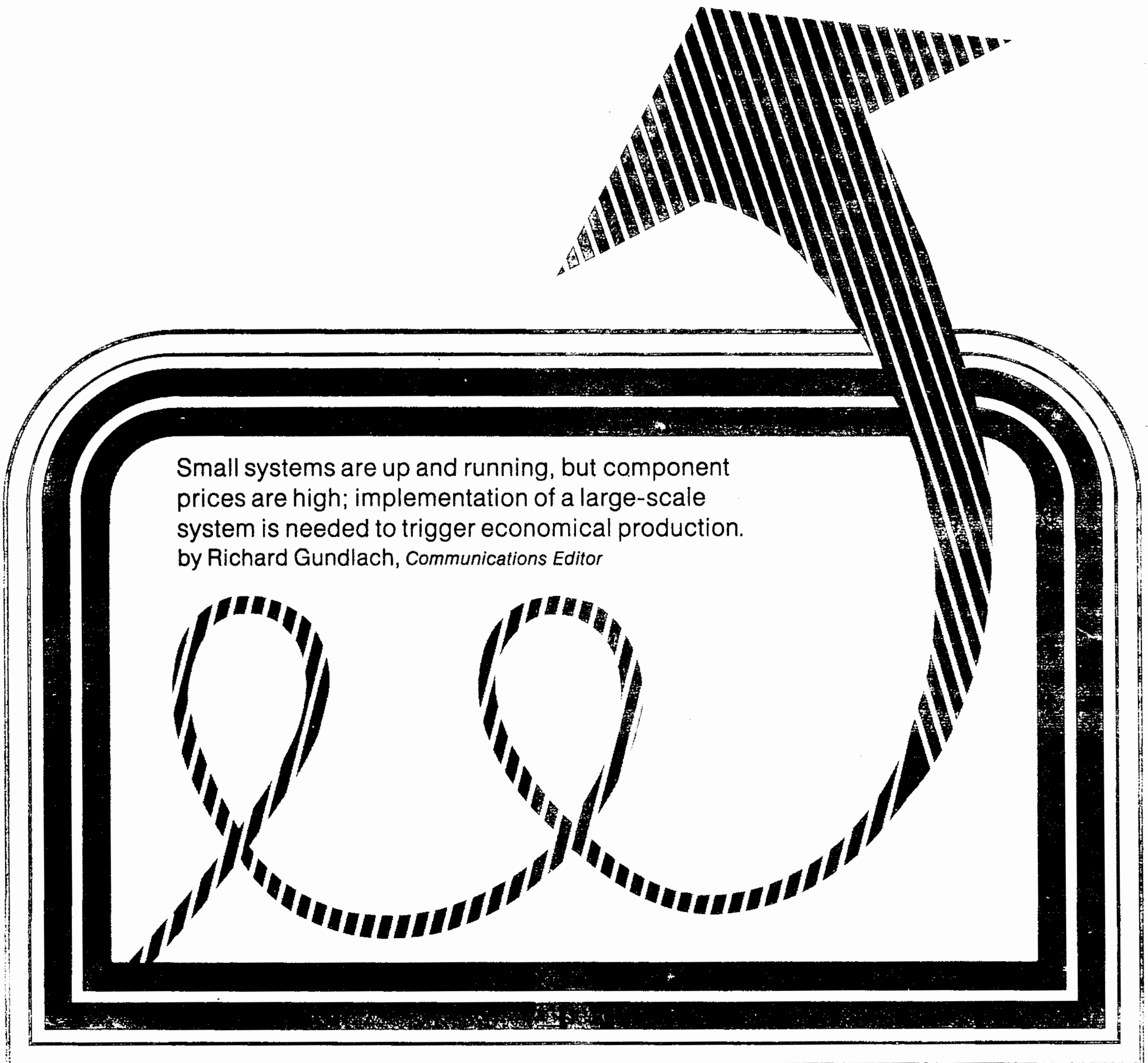
FIBER-OPTIC DEVELOPMENTS SPARK WORLDWIDE INTEREST



Small systems are up and running, but component prices are high; implementation of a large-scale system is needed to trigger economical production.

by Richard Gundlach, *Communications Editor*

☐ The advances made in the last year in fiber-optic communications have delighted even the most optimistic. New systems have done better than expected in rigorous field trials. Improved components—more efficient light sources, less noisy photodetectors, and more rugged cables—have become available off the shelf. Single-fiber cables, plus matching connectors, are starting to surface, while production techniques are attracting the kind of attention that's the due only of nearly mature technologies.

Commercial applications, in fact, have leapt into prominence, both in the U.S. and overseas, and the military remain as dedicated as ever to the pursuit of the interference-free, lightweight attractions of fiber-optic systems. For the time being, to be sure, cost remains a problem. Other difficulties include a lack of standards (though several groups are already at work in this area) and the unfamiliarity of the wider engineering community with such a new technology. However, there seems to be no doubt that by the 1980s optical fibers will often be a practical alternative to copper wire.

When that time comes, one of the major fiber-optic users will be the telephone system, and John deButts, chairman of AT&T has apparently firmly committed the Bell System to developing fiber optics. "I anticipate that by the early 1980s cables of glass fibers will be carrying thousands of simultaneous messages between major switching centers in our cities," he recently stated. The fibers not only offer large bandwidths for such multichannel transmissions but, more important initially, they easily interface with existing telephone equipment. With their lower losses, too, repeaters can be more widely spaced than is possible with present conductive-cable systems. This aspect is also attractive to Bell Canada. It will probably use fiber optics to obtain repeaterless connections between telephone exchanges, according to W. C. Benger, group vice president of Northern Telecom Ltd., a major supplier to the Canadian telephone company.

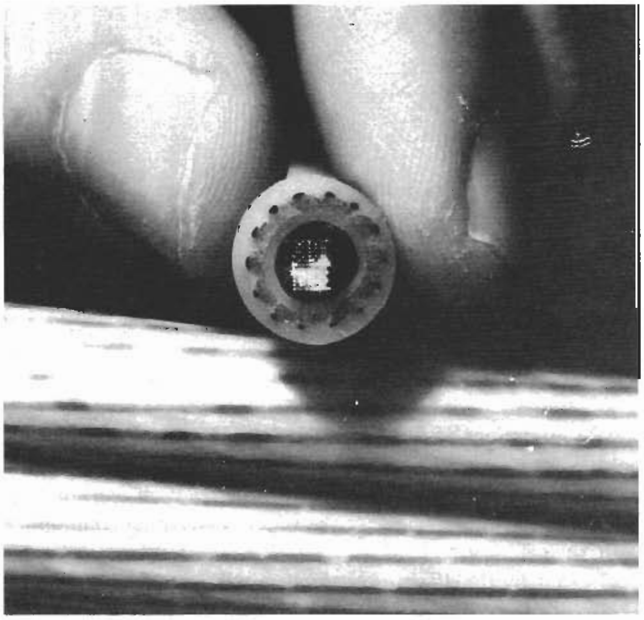
For large data-processing systems, on the other hand, the large bandwidth capability and the freedom from electromagnetic interference are perhaps the biggest attractions of optical-fiber cable, which is already being used to link central processors to peripherals. The absence of the spark hazards of electrical signals will be a major asset in many industrial processing applications. Other applications will be won over, eventually, by the cost savings of glass fiber over coaxial cable.

