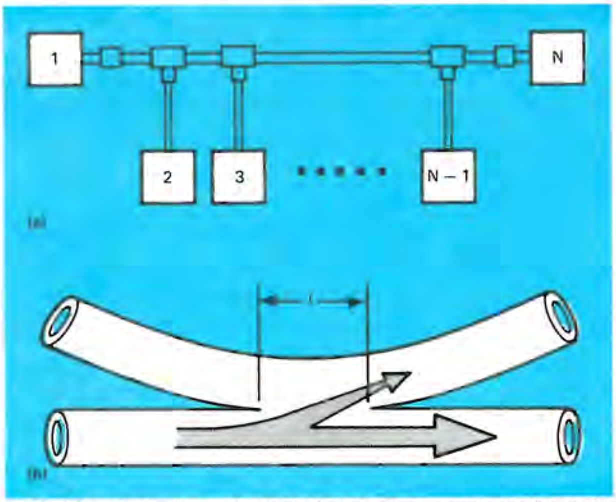

Fig 2—Terminals tap off or inject optical energy onto the main trunk in the in-line bus configuration **(a).** One approach to the T-coupler implementation of this configuration is to fuse the fibers together **(b);** the amount of light coupled varies with interaction length, l, and core-to-core proximity.

lems. For example, when addressing the most remote station, the transmitter must output enough power to overcome worst-case losses. When this transmitter communicates with its nearest neighbor, however, the signal can be so strong (because of reduced losses) that it drives the receiver into distortion.

The results of an interesting loss-comparison analysis by Barnoski **(Ref 3)** appear in **Fig 4,** in which worst-case system losses are plotted against the number of terminals for both in-line and star-coupled configurations. Barnoski assumes a constant 10 dB tap loss, plus a 2 dB insertion loss for T couplers and a 7 dB insertion loss for the star design. He also assumes values of 1 and 3 dB for connector and I/O splitting losses, respectively. From these curves, you see that the star design has lower loss for systems with more than about four terminals.

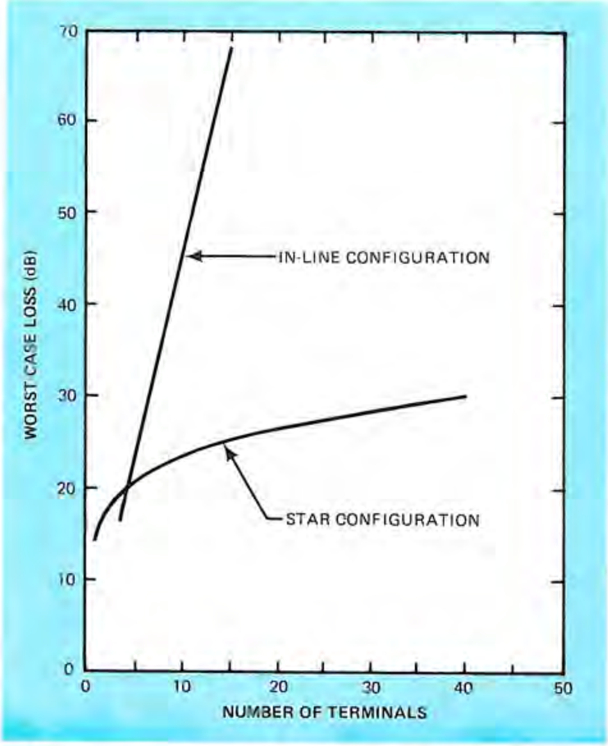

Fig 4—The star configuration proves superior as the number of terminals increases. Because there's only one coupler loss to contend with in this configuration, this result is not too surprising **(Ref 3).**

Stacking up the signals

If you must transmit several individual signals, you'll need to employ some form of multiplexing. What are your options?

In one of them, ***space-division multiplexing*** (SDM), you use a separate fiber for each signal—a fine technique for a small number of channels. However, fiber cost soon becomes prohibitive if you must transmit many signals.

Frequency- and ***time-division multiplexing*** (FDM and TDM) are two schemes available for combining several channels onto one fiber. In the first, separate channels are interleaved in the RF (rather than optical) domain, and the resulting composite RF signal intensity modulates a light source. In the second, signals are interleaved over time. The two techniques have seen use for a long time, so there's nothing really unfamiliar here.

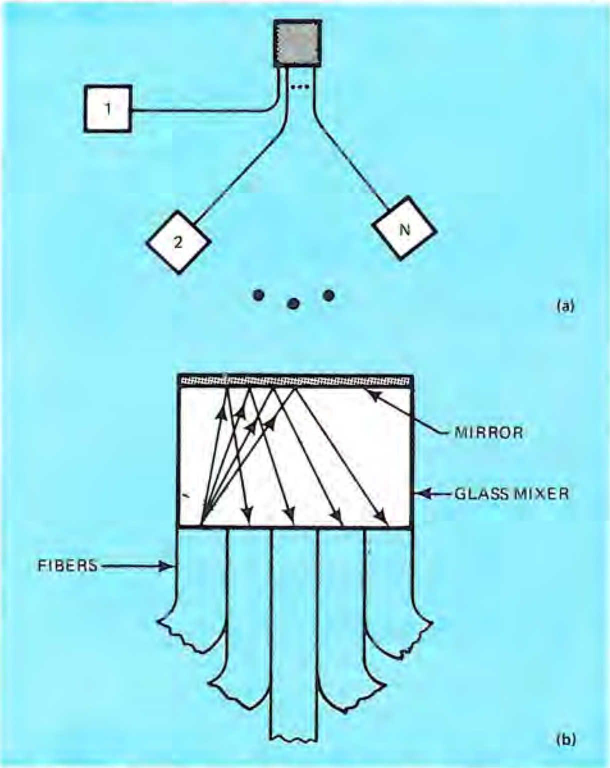

Fig 3—One terminal can communicate with all others when you employ the star-coupler configuration **(a).** Light entering at one port spreads out in the glass mixer **(b)** and reflects from the mirror into all other ports.

A new technique, ***wavelength-division multiplexing*** **(Ref 8),** uses sources of distinct wavelengths to separate various channels. Although optical filtering is required at the photodetectors to select the appropriate channel, WDM further increases the bandwidth advantage of optical fibers.

Then there's the matter of modulation

You can modulate both the LED and ILD simply by varying the current flowing through them. However, there are several ways to vary the current to get information onto the optical carrier. First, let's consider methods appropriate for modulating analog information.

The most obvious option is ***baseband analog-intensity modulation,*** where an input voltage signal (voice or video, for example) at baseband is converted to current variations through an LED. The LED's optical power output varies in almost

Not only components are available

You say you don't want to design and construct your fiber-optic system? Well, you don't have to; several manufacturers deal in overall system design. We list some of these manufacturers below, and the **table** summarizes the features of a few of the products they offer. For more details, contact them directly.

Harris Corp
Electronic Systems Div
Box 37
Melbourne, FL 32901
(305) 727-4000
ITT
Electro-Optical Products Div
7635 Plantation Rd
Roanoke, VA 24019
(703) 563-0371
Meret Inc
1815 24th St.
Santa Monica, CA 90404
(213) 828-7496

Spectronics Inc
830 E Arapaho Rd
Richardson, TX 75080
(214) 234-4271
Sperry Univac Defense Systems
Univac Park
Box 3525
St. Paul, MN 55165
(612) 456-2222

SOME AVAILABLE FIBER-OPTIC SYSTEMS

MANUFACTURER	MODEL	ANALOG (A) OR DIGITAL (D)	BANDWIDTH OR DATA-RATE RANGE	ANALOG SNR OR DIGITAL BER*	LENGTH	SINGLE FIBER (S) OR BUNDLE (B)	PRIMARY APPLICATION	COMMENTS
HARRIS CORP	ESD-3121/3321	D	10k BPS-45M BPS	10^{-9}	1 km	S	T1, T2, OR T3 TRUNKING	2 FULL-DUPLEX CHANNELS
	ESD-4363	D	9.6k BPS-6.312M BPS	10^{-9}	1 km	S	COMPUTER/COMPUTER COMPUTER/PERIPHERALS	14 FULL-DUPLEX CHANNELS
	ESD-4364	A	65 MHz (25-90 MHz)			S	IF TRANSMISSION LINK	2 CHANNELS
	ESD-4365	A	SEE COMMENTS	BASEBAND VIDEO = 46 dB VSB VIDEO = 47 dB FM STEREO = 52 dB	2.3 km	S	CATV SUPERTRUNK	DOWNLINK CHANNELS: 6 BASEBAND VIDEO & AUDIO 6 VSB VIDEO & AUDIO 12 FM STEREO UPLINK CHANNELS: 3 BASEBAND VIDEO
ITT	2D-AS	D	100k BPS-20M BPS	10^{-8}	2 km	S		AVAILABLE ALSO WITH PIN RECEIVER FOR SHORTER LENGTH APPLICATIONS
	2A-AS	A	300 Hz-20 MHz		2 km	S		
	2V-PS	A	10 Hz-4.5 MHz			S		TWO 10 Hz-8 kHz CHANNELS ARE FREQUENCY MULTIPLEXED ONTO THE MAIN CHANNEL ABOVE 4.5 MHz.
MERET	MDL 2255-TV	A	20 Hz-6 MHz	40 dB			CCTV	
	MDL 2365-TV	A	6 Hz-20 MHz	40 dB			CCTV	
SPECTRONICS	SPX 2672	D	DC 100k BPS	10^{-8}	100 FT	B		
	SPX 2674	D	10M BPS	10^{-8}	150 FT	B		
	SPX 2673	A	10 Hz-5 MHz		100 FT	B		
SPERRY UNIVAC	VARIABLE DATA-RATE MODULES	D	6 BPS-20M BPS			B		MILITARIZED COMPONENTS

*SEE MANUFACTURER'S DATA SHEETS FOR CONDITIONS

direct proportion with the electrical input signal. Observe certain precautions with this method, however. You must bias the LED at an appropriate level to avoid overmodulation (clipping). Signal detection occurs through a square-law (optical power to electrical current) photodiode and a current-to-voltage front-end amplifier.

In certain designs, the electrical-input interface to your system might not be at baseband. And if you intend to frequency-division multiplex several signals, you'll want to preprocess the baseband analog signal before optical modulation. In these instances, ***subcarrier analog-intensity modulation*** **(Fig 5)** finds use.

In this scheme, the baseband analog signal modulates an RF subcarrier, which then intensity modulates the optical source. You can use any of the old familiar schemes (AM, SSB, FM, for example) to modulate the intermediate subcarrier. To prevent overmodulation distortion, select appropriate modulation indices **(Ref 4).**

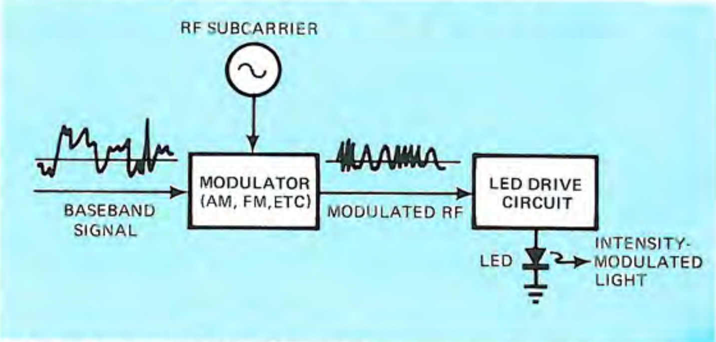

Fig 5—Using subcarrier analog modulation, you first modulate an RF carrier and then modulate the LED output.

Putting everything in its place

For analog baseband signals of modest bandwidth, you might consider ***pulse-position modulation*** (PPM). Analysis shows **(Refs 4** and **5)** that by exploiting the available bandwidth of fiber optics, PPM can yield a healthy signal-to-noise-ratio (SNR) improvement over baseband analog-intensity modulation.

In PPM **(Fig 6),** the baseband analog signal is first voltage sampled at a rate of at least twice the signal bandwidth. Each sample is encoded positionally as a narrow pulse within a time slot dedicated to it. The displacement of the pulse from the center of the nth time slot is proportional to the nth voltage sample. A pulsed LED or ILD then transmits this information.

Because the pulse position contains the information, a PPM receiver must determine the arrival time (rather than the amplitude or detailed shape) of the incoming signal. The PPM detector extracts pulse-time displacements, converts them to uniformly spaced voltage samples and filters them to reconstruct the baseband analog signal.

Because of the narrow pulses involved, PPM requires a bandwidth expansion of the baseband signal. PPM bandwidth requirements can be 300× greater than the original baseband information's bandwidth; exact expansion depends on the SNR specified for your system **(Ref 6).** However, if your baseband-signal bandwidth is modest (say, a few 4 kHz voice channels), you can utilize the fiber's bandwidth capacity to achieve an improved SNR or a longer link.

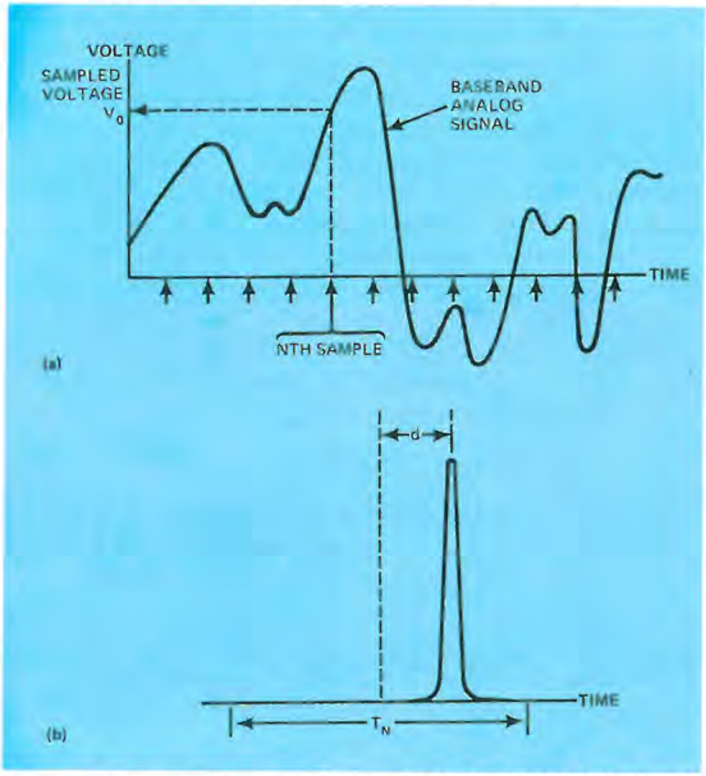

Fig 6—You can exploit the available bandwidth of fiber optics if you opt for pulse-position modulation. First, sample the analog signal **(a),** then encode the nth sample as a pulse of light during the time slot T_N **(b).** The narrow pulse requires expanding the channel bandwidth over the bandwidth of the baseband.

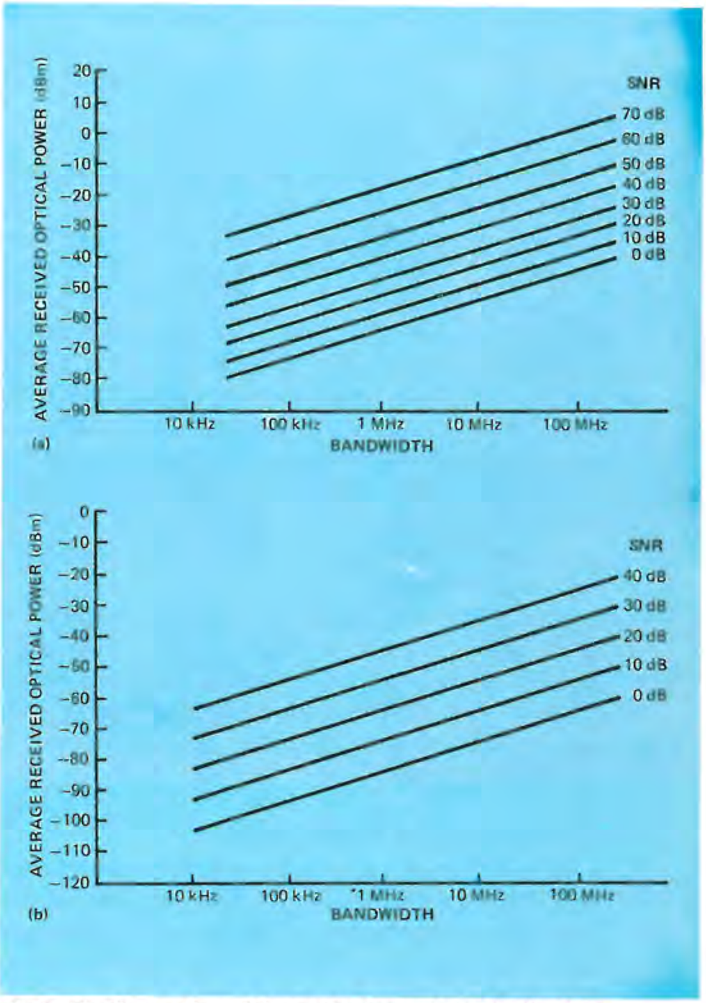

Fig 7—The figure of merit for analog transmission is signal-to-noise ratio (SNR). These plots of average received optical power vs bandwidth for several SNR values illustrate the capability of PIN **(a)** and APD **(b)** detectors **(Ref 7).**

Pulse-code modulation (PCM), wherein you digitize the baseband analog signal, represents another alternative. With this technique, you also sample the baseband signal and encode each sample into a series of bits. The system then uses this binary digital data to turn the light source ON and OFF. The fidelity of the recovered signal increases in proportion to the number of bits used to encode the sample. PCM also requires an increase in channel bandwidth over the baseband, but this increase is generally not as great as that called for in PPM.

Noise levels can be crucial

When all is said and done, SNR is what determines how well your system transmits analog signals. Fortunately, you have some control here, because the SNR is determined by the photodiode and front-end amp you use as the receiver—a choice that depends on the detector's bandwidth and the average optical power level you can deliver.

Fig 7 shows average received-optical-power-vs-bandwidth performance curves plotted for state-of-the-art PIN and APD analog receivers. But what about PPM and PCM systems?

To form a basis for comparison, consider a PIN detector, fix the SNR at 60 dB and examine the required power with respect to information bandwidth **(Fig 8).** Note that to maintain the 60 dB SNR, PPM requires 30 dB less optical power than analog-intensity modulation. For typical 20 dB/km fiber cable, this difference can increase link length by at least 1.5 km. Similarly, 11-bit PCM can provide a gain margin of approximately 18 dB. So what's the catch?

As noted, that catch (or tradeoff) lies in the bandwidth-expansion requirement of both PPM and PCM. Although PPM provides an extra power margin, the limitation surfaces for both techniques when you consider allowable system dispersion **(Fig 9).**

What about digital modulation?

When fiber-optic systems call for transmission of binary digital data, ON/OFF keying of the optical source is the most straightforward scheme to implement. Here, bit error rate (BER) replaces SNR as the measure of performance.

