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## LIGHTWAVE SPLICING AND CONNECTOR TECHNOLOGY

### Introduction

The functions of splices and connectors are to interconnect the transmission media and to connect the media to optical devices. Splices are for the most part intended to stay permanently connected, although some designs offer the opportunity of separation and rejoining. Connectors, on the other hand, are designed for frequent separation and rejoining. Connectors may possibly require cleaning when rejoined, whereas splices require replacement of matching gels or adhesives and possibly repolishing. The most operationally significant system parameter of these components is optical loss. The loss is dependent on alignment of the fibers, the end conditions of the fibers, and the fiber-core parameters (primarily core diameter and peak index difference in multimode fibers and mode-field diameter in single-mode fibers). These fiber-core parameters are not under the control of the splice or connector design and will not be covered further here.

In the few years since lightwave systems have been in use, the technology has shifted from the graded-index multimode (MM) fiber to single-mode (SM) fiber that operates at 1310 nm and/or 1550 nm in essentially all systems. Present exceptions are local area networks (LANs), computer interconnections, and possibly residential distribution, but these may be SM in a few years. The smaller core size of SM media makes splicing and connecting much more difficult. Most SM cores are

about 8  $\mu\text{m}$  in diameter compared to 50 or 62.5  $\mu\text{m}$  for MM cores. To get a feel for how small this is, an ordinary sheet of notebook paper is about 50  $\mu\text{m}$  thick. Therefore, six SM-fiber cores laid side by side are less than the thickness of a sheet of notebook paper.

The optical loss of a splice or a connector is directly related to the accuracy of the alignment, and for a given process, the cost increases with accuracy of alignment. The cores of SM fibers must be aligned to within 1  $\mu\text{m}$  in a connector, with no Fresnel reflection loss, to obtain a loss of a few tenths of a dB. Misalignment can be up to 3  $\mu\text{m}$  if a loss of 2 dB is allowed. The cost of the connectors tends to differ inversely by about the same ratio.

Optical-loss requirements are not the same for all applications. Low-loss components are needed for long-haul intercity trunks to get maximum spacing between regenerators.

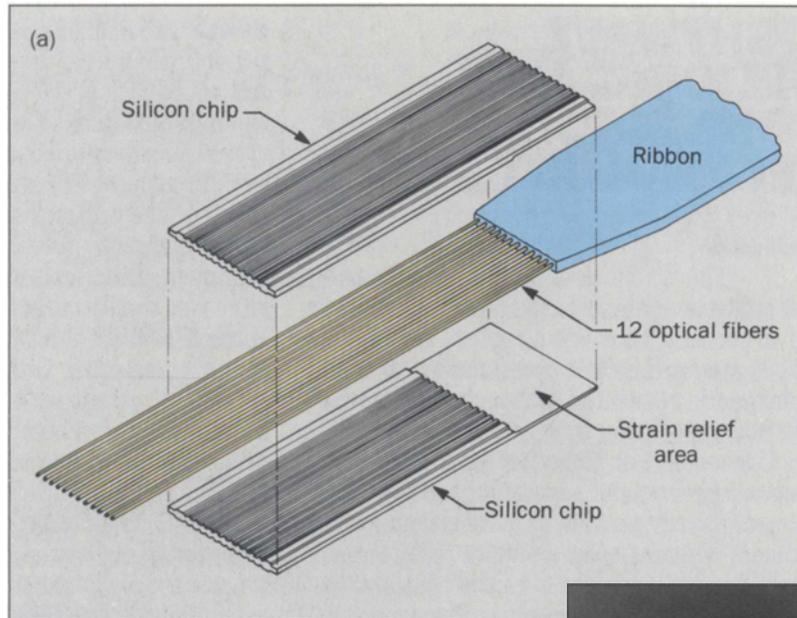
In metro trunks, loops, LANs, and computer interconnections, low optical loss can be traded for components with reduced cost and/or shorter installation times. The choice between optical performance and cost can be optimized for any given application.

Development programs and AT&T's product line allow the customer