In sum, the appeal of fiber optics is multifaceted and could (say the top analysts) rocket demand to billion dollar heights before the 1980s are out.

The actuality

This vision of the technology's future gains substance from several systems already in existence, particularly an experimental fiber-optic telephone link started by Bell in Atlanta, Georgia, last January. There, a team from Bell Laboratories and Western Electric managed to put together, using as many as 18 low-loss splices, a 10.9-kilometer repeaterless link. The system encountered no problems when transmitting data at 44.7 megabits per second. Average loss of the cable when in place was 6 decibels/km—2 dB better than the design goal. The experiment proved that it's possible to run fiber-optic links long enough to avoid the need to put repeaters in manholes every mile or so, as is necessary with coaxial-cable systems in large metropolitan areas like New York or Chicago. Just as important, the link interfaced successfully with existing telephone equipment, as the technology will have to do when it first enters the present telephone network.

Also eliminated by the experiment was the uncertainty whether practical connectors could be produced to splice together

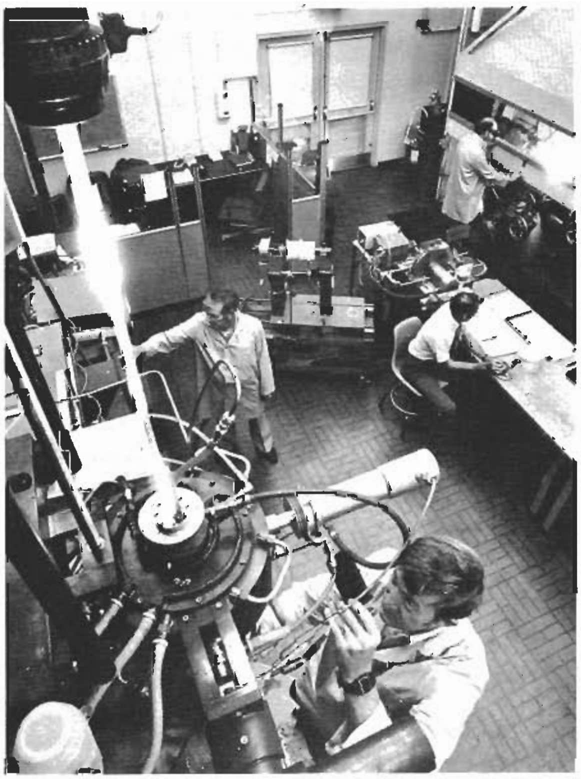


1. Looking into fibers. The optical-fiber cables used in Bell's field experiment in Atlanta are only half an inch in diameter, yet their 144 fibers operating at a 44.7-Mb/s data rate can carry the equivalent of over 48,000 simultaneous telephone conversations.

Making fibers

A Western Electric pilot production line for optical fibers is already in operation. Making the fibers takes several hours, and the slightest variation in the process at any point renders the fiber unusable. First, oxides are deposited by chemical vaporization on the inside of a 3-foot-long tube of quartz glass, called a preform (shown upper right). Next, the preform is collapsed and pulled into a hair-thin optical fiber. A torch heats the preform as it moves at a preset rate. This builds up the several core layers of germanium-doped silicon dioxide that are needed to produce the varying refractive index of a graded-index fiber.

These high-silica-content glass preforms are then softened in a furnace (shown upper left) and pulled under slight tension into thin glass fibers. The pure fibers are coated before reaching the take-up reel with a polymer to preserve their strength. Although glass in the pure state is stronger than steel, any impurities that touch it before the protective coating is applied degrades its strength considerably.



in the field cable containing 144 separate fibers, each a mere 2 mils in diameter. The answer was a kind of club sandwich connector, with a dozen 12-fiber ribbons as the filling and 13 precisely grooved aluminum chips as the slices of bread.

Another fiber-optic system carries television signals. TelePrompTer Manhattan Cable Television Cable Inc. just recently installed an 800-foot fiber-optic link to carry cable TV signals from a roof antenna to its head-end equipment 34 floors below. And General Telephone and Electronics Corp. is firming up plans for its scheduled field trials later this year that will carry actual commercial voice traffic between operating telephone exchanges in California. It will use cable made by General Cable Corp. of Greenwich, Conn.

Over in France—to focus on just one major overseas application of fiber optics—the Centre National d'Etudes des Télécommunications has already completed one experimental digital transmission system. (It's the start of an ambitious effort to develop the hardware and systems know-how that the government-run telephone network will need for the fiber-optic links it plans to have in full service by the mid 1980s.) The CNET's first optical system used 3 km of Corning fibers and, after running for some 20 months at 2 Mb/s, has been modified to accept data at 8.4 Mb/s. Now the CNET also has parts of a 3.4-Mb/s system working and hopes to have firm specifications for its first trial system by early 1978, with operation starting in 1980.

Nor have the military, back in the U.S., been idle. All three services were from the beginning attracted by the small size, light weight and freedom from interference of optical fiber—all major concerns aboard aircraft or ships or for secure tactical and strategical links under water or on land. The Navy and Air Force naturally concentrated on data busing for signal transmission in aircraft and on ships, while the Army is concerned mostly with secure land communications links.

More specifically, a fiber-optic sonar link recently underwent trials aboard a submarine [*Electronics*, May 27, p. 39], while a fiber-optic telephone system has now operated without failure in the fiber-optic portion for three years aboard the U.S.S. Little Rock. "Fiber installations have proved very successful," sums up Don Williams, program manager at the Naval Electronics Laboratory Center in San Diego.

Williams estimates that the 450 pounds of copper wire now used in fighter aircraft could be replaced with only 50 pounds of fiber cable. In the Navy A-7 aircraft, for example, 13 optical-fiber cables have supplanted 115 wire signal channels representing 302 separate conductors, almost a mile of electric cable being replaced with only 224 feet of fiber. Williams also points to the fiber-optic link used between antenna and transceiver of the AN/PPS-18, a general battlefield-surveillance radar. "If funding comes through, this would be the first military system to go into production using fiber optics."