Fig 10 shows the optical power required by state-of-the-art PIN and APD receivers. You can clearly see the enhanced sensitivity of the APD receiver. For example, at a data rate of 10M bps, a PIN-diode receiver requires an average received optical power of about −43 dBm. On the other hand, an APD requires around −60 dBm—an excess margin of 17 dB.

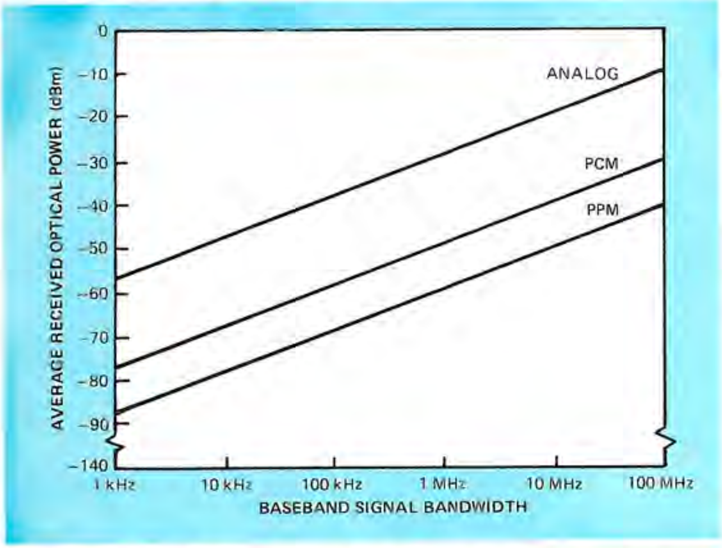

Fig 8—Pulse-position modulation (PPM) requires less optical power to maintain a given SNR. This advantage can significantly increase link length or enhance signal quality **(Ref 6).**

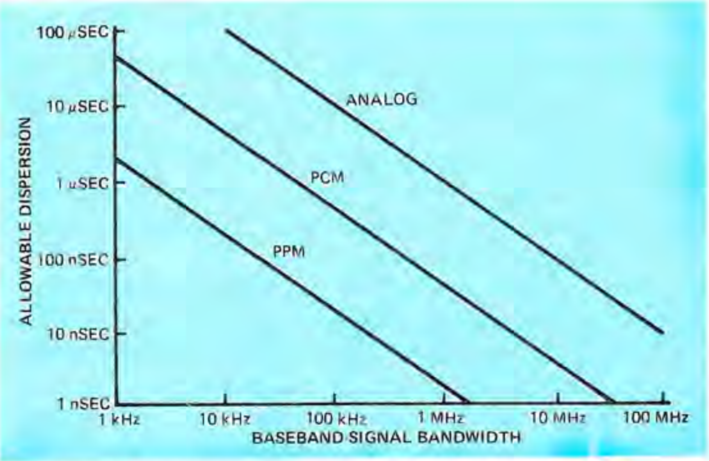

Fig 9—The shortcomings of PPM appear in these plots. Although PPM provides an extra power margin, it suffers with regard to allowable dispersion **(Ref 6).**

You might also opt to use a hybrid subcarrier-modulation scheme. As in analog subcarrier modulation, you would first digitally modulate an RF carrier (using frequency-, amplitude- or phase-shift keying, for example). This modulated carrier would then modulate the intensity of the light source.

Budget your system losses

To ensure satisfactory performance, you must budget the optical losses in your system. Curves like those in **Figs 7, 8** and **10** allow determination of the average optical power P_R required by a photodetector to maintain a proper SNR or BER. If you're considering a light source with a total radiant power of P_S, your loss limit is $L = P_S - P_R$.

In a point-to-point link, you'll encounter input-coupling losses (ICL) between the source and fiber, connector and/or splice losses (CSL), attenuation loss (AL) within the fiber, and output-coupling losses (OCL). Measured in decibels, your link loss budget is then

$$L = ICL + CSL + AL(D) + OCL,$$

where D is the ***power-limited distance*** of the link.

Beyond distance D, the power received will not maintain SNR or BER performance. Assuming that dispersion is no problem, D dictates the maximum repeater spacing. As a safety margin, it's a good idea to add a few decibels to your loss budget to account for such factors as source-power temperature degradation.

For multiterminal systems, loss budgeting is a bit more difficult, for here you must account for such factors as coupler tap-ratio losses, insertion losses, varying distances to terminals and dynamic-range considerations.

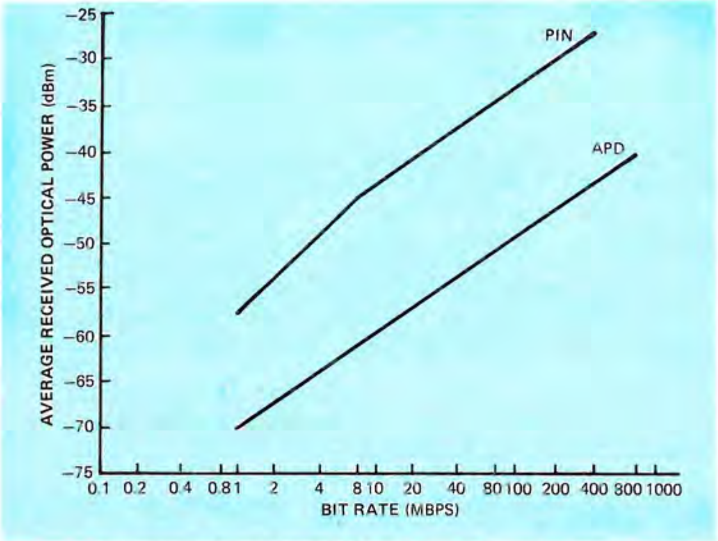

Fig 10—Enhanced sensitivity of the APD receiver appears when you consider the optical power required by state-of-the-art detectors **(Ref 7).**

Don't overlook signal degradation

Noise and distortion are responsible for signal degradation, and the receiver is the major source of noise in a fiber-optic system.

Nonlinearities in a light source's output-power-vs-drive-current characteristic can harmonically distort a signal. In particular, an ILD has a strong nonlinearity at the lasing-current threshold and requires proper biasing to avoid clipping. Even then, there are some troublesome kinks in the curve.

Thus, even though your photodetector receives the prescribed average optical power for the specified SNR or BER, nonlinear distortion can degrade system performance. Digital systems using ON/OFF keying can tolerate more harmonic distortion and exploit the advantages of the ILD. However, in analog-modulated systems, be aware of the major nonlinear distortion components produced by the source.

Material and modal dispersion cause distortion, evident in the form of intersymbol interference for pulsed systems or band-limited amplitude distortion for analog transmission. With LED sources (spectral widths between 30 and 50 nm), material dispersion measures about 4 nsec/km, but this component is negligible for ILD's (spectral widths between 2 and 4 nm). For perspective, note that pulse spreading due to fiber modal dispersion is about 15 nsec/km for ITT's glass step fiber but only 2.5 nsec/km for the firm's graded-index type (See Part 1 of this series in the January 5, 1978 issue of EDN).

Finally, you must consider source and detector rise times because they can also distort the shape of a signal. Typically, they range from 5 to 15 nsec for LED's and 0.1 to 2 nsec for ILD's. At the other end of the fiber, PIN's and APD's have rise times between 1 and 4 nsec.

Total system rise-time calculations must in-

Loss budgeting in system design

Assume you want to transmit a 10 MHz analog signal over a distance (D) of 2 km with an SNR spec of 40 dB. You've also decided to analog-intensity modulate an LED source (an analog-modulated ILD would give rise to too much harmonic distortion).

Your first decision involves the detector—should you use a PIN or APD receiver? A look at **Fig 7** shows that at 10 MHz, both need about the same amount of power for a 40 dB SNR ($P_R=-35$ dBm). Because it costs less, then, you'll use a PIN diode.

Consider a Lambertian-emitter LED source with a total radiant power of 2 mW; this implies $P_S=3$ dBm. Thus, loss limit $L=P_S-P_R=38$ dB.

If you assume the LED's emitting area is smaller than the fiber core area and that the LED has a good pigtail, input-coupling losses will come mostly from the NA of the fiber (plus a 0.2 dB reflection loss). If you choose a fiber with an NA of 0.25, NA loss equals (see Part 2 of this series in the January 20, 1978 issue) 10log $[(0.25)^2]$ or 12 dB. When you add reflection loss, ICL totals 12.2 dB.

Let's further estimate the OCL to be 1 dB and assume three connector losses (one connector at each end and one in the middle) of 1 dB each, making CSL=3 dB. Loss budget then becomes

$$\begin{aligned} L &= ICL + CSL + AL(D) + OCL + SAFETY \\ &= 12.2 + 3 + AL(D) + 1 + 3. \end{aligned}$$

Therefore, AL(D)=18.8 dB.

Suppose you're considering two single-fiber cables: One has an attenuation of 10 dB/km, the other a lower loss of 6 dB/km. Can you use the first fiber in the 2-km link? No. With the first fiber, D is only 1.88 km. You need the lower loss fiber because it yields a D of 3.1 km, which is more than sufficient. Of course, in an actual design, you might also consider using a more powerful source with the higher loss fiber.

clude the individual rise times of the source, fiber and detector. A fiber's 10 to 90% rise time arising from modal dispersion measures about 70% of the 3 dB modal dispersion figure (in nanoseconds/kilometer). The situation is similar for material dispersion. You can calculate system rise time as

$$T_{SYSTEM} = 1.1\sqrt{T^2_{SOURCE} + T^2_{MODAL} + T^2_{MATERIAL} + T^2_{DETECTOR}},$$

where the T's on the right are the 10 to 90% rise times. Then, calculate the system's 3 dB bandwidth from $0.35/T_{SYSTEM}$.

Ref 7, which discusses these rise-time considerations, suggests some guidelines for upper limits on T_{SYSTEM}. It should be less than 70% of the bit interval for NRZ-formatted data and less than 35% for RZ format. Because T_{MODAL} and $T_{MATERIAL}$ depend linearly on fiber length (neglecting mode coupling), you can determine a system's dispersion-limited distance by specifying a value for T_{SYSTEM} and solving the equation for the allowable length beyond which the system rise-time spec is exceeded.

Bringing everything together

This installment takes you a step beyond the component level to considerations of other aspects of fiber-optic systems. We've highlighted the tradeoffs involved in sorting out the alternatives in component selection, system performance and system configuration. We'll devote the final installment to some of the practical aspects of working with fiber optics. □

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Designer's Guide to: Fiber optics—Part 4

So far, this series has concentrated on the theory of fiber optics. It's time to roll up your sleeves and apply what you've learned.

Charles Kleekamp and **Bruce Metcalf,** Mitre Corp

The first three parts of this series (EDN, Jan 5 and 20, Feb 20) introduced you to the nomenclature of fiber-optic components and the concepts of system design. Now you're ready to go into the lab and build a system. This article will unfold practical experience in the field of single-fiber components—cables, splices, connectors, sources and detectors.

Start with cabled optical fibers. The essential question here is how to terminate the fiber end to make a splice or connection. By themselves, bare glass waveguides find little use. Although the pristine glass, as drawn, has very high tensile strength (over 10^5 psi in some cases), it is highly susceptible to surface abrasion. The fiber is very fragile; dust, moisture and handling quickly degrade its strength.

To avoid this problem, manufacturers coat the glass with some type of plastic buffer as the fiber is drawn. To eliminate confusion between this protective coating and the fiber's cladding material, we term the coating the ***jacket.*** Though this article focuses on glass cladded, glass-core fibers, you might recall that some manufacturers also offer inexpensive step index, plastic cladded, glass-core fibers, which rival the all-glass types with regard to low attenuation. DuPont even makes an all-plastic fiber. Essentially, the techniques are the same for both plastic-cladded and all-glass fibers.

Material in this series is based on work sponsored by the Electronic Systems Div of the US Air Force Systems Command under contract F19628-78-C-0001.

Cable configurations vary

The jacketed fiber finds little use by itself. It still lacks the total strength and abrasion resistance necessary to allow pulling through conduits or cable trays. Therefore, manufacturers often cable together several jacketed fibers to provide multichannel configurations; these cables also include longitudinal strength members. To enhance product durability, manufacturers also provide various casements, based on their own design philosophies.

Cable manufacturers currently advocate two methods of fiber containment. In the ***tightly***

bound technique **(Fig 1a),** the jacketed fibers are embedded within a plastic material or laid between filler yarn strands. Some manufacturers champion the ***loosely bound*** technique **(Fig 1b),** wherein jacketed fibers are laid within a tube of much larger diameter.

Proponents of this latter method argue that it mechanically decouples localized stress from the optical fibers and prevents cabling loss arising from small disturbances called microbends. Advocates of tightly bound cable also claim high strength, impact and abrasion resistance for their designs. For their premium products, both camps offer cables with attenuation specs of only 6 dB/km.

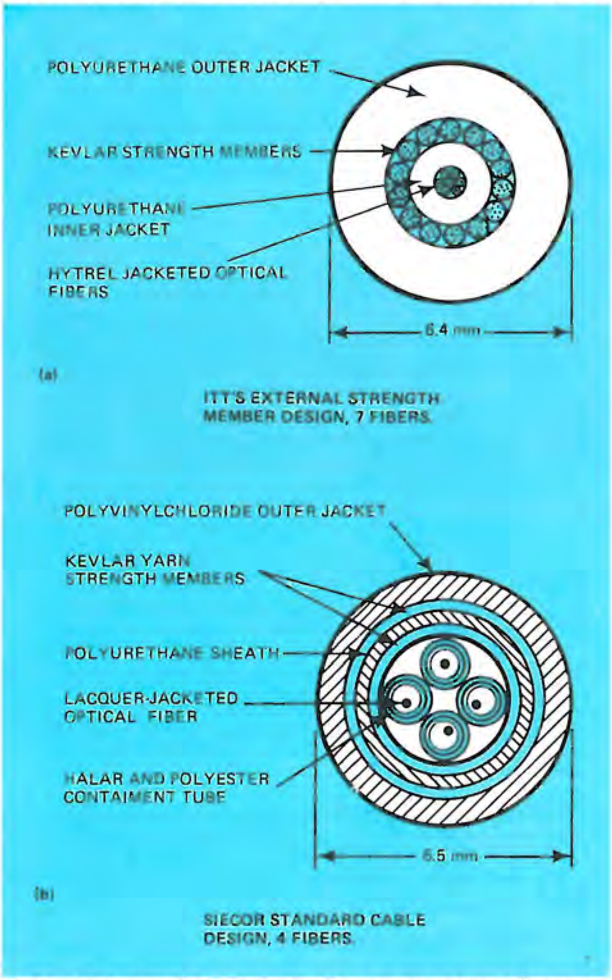

Fig 1—Fiber containment methods vary among manufacturers. The tightly bound technique **(a)**, employed by ITT in this design, embeds the fibers in a plastic material. Siecor favors the loosely bound design **(b)**, wherein the fibers are simply laid within a large tube.

Based on your application and analysis of data sheets, the final choice is up to you. However, before you order any large quantities, it might be wise to test various product samples. Construction and terminating techniques vary considerably, and such conditions can adversely affect your system's optical and mechanical performance.

Table 1 lists a sampling of several products offered by cable manufacturers. Because new products make the scene so rapidly, the list is in no way complete. So request complete information directly from each manufacturer.

Having purchased your fiber cable, you now face the task of removing the outer jackets and strength members—a problem not unlike that encountered with conventional metallic cables. Just as you must be careful not to nick a copper conductor, you must also avoid nicking or scratching the glass while isolating the fiber.

Cable-end preparation can be crucial

Obviously, you must remove the fiber jacketing material before effecting a termination of the glass fiber. Depending on the manufacturer's jacketing design, two removal techniques are available: chemical and mechanical.

Some Corning (Siecor) fibers are coated with a thin (4-μm) layer of cellulose acetate lacquer **(Fig 2a).** With this arrangement, a cotton swab saturated with acetone can easily dissolve and wipe away the lacquer with no danger of scoring or damaging the fiber.

ITT, on the other hand, uses a double jacket on its cables **(Fig 2b).** Here, a soft silicon compound serves as the inner jacket, and a tough outer Hytrel jacket provides abrasion resistance and

TABLE 1—REPRESENTATIVE SAMPLINGS OF OPTICAL FIBER CABLES

MFG	DESIGNATION	NUMBER OF FIBERS	CABLE TYPE	FIBER TYPE	ATTENUATION (dB/km)	BANDWIDTH (−3 dB) OR DISPERSION (3 dB WIDTH)	FIBER CLADDING/ CORE DIAMETER (μm)	CABLE DIA (mm)	CABLE WEIGHT (kg/km)	MIN BEND RADIUS (cm)	TENSILE STRENGTH (kgf)	COMMENTS
DUPONT	PFX-S120R	1	T	PS	50		600/200	2.4	6	0,3	68	
ITT	ESM-6-GG (7) ESM-6-GS (7) S-2-GG (2)	7 7 2	T T T	GG GS GG	8 6 6	2.5 nSEC/km 15 nSEC/km 2.5 nSEC/km	125/50 125/50 125/50	6.4 6.4 2.5 × 5	30 30 –	5 5 –	100 100 –	PLASTIC-CLAD FIBERS ALSO AVAILABLE
SIECOR	PREMIUM STANDARD PREMIUM	6 4 2	L L L	GG GG GG	6 10 6	400 MHz 200 MHz 400 MHz	125/62 125/62 125/62	7.3 6.5 5 x 5.4	45.5 33 26.6	5 5 5	40 40 40	1-, 6- AND 10-FIBER CABLES AVAILABLE
TIMES	GP1/GA7-50 GP3/GA10-90	1 3	L L	GS GG	7 10	50 MHz 200 MHz	125/50 125/90	2.8 5.6	9.5 22	2.8 5.6	68 90	2-, 4-, 6- AND 10-FIBER CABLES AVAILABLE
VALTEC	LD-5004-01 HD-PC10-02 XD-MG05-06	1 2 6	– L L	GS PS GG	<10 <15 <5	<1 nSEC/km 10 MHz 400 MHz	100/5 430/250 125/62	3 5 x 9 15	– – –	– 2 –	– 100 900	SINGLE MODE TELEPHONE CABLE

CABLE TYPE: T—TIGHTLY BOUND; L—LOOSELY BOUND
FIBER TYPE: PS—PLASTIC CLAD, STEP INDEX; GS—GLASS CLAD, STEP INDEX; GG—GLASS CLAD, GRADED INDEX

protection from most solvents. Accordingly, this process mandates a mechanical method of jacket removal.

The simplest technique requires a surgeon's scalpel **(Fig 3)**: You cut away one side, turn the fiber over and strip away the remaining jacket with a second cut. If you're careful to maintain a low angle with the cutting blade, you can avoid fiber scratching.