As for the Army, its budget for fiber-optic development in fiscal 1977 has increased "significantly" over last year, according to Larry Dworkin, acting chief of advanced techniques at the Army Electronics Command, Fort Monmouth, N.J. He points to several contracts they are close to letting—one for field-deployable optical-fiber cables for use in ground tactical and strategic telecommunications, and another to develop connectors for six-fiber cables that can withstand the rigors of military environments.

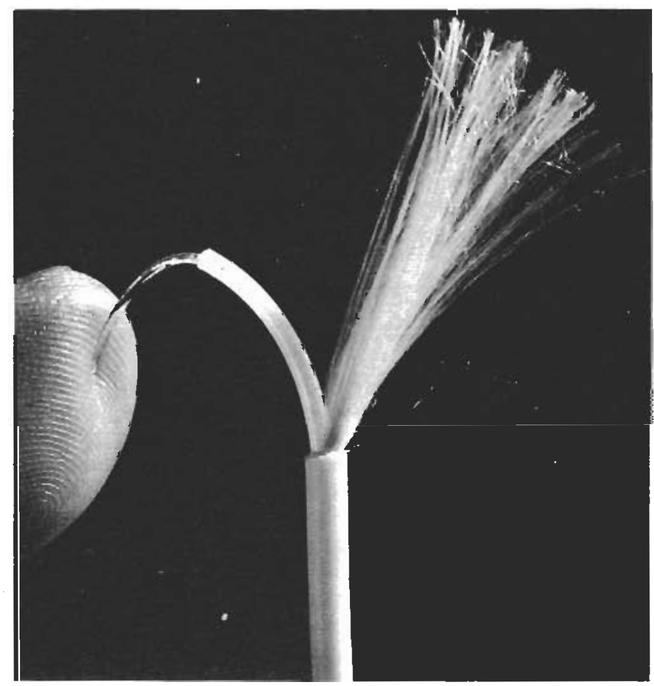
According to Dworkin, RCA has a contract with the Combat Surveillance and Target Acquisition Laboratories to investigate high-radiance light-emitting diodes and lasers operating in the 820-nanometer range that is typical of fiber-optic systems. He also adds that the Army is about to embark on its first major production-type commitment—an investigation of methods of manufacturing light sources (LEDs and lasers) and photodetectors (silicon p-i-n diodes and avalanche photodetector devices).

Meanwhile, the Air Force is developing, among other things, multiple fiber-optic systems with optical switching at data rates of less the 50 Mb/s.

Great growth

It's as a result of this kind of work that fiber optics has aroused industrywide interest. Individual applications, particularly in computers, will be described later. Overall, so encouraging are the signs that Gnostic Concepts Inc., a Menlo Park, California-based market-research firm, is predicting that the world market for fiber-optic systems will grow to over $1.58 billion by 1990. Jeff D. Montgomery, Gnostic's vice president, foresees initial growth in applications where the unique advantages of fiber optics justify its slightly higher price. But within the next decade or so he predicts an explosive growth in the use of optical components in production systems. "In the U.S. this number should reach $64 million by 1980 from a little over $1 million in 1975, and should jump to $833 million by 1990," says Montgomery. At that time he sees the major markets as follows: commercial communications will account for 74% of those applications, up from 54% in 1980; commercial computers, although dropping from 17% in 1980 to 9% in 1990, will have a much larger volume, and the market for industrial process control will remain steady at 7%, but again this will account for increased dollars.

Martyn F. Roetter, technical director of Arthur D. Little Inc.'s program on optical technology and markets, pretty much agrees with the major growth areas singled out by Montgomery. However, he points out that much of what happens worldwide



2. Flexible fiber. Although most people think of thin glass fibers as extremely brittle, Du Pont's new pure-silica-core fibers illustrate the toughness possible—this 8-mil-diameter cabled fiber does not break even when bent in a radius of less than 0.125 inch.

will depend on the policy set by Bell in the U.S. and the telephone companies overseas. He thinks it will be 1981 before Bell is sufficiently convinced that fiber cables in the ground can last 20 years and implements such systems. However, he does see new computers introduced within the next several years and industrial control systems as nearer high-growth areas.

As part of its investigations, Arthur D. Little is developing digital and analog optical-fiber communications systems to carry voice, data and video signals for short-haul use. This the firm sees as the most promising near-term application of fiber optics. "We feel that the benefits and applications of the technology cannot be realized without a greater understanding and experience in design, construction, testing and total costing of such systems," says Herb Elion, Arthur D. Little's program manager. And, one might add, greater understanding and experience of the components of fiber-optic systems.

The components

Even though light sources and detectors, splices and connectors are essential elements in fiber-optic communications, it's been the optical fiber that has paced its progress. And only as the cost of the fiber becomes competitive with existing coaxial cabling, will fiber-optic technology really catch on, whether in systems that must perform well in high-voltage areas or in instrumentation linking remote sensors with central processing units, whether within mainframes of computers or in linking computers to peripherals in noisy environments.

For some high-performance applications even now, optical-fiber cable is preferable to existing coaxial transmission systems. For example, presently available coaxial-cable loss in a 100-Mb/s-system can be as high as 30 dB/km, whereas for the same bit rate a graded-index optical fiber has a loss of about 5 dB/km. Low-loss optical fibers with increased bandwidth capability in lightweight cabling make them ideal for communications links where crowded cable ducts now pose a problem—the lower signal attenuation allows longer cable runs before any signal processing is needed. In weight-sensitive applications, over a ton of wire cables can be replaced with fiber cables weighing less than 1% of that. Moreover, wherever miles of cable are used in conjunction with low-level digital signal transmission, electromagnetic interference becomes a horrendous problem. Here, interference-free optical fibers eliminate the costly transformer isolation and cable shielding needed for conventional wire conductors.

Different direction

With the rapid progress being made in fiber-optic technology, attention is shifting from the more theoretical aspects to operational and manufacturing problems. For example, the emphasis is now less on reducing the loss of fibers and more on the production of fibers with tighter tolerances and low-cost cables that are rugged in the field. A number of good, low-cost p-i-n detectors are already available, but the development direction is toward low-voltage avalanche photodetectors for more demanding applications. Still missing are economical light sources with long life, which are essential to all potentially major users, especially the telephone companies.

And one of the biggest problems is the scarcity of inexpensive yet reliable single-fiber-per-channel connectors suitable for use by unskilled workers in the field. Within the last year both metal- and plastic-shelled connectors have been available for bundle fibers, but only recently have commercially available single-fiber-per-channel connectors surfaced. These connectors are designed to couple fiber to fiber, fiber to source, and fiber to photodetector.

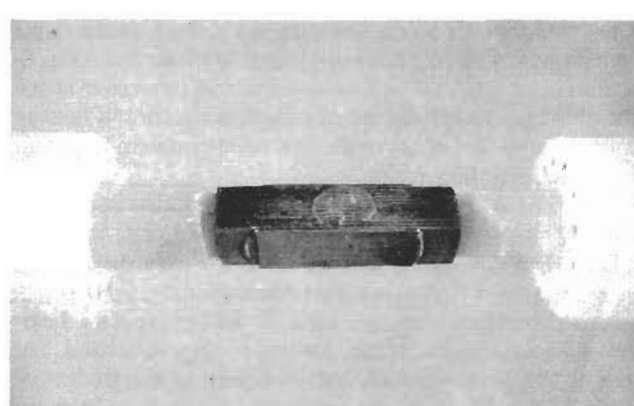
Setting standards

With the very small diameter of single fibers, connector tolerances in the order of 0.1 mil are required to keep losses low. This, in itself, creates production problems, but with fiber and cable dimensions not yet tight enough and the proliferation of different fiber sizes from many different manufacturers, most connector makers feel they cannot design inexpensive, practical devices until the fiber makers get together on some standard. That would have to involve companies such as Corning, ITT, Galileo, Valtec, Fiber Communications Inc., Du Pont, Polyoptics, and Fiber Optic Cable Corp., as well as several overseas suppliers.

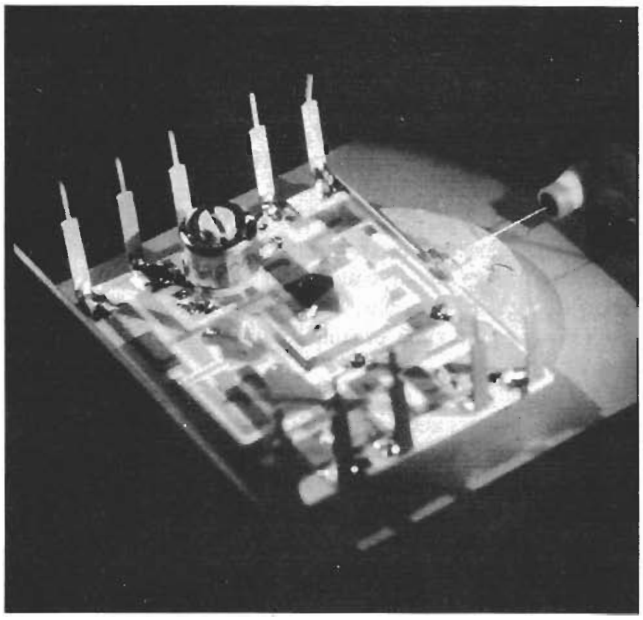
Sets of standards, in fact, are needed for all fiber-optic components, not just for fibers and connectors. Several agencies

Fiber optics in the car

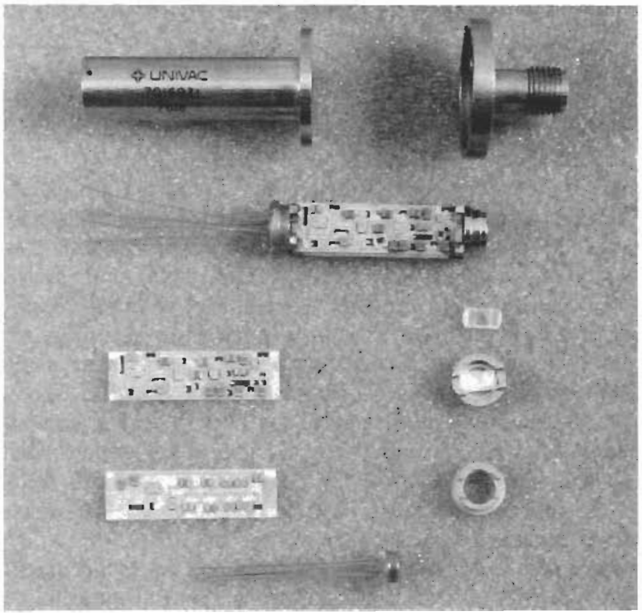
Fiber-optic communications systems are not only immune to the high noise levels of automobiles—they can reduce cabling harness weights, material cost, and processing time. An experimental fiber-optic harness system has been developed by General Motors Engineering to transmit vehicle control signals over a single-optical-fiber link, instead of over conventional wires. Such a system, perhaps built into the steering column or into a modified turn-signal control arm, would transmit separate signals over the fiber to an optical receiver, which would then convert them into electrical signals so as to switch on headlights or control turn signals, windshield wipers, and the hazard blinker. Such a system, once it passes the experimental stage, should open up a tremendous market for fiber optics.



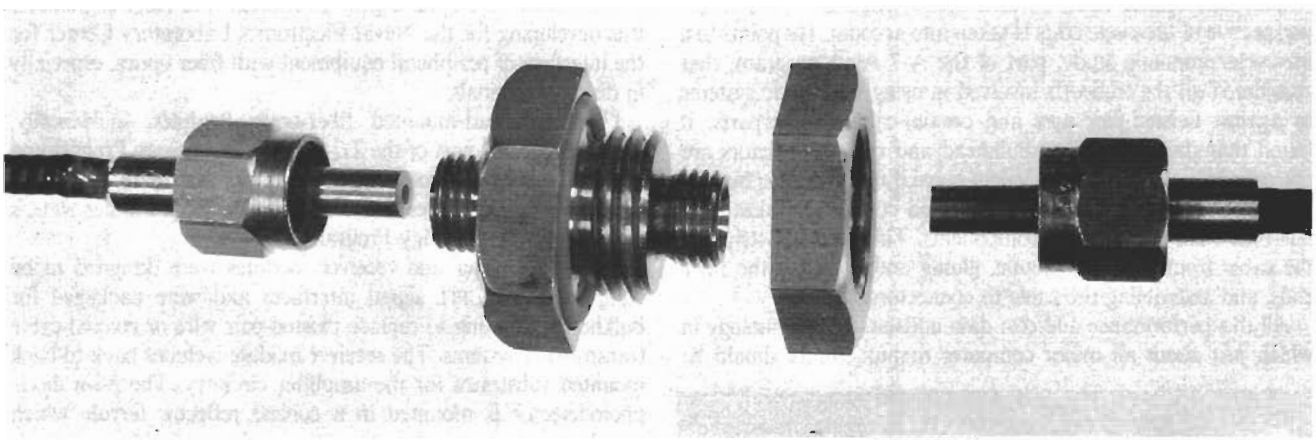
3. Atlanta connection. Cable connectors used in Bell's optical-fiber experiment interleave layers of precision-grooved aluminum chips (dark areas) with rows of fibers. The complete splice accurately aligns all 144 fibers in each cable.