Once you've reached the bare glass, you must next produce a clean, flat end on the fiber. Again, two techniques are available. One involves breaking, grinding and polishing the end; the other simply requires cleaving the end. The cleaving method is preferable, because the polishing technique becomes time consuming.

For a highly reproducible result, you can best cleave a fiber by following the guidelines found in a technical paper by Bell Labs **(Ref 1).** In theory, if you bend a fiber over a mandrel, apply tension and scribe it lightly, the resultant flaw should propagate straight across the fiber **(Fig 4).**

Mandrel radius and tension requirements depend on the fiber's diameter. For 125-μm-dia fibers, a radius of 5.7 cm and a tension of 150 g's are satisfactory. While these values are not critical, any large deviations from them can produce cleaving degradations such as lips or hackles.

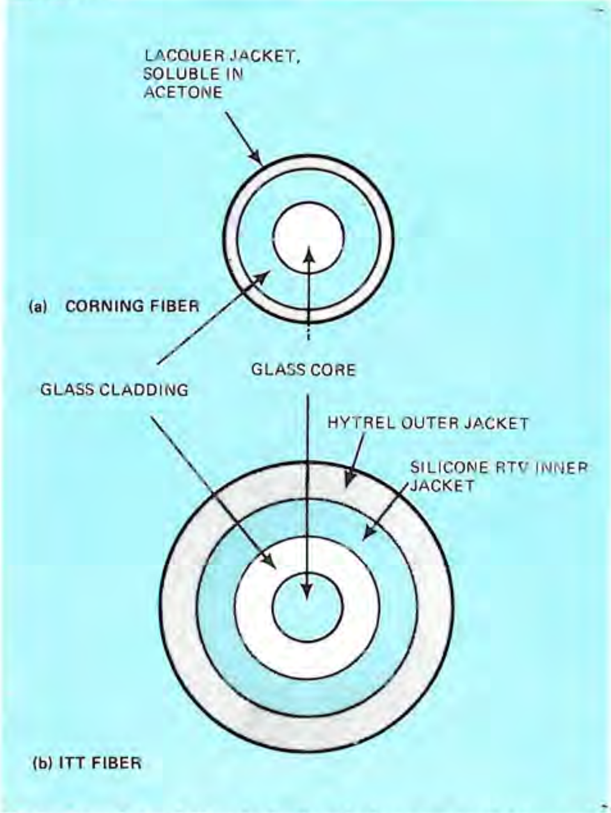

Fig 2—A variety of fiber jacketing designs are available; some jacketing materials **(a)** are easily removed with solvents, while others **(b)** require mechanical removal with a scalpel or other stripping implement.

A simpler cleaving method, and one that's usually efficient, involves breaking the fiber over your finger. However, good results require some practice. First secure the free end of the fiber to a table top. Grip the fiber between thumb and middle finger to apply tension and bend the fiber over the radius of the index finger. If you then lightly scribe (just touch) the fiber with a sharp tool such as a carbide edge **(Fig 5),** the fiber will cleave. There's also a variation on this technique. First lightly scribe the bare fiber, then apply tension by pulling it straight until rupture occurs.

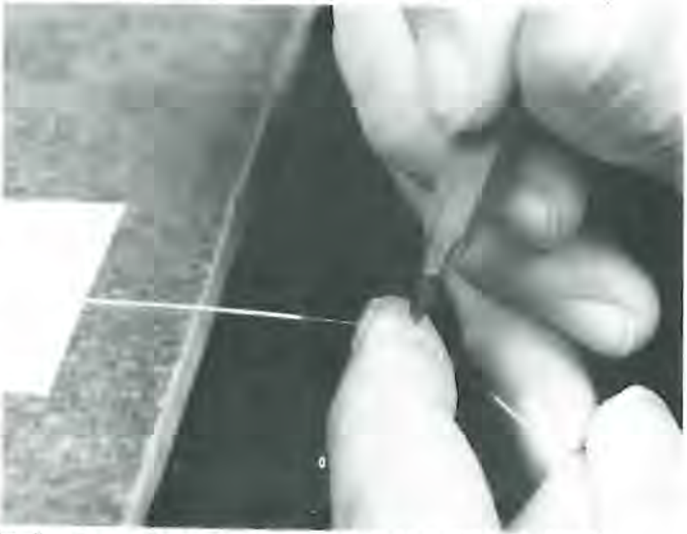

Fig 3—To avoid scoring the glass when removing the tough jacket material from an ITT cable, keep the blade angle low.

Experiment with these techniques and examine the results under a microscope (30 to 60 power) to determine which method works best for you. Once you're satisfied with the fiber's end preparation, you're ready for splicing or connector attachment.

Keep everybody in line

To maximize the transfer of light between its ends, the optical-fiber splice demands highly accurate alignment. Assuming that you've effected an excellent end finish on the fibers, you still must cope with three extrinsic splice loss phenomena **(Fig 6)**: lateral displacement of the fiber axes **(a),** fiber end separation **(b)** and angular misalignment **(c).** The latter two loss parameters vary with the fiber's numerical aperture (the higher the NA, the worse the loss).

You must add reflection losses to these offset losses; typically, such losses amount to about 0.4 dB. You can reduce both reflection and end-separation losses by using an optical matching substance whose refractive index closely matches that of the fiber core.

There's a problem with index-matching fluids, however. They are difficult to contain and sometimes float dirt particles into the gap. On the other hand, when you join a splice with a cement such as Aron Alpha cyanoacrylate (n=1.49), the substance serves the dual purpose of index matching and fiber bonding.

Diameter variations of the fiber core and cladding, along with eccentricity of the core within the cladding, can also produce splicing losses. Even if alignment and end finishing are perfect, splicing a 1% oversized core to a 1% undersized core results in a loss of $10 \log [(1.01/0.99)^2]=0.17$ dB. Of course, the fiber, and not the splicing technique, accounts for such losses.

A look at splicing mechanics

The ***V groove*** technique **(Fig 7a)** helps align fibers for splicing. Here, a sharply formed V guides the prepared fibers, which are then butted under slight pressure. A drop of index-matching adhesive secures the joint. Losses averaging 0.2 dB have been reported **(Ref 4).**

The ***square-tube splice*** technique **(Fig 7b)** uses the same alignment principle. The tube is prefilled with index-matching epoxy; you then insert

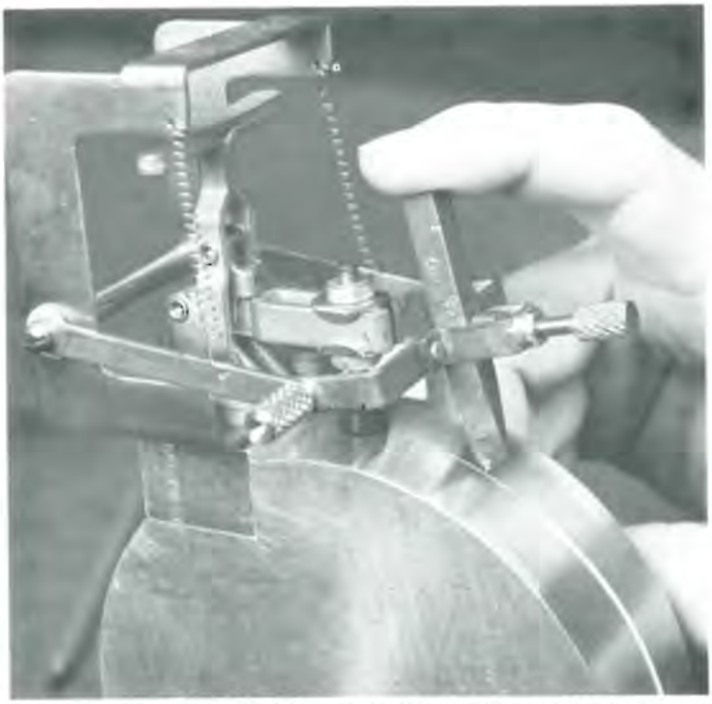

Fig 4—This setup yields highly reproducible cleaving results. A hanging weight applies tension to establish a tensile stress pattern in the curved section of bare glass. A tiny surface flaw, introduced by a light touch of the diamond scribe, propagates across the fiber to produce a mirrorlike perpendicular cleave.

Don't let your measurements fool you

Recall from Part 1 that typical multimode fibers can sustain a large volume of bound or propagating modes. You can assume that sources with broad Lambertian beam profiles (such as a surface-emitting LED) uniformly excite all of the fiber's propagating modes. However, that's not true for the more collimated laser sources (ILD's, helium-neon, neodymium YAG), which mainly excite only the lower order modes (near the axial ray).

Therefore, the source you use in making certain measurements can affect the outcome of those measurements. For example, because of the presence of the high-order (steeper angles) modes, an LED source yields relatively higher values than a laser source for fiber-splice or connector loss measurements. Additionally, with regard to fiber impulse-response, bandwidth or rise-time measurements, this type of source gives worst-case results compared with a laser.

Two factors contribute to this problem. Obviously, because it excites more modes than the laser source, modal dispersion is greater with an LED source. Secondly, because the LED's spectral linewidth is much greater than that of the laser, more pulse spreading arising from material dispersion occurs.

The so-called "leaky" and cladding modes can also contribute to measurement error. In long fiber lengths, these modes will eventually be lost, but in short lengths, they can sometimes mask your measurements.

For example, the measurement of input coupling from a source into a short pigtail includes cladding-mode power. Because this cladding-mode energy won't reach the detector in a long-haul system, you shouldn't include it as coupled power. Also, cladding modes can mask lensed-pigtail measurements.

To eliminate such modes, you must force them to radiate out of the fiber. One solution is to immerse the fiber (after removing the jacketing) in a fluid whose refractive index is higher than the cladding index. This technique induces radiation by eliminating total internal reflection within the cladding. As a result, you'll be able to watch the cladding modes radiating out of the fiber if you use a visible source.

Another technique simply uses long fiber lengths (0.5 to 1 km) for your measurements. If you can afford it, this technique seems to do a thorough job of cladding-mode stripping.

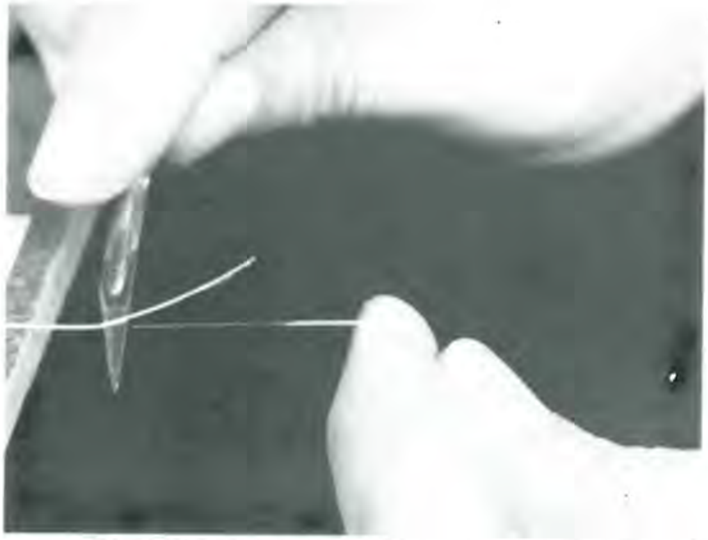

Fig 5—While it's a very simple procedure, cleaving a fiber by hand requires some practice. Tension and radius of the fiber's curvature determine the quality of the cleave.

the fibers and butt them with a slight bending pressure.

Bell Labs has developed another V groove technique **(Fig 7c)** for splicing multiple fibers in one operation. This "mass" splice uses silicon chips with 12 precision V grooves, which stack to accommodate several layers (or ribbons) of individual fibers. The fibers are embedded in epoxy within the grooves; the whole assembly is then polished in preparation for butting against a similarly prepared block. Bell Labs has reported losses on the order of 0.2 dB **(Refs 5** and **6).**

In the ***3-rod splice*** **(Fig 8),** another widely reported technique **(Refs 7** and **8),** fibers are inserted into the interstices of three parallel rods that touch tangentially. The geometry of this situation demands alignment rods 6.464× larger than fiber OD. Thus, for 125-μm (4.92-mil) fibers, the alignment rods must be about 31.8 mils in diameter. For such fibers, you can use inexpensive #67 gauge (32-mil) drill blanks held in position with a piece of heat-shrinkable tubing. When the fibers are butted within the 3-rod arrangement, apply a low-viscosity adhesive. Capillary action then wicks in the adhesive for uniform bonding of all elements.

Be careful when making this splice, for the exposed glass resulting from end preparation is vulnerable to breakage. To overcome this problem, you can use ferrules with an inner diameter 2.155× that of the drill rods; slip them over each end and cement them in place **(Fig 8b).** Because it is filled with adhesive, the ferrule need not have a precisely determined inner diameter.

In a final splice method, the ***fusion*** or ***hot-splice*** technique, fibers to be joined are butted and heated with a flame, electric arc **(Ref 9)** or other heater **(Ref 10)** until softening and fusion occur. These techniques result in average losses of about 0.26 dB. Tensile-strength tests show that the average hot-spliced fiber's strength is about 60% of the original's. Breaks occur some distance from the joint and probably arise from handling damage to uncoated fibers.

Connectors are a bigger problem

At this time, the lack of a suitable low-cost connector represents the largest roadblock to

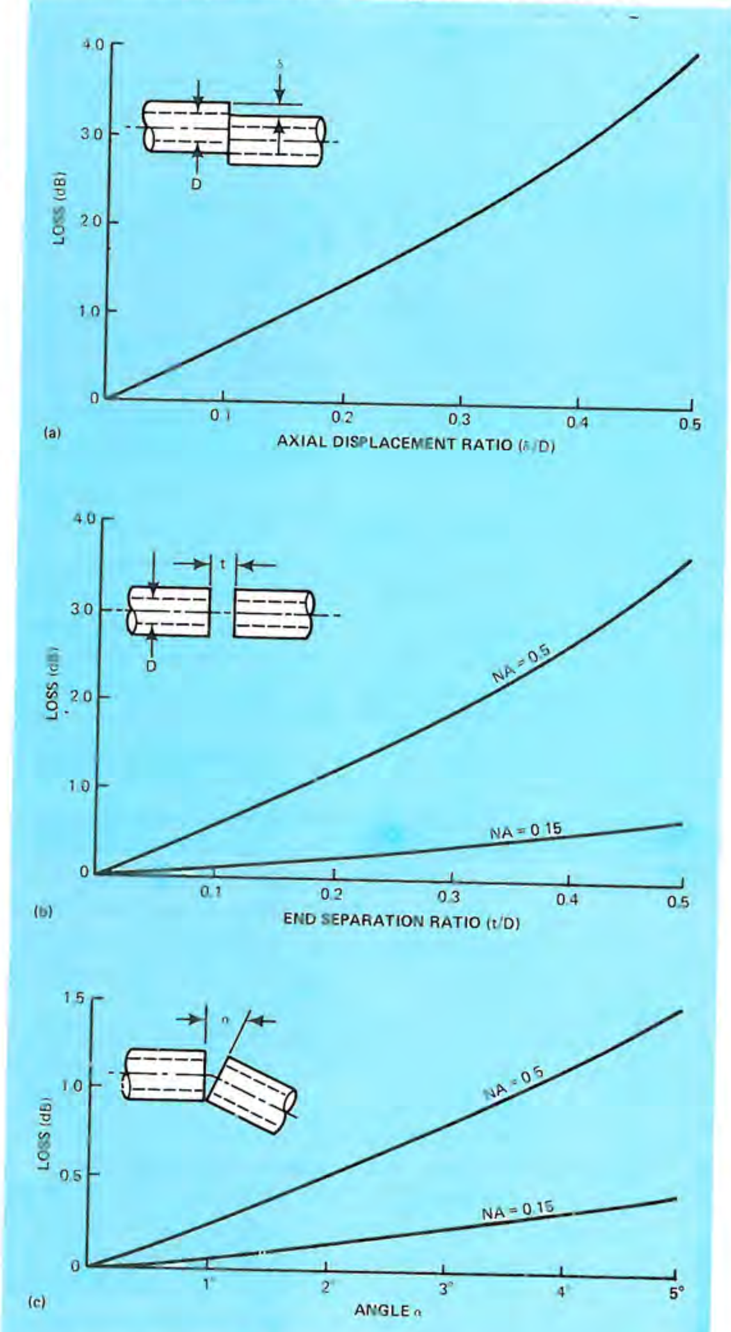

Fig 6—Losses in fiber splicing come from axial misalignment **(a),** end separation **(b)** and angular offset **(c).** The latter two factors depend on the fiber's numerical aperture. The curves shown describe multimode step-index fiber **(Ref 3).**

widespread growth of single-fiber systems. Precision instruments are necessary to overcome the lateral displacement problem in fiber axes; until recently, these instruments did not appear at affordable prices. However, within the past few months, several manufacturers have announced product offerings (**Table 2** presents a partial list).

While splices evidence losses as low as 0.2 to 0.5 dB, most connector manufacturers now shoot for a 1.5 to 2 dB loss spec. Even if several connections are required, this figure is still reasonable for most point-to-point systems.

TABLE 2—A SAMPLING OF SINGLE-FIBER OPTICAL CONNECTORS

MFG	DESIGNATION	NUMBER OF FIBERS	FIBER DIA (µm)	INSERTION LOSS (dB)	COMMENTS
AMP	OSC 22658	2	400	2	FOR DUPONT PFX P SERIES OF PLASTIC FIBER CABLES
AMPHENOL	906 SERIES	1	125	1.5-2	TERMINATES SEVERAL MFGS' SINGLE FIBER CABLE
	905 SERIES	1	500	2	PRIMARILY FOR BUNDLES BUT ACCOMMODATES DUPONT PFX S120R PLASTIC CLAD SILICA FIBER
CANNON	UNILUX/FOS	1	100-325	2	ACCOMMODATES STRENGTHENED OUTDOOR ENVIRONMENT CABLES
ITT	MULTIWAY	4 OR 8	50-200	2	FACTORY ASSEMBLY OF CONNECTORS TO CABLE RECOMMENDED
T&B/ANSLEY	998-100	1	125	1.5	CABLE STRAIN RELIEFS AVAILABLE FIBER CLEAVING AND ALIGNMENT TOOLS AVAILABLE
	SPLICE	1	125	—	NARROW PROFILE SPLICE FOR PERMANENT CONNECTIONS. USABLE WITH INDEX MATCHING EPOXY
	998-500	2	400	3-4	FOR DUPONT PFX P SERIES OF PLASTIC-FIBER CABLES

The first commercially available single-fiber connector, designed by ITT's Components Group in England, uses a precision watch jewel pressed into a stainless-steel ferrule to terminate the fiber (**Fig 9a**), whose end is epoxied into the tube and then polished. Various jewel-bore sizes accommodate a wide range of fibers in 10-µm steps from 50 to 200 µm. To achieve a butt connection, two ferrules slip into a concentric alignment sleeve with appropriate locking nuts.