4. Light coupling. The tiny optical fiber can be seen as it enters the Bell Laboratories' experimental transmitter module. The light generated by the source is coupled with not only the fiber but also a feedback circuit on the substrate to maintain constant output.



5. Matched pair. Sperry Univac's fiber-optic receiver and transmitter were designed to replace existing wire transmission systems. The receiver shown uses hybrid circuitry on substrates; p-i-n photodiode mounts in a conical ferrule that attaches to the substrates.



6. One of a kind. The first optical-fiber connector to be MIL qualified was developed by the Naval Electronics Laboratory Center for use with fiber-bundle cables and is fully compatible with other fiber-optic components and hardware under development by the Navy.

have groups working on the problem. The Electronic Industries Association, Washington, D.C., has a task force concerned with all phases of development and trends in fiber-optic terminations and junctions. This group, chaired by Philip Dann of IBM Federal Systems, Oswego, N.Y., is committed to meeting the Department of Defense's goal of having standards available by 1980. And DOD itself has in operation a tri-service group working to develop standards for all the services for fiber-optic systems.

At the Society of Automotive Engineers, too, another group is developing test procedures for optical-fiber cables. Under the guidance of W.D. Watkins of the Naval Avionics Facility, Indianapolis, Ind., this group will supply information to DOD to enable it to issue preliminary military specifications on optical-fiber cables in 1977. There is close liaison among groups.

As for sources, reliability is also a headache. For practical optical-communications applications, their lifetimes should reach at least 100,000 hours and, although extrapolated test data for both lasers and LEDs points to this being possible, the big question is when. Work on the problem is in progress at Bell Labs, which has the formidable task of developing practical long-lived lasers for the Bell System's greater-than-20-year life requirements. And such companies as RCA, BNR, TI, HP, ITT, Monsanto, Spectronics, Laser Diode Laboratories, Plessey, GE, and Fairchild are among those that have LED and laser sources commercially available.

The cost factor

Second only to the need for standards is the problem of cost. A major contractual commitment to a large-scale system or systems needs to be made, whether by Bell, IBM, or the military, since otherwise it's likely that practical components will remain expensive and not widely available.

The cost of today's fiber-optic components doesn't reflect what could happen in a volume business. A go decision by the telephone company, for instance, would trigger a tenfold shift downward in the cost of fibers, says Charles J. Lucy, general manager of the Telecommunications Products division of Corning Glass Works, Corning, N.Y. "Graded-index fibers with under 5-dB loss and greater than 500-MHz bandwidth could cost as little as 5 cents per meter in 500,000-km lengths in about five years," claims Lucy. This is close to the cost of cabled copper wire today, and the cost of copper is certain to have risen by then. And Richard A. Cerny, marketing manager for advanced fiber communications at Valtec Corp., West Boylston, Mass., thinks there will be sufficient demand by 1978 to bring prices down to around 25 cents per meter for cabled low-loss fiber channels. Prices now range from about $1.50 to $2.50/m of graded-index-fiber cable in quantities of up to 50 kilometers. Step-index fibers are less expensive.

According to Martyn Roetter of Arthur D. Little Inc., lasers could drop similarly to about $25 each in production quantities of 100,000. He bases this prediction on what has happened with other microwave devices.

The Navy's Don Williams is in full agreement with this kind of thinking. "It will not be long before we can compare fiber and wire costs on a foot-by-foot basis," he says. But even now, he emphasizes, optical fiber is economically superior if the larger perspective of life-cycle costs is taken into account. He points to a life-cycle/economic study, part of the A-7 Aloft program, that considered all the tradeoffs involved in using fiber-optic systems as against twisted-pair wire and coaxial-cable counterparts. It found that the optical-fiber bulkhead and cable connectors are not only half the cost of equivalent coaxial terminations, but the assembly time of optical fiber-cable and connectors takes 30% less time than with coaxial components. This included stripping the cable from the fiber bundle, gluing and polishing the fiber ends, and assembling the cable to connectors.

All this performance and cost data adds up to a technology in which just about all major computer manufacturers should be interested. And they are. Optical fibers offer them the large bandwidth needed to move massive blocks of data at high speeds and then throw in small size and weight, too. The ease of installing optical-fiber cable compared to multiple coaxial cables, along with its immunity to the large electromagnetic interference levels in and around computers, are other factors in its favor.

The computer connection

Computer hookups need wires routed through conduit to prevent sparking, and it costs about $4/foot to lay conduit. Fibers don't need conduits. In fact, no wiring changes are required to equip some existing computers with optical-fiber links.

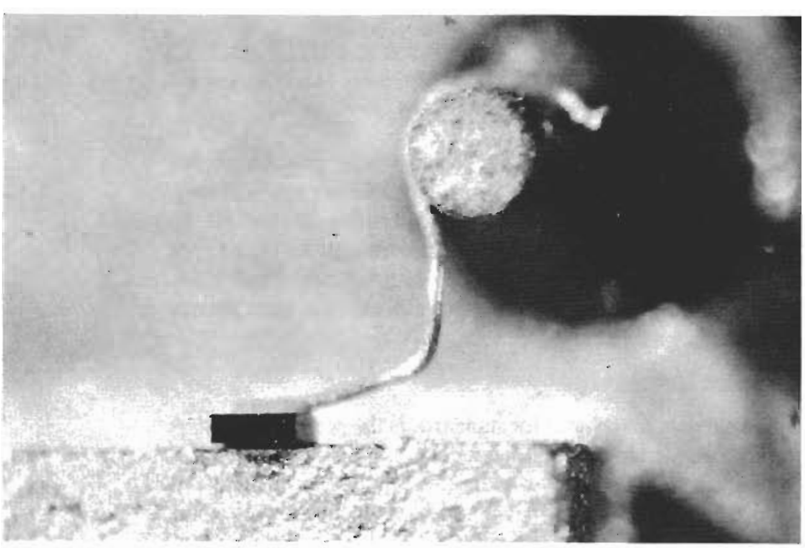
Consequently, fiber optics will be widely used for interconnecting mainframes and peripherals. Moreover, the trend toward distributed data systems is certain to create the need for much greater bandwidth as numerous intelligent terminals, minicomputers and more memories are all interconnected. Initially, though, a computer could have a hybrid interface with one or two parallel coaxial lines and the remainder in serial fiber optics.