It's not difficult to see how 10 or 15 µm of lateral offset can creep into such an arrangement. With a 50-µm core, a 2 dB loss could result. Four- and 8-fiber versions of this connector are available from ITT's Electro-Optical Products Div, Roanoke, VA. Cannon Electric, Santa Ana, CA, now manufactures the single-fiber version.

T&B/Ansley also advocates the concentric-sleeve approach. Its Series 998 single-fiber connector specifically suits 125-µm fibers and specs at a 1 to 1.5 dB insertion loss. The firm also sells special tools for fiber cleaving and alignment.

The Amphenol RF Div of Bunker Ramo Corp offers a single-fiber termination that employs a 4-rod approach to contain the fiber (**Fig 9b**). The firm claims typical maximum lateral displacements of 5 µm for this Series 906 connector; along with end-separation figures, this estimate yields total insertion losses of 1.5 to 2 dB.

AMP Inc features a novel connector that compensates for fibers of different diameters (**Fig 9c**). The design features optical self centering of the fibers in grooved sections of elastomeric material. While the company's OSC product line currently consists of a 2-fiber configuration for 400-µm fibers, inserts for 125-µm units could evolve.

Other manufacturers, such as Sealectro and Deutsch, are now developing capabilities to produce connectors for single-fiber cables. The trend seems to point to the 125-µm glass-cladded fiber as the first de-facto standard. Unfortunately, cable manufacturers have not established standard outer-jacket construction techniques—a fact that makes it difficult for connector manufacturers to design cable strain reliefs. Undoubtedly, they'll meet this challenge by developing a variety of these reliefs for specific products.

Considering the variety of emerging connector products, it might seem that you've overcome the Achilles heel of the single-fiber optical link. However, you're not home free yet in your system design.

Getting a good start is important

As Part 2 indicated, you can reduce or eliminate unintercepted-illumination input-coupling loss

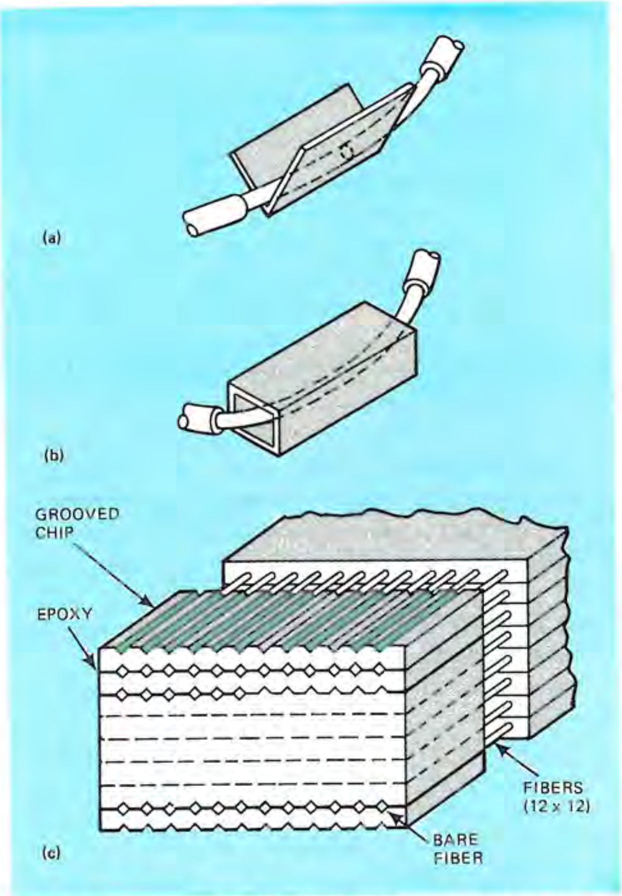

Fig 7—Alignment in a V groove (a) is a standard technique for splicing fibers. The same principle applies to the square-tube splice **(b)** and the mass splice **(c)**, which Bell Labs uses to join 144 fibers.

by aligning and attaching a length of fiber to the emitting region of the source. You then splice the free end of this pigtail or connect it to a fiber in the main cable. The topic of source pigtailing divides into two areas—optical and mechanical.

You must prepare the input end of the fiber pigtail before mechanical alignment. For many applications, you can simply cleave and use a flat-ended pigtail, but, in systems using low-loss fiber cable, a microlens on the input end of the pigtail can reduce required cable costs, add an extra power margin or extend the length of the link. These benefits accrue because the pigtail lens helps reduce the NA input coupling loss by increasing the acceptance-cone angle.

Analysis of a hemispherically lensed step-index fiber **(Ref 11)** with core diameter d and core/cladding indices n_1 and n_2 **(Fig 10)** shows that the following equation gives the resulting acceptance-cone angle θ:

$$\theta = \sin^{-1}\left[\frac{n_1}{n}\sin\left(\cos^{-1}\frac{n_2}{n_1}+\sin^{-1}\frac{d}{2r}\right)\right] - \sin^{-1}\frac{d}{2r}.$$

Here r is the lens' radius of curvature and n is the refractive index of the medium between the source and pigtail lens (for an air gap, n=1). You can calculate effective focal length f from

$$f = \frac{d}{2\tan\theta} - r\left[1-\cos\left(\sin^{-1}\frac{d}{2r}\right)\right]$$

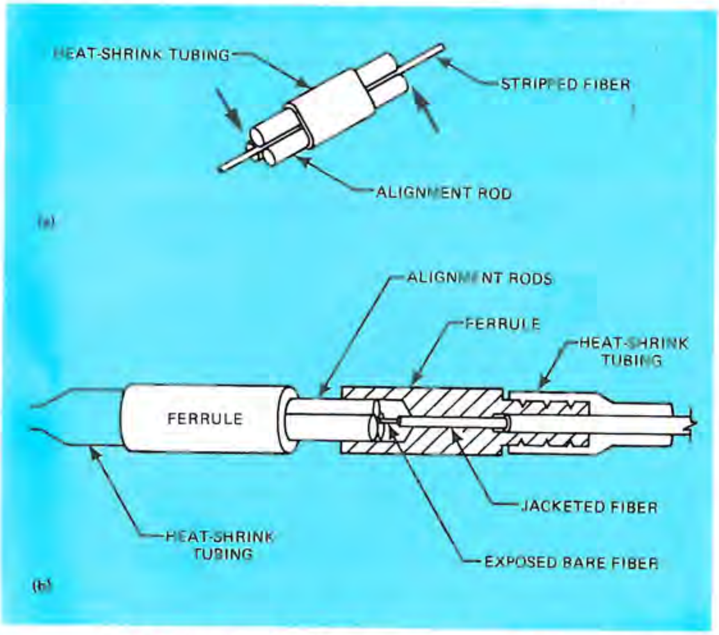

Fig 8—The 3-rod splice is another widely used technique. Stripped and cleaved fibers are inserted in the interstitial gap formed by the three rods, held by heat-shrinkable tubing **(a).** Ferrules with heat-shrink tubing **(b)** prove an excellent method of protecting the fiber's vulnerable breaking areas (indicated by arrows).

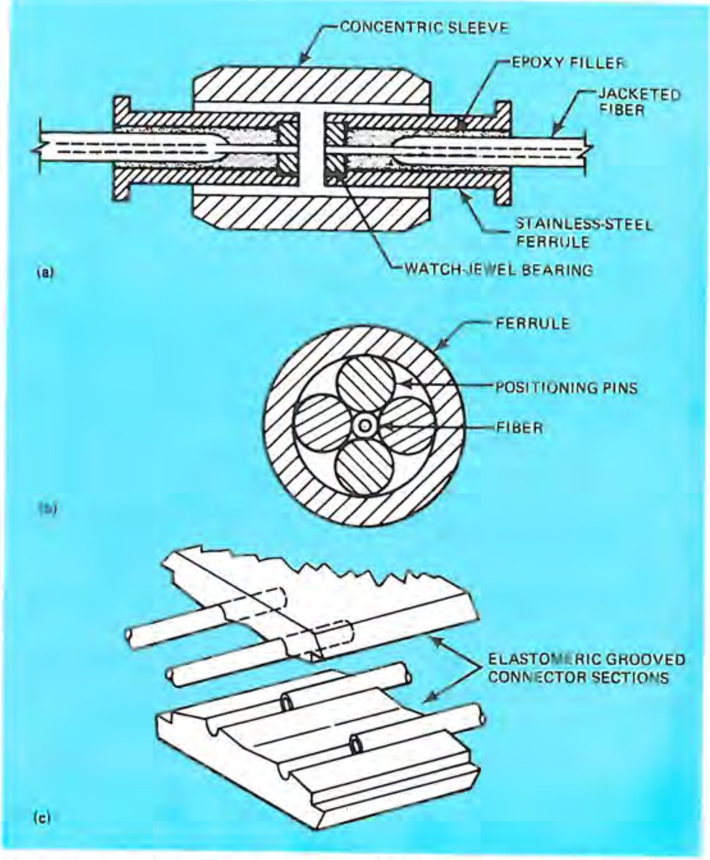

Fig 9—The single-fiber connector problem has generated a wide range of design solutions. The ITT watch-jewel connector **(a)** uses a concentric sleeve, while Amphenol aligns the fibers with four positioning pins **(b)** and then mates the ferrule in a concentric sleeve. AMP utilizes grooved blocks of an elastomeric material to achieve alignment **(c).**

Fig 11 plots acceptance angle and effective focal length as functions of lens curvature for a step-index fiber with typical values of n_1=1.48, n_2=1.46, d=50 μm and an air gap (n=1) between the source and lens. A flat-ended fiber (no lens) corresponds to an infinite radius of curvature (d/2r=0); this case results in the normal acceptance angle of the fiber, 14°. As the lens becomes more and more curved, the acceptance angle increases considerably. At the same time, the focal length shortens, so you must close up the space between the source and fiber lens to optimize coupling.

While it might seem otherwise, putting a tiny lens on the end of a fiber is not really a tough job. First strip the fiber and cleave it flat using the techniques already discussed. Then place it in a pin vise (or self-locking tweezers) and put it under a microscope (30× magnification is sufficient to see the lens formation). To make the lens, employ an oxy-acetylene mini torch with a #2 tip (orifice diameter 6 mils) and operate under low pressure with a flame length of about 1/8 in.

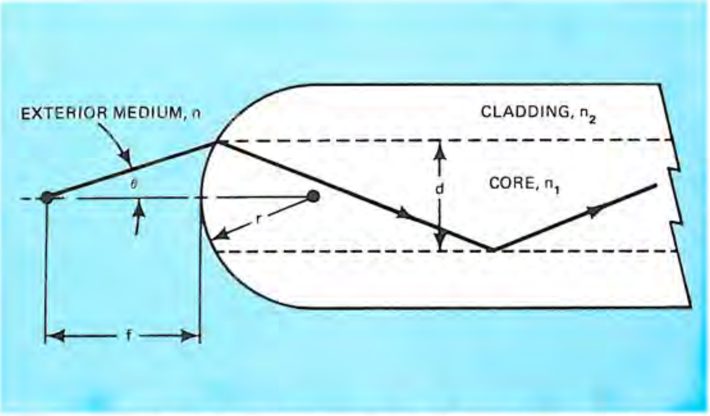

Fig 10—You can increase optical-power input coupling by hemispherically lensing the source fiber pigtail. The lens' radius of curvature (r), fiber core diameter (d) and core/cladding indices (n_1 and n_2) determine the acceptance angle θ and focal length f.

After fixing the fiber and flame in the microscope's view, gently touch or "tease" the fiber end with the flame for a few seconds. After several short-duration touches, you'll begin to see a brilliant incandescence, and the fiber's acceptance cone will grow visible in glowing white. Once you see the edges of the fiber soften out, another touch or two of the flame will sufficiently melt the glass. Natural surface tension in the soft glass molds the lens; the volume of melted material controls its radius of curvature.

This flame-lensing technique requires practice, so don't be discouraged by a few initial failures. In the beginning, you might overheat the fiber. If you do, you'll wind up with either microbubbles in the glass, a banana-like curve in the fiber or an oversized or lopsided "bulb" lens.

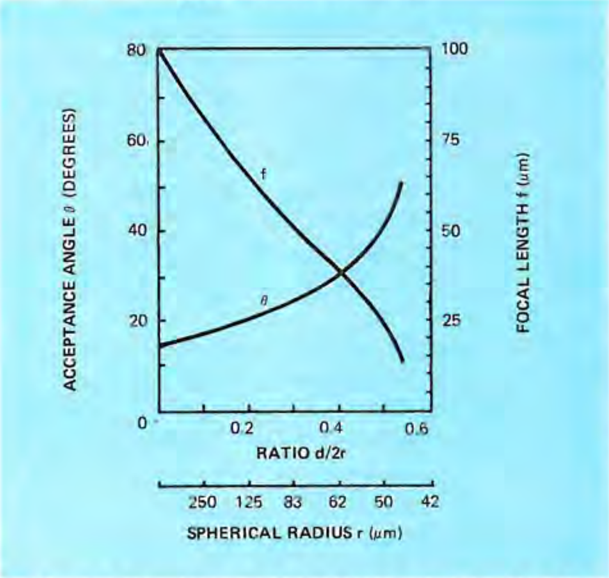

Fig 11—The acceptance angle increases when you put a lens on the fiber pigtail. However, the focal length decreases, so you must move the fiber closer to the light source.

Results make the effort worthwhile

What are the system implications of this increased acceptance angle provided by lensing the pigtail? To answer this question, consider the NA input loss for coupling a Lambertian LED to a step-index fiber (d=50 μm) with an acceptance angle of 14° (NA=sin14°=0.24). When you use a flat-ended fiber pigtail, the NA loss equals (see Part 2) $10\log[(NA)^2]=-12.4$ dB.

If the step-index fiber has a cladding OD of 125 μm, you can realize a spherical lens radius of 62.5 μm on the end of the fiber. Looking up the corresponding acceptance angle **(Fig 11)** of the lensed fiber, you'll find that when r=62.5 μm, θ=30°. The effective focal length of this lens will be 38 μm. With the NA of the lensed pigtail now equal to 0.5, NA loss reduces to $10\log[(0.5)^2]=-6$ dB—a better than 6 dB improvement over the flat-ended pigtail. Experiments at Mitre Corp have achieved a 3 dB improvement with an ILD coupled to a lensed step-index fiber.

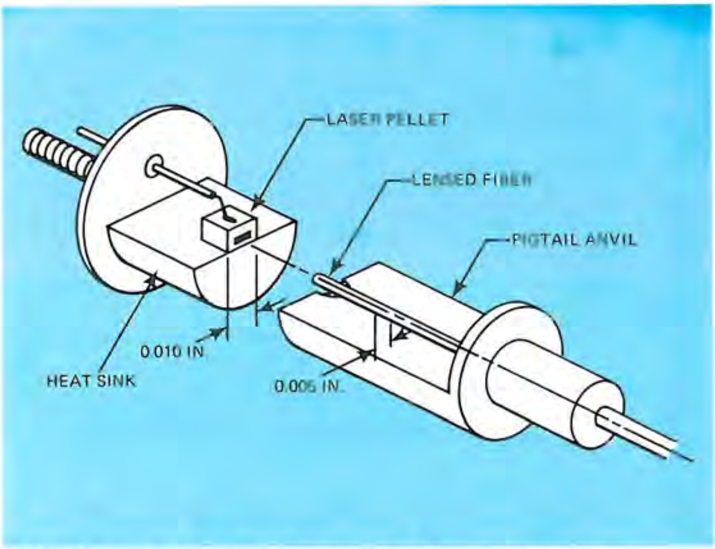

Fig 12—You can use an anvil to support and secure the source fiber pigtail. The prepared fiber is bonded in a trough in the anvil; after alignment, the anvil is permanently bonded to the source heat sink.

This coupling improvement has two obvious implications. In a fixed-length system, the 3 to 6 dB reduction in total cable losses might let you use less expensive, higher loss cable. On the other hand, if you're using 6 dB/km cable in a long-haul link, the small additional effort of flame lensing the pigtail increases link repeater spacing by 0.5 to 1.0 km.

Notice from **Fig 11** that a radius of curvature smaller than 62.5 μm would improve coupling even further. Unfortunately, it's geometrically impossible to obtain a spherical radius less than that value with a 125-μm OD fiber. However, by chemically etching away the fiber cladding, you can realize a smaller lens curvature and attain higher coupling efficiencies.

In addition, when you remove the cladding glass before lensing, you avoid any difficulties from cladding flow-down, wherein the core and cladding materials intermix when flamed. Coupling efficiencies as high as 80% have been realized with this technique **(Refs 12 and 13).** Other techniques for forming the microlens include photoresist exposure and dipping in optical epoxy or low-melting-point glass.

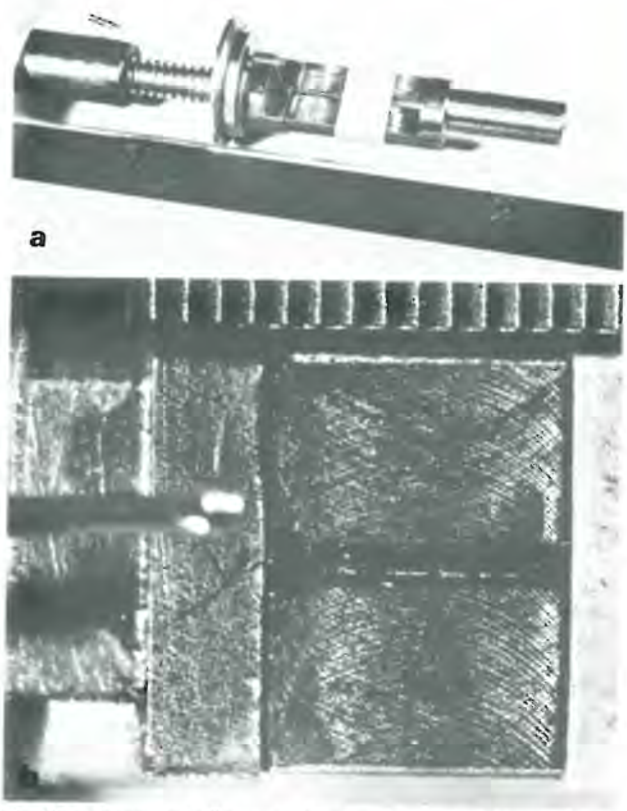

Fig 13—Permanent alignment for input coupling results from bonding the anvil to the source's heat sink **(a).** A closeup view **(b)** of the coupling region shows the lensed pigtail lined up with the laser diode pellet. The trough containing the fiber is filled with cement to hold the fiber rigid, but the lensed end is suspended in air. Markings on top are 1/64 in. apart.

Perhaps you wonder why a transparent index-matching adhesive or epoxy can't maintain alignment between the source and pigtail. After all, this index-matching trick reduces reflections in fiber-to-fiber splices. However, the physics of the input-coupling situation shows that index matching is not advisable. In fact, it makes matters worse.