Du Pont, for instance, is looking into replacing the four-wire cable and conduit connecting two Digital Equipment Corp. PDP-11 minicomputers with two optical-fiber channels.

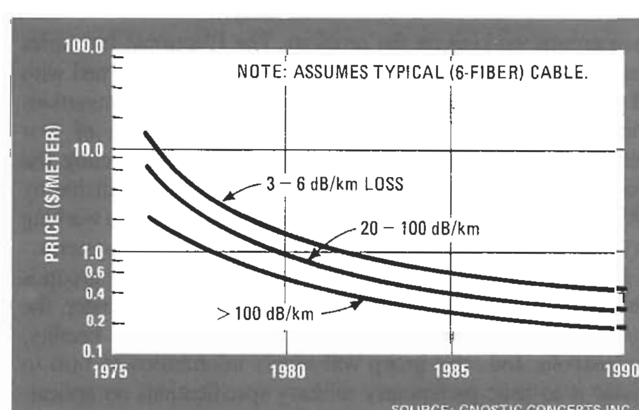
And Sperry Univac's Fiber Optic/Hybrid Component Development Group at St. Paul, Minn., is looking into using the miniaturized fiber-optic digital transmitter and receiver modules it is developing for the Naval Electronics Laboratory Center for the interface of peripheral equipment with fiber optics, especially in display terminals.

(The bulkhead-mounted fiber-optic modules, incidentally, were designed as part of the Tri-Service Technology Program on standard fiber-optic components. The modules mate with standard optical-fiber cables and connectors developed under NELC's Fiber Optics Technology Program.)

Both transmitter and receiver modules were designed to be compatible with TTL signal interfaces and were packaged for bulkhead mounting to replace twisted-pair wire or coaxial-cable transmission systems. The receiver module includes back-to-back mounted substrates for the amplifier circuitry. The p-i-n diode photodetector is mounted in a conical reflector ferrule which attaches to the substrates. The other end mates with an optical-fiber cable. The transmitter module is physically similar to the



7. Tiny sources. RCA's experimental continuous-wave gallium-aluminum-arsenide laser diode is shown mounted on a TO-46 header. The laser chip is attached to a metal block to dissipate heat and is connected to the header pin by a small wire.



8. Downward trend. The cost of all single-fiber-per-channel cable will continue to drop. For instance, by 1990 a typical six-fiber cable with an attenuation of from 20 to 100 decibels per kilometer should cost less than 30 cents per meter—down from about $6 today.

receiver. It uses a hybrid driver circuit mounted on ceramic substrates and, for military environments, is hermetically sealed in a cylindrical case similar to the receiver's.

Many overseas companies are thinking of fiber optics in terms of high-capacity telecommunications lines. U.S. companies are more inclined to look at fiber-optic links as replacements for short-haul trunking and lower-priced communications systems now, although eventually they will displace existing high-capacity lines as well. But at present, the main thrust is towards telecommunications applications like interoffice trunking and commercial applications like short-haul data transmission between computer peripherals, machine tools, and programed instruments.

Other applications abound

One such system designed by AEG-Telefunken of Germany, called V300P, is already on the market [*Electronics*, Feb. 20, 1975, p.40]. And a follow-up system intended for high bit-rate color-TV signal distribution within large apartment buildings is in the works. Other applications for the system are to link computers and peripherals, to distribute CATV signals, or to carry signals from sensors to a process-control computer.

In England, Rediffusion Engineering Ltd., a TV rental and distribution company, last April installed what it claims is the first operational fiber-optic link carrying live traffic over a 1.5-km stretch of two-fiber cable buried in the pavement and grassland at Hastings, Sussex. The cable carries two full-bandwidth color-TV channels amplitude-modulated on the lower sideband of an 8.9-MHz carrier, the same signal as is used by the company for normal coaxial-cable traffic. "It's serving 34,000 subscribers and has been working constantly with no deterioration of anything," says Kenneth C. Quinton, the firm's director of research.

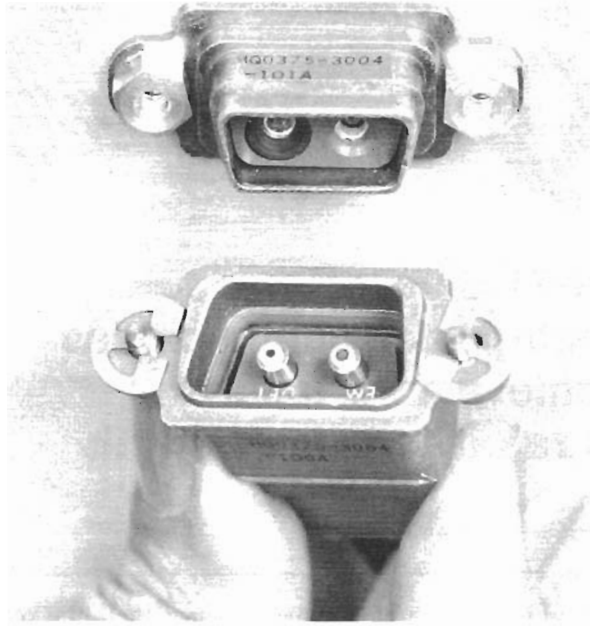
In Japan, fiber optics is being considered for telecommunications applications and has actually been used to control power facilities. The cables are threaded through tunnels containing high-voltage power lines and will replace microwave systems whose signals are often blocked by tall buildings and the like [*Electronics*,Aug. 7, 1975, p.45]. Nippon Electric Co. Ltd. carried out a field test recently in the high-voltage power station in Tokyo.

To round out the list, an experimental optical-fiber communications link is planned for the city of West Berlin jointly by Germany's post office authorities and ministry for research and technology [*Electronics*, Nov. 13, 1975, p.56].

Off the shelf

Within the last year analog and digital fiber-optic systems have been offered by many companies, such as ITT's Electro-Optical Products division, Roanoke, Va., and Harris Electronic Systems division, Melbourne, Fla., not to mention Meret Inc., Santa Monica, Calif., Spectronics Inc., Richardson, Texas, Bell Northern Research, Ottawa, Canada, Valtec Corp., West Boylston, Mass.

Typical examples come from ITT and Harris. ITT's system is capable of data rates of up to 25 Mb/s over several hundred feet. Input and output are TTL-compatible with amplitude-regenerated data out. The analog system has one wideband channel, plus two narrowband channels that are fm-multiplexed onto the wideband channel so that only one optical channel is needed for transmission. Harris's 32-channel digital data link, on the other hand, is geared to computer-to-peripheral installations of up to 1,500 feet at data rates of 16 Mb/s.



9. Two-way. The bulkhead side of Spectronics' optical-fiber pluggable interface connector houses both the light-emitting-diode source and p-i-n photodiode detector needed to send and receive signals in a duplex fiber-optic transmission system.

Perhaps Charles P. Sandbank, manager at the advanced Communication Systems division of Standard Telecommunications Laboratories, Harlow, Essex, England, sums it up best: "Fiber optics was once a matter of 'if to' and 'when,' but it will soon be a matter of 'when' and 'how much'." Worldwide commitment is very great indeed. And the rugged low-cost fiber cables and other needed optical components are just about here to support the accelerated growth that's now happening. It's therefore important that design engineers become familiar now with all available components for such systems.

The necessary knowledge

It's partly the sheer unfamiliarity of fiber optics, in fact, in addition to its still rather high cost and the lack of standards, that is delaying the widespread adoption of this exciting new communications technology. Potential users need a better understanding of what fiber optics can do for them, and system designers need to overcome their resistance to change—much as an earlier generation did in making the switch from tubes to transistors.

To help remedy this state of affairs, the following nine articles will bring the engineer up to date in fiber-optic technology. They detail what's available in fiber-optic components and how to work with each of them. All are written by leading experts in their respective fields and have been structured to give the engineering community an in-depth, timely perspective on fiber cables, light-emitting and laser diodes, connectors, photodetectors and optical coupling techniques.

Subsequent issues of *Electronics* will include articles that focus on the systems design considerations with fiber optics. They will translate user specifications into systems, and their focus will be on the steps needed to specify optical fibers and components that best fit the overall requirements for both analog and digital fiber-optic communications systems.

FIBERS
High-performance cables achieve zero failure at rated tensile strength

by R. Love
Corning Glass Works, Corning, N.Y.

Optical waveguides have come far since 1970, the year in which fiber attenuation was finally brought within range of high-speed data-transmission requirements. Today, some commercial large-bandwidth graded-index fibers achieve an attenuation of only 5 dB/km—a quarter that attained in the laboratory six years ago. In the meantime, light sources have also been improving, and by now it seems generally agreed that single-fiber system configurations represent the best cost-performance tradeoff for most applications.

A rugged optical-fiber cable with six single fibers introduced in 1975 proved cost-competitive with coaxial cables in a number of communications applications and, in many cases, offered much better system performance. Now second-generation single- and multiple-fiber cables reduce incremental fiber attenuation due to cabling to less than 2 decibels per kilometer and, for the first time, are warranted for zero failure at the rated tensile strength. The important parameters of several optical fibers recently introduced by Corning Glass Works are listed in the table.

Starting from strength

Glass is inherently much stronger than metal—tiny strands of glass theoretically can withstand tensile loads upwards of a million pounds per square inch of cross section. But in field use, glass has seldom revealed much more than a hundredth of the fracture strength predicted of it. This strength, it has now been determined, is severely limited by the presence of infinitesimal surface flaws, and fracture always involves two independent processes: flaw initiation, and flaw propagation. Because of the random nature of flaw depth and spatial distribution, the probability of failure for a glass fiber depends upon its length. Also, since failure always occurs at the weakest flaw, or deepest crack, two seemingly identical fibers of equal length will not fail at the same stress level, or at the same time for an equally applied stress, unless the weakest flaws are also identical in depth.

In short, the strength of optical fibers, unlike that of copper wire, is an inherently statistical phenomenon. Therefore conventional strength parameters such as tensile strength or yield stress are not easily applicable to them.

A better approach is to characterize glass fibers in terms of their failure probability, by carrying out fast-fracture and time-to-failure experiments on a large number of fibers of the same gauge length. From the resulting data, failure probability for various combinations of applied stress, time, and fiber length can be derived on the basis of fracture-mechanics theory.

Alternatively, a minimum time to failure under constant load may be specified if fibers have been subjected to on-line screen testing. This involves applying a uniform tensile stress to the fiber at the time of manufacture and prior to final reeling. Survival of the screen test guarantees that no flaws greater than a certain depth exist in the final fiber, since otherwise failure would have occurred.

From the viewpoint of fracture-mechanics theory, screen testing sets the initial condition on flaw depth. If other material constants are known, the minimum time to failure as a function of applied stress can be calculated. Screen-test stress levels required to guarantee zero failure in 20 years are plotted as a function of service stress. This approach to characterizing fiber strength doesn't depend on fiber length. The long-term service stress for zero failure is analogous to the yield stress properties of copper wire in electrical cables.

Microbends multiply losses

During the early phases of optical cable development, it was observed that numerous "microbends" (small axial distortions in fiber geometry) caused a significant

SOME SECOND-GENERATION OPTICAL FIBERS

Product No.	Index profile	Minimum bandwidth (MHz at 1 km)	Maximum attenuation, λ = 820 nm (dB at 1 km)	Core diameter (μm)	Numerical aperture (± 0.02)
1150	Graded	200	10	62.5	0.16
1156	Graded	200	6	62.5	0.16
1151	Graded	400	10	62.5	0.16
1157	Graded	400	6	62.5	0.16
1152	Graded	200	10	62.5	0.20
1158	Graded	200	6	62.5	0.20
1153	Graded	400	10	62.5	0.20
1159	Graded	400	6	62.5	0.20
1025	Step	20	10	85	0.18
1028	Step	20	6	85	0.18

Corguide fiber diameter (μm) 125 ± 6 EVA buffer diameter (μm) 250 ± 25 increase in fiber attenuation. Microbends tend to continually couple light energy back and forth between low- and high-order modes. The latter are more highly attenuated and may even be scattered out of the fiber entirely. Continuous axial distortions, as small as 1 micrometer in amplitude and spaced 1 millimeter apart, are sufficient to cause 20 dB/km of incremental attenuation.

(It is important to distinguish between this effect and the attenuation due to "bending" losses described on page 91. An occasional small-radius bend in a fiber merely radiates out higher-order modes, occasioning a low, one-time loss. Provided light energy is not coupled back into these modes, no further increase in attenuation will result when additional bends are encountered.)