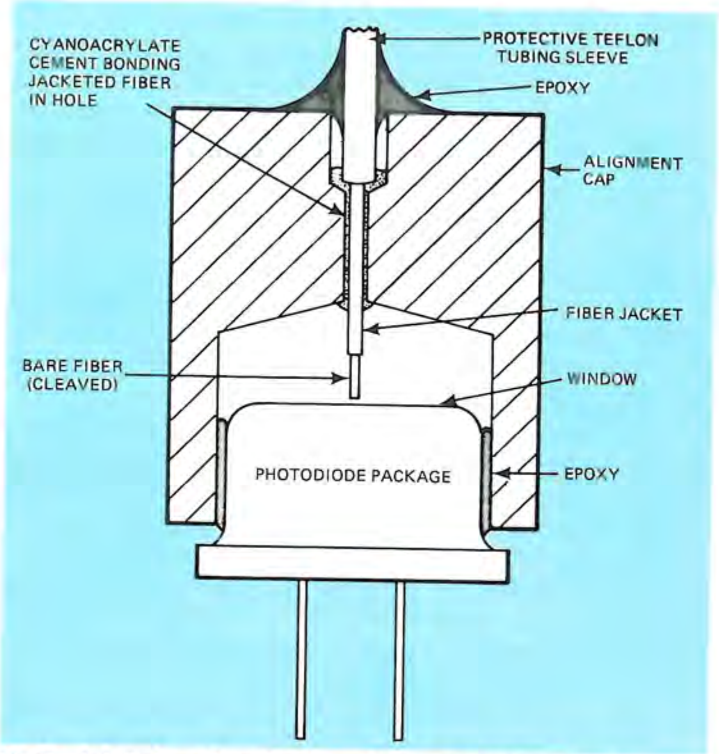

Fig 14—A drilled metal cap fitted over the photodiode package easily accomplishes receiver fiber pigtail alignment. Usually, you needn't even remove the window from the package.

Consider again the formula for the lensed pigtail's acceptance angle θ. When you insert an index-matching medium ($n=n_1$), the acceptance angle becomes $\theta=\cos^{-1}n_2/n_1$; there's no dependence on lens curvature. In effect, index matching destroys the lens.

With typical values of $n=n_1=1.48$ and $n_2=1.46$, the indexed-matched acceptance angle equals 9.4°—less than the 14° acceptance angle of the flat-ended fiber in air. For light collection, refraction (or inward bending) of light rays at the air/core interface is desirable. For input coupling, index matching removes this refraction and reduces efficiency. In the final analysis, it's best to leave an air gap between the source and pigtail.

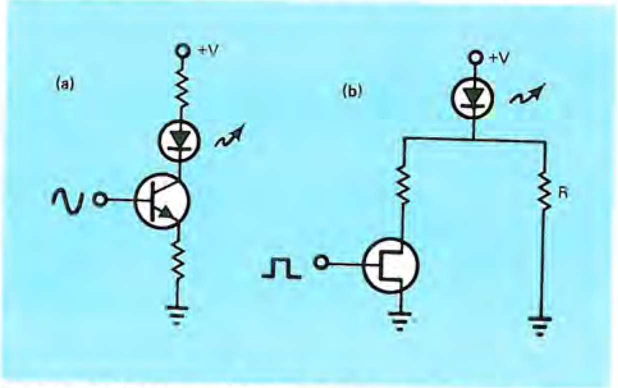

Fig 15—Straightforward basics suffice when designing source drive circuits. A simple transistor circuit **(a)** works well for analog-intensity modulation, and you can use an FET circuit **(b)** for pulsed-modulation schemes.

Pigtailing's a matter of mechanics

Practically speaking, pigtailing is a multifaceted problem. First, you must accurately align and focus the pigtail to the source's emitting region. Then you must rigidly bond the assembly while leaving an intermediate air gap.

A pigtail anvil **(Fig 12)** accomplishes this task most easily. The prepared fiber is inserted through the hole, made large enough to accommodate the fiber jacketing. Once it's flush with the end of the anvil, cement the fiber in the trough, taking care not to get cement on the lensed end.

Next, hold the light source on an optical-bench jig and place the anvil in an XYZ micropositioner. Using a microscope, "eyeball" the anvil into alignment with the source (under no circumstances look at the powered source unless you are wearing eye goggles with filters appropriate to the source's wavelength). Make the final adjustments with the source under power while monitoring the pigtail's free end with a radiometer. You'll find that horizontal and vertical positioning (ie, transverse to the fiber axis) are far more sensitive than longitudinal positioning. However, in the longitudinal positioning, you will observe passage through the lens' focal length (a peak reading on the radiometer).

After locating the optimum position, cement the anvil to the source's heat sink. With a hypodermic syringe, apply very tiny drops of a low-viscosity cyanoacrylate cement to the edges of the bond line, taking care not to engulf the lens in cement. Enlarging the lens end of the anvil's trough helps keep the lens suspended in air.

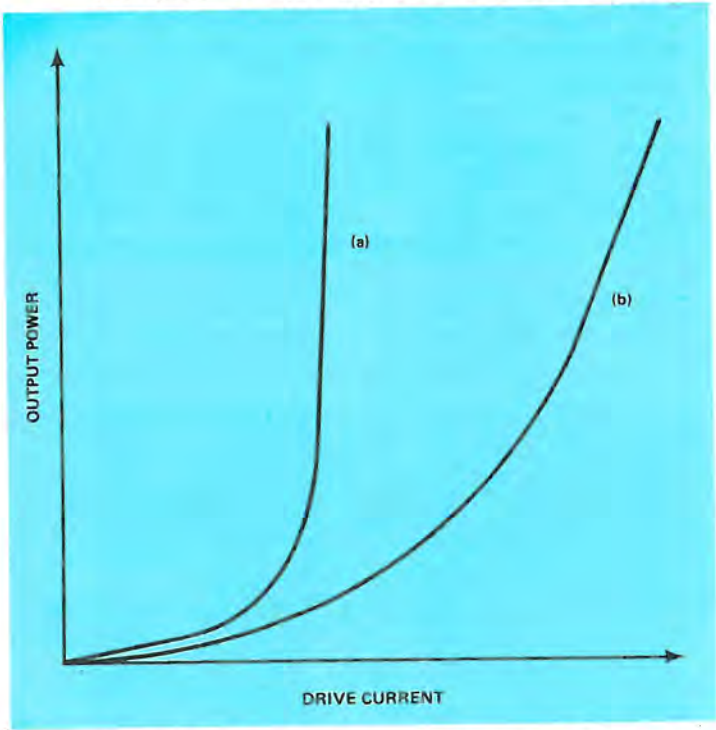

Fig 16—Problems crop up when you use an ILD as a light source, because the laser's output-power-vs-drive-current characteristic varies from device to device. Some devices evidence a very sharp transition into the lasing region **(a),** while other devices within the same product line experience a very soft transition **(b).**

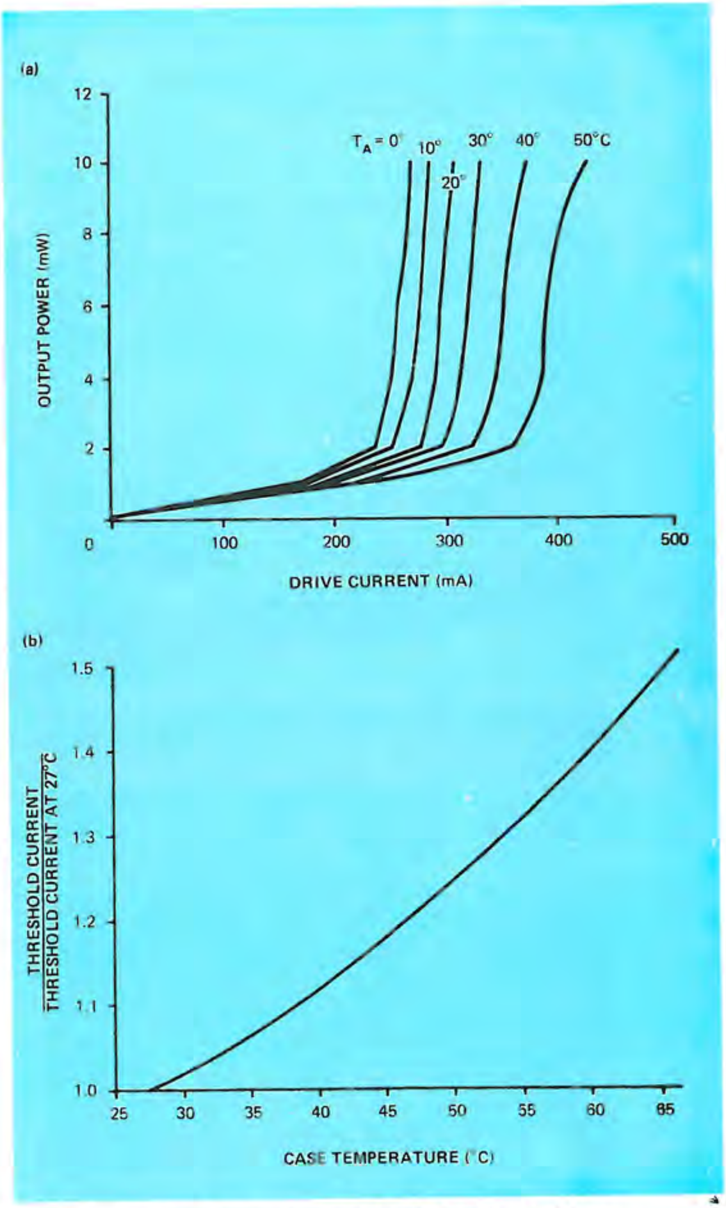

Fig 17—Temperature dependence of the lasing threshold can cause considerable variation in output power for a given drive current. Because the threshold current increases with temperature **(b),** the ILD's characteristic curve shifts to the right **(a).**

The source package will now resemble the one shown in **Fig 13a.** An enlargement of the coupling region **(Fig 13b)** shows how it looks under the microscope; notice that the lensed end is rigidly suspended in air. A cylindrical sleeve then covers the entire assembly to protect it and keep dust and dirt from the coupling interface.

If you can't or don't want to do your own source pigtailing, the source vendor can do it for

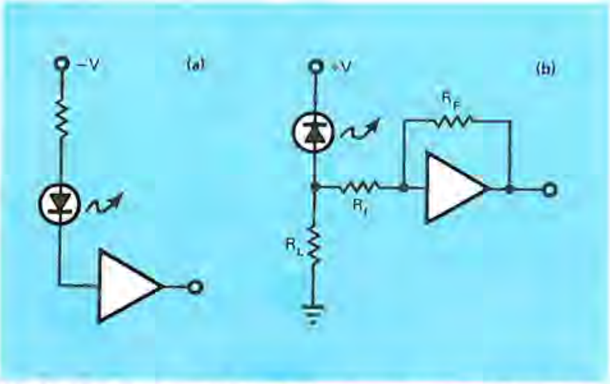

Fig 18—You have much flexibility when designing photodiode receiver circuits. The transimpedance amplifier **(a)** suits current sources like the PIN or avalanche photodiode. You can also operate the receiver in a voltage-gain mode **(b)** by using an op amp.

you. Typically, vendor pigtailing is accomplished without a lens and adds between $100 and $200 to the source's cost.

The job of coupling the fiber to a photodiode is not nearly as critical as source pigtailing. One simple solution **(Fig 14)** is to place a cap, which has a hole for the fiber, over the face of the photodiode. Then insert the cleaved fiber through the hole and epoxy it in place. In most cases, removal of the glass window from the photodiode package is not necessary.

This completes the optical portion of the link; now it's time to consider the electronics required to drive and receive the optical signals.

No new problems here

Basic drive circuits for diode light sources are rather straightforward; **Fig 15** shows two such skeleton circuits. For linear analog-intensity modulation **(Fig 15a),** you control current flow through the LED with the biased signal current applied to the transistor base. LED and ILD manufacturers usually specify maximum forward currents for each individual unit; for CW operation, maximum currents are typically a few hundred milliamps.

For pulsed-modulation techniques, such as PPM or digital ON/OFF keying, you can use an FET to switch an LED or ILD **(Fig 15b).** If you're using an ILD with a sharp "knee" at the lasing threshold current, you might want to adjust R to bias the ILD just below threshold. This action will increase switching speed because you won't have to begin at zero current.

Designers do face one problem when working with ILD's—the laser's output-power-vs-drive-current characteristic varies from device to device. Some ILD's show a very sharp transition into laser action at the threshold current, while other units in the same product line exhibit a gradual output-power increase with current **(Fig 16).** In the latter case, the lasing-current threshold is rather ill defined.

Shifts with temperature in the lasing-current threshold also complicate laser drive circuitry. Because the power curve above threshold is so steep **(Fig 17),** temperature changes can cause considerable variations in output power. Stabilizing the ILD's temperature is one approach to this problem, accomplished by using a thermistor sensor in a control loop that contains a small thermo-electric cooler **(Ref 15).**

A second solution to the temperature problem uses optical feedback; you monitor the ILD's light output and adjust the drive current accordingly. Bell Labs exploits light emission from both ends of an ILD; researchers mount a photodiode in their transmitter package to pick up the ILD's back emission. Forward emission is naturally coupled into the pigtail **(Ref 16).**

Bell Labs has also explored a purely electronic technique, wherein it monitors the ILD's junction voltage. Voltage changes indicate whether the diode is operating above or below threshold; users adjust the drive current as needed **(Ref 17).**

Now consider some basic photodiode receiver circuits **(Fig 18).** The transimpedance amplifier **(a)** is designed for current sources like PIN or avalanche photodiodes. In a voltage-gain mode **(b),** an op amp boosts the voltage developed across the load R_L.

When choosing the load resistance value, you must make tradeoffs in optical sensitivity vs response speed. For a given photodiode, large loads (R_L=5 MΩ) reduce thermal noise currents from the resistor, lowering the NEP and allowing detection of lower light levels. In this case, the photodiode's dark-current shot noise limits signal detection.

On the other hand, small loads (R_L=50Ω) lower the RC time constant of the load and diode-junction capacitance, leading to shorter rise times. Design nomographs **(Ref 18)** help you evaluate this tradeoff.

Most photodiode manufacturers **(Table 3)** offer hybrid modules that integrate a photodiode and preamp in one package. The responsivity figure of merit for these hybrid modules is specified in output volts/input optical watt.

Note finally that temperature variations also complicate the design of APD receiver circuitry. The problem here is responsivity, which varies dramatically with temperature at a given reverse bias voltage. Typically, a temperature-tracking bias circuit takes care of responsivity stabilization or automatic gain control. Temperature-compensated APD/preamp modules are available from RCA, TI and others.

What's the latest?

Participants at the January 1978 IEEE/OSA conference on integrated and guided wave optics presented several interesting papers that make the future of fiber-optic system design even brighter. For example, some researchers have made progress in ironing out the kink in the ILD's power curve. Others have developed APD's with high quantum efficiencies in the 1.3- to 1.35-µm wavelength range, in which silica fibers have very low loss and exhibit zero material dispersion. Finally, long length single-mode fibers have also been developed to operate in this wavelength range. In the area of integrated optics, investigators have made progress in such areas as electro-optical switching, optical signal processing and wavelength-division multiplexing.

TABLE 3—HYBRID PHOTODETECTOR MODULE PARAMETERS

MFG	MODEL	DIODE TYPE	RESPONSIVITY (V/W) λ = 0.9 µm	RESPONSIVITY (V/W) λ = 1.06 µm	BANDWIDTH (MHz)	RISE TIME (10-90%) (nSEC)	DIODE'S ACTIVE AREA (mm²)
BELL & HOWELL	539-003-1	PIN	1.8×10^4	—	12	28	0.8
	539-01-5	PIN	6×10^4	—	4	90	5.0
EG&G	HAD 1000A	PIN	6×10^5	—	2	10	5.1
	HHZ-018Y	PIN	4×10^4	3×10^4	[illegible]	10	5.1
MERET	MRA431	PIN	5×10^5	—	1	—	—
	MDA7710	PIN	1×10^2	—	100	—	—
RCA	C30818	PIN	1×10^4	2×10^3	10	35	0.8
	C30819	APD	3×10^5	5×10^4	40	10	0.5
TI	TIXL 452	APD	2×10^5	—	50	—	0.45

Faced with these developments and armed with the expertise you've gained in this series, you should be well equipped to utilize fiber optics in your communication-system designs. ☐

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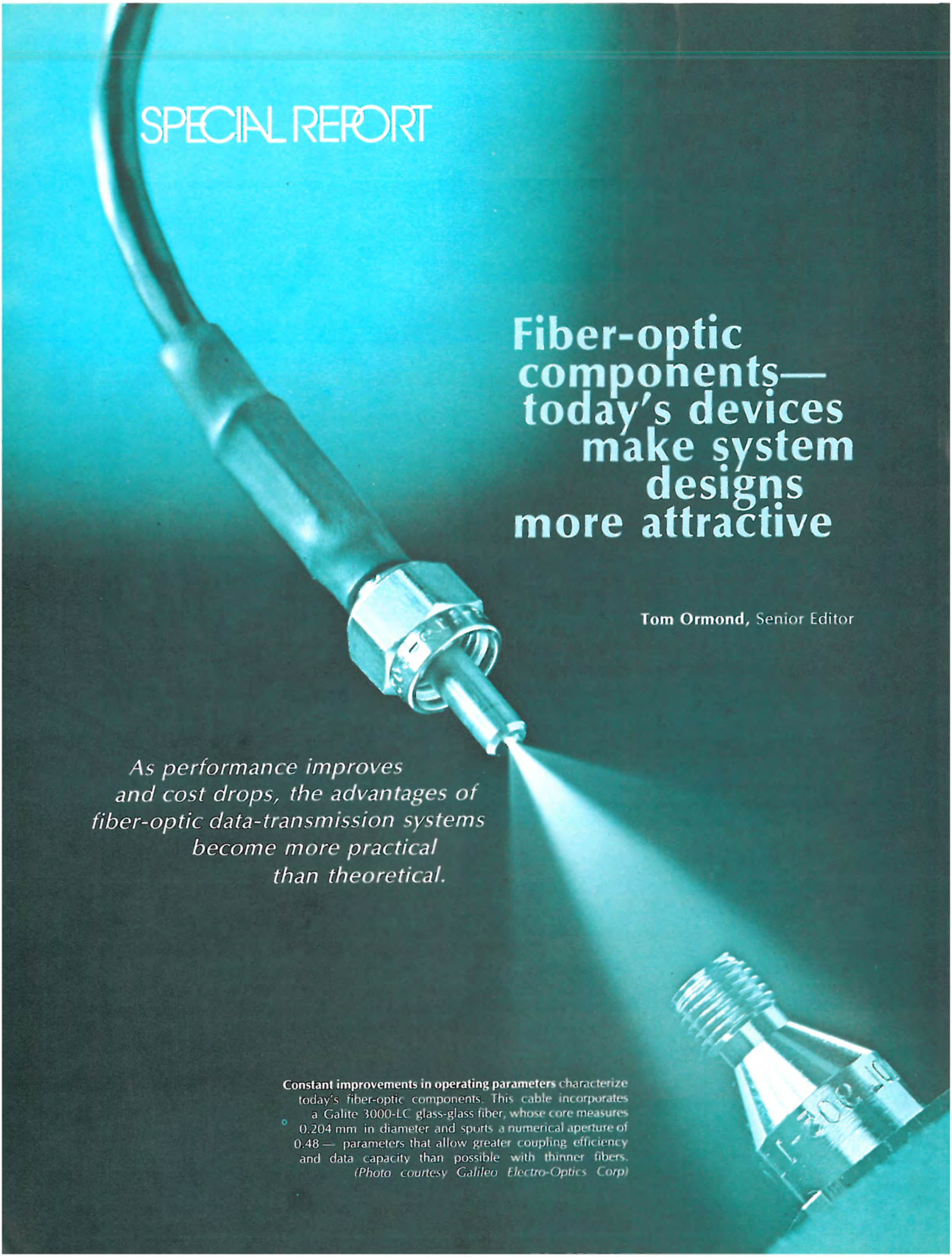
SPECIAL REPORT

Fiber-optic components—today's devices make system designs more attractive

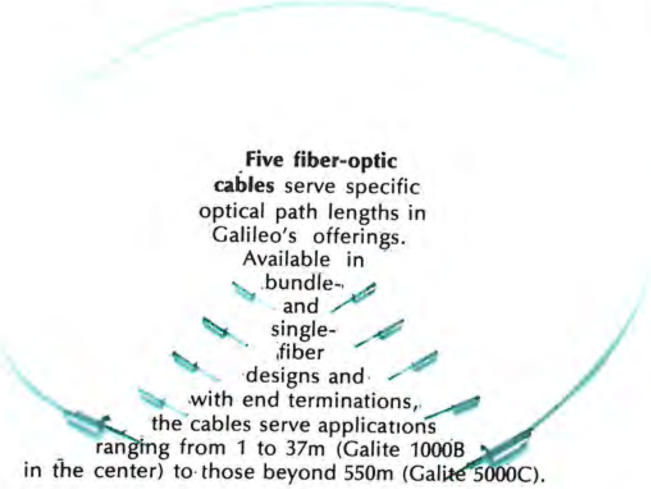
Tom Ormond, Senior Editor

As performance improves and cost drops, the advantages of fiber-optic data-transmission systems become more practical than theoretical.