To minimize microbending losses, optical cable is designed to mechanically isolate the fibers from small material or geometrical irregularities in the cable structure. In this, the new second-generation optical cables are particularly successful—any of the fibers listed in the table can be cabled with less than 2-dB/km excess attenuation. They are encapsulated in ethylene vinyl

Looking into fibers

Although three types of fiber exist—single-mode, step-index multimode, and graded-index multimode—only the last two have gone public. Single-mode fibers can propagate optical signals with a very low loss at extremely large bandwidths but are still in the research stage.

Of the other two, the less costly step-index fiber consists of a glass core of uniform refractive index surrounded by a cladding glass of slightly lower index of refraction. The more costly graded-index fiber has a core with a refractive-index profile that is radially symmetric and approximately parabolic in shape, being highest at the center of the core and decreasing parabolically till it matches the cladding refractive index at the core-clad interface.

Light launched into the core of either fiber at an angle less than the critical acceptance angle (numerical aperture) is reflected internally upon striking the core-cladding interface and therefore continues to propagate within the fiber core.

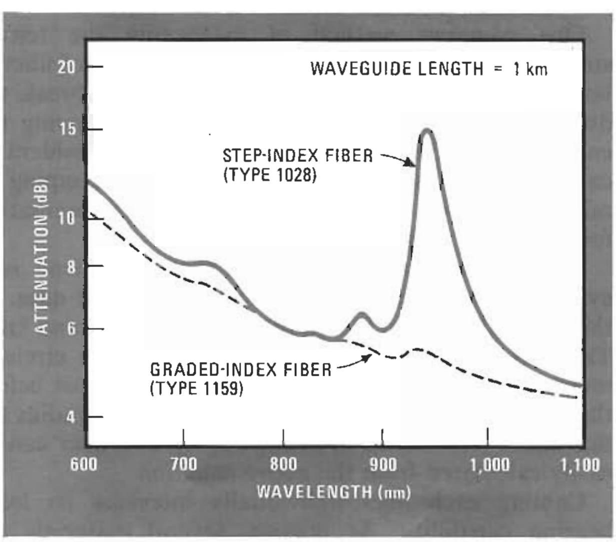
In both step- and graded-index fibers, the light signal is carried in a large number of modes, each with a characteristic velocity and propagation time. Graded-index fibers, however, because they minimize the propagation delay differences between various modes, can handle large bandwidths. As a rule of thumb, commercially available step-index fibers can handle data rates of up to 50 megabits/km, and graded-index fibers up to 500 Mb/km. The as-yet experimental single-mode fibers are capable of still greater things—more than several gigabits per kilometer.

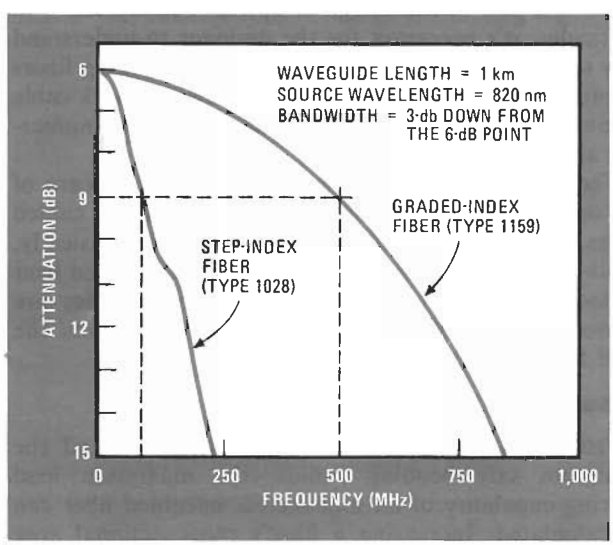
As with electrical conductors, the signal-transmission properties of optical waveguides are characterized in terms of attenuation versus frequency. This transfer function depends on fiber attenuation (absorption and scattering) and signal dispersion (pulse spreading).

Both parameters depend in part on fiber materials. For example, absorption in the near-infrared portion of the spectrum is due mainly to OH radical vibration bands. On the other hand, Rayleigh scattering from the thermal fluctuations of constituent atoms is the primary scattering mechanism. Spectral attenuation curves include the effects of all these parameters.

The spectrum width of the light source and material dispersion in the fiber determine pulse spreading. For example, a 1-km length of a doped-silica optical fiber driven by light-emitting-diode with a spectral width of 50 nanometers exhibits a pulse spreading of approximately 3 nanoseconds. With laser diodes having spectral widths of about 2.5 nm, pulse spreading drops to about 0.3 ns.

To determine the transfer function of an optical fiber, attenuation and pulse spreading measurements are carried out on a standardized but arbitrary length, usually 1 km. The transfer function of an available Corning fiber results from superimposing the signal dispersion, which depends on frequency, on the fiber attenuation due only to scattering and absorption of light.





acetate to isolate them mechanically and buffer them against any small geometrical irregularities or distortions found in the jacketing or reinforcing components. The encapsulation also helps protect the fibers from damaging impact or abrasion during the reeling and handling operations. Their rated tensile strength is based on fiber screen-test stress, which may be derated with respect to time and applied load. As a rule of thumb, long-term (more than 20 years) tensile stress rating for zero failure is about one third of the fiber screen-test stress (Fig. 1).

Virtually any degree of tensile strength or crush resistance can of course be provided by appropriate reinforcing components and armoring. But just as in wire cables, ruggedness must be traded off against cable flexibility and cost.

Coax contrasted

Optical cables are installed in the ground in much the same manner as wire cables, except that a longer pull length for the same rated tensile strength is possible. For example, Corguide cable can be pulled through straight ducts longer than 1 km. This is because frictional forces are proportional to cable weight, and optical cables of the same diameter as coaxial cables are approximately four times lighter.

Moreover, beyond bandwidth requirements of a few megahertz, graded-index fiber cables are far superior to all but the most expensive, largest-diameter, coaxial cables. And lower-bandwidth-capability step-index fiber cables outperform all but RG-17/U coax cables up to 100 MHz.

Also the dielectric nature of optical fibers makes them immune to electromagnetic interference. They do not conduct electricity, thus avoiding ground loop problems and offering a degree of transmission security. Moreover, in ordinary cable environments, optical cables show much less change in their transmission properties (attenuation, pulse distortion) than their metallic counterparts.

Performance data shows that optical cable is superior to coaxial cable on a single-channel basis, above a few megahertz. In addition, 10 or more fibers (channels) can be packaged in a single cable the size of RG-63/U with cross talk more than 80 dB down over a 1-km length. Cost on a per-channel basis now ranges between $0.60/ft and $2/ft for optical cables compared to $0.15/ft to $1.50/ft for coaxial cables.