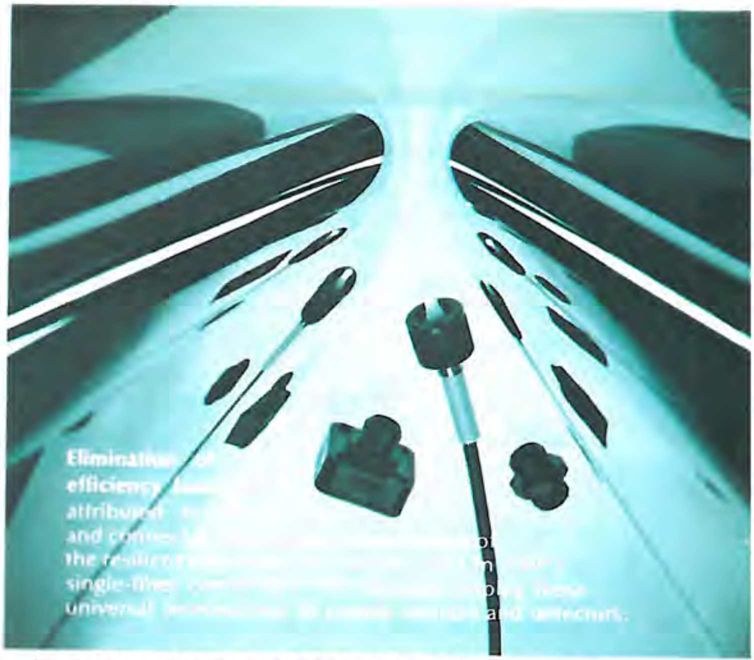


Constant improvements in operating parameters characterize today's fiber-optic components. This cable incorporates a Galite 3000-LC glass-glass fiber, whose core measures 0.204 mm in diameter and sports a numerical aperture of 0.48 — parameters that allow greater coupling efficiency and data capacity than possible with thinner fibers. *(Photo courtesy Galileo Electro-Optics Corp)*

Not long ago, performance problems, technical limitations and prohibitively high component costs deterred implementation of fiber-optic technology. However, large-scale development programs generated by device manufacturers have dramatically changed this picture. Sources and detectors have been developed that are far more compatible in size with the fibers with which they must interface. Glass-fiber manufacturing has evidenced great improvements; you can readily attain 5 dB/km attenuation figures with today's production cables. At the same time, connector manufacturers have essentially licked the single-fiber interconnect problem.



Five fiber-optic cables serve specific optical path lengths in Galileo's offerings. Available in bundle- and single-fiber designs and with end terminations, the cables serve applications ranging from 1 to 37m (Galite 1000B in the center) to those beyond 550m (Galite 5000C).



Elimination of efficiency [illegible] attributed [illegible] and conne[illegible] the resilient [illegible] single-fiber [illegible] universal [illegible] sources and detectors.

However, these component improvements do not signify that system-design problems have just disappeared. Designing a fiber-optic system is still a complex problem. Total system component compatibility is an absolute must; you still must match your source (and detector) to your optical fiber (or cable) and then make sure you don't throw all that careful design away by selecting the wrong connector. Designers must still exercise good judgment to expect success.

This report focuses on three areas—fibers/cables, sources/detectors and connectors. Our lineup does not imply any order of importance; each area weighs equally in a successful system design.

Fibers and cables

If every manufacturer provided all the components necessary to construct a fiber-optic system, designers would certainly find life a lot easier. For one thing, such a move would lessen the problem of matching light-source/fiber-attenuation wavelengths. All too often, designers get into trouble by locking into a specific light source and then trying to force fit a cable to match that source.

When those designers do more initial homework, they soon discover many potential source-

Fiber-optic glossary

Acceptance cone—A parameter that defines acceptable light-launching angles. Only light launched at angles within this cone will be waveguided.

Cladding—The low-refractive-index material that jackets a fiber core and provides optical insulation and protection.

Core—The central region of a fiber. The core's refractive index must be higher than that of the cladding.

Graded-index fiber—A fiber whose refractive-index profile progressively decreases away from the center.

Material dispersion—Broadening of light impulses arising from wavelength-dependent differential delay of light in a waveguide material.

Modal dispersion—A fiber bandwidth-limiting factor caused by differences in the propagation characteristics of the various modes in a multimode fiber.

Multimode fiber—A fiber that supports propagation of more than one mode of a given wavelength.

Numerical aperture—A measure of a fiber's light acceptance.

Packing fraction—The fraction of total cross-sectional area composed of the fiber cores in a fiber-bundle assembly.

Refractive index—The ratio of the velocity of light in a vacuum to the velocity of light in the specified medium.

Single-mode fiber—A fiber waveguide that supports only one mode of propagation.

Step-index fiber—A fiber that evidences an abrupt change in its refractive index at the core-cladding interface.

fiber combinations. Some complement each other better than others, and checking with the cable supplier can prevent a lot of problems.

Not paying attention to environmental, mechanical and termination considerations can also mean trouble. Cables come in a wide variety of constructions. An important factor involves matching the sheathing to the environment of your application; if you don't, you're asking for trouble. If you bend single glass fibers too sharply, you'll undoubtedly shorten their life. And you'll produce the same results when you use plastic fibers above their 80°C recommended continuous operating-temperature limit.

One additional problem area in selecting the proper optical fiber centers on total system loss budgeting. Manufacturers can specify fiber propagation losses very exactly, but that's as far as they can go. The rest of the system budget is up to you, and if you underestimate coupling losses (source-to-fiber, connector), you could be out of business.

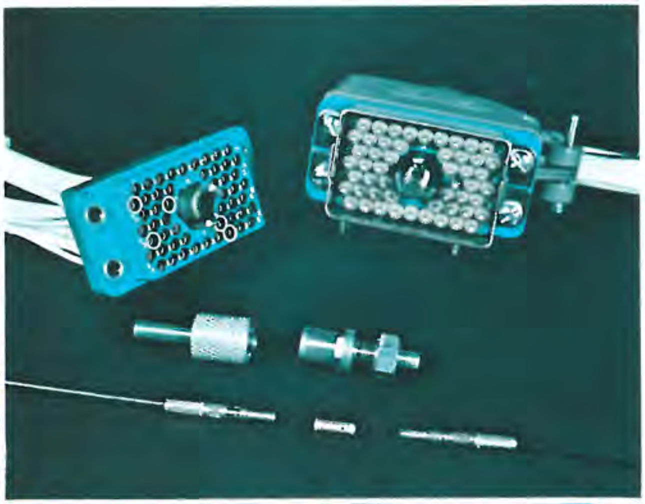
Make sure you're getting what you need

Generally speaking, most specs are subject to differences in measurement techniques among suppliers. Until meaningful standards are established, designers should be aware of these differences and the impact they might have on system performance. You can minimize these problems if you work closely with a cable/system house. In the final analysis, the best way to avoid confusion with performance-characteristic specs is to obtain fiber cable samples and test them in an actual system environment.

With regard to specifics, numerical aperture (NA) and attenuation specs probably cause the most confusion. Attenuation depends heavily on the wavelength of the propagated light. Slight variations in that wavelength can produce dramatic changes in fiber attenuation levels. Very few manufacturers spec attenuation over a wide range of wavelengths, so source-to-fiber wavelength compatibility is of paramount importance.

On the other hand, even with such compatibility, the fiber with the lowest attenuation spec will not necessarily yield the best results in all circumstances. Here's where the NA specification enters (and confuses) the picture. In certain applications, especially for short- and medium-length fiber runs, you must consider tradeoffs between attenuation and NA. Despite their high attenuation figures, large-core-diameter/large-

Less than 1 dB insertion loss results from the contact technique developed at Hughes to accommodate both bundle and single fibers. The contacts work with existing connector housings and permit mixing of optical and electrical signals within one connector.



Simple, easy to assemble and easy to use, ITT Cannon's FSMA single-channel bundle connectors come with or without integral detectors and sources, or in cable assemblies with or without interface electronics.

Added strength and reduced microbending effects are the benefits of the ribbon construction used in General Cable Corp's Type AT cable. The ability to handle all fibers together greatly simplifies problems during a splicing operation.

NA fibers could well capture more light from inexpensive LED sources than do low-loss, telecommunications-type fibers. Higher capture could mean higher overall delivery, so at the bottom line, high-attenuation fibers could prove the better solution in some applications.

By now, you should be aware that proper fiber selection requires more than cursory attention. You must face up to many problems, but a wide variety of available fiber products should satisfy your needs.

Complete digital receivers combine high-speed PIN photodiode, transimpedance amplifiers, comparator and gates in a Superdip package. Meret also offers the units in TO-5 cans that you can incorporate with an SMA connector.

There's an easy way to get started

You don't have to go through the process of selecting and matching all the individual components of a fiber-optic system. Several manufacturers offer kits that contain all the components required for getting an instant start in fiber optics.

The combination of driver, emitter, cable assembly, preamp and detector included in Augat's offering provides all the necessary elements for a complete TTL-compatible digital fiber-optic system. You need only a power supply and a trimming pot to activate it.

The ends of the 5m-long bundle cable are ground and polished, then terminated with ferrules. The LED emitter (880-nm spectral peak) and detector are closely matched for maximum efficiency. Driver and preamp modules are configured in 24-pin DIP's to facilitate pc-board mounting.

Typifying the versatility of today's fiber-optic kits is this offering from Augat. It contains all the necessary elements for a complete TTL-compatible digital fiber-optic system.

Used with the supplied detector, the preamp is temperature referenced to operate from dc to 5M bps. All connectors use gold-plated brass construction to ensure integrity of shielded enclosures. The kit also includes mounting brackets and sockets for the emitter and detector. A comprehensive instruction manual provides schematics for users who wish to build their own preamps and drivers.

Centronic offers two fiber-optic kits with an applications handbook that illustrates the basic circuitry required to replace any existing metallic transmission system. Both kits contain emitters, cable, detectors and terminations. Kit K-1-HD contains two LED emitters—the FTIR-1, which radiates in the 940-nm IR range, and the FTVR-1, which displays peak emission at 650 nm. Two detectors are also included. The FRD 1-2 is a photodiode suitable for detection of both visible and IR radiation, while the FRI 1K is a photodiode and preamp hybrid. The fiber-optic cable is 5m long and terminated with Hellermann Deutsch connectors; it has an attenuation spec of 1 dB/m. Kit K-2-HD contains two emitters, two detectors and two lengths (5 and 20m) of 1 dB/m fiber. One emitter is the FTIR-1; the other, the FTIR-2, is a high-power laser diode with an 890-nm radiation peak. Both detectors in this kit are high-speed diode devices.

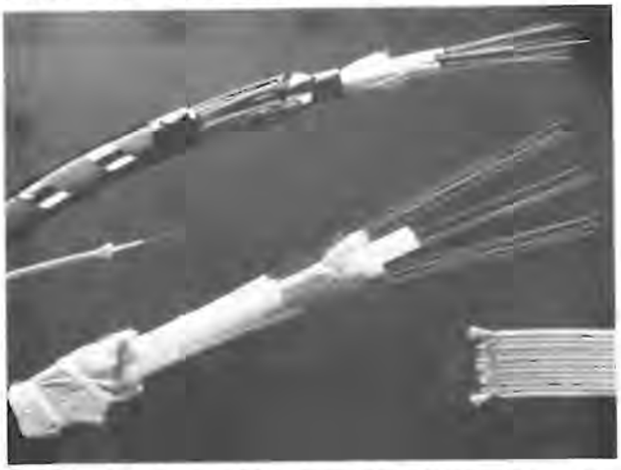
Along with individual components, Radiation Devices Co has offered the LWK-1 since 1976. It contains all the basic hardware and information necessary to build a fiber-optic link: two terminals that accept a TO-46-cased detector or encapsulated emitter, 2m of optically polished, multimode glass step-index bundle cable, two sources and one detector. One of the sources is an IR-emitting diode that operates at 940 nm with rise and fall times of less than 100 nsec. The second is a visible LED operating at 635 nm with rise and fall times below 90 nsec. The kit also includes a silicon PIN photodiode which has a spectral response from 0.4 to 1.1 nm and less than 5-nsec rise and fall times when properly biased and loaded. To round out the kit, a set of application notes catalogs device characteristics and illustrates circuits for analog, digital and pulse transmitter and receiver designs.

Valtec's PC10 system consists of a terminated length of the company's general-purpose PC10 cable (20 dB/km attenuation at 800 nm), panel connectors and compatible LED and PIN diodes. The basic kit includes 100m of cable with AMP plastic end terminations installed. The technical information provided allows users to design and build the electronics around the specifications provided for the diodes.

AMP has packaged an assortment of bushings (emitter, detector and polishing), several sizes of ferrules, a polishing plate, a hand tool for cable termination and sample lengths of fiber-optic cable in its kit offering. Designed to accommodate most common sizes and types of cables, emitters and detectors, the kit allows engineers to experiment and build a variety of prototype fiber-optic systems. Its instruction booklet provides cross-referenced data on semiconductor emitters and detectors as well as fiber-optic cables. The kit contains enough components to house 25 emitters or detectors, make five free-hanging and five bulkhead-mounted splices and terminate 20 fiber-optic cables.

Distance, wide bandwidths need glass fibers

There are three basic fiber types—single mode, multimode step index and graded index. Both Times Fiber Communications Inc and Valtec Corp (the latter in its type SM05) produce single-mode fibers, which offer the ultimate in bandwidth capability. Unfortunately, however, fiber development far exceeds component development, making interfacing a problem. Connectors, sources and detectors capable of handling these fibers' small core diameters aren't available.



Special cables for special systems, from Siecor, include the unit at the lower left, which contains a tube for the transmission of fluid or gases. The high-performance ribbon cable (right) comes in lengths as long as several hundred meters.

So the choice narrows down to step- or graded-index fibers. The application helps you make the decision. Whenever you need lowest dispersion over long distances, choose graded-index fibers. However, at shorter distances (up to 1 km), even high-bandwidth (up to 10M-bps) applications can make good use of step-index fibers. Their high NA and large core diameters also facilitate lower loss interconnections. Whatever your problem, there are several solutions.

Galileo offers an extensive line of step-index fibers. Each type is manufactured for optimum performance and lowest cost for specific optical communication-path lengths (70 to 330m for type 3000C, for example). NA specs run from 0.48 (type 3000C) to 0.2 (type 5000C). Attenuations are ≤60 dB/km (800-900 nm) for the 3000C and ≤18 dB/km (820 nm) for type 5000C (designed for applications beyond 500m). Upon request, Galileo will also supply its cables complete with end terminations.

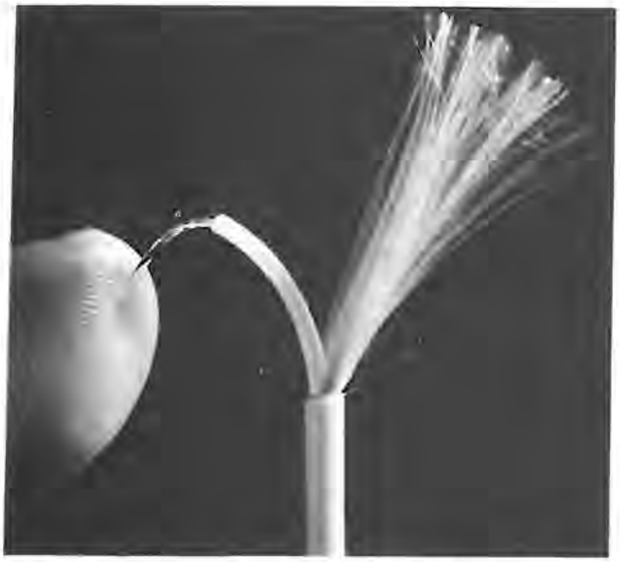
Six cables (1-, 2-, 4-, 6-, 8- and 10-fiber) are available from Siecor. The firm offers two performance grades: standard, with attenuation (at 820 nm) of 10 dB/km and a 3 dB bandwidth (1 km) of 200 MHz, and premium designs with specs of 6 dB/km and 400 MHz. The fibers have an uncoated outside diameter of 125 μm (a figure that's becoming somewhat of a standard among manufacturers), an NA of 0.21 and a typical splicing loss of 0.24 dB.

A variety of single- and multiple-fiber cables is also offered by Times Wire & Cable and ITT Electro-Optical Products. The first firm's product line includes a cable, designed specifically for CATV application, in which a single graded-index fiber is flanked by two galvanized steel messengers to provide strength. Pertinent specs include 7 dB/km attenuation (at 800 nm) and 250 MHz-km bandwidth. Times also offers a line (1-, 3-, 6- and 10-fiber) of heavy-duty cables with both step- and graded-index profiles, and its HT Series of single-fiber cables operates to 150°C.

ITT's offerings include single fibers in both step- and graded-index profiles, as well as multiple-fiber (6 to 19) cables. Attenuation specs for both the step-index (GS-02 Series) and graded-index (GG-02 Series) single fibers range from 3 to 8 dB/km at 1060 nm (5 to 12 dB/km at 820 nm). The firm's multiple-fiber cable offerings feature designs that include external (Type ESM) or internal (Type ISM) strength members, as well as the 7-fiber Type LD version aimed at applications where high-strength, rugged cables aren't required.

Valtec's MG05 and Times Fiber Communications Inc's GA Series of graded-index fibers serve high-bandwidth, long-transmission applications. MG05 fibers have a 10 dB/km max attenuation spec (at 820 nm), but their maximum pulse dispersion is only 5 nsec/km. The GA fibers have attenuations of 10 dB/km (type 10-90) or 15 dB/km (type 15-90) and 300 MHz-km bandwidths. These

Weight and space savings inherent in fiber optics leap out in this graphic comparison. The six Valtec optical fibers in the reinforced cable on the right match the signal-carrying capacity of the 900 pairs of conventional copper telephone wires at the left.



A minimum bending radius that approaches the cable diameter and tensile strength of 30 kg highlight DuPont's PFX-S cables. A sheath of Kevlar aramid fiber reinforces the plastic-clad, silica-core fiber. The jacket is Hytrel polyester elastomer.

specs illustrate why graded-index designs are superior in such applications.

Filling the void between glass and plastic

The preceding paragraphs have catalogued some of the all-glass fibers available today. However, fiber selection does not narrow down to a choice between glass and plastic constructions. You can also opt for plastic-clad, silica-core fibers. Manufacturers claim that such designs offer the best of both technologies. Core diameters are larger because the less brittle cladding can extend out to larger diameters than are possible with glass-cladded fiber designs.

Galileo's 4000C Series serves applications with runs ranging from 330 to 550m. The fibers have a core diameter of 100 μm and an acceptance-cone angle of 47°. Standard configurations are available in 1-, 7- or 19-strand fiber bundles. As with its entire product line, Galileo will supply the 4000C fibers complete with end terminations.

ITT's PS-05 Series also features a large core diameter (125 μm). The fibers have an NA of 0.3, a pulse-dispersion spec (3 dB width) of 30 nsec/km and attenuation (at 790 nm) ranging from 10 to 35 dB/km.

Both single(120)- and dual(220)-channel PFX-S cables, with calculated NA's of 0.4 and core diameters of 200 μm, are available from DuPont. Attenuation is spec'd at two wavelengths: 775 nm (40 dB/km) and 820 nm (50 dB/km). These figures demonstrate how much a slight variation in wavelength can change system loss figures.

Light-duty single-fiber/channel applications are made to order for ITT Electro-Optical's Type LD cable. While standard designs contain seven fibers, ITT can supply up to 19 in a choice of plastic-clad silica, glass step-index or glass graded-index fibers.

Valtec offers two plastic-clad glass-fiber designs: the PC05 with a core diameter of 125 μm and the PC10 with a core diameter of 250 μm. Both designs have NA's of 0.3 and pulse-broadening specs of 40 nsec/km. Over a band of 633 to 1060 nm, attenuation ranges from 30 to 60 dB/km (type 05) to 15 to 20 dB/km (type 10).

Bundles vs single-fiber plastic: a tossup

Single plastic fibers and fiber bundles of either glass or plastic serve essentially the same application area—short-distance transmission. Basically, both are high-loss media and offer good durability and a high degree of flexibility (minimum bending-radius specs range down to 5 mm for plastic fibers).

Some industry observers feel that the fiber-bundle concept has virtually died. However, bundles do have one advantage—the redundancy

What is a FOCIS?

One of the biggest problems facing designers contemplating a new technology is lack of information about the availability and characteristics of components. The Fiber Optic Communication and Information Society (FOCIS) was conceived to eliminate this obstacle by fostering communication.

Despite its tender age (the group was formed informally in June 1976), the organization has grown dramatically and now has more than 500 members. FOCIS has already sponsored one technical show and will also sponsor the technical sessions at Fiber Optic Con's show on May 22 and 23 at the Park Plaza Hotel in Boston.

An extensive program of technical papers at this show will cover such topics as the changeover to mass production, component-design considerations in fiber-optic links, field applications, military applications, performance standards and testing standardization. Exhibits highlighting some of the latest innovations in fiber-optic technology will augment the sessions.

For more information on FOCIS, contact the group at 94 Charles St, Boston 02114. Phone (617) 367-4735.

provided by fiber multiplicity. One broken fiber in a bundle minimally increases system loss; a broken fiber in a single-fiber channel shuts the system down. Bundles also have a slight edge with regard to coupling light from LED sources.

DuPont is the champion of the plastic-fiber concept. Its Crofon line comes in both single- and bundle-fiber designs and is primarily aimed at the automotive, sign-and-display, medical-instrumentation and photography markets. DuPont also features a line (PFX) of plastic fibers intended for data transmission.

The PFX-P140 R is a single-fiber design, while the PFX-P240 R is a dual-fiber cable designed for 2-way communication (the inner cables are color coded for easy identification). Both products feature attenuation of 470 dB/km at 656 nm and an acceptance angle of 64°.

PFX-PIR140 infrared plastic fibers have an optical window at 790 nm, which allows them to interface with GaAlAs LED's. The fibers have a maximum attenuation of 340 dB/km at 790 nm (320 dB/km at 690 nm), 368-μm core diameter and numerical aperture of 0.53. Thus, PFX-PIR140 fibers greatly increase the run-length capability of plastic-fiber cables.

Galileo, Valtec and Welch-Allyn Inc offer bundle-fiber products. Valtec's RT03 suits short-length data-transmission and monitoring applications. These glass fibers, designed for use in cables with various bundle diameters, have a peak NA of 0.56 and attenuation (at 820 nm) of 380-560 dB/km.

It's easy to maintain system compatibility when you buy all the components from one supplier. Texas Instruments' TXE family includes two GaAlAs IR emitters, a PIN photodiode detector and a variety (eight pieces ranging from 1 to 50m long) of plastic-fiber cables.

Welch-Allyn offers two series (FLP and ULP) of fiber-bundle light pipes for use in read heads and scanning and monitoring applications. The ULP bundles use fused-quartz fibers clad with a fluorocarbon resin. They allow useful transmission over a 200- to 1300-nm range but primarily operate below 400 nm—beyond the transmission range of the FLP Series lightpipes.

Galileo's types 1000B (1-37m recommended run length) and 2000C (37-70m runs) are normally collated as bundles of 210 fibers to fill a 45-mil-dia end termination. The cables have a large NA of 0.66, an acceptance-cone angle of 82° and attenu-

Cost considerations

In addition to considering performance tradeoffs among the fiber-optic components discussed in this report, you must also come to grips with prices. Because they're changing so rapidly, it's hard to give any firm numbers, but we can cite some ballpark figures and note trends predicted by manufacturers.

With the exception of single-mode designs (still in the $10/m range), optical fibers are already cost competitive with coaxial cable. Prices range from $0.80/m for plastic-clad, silica-core fibers to $1.25/m for graded-index glass fibers. More importantly, single-fiber cable prices are also down.

A single-channel, all-plastic cable runs about $1.50/m, and you can get plastic-clad, silica-core, single-fiber cables for $1/m. All-glass cables are slightly more expensive, ranging from $2.27/m for a 1-fiber cable to about $20/m for a cable with 10 fiber channels. All indications point to a steady price reduction in the future, because today's cable prices are based on rather limited volume.

In the source/detector area, the current pricing picture is not as bright. LED sources cost anywhere from $6 to $500, depending on performance specs. PIN-detector prices are a little better, but still high (anywhere from $3 to $200). And ILD and APD prices, ranging from $450 to $650, are still very high.

However, the future looks promising in this area, too, and again volume is the key. LED's, ILD's, PIN's and APD's are semiconductor devices, and their pricing profiles should follow the classical semiconductor curve—as volume doubles, prices drop approximately 20%.

Depending on technology, today's connector prices are both good and bad. You can buy fiber-bundle connectors for $3, and projections indicate that they could well drop to the $1 to $2 level in the near future. But single-fiber connector costs range between $20 and $100, though manufacturers look to the future with optimism. Based on a reasonable volume increase and improved manufacturing techniques, they predict that prices for these components could drop to $2 to $10 in unit quantity. Naturally, these numbers would be significantly lower for large-quantity purchases.

ation of <650 dB/km for the 1000B and 400-500 dB/km for the 2000C at 800 to 900 nm.

Something with a little different look

While most cables are round, alternative designs are available. One, developed by Siecor, includes nine parallel channels, each containing an optical fiber within a loose buffer jacket, located side by side in a flat configuration. Designed for computer interconnect applications, the strengthened cable comes in lengths of up to several hundred meters.

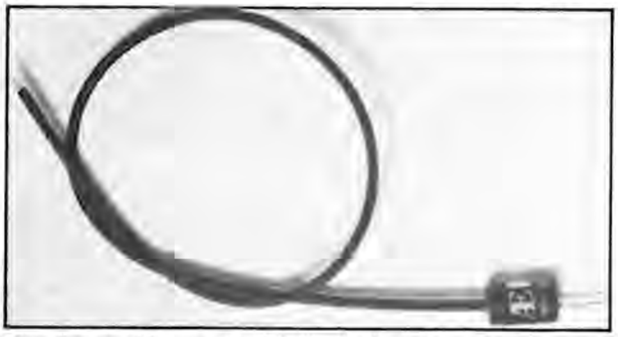
General Cable Corp also makes a flat-ribbon cable design. Its Type AT is 6 mm wide and contains up to 12 fibers; the ribbon is color coded for fiber identification.

Hybrid cables that include a combination of metallic wires and optical fibers are also available. Such cables serve applications where you must apply power with optical signals (repeaters).

Sources and detectors

Once you've selected your fiber cable, the next step is to come to grips with the problem of providing a light source and detector. Two primary considerations should govern your choice of these components. The first, and most obvious, is to ensure wavelength compatibility with the fiber. Second, you must minimize coupling losses.

Source selection boils down to a choice between LED's and ILD's (injection laser diodes). RCA, ITT Electro-Optical Products, Laser Diode Laboratories, Spectronics and General Optronics Corp all offer the latter, which can handle almost any application. They have a high power output that's very directional and spectrally pure, and they are very fast (rise times in the nanosecond range are typical). Unfortunately, they also have disadvantages.



Coupling problems are minimized when you use a pigtailed device. Aborn offers both sources and detectors with integral pigtails (in either plastic or silica), with or without connectors.

ILD's are very temperature sensitive, have relatively short lifetimes and are relatively expensive. They'll certainly do the job, but to prevent overkill you'll have to determine whether their advantages outweigh their disadvantages for your application.

LED's, on the other hand, can provide a cost-effective solution for the bulk of applications where cable run lengths measure less than 1 km. Compared with ILD's, they have longer lifetimes and lower temperature sensitivity. However, they, too, have problems, both intrinsic and extrinsic.

The LED is basically a power device, and you must treat it accordingly with regard to heatsinking. Inadequate rise times can also cause problems. LED's typically achieve the 20- to 30-nsec range, so they require some sort of speed-up circuitry for data rates above 10M bps. You can create problems by using excessive drive current in an attempt to obtain maximum output power. The end result will be a reduction in LED lifetime.

Historically, the biggest problem with LED's has been low source-to-fiber coupling efficiency caused by broadly divergent emission beams. However, manufacturers have addressed this problem and generated several solutions.

Aborn Electronics offers its sources with integral pigtails. Models ALX-100, -101 and -105 come with a plastic (DuPont PFX-P140R) pigtail. They have typical power outputs of 20, 35 and 150 µW, respectively, peak wavelength of 660 nm, spectral bandwidth of 20 nm, and rise and fall times of 10 nsec. The ALX-110 comes with a silica pigtail (DuPont PFX-S120R). It differs only in its 5 µW power-output spec.

ITT offers pigtails on both its surface (type 851-S)- and edge(801-E)-emitting diode sources. Both devices have 840-nm peak emission wavelengths. The 801-E has an output of 400 µW and rise/fall times of 7-10 nsec; comparable specs for the 851-S are 750 µW and 20 nsec. The firm will also lens the end of the pigtail to enhance coupling efficiency.

Texas Instruments also adopts the pigtail (a DuPont PFX-PIR140) philosophy in its TXES475/476 Series of GaAlAs IR sources, which have a peak emission wavelength of 790 nm and rise times of 25 nsec. The units are housed in TO-18 cans and have typical power outputs (for a 25-cm pigtail) of 50 to 75 µW.

Increasing efficiency their own way

While some LED source manufacturers will supply pigtailed devices upon request, they feel that their nonpigtailed designs offer a better solution to coupling problems.

Spectronics employs optical elements within its packages to collect and collimate the emission pattern so it can be efficiently coupled to the source interface. Most of the firm's product line is optimized for interfacing with 45-mil fiber bundles. One representative unit (SE 2231) has a peak output wavelength of 907 nm, fall time of 30 nsec and output power (at 50 mA forward current) of 1.6 mW. Beam angle (half angle for $P_0/2$) is 15°.

Plessey contends that its etched-well structure maximizes coupling into single glass fibers. The company's HR family (700, 800, 930, 950 and 980 Series) has an emission wavelength peak at 900 nm and an emission linewidth of 30 nm.

By placing the emitting surface of the LED within 8 mils of the package interface, Meret improves coupling efficiency in its ML30 Series. The ML32 has a peak wavelength of 885 nm, radiated power >1.5 mW, and typical rise and fall times of 80 nsec.

Motorola employs a selected lens profile on its MFOE100 package to minimize beam divergence. The product has a peak wavelength of 900 nm, a half-angle cone (for 50% P_0) of 11°, power output of 300 μW, and rise and fall times of 50 nsec.

Try to get as much light as you can

The photodetector you choose should obviously complement source and fiber characteristics. Two types of devices are commonly used with fiber-optic systems—the PIN diode and the avalanche photodiode (APD).

PIN's are inexpensive and easy to operate. They require lower bias voltage and simpler bias circuitry. They have high quantum efficiency and a wide operating-temperature range, and they require only simple electronics to amplify the photocurrent. On the negative side, they have low sensitivity and limited bandwidth (100 MHz is about maximum).

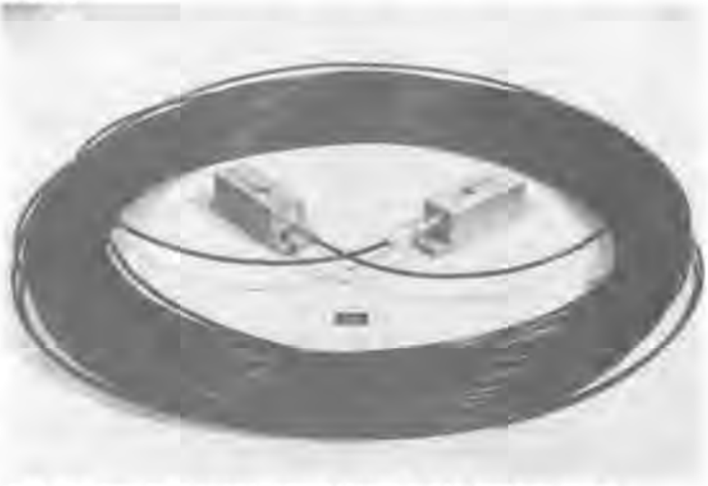
APD's have a high responsivity, fast response (<1 nsec) and a larger gain-bandwidth product (80 to 100 GHz figures are typical). Unfortunately, they are both very temperature sensitive and expensive, requiring high bias voltage and very complex bias circuitry.

You can see that APD's serve best in applications where cable run lengths are long and receiver sensitivity is at a premium. PIN diodes work well in applications where run lengths are 1 km or smaller and bandwidth requirements under 100 MHz. Because many applications fall into the latter category, the product market now leans toward the PIN device.

By matching their MFOD100, TXED453 and APX 200/200A PIN devices with their respective sources, Motorola, Texas Instruments and Meret make it much easier for designers to realize source-detector compatibility. Designed to detect IR radiation and housed in a TO-18 can that incorporates a convex lens to augment light capture, the MFOD100 has a typical responsivity spec of 0.5 A/W at 900 nm, a dark current of 2 nA (at 25°C) and a response time of 1 nsec.

TI's TXED453 detector comes with an integral pigtail (25, 50 or 100 cm long). Designed to operate in a reverse-bias mode, it also has a 2 nA dark-current spec. This detector has a peak responsivity at 790 nm and uses a guard-ring structure to provide low noise characteristics.

Meret's APX 200/200A also comes with a pigtail (DuPont type PFX-P140R). Light sensitivity specs out at 0.25 μA/μW at 660 nm. Rise and fall times are 1 nsec, and noise equivalent power is 2×10^{-14} W/Hz.



You can buy high-speed/long-distance digital systems ready made. Plessey's OML 40D link allows reliable transmission of data at rates up to 30M bps over distances ranging to 2 km.

Centronic's BPX 65 features a 1-nsec response time over visible and IR wavelengths (less than 400 to longer than 1000 nm). It has a peak responsivity at 850 nm and a typical dark-current spec of 1 nA.

Designers at Galileo developed the GEOC 3103-0029 to interface with fiber bundles. It has a responsivity (at 950 nm) of 0.5 μA/μW and a 3 dB spectral bandwidth of 550 to 1000 nm. The unit has a dark current of less than 20 nA, rise time of less than 5 nsec and an acceptance angle (−3 dB) of more than 10°.

The condenser cone design in Spectronics' SD 2232 provides efficient coupling without intimate fiber-detector contact. Hermetically sealed in a TO-46 case, the SD 2232 has peak response at 907 nm, dark current of 1 nA, response time of 1.1 nsec and flux responsivity of 0.5 A/W.

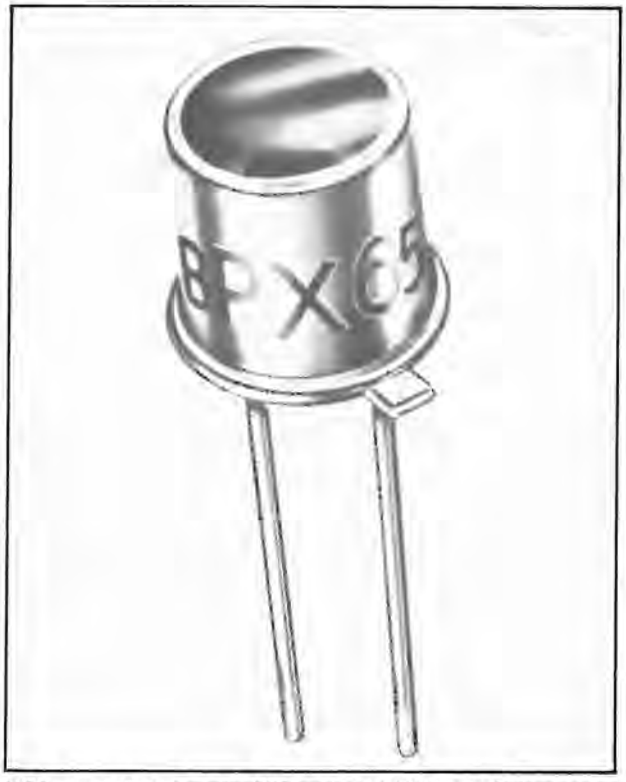
Buy it if you can

Don't bother designing driver and receiver circuitry to supplement your source and detector devices; several manufacturers provide transmission systems that contain all the components you need to get an optical system up to speed instantly. Galileo, Valtec, Hewlett-Packard, RCA, ITT, Meret, Radiation Devices, Spectronics, Plessey and Siecor offer simplex and duplex data links—in a variety of analog and digital systems over a range of data rates—as off-the-shelf components.

Radiation Devices' FDT-4-A is a TTL-compatible transmitter capable of interfacing with either bundle or single fibers. It has a 10M-bps bandwidth, a spectral peak at 880 nm, and rise and fall times of 40 and 15 nsec, respectively.

Siecor's transmitter/receiver sets operate in the RTZ (return to zero) mode and provide bandwidths to 1 and 5M bps. The transmitter includes a logic input stage and a driver circuit for the LED, while the receiver contains a PIN diode, 3-stage preamp and pulse-shaping circuit. Both subsystems come with separate electrical I/O connections for TTL and CMOS signals.

Model 2-D from ITT is a digital system capable of data rates ranging from 100k bps to 20M bps over several kilometers. Inputs and outputs are TTL compatible, and the transmitter employs a high-brightness LED with four switch-selectable drive settings. The receiver features an APD detector, and the design includes a hybridized high-voltage supply for the APD, with AGC (automatic gain control)-monitored output voltage. When maximum sensitivity is not required, ITT supplies the receiver with a PIN detector.



Wide acceptance angle (50°) and a 50 MHz cutoff frequency are two features of the BPX 65 photodiode from Centronic. It features a short response time (1 msec typ) over the visible and IR wavelengths from 400 to over 1000 nm.

RCA's C86003E is a 20M-bps digital data system. The transmitter contains an RCA high-speed GaAlAs LED and associated drive-circuit electronics. A fiber cable is internally coupled from the LED chip's emitting region to an optical bulkhead connector. Minimum peak output power is 100 μW, and the receiver includes a PIN diode, amplifier and threshold circuitry. Optical sensitivity is 2 μW.

Galileo offers both discrete-component (DL-2) and hybrid (DL-1) transmitter/receiver sets. Intended for short-haul (~100m) applications, the TTL-compatible DL-1 system has a data-rate range of 5M bps and a 905-nm optical-wavelength peak. It employs a GaAs LED transmitter and a PIN diode receiver. Model DL-2 TTL-compatible asynchronous system finds use over distances up to 1 km. Data rates range to 10M bps for biphase inputs and 20M bps for NRZ (nonreturn to zero) input data.

As part of its SPX 2600 line, Spectronics offers both analog and digital links. The analog system (2673) provides a 5 MHz video-transmission bandwidth, and the digital system (2674) provides data rates up to 10M bps in any serial format at TTL Levels. Transmitters and receivers come in self-contained metal modules that include Amphenol 905 connectors.

Plessey also offers both analog (OML 50A) and digital (OML 30D and OML 40D) links. The OML 50A has a bandwidth (±1 dB) of 10 Hz to 6 MHz and transmission-length capability to 2 km when used with 0.16 NA step-index fiber and 3 km with a 0.26 NA graded-index fiber. Both digital links are TTL compatible and have data rates of 30M bps. The OML 40D transmitter contains a GaAs IR emitter, and the receiver employs a PIN diode. The OML 30D link normally comes with an APD detector module (PIN diode module also available) in either simplex (option 001) or duplex (option 002) system designs.

Meret offers several receivers in addition to complete links. The firm's MDL 421/422 links have data rates to 2M bps (421) and 4M bps (422). The transmitters employ an IR LED, and receivers include a photodiode, transimpedance amplifier and comparator. The units come in SMA receptacles, Superdips or minibox packages. The latter two packages come with internal power-supply decoupling and transmitter "fail-safe."

Among Valtec's many transmission-system offerings is a low-cost RS-232C data link. Model RSH-D1 asynchronous full-duplex link handles data rates to 20k bps. A standard 25-pin connector accommodates electrical input and output signals. The link has a transmission-length capability of 100m and comes complete with optical connectors designed to mate with the company's PC-10 duplex cable.

Hewlett-Packard has developed two monolithic IC chips which, when used with external sources and detectors, provide all the electrical functions necessary for a 15M-bps data link to extend to 1 km. The transmitter IC accepts digitally differential TTL inputs to generate a bipolar encoded optical pulse signal. The receiver chip incorporates AGC capability to provide the dynamic range necessary to ensure proper link operation.

Connectors and splices

There's little question that connectors have kept pace with the performance improvements realized in other fiber-optic component areas. Bundle connectors are, of course, mature parts and present no problems. The big news is that single glass-fiber connectors are no longer lab curiosities. Low loss, low-cost single-fiber connectors are available as production items from several manufacturers, and they're easy to handle and install in the field.

Currently available single-fiber devices have loss specs in the 1 to 1.5 dB range. Some manufacturers feel that further development can produce a connector with losses below the 1 dB level. Most maintain, however, that technological breakthroughs are most likely to occur in the area of manufacturing technology rather than in basic design. Amphenol, for one, claims that performance requirements are fairly well satisfied right now. Manufacturing today's hardware economically and devising automatic high-volume termination techniques are the areas that need further development.

You can choose termination style in these sources from Radiation Devices. Either buy simple pigtailed versions or opt for assemblies that come complete with connectors.

The biggest problem facing prospective users is selecting the connectors that maintain system compatibility. There are different design philosophies in the connector area—metal vs plastic designs, for example. Thus, evaluate your installation requirements carefully. Also, the type of fiber you've chosen could make a difference in connector performance. None of these questions pose any real problems, but they do require investigation.

Some manufacturers, including AMP, feel strongly that plastic devices can effect low-loss connections in all industrial and consumer applications. This idea proves especially true in cases that don't require high precision. Other manufacturers straddle the fence by using both plastic and metal. They believe that plastic can serve all but the few components that perform the actual fiber alignment.

Still other vendors feel that single-fiber technology requires the tight tolerances and precision that only metal bodies can afford. They reason that parts that come in contact with or are used to align the fibers must have the lowest possible coefficient of thermal expansion to retain those tight tolerances.

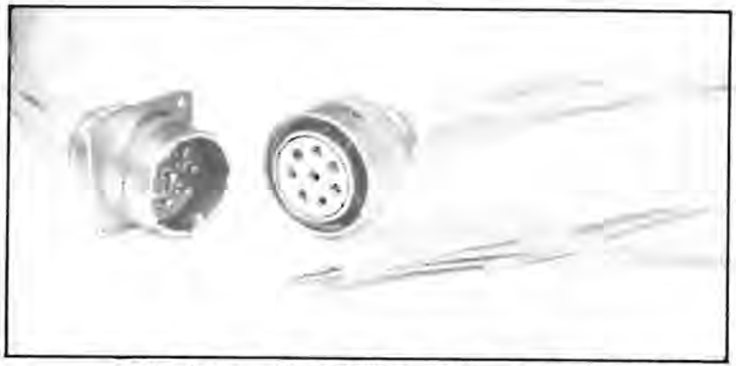
Connector considerations are much the same with regard to all-plastic and all-glass fibers. Because plastic fibers generally have large core diameters, fiber alignment is not as critical. However, to maintain the identical coupling-loss level, alignment of both plastic and glass fibers requires the same percentage displacement of core diameters.

Some unique connector problems crop up with regard to plastic-clad silica fibers, especially in designs where cladding-to-core bonding is weak or nonexistent. The problem is that there's no appropriate material for good bonding to the silicone cladding.

Even if you achieve a bond, you can still experience problems. The silica core will tend to slide within the cladding when a cable assembly is flexed. You can overcome these mechanical bonding problems by removing some cladding within the termination area and bonding on another, mechanically superior, cladding. But even this solution generates problems. Unless the bonding agent matches the refractive index of the original cladding, you'll run into trouble with NA losses.

It helps to check with manufacturers

End-surface preparation can be very critical when you're trying to effect a low-loss connec-



Both single- and multifiber cables can be terminated in Amphenol's Series 801 multichannel environmental connectors. You accommodate various cable diameters by changing the rear end of the contacts.

tion in the field, and manufacturers differ on the required techniques. Some feel that end-polishing methods are required, while others believe that simpler cleaving techniques work just as well. The arguments revolve around the question of obtaining the correct lateral displacement between fiber ends.

Working closely with manufacturers can help you avoid any problems caused by the current lack of cable-dimension standardization. Most connector designs sport a variety of cable-entry designs that accept commonly available cable sizes. However, because cable manufacturers don't necessarily assign product dimensions with specific connectors in mind, you'd be wise to check whether you can get a connector that will accept and efficiently terminate your fiber.

A wide variety of physical connector designs is available today. In the future, it's likely that some styles will become dominant. However, it's just as likely that a standard for all cases will not emerge. A standard type will probably evolve within each performance class; the design that wins out will be the one that provides the most cost-effective termination system.

It's time to do some shopping

AMP offers two lines of plastic connectors—a resilient-ferrule design and an overlapping style. Designed to provide optimum packing fraction and simplify end polishing, the resilient-ferrule connectors accommodate a wide variety of fiber bundles. During termination (and when connected), the resilient nose of the thermoplastic ferrule is compressed radially, compacting the fibers into a minimum-diameter bundle on the centerline of the termination. This feature lets the termination absorb the tolerances normally associated with the number and diameter of fibers in a bundle. Dry-splice insertion loss of these units measures approximately 3 dB; use of index-matching fluids lowers the loss to 2 dB.

AMP's overlapping-style connector terminates large-diameter fibers (DuPont's PFX line). When mated, elastomeric support members surrounding both fiber pairs conform under pressure to the exact fiber diameters. The resultant radially applied forces center each fiber on the axis of its mating fiber. Insertion losses equal less than 1 dB for matched-diameter fibers and rise to only 3 dB max when you mate dry fibers with a 4-mil-dia mismatch.

Amphenol also offers bundle (905 Series) and single-fiber (906 Series) connectors. Series 906 units terminate 125-μm fibers and provide loss of 1.5 to 2 dB. Typical specifications include 0.0002-in. lateral displacement, less than 1° of angular displacement and end separation of 0.001 to 0.0013 in. The units terminate single fibers offered by Galileo, ITT, Siecor, Times Wire and Valtec.

The SMA-type 905 connectors terminate bundles ranging to 91 mils in diameter. They feature an all-metal construction and come in both epoxy- and crimp-style designs to accommodate a wide variety of cables. A special holding tool simplifies end polishing and ensures proper fiber alignment.

By melting the fiber into the connector nosepiece with this semi-automatic tool, you can install Cablewave Systems' connectors without ever handling the delicate cable fiber. Fiber alignment is also independent of core concentricity.

ITT Cannon manufactures both single- and multichannel connectors for single fibers. SMA and BNC styles come with or without integral detectors and sources, or in cable assemblies with or without interface electronics. Fiber-to-fiber coupling losses spec out at 3±0.5 dB. The firm's Unilux family includes the environmentally

Fiber-optic component manufacturers

Aborn Electronics
1928 Old Middlefield Rd
Mt View, CA 94043
(415) 327-7424

Amphenol/Bunker Ramo Corp
33 E Franklin Ave
Danbury, CT 06810
(203) 743-9272

AMP Incorporated
449 Eisenhower Blvd
Harrisburg, PA 17105
(717) 564-0101
Circle No 386

Ansley Electronics Corp
3208 Humboldt Ave
Los Angeles, CA 90031
(213) 223-2331

Augat Inc
33 Perry Ave
Attleboro, MA 02703
(617) 222-2202

Belden Corp
2000 S Batavia Ave
Geneva, IL 60134
(312) 232-8900

Bell Northern Research Ltd
Box 3511 Station C
Ottawa Canada K1Y4H7
(613) 596-2210

Bendix Corp
Sherman Ave
Sidney, NY 13838
(607) 563-9511

Berg Electronics
York Expressway
New Cumberland, PA 17070
(717) 938-6711

Burndy Corp
Richards Ave
Norwalk, CT 06856
(203) 838-4444

Cablewave Systems Inc
60 Dodge Ave
North Haven, CT 06473
(203) 239-3311

Canada Cable & Wire Co Ltd
80 Bloor St West
Toronto, Canada M5S2V1
(416) 923-7067

Centronic
1101 Bristol Rd
Mountainside, NJ 07092
(201) 233-7200

Corning Glass Works
Corning, NY 14830
(607) 974-8012

Deutsch Co
Municipal Airport
Banning, CA 92220
(714) 849-7844

Devar Inc
706 Bostwick Ave
Bridgeport, CT 06665
(203) 368-6751

DuPont Co
1542 Farmers Bank Bldg
Wilmington, DE 19898
(302) 774-2135

E G & G Electro-Optics Div
35 Congress St
Salem, MA 01970
(617) 745-3200

Fairchild Semiconductor
464 Ellis St
Mt View, CA 94040
(415) 962-5011

Fiber Optic Cable Corp
Box 1492
Framingham, MA 01701
(617) 875-5530

Galileo Electro-Optics Corp
Galileo Park
Sturbridge, MA 01518
(617) 347-9191

General Cable Corp
500 W Putnam Ave
Greenwich, CT 06830
(203) 661-0100

General Optronics Corp
3005 Hadley Rd
South Plainfield, NJ 07080
(201) 753-6700

GTE Sylvania
Titusville, PA 16354
(814) 589-7071

Hewlett-Packard Co
640 Page Mill Rd
Palo Alto, CA 94304
(415) 493-1212

Hitachi America Ltd
2700 River Rd
Des Plaines, IL 60018
(312) 298-0840

Hughes Aircraft Co
17150 Von Karman Ave
Irvine, CA 92714
(714) 549-5701

International Audio Visual Inc
15818 Arminta St
Van Nuys, CA 91406
(213) 784-4400

PC-board mounting applications are easy with these SMA connectors from Spectronics. You can purchase units complete with emitters and detectors if you desire.

sealed FOS Series and the FOT Series, aimed at controlled-environment applications. These devices evidence a typical coupling loss of 2 dB (1 dB possible). Available termination kits ensure that fiber ends are chip free, flat and perpendicular to the fiber centerline.

The most important feature of Cablewave Systems' connectors is the company's method for bringing the fiber to the connector interface. The cable's glass fiber and inner jacket are inserted into the connector's nosepiece; the nosepiece is then heated and the plastic jacket around the fiber melted. The fiber itself is never handled, thus preventing any loss-increasing fractures in the glass. Users have realized insertion losses as low as 0.56 dB when terminating DuPont PFX-S120R fibers.

Heart of the Hughes fiber-optic connector is its alignment system, in which a bushing/split-sleeve technique achieves a high degree of precision. Designed for both bundle- and single-fiber applications, the connectors have less than 1 dB insertion loss. One MIL-spec housing accommodates both electrical and optical connections.

New designs could be coming

Manufacturers are continuing to investigate new connector designs. AMP, for example, offers connectors that accomplish a glass-to-plastic-fiber interconnect. Berg is also working on such a design, although it's still in the developmental stage and thus too early to discuss. Finally, Cannon is investigating units designed to terminate ribbon cables. □

ITT Cannon Electric
666 E Dyer Rd
Santa Ana, CA 92702
(714) 557-4700

ITT Electro-Optical Div
7635 Plantation Rd
Roanoke, VA 24019
(703) 563-0371

Laser Diode Laboratories Inc
205 Forrest St
Metuchen, NJ 08840
(201) 549-7700

Litronix Inc
19000 Homestead Rd
Cupertino, CA 95014
(408) 257-7910

Meret Inc
1815 24th St
Santa Monica, CA 90404
(213) 828-7496

Monsanto Commercial Products
3400 Hillview Ave
Palo Alto, CA 94304
(415) 493-3300

Motorola Semiconductor
5005 E McDowell Rd
Phoenix, AZ 85008
(602) 244-6900

National Semiconductor Corp
2900 Semiconductor Dr
Santa Clara, CA 95051
(408) 737-5000

NEC America Inc
3070 Lawrence Expressway
Santa Clara, CA 95051
(408) 738-2180

Plessey Optoelectronics & Microwave
1641 Kaiser Ave
Irvine, CA 92714
(714) 540-9934

Poly-Optics Inc
1815 E Carnegie
Santa Ana, CA 92705
(714) 546-2250

Quantrad Corp
138 Illinois St
El Segundo, CA 90245
(213) 322-2086

Quartz Products Corp
688 Somerset St
Plainfield, NJ 07061
(201) 757-4545

Radiation Devices Co Inc
Box 8450
Baltimore, MD 21234
(301) 628-2240

Rank Fiber Optic
West Nyack, NY 10994
(914) 358-4450

Rank Precision Industries
411 E Jarvis Ave
Des Plaines, IL 60018
(312) 297-7720

RCA Solid State Div
Rte 202
Somerville, NJ 08876
(201) 685-6423

Rockwell International Corp
1700 E Imperial Hwy
El Segundo, CA 90245
(213) 647-5000

Sealectro Corp
225 Hoyt St
Mamaroneck, NY 10543
(914) 698-5600

Siecor Optical Cables Inc
631 Miracle Mile
Horseheads, NY 14845
(607) 739-3562

Siemens Corp
186 Wood Ave South
Iselin, NJ 08830
(201) 494-1000

Spectronics Inc
830 E Arapaho Rd
Richardson, TX 75080
(214) 234-4271

Texas Instruments Inc
Box 512
Dallas, TX 75222
(214) 238-2481

Thomas & Betts
36 Butler St
Elizabeth, NJ 07207
(201) 354-4321

Times Fiber Communications
550 Research Parkway
Meriden, CT 06450
(203) 634-2171

Times Wire & Cable
358 Hall Ave
Wallingford, CT 06492
(203) 265-2361

TRW Cinch
1501 Morse Ave
Elk Grove Village, IL 60007
(312) 439-8800

United Detector Technology
2644 30th St
Santa Monica, CA 90405
(213) 396-3175

Valtec Corp
99 Hartwell St
West Boylston, MA 01583
(617) 835-6082

Welch Allyn Inc
Skaneatles Falls, NY 13153
(516) 685-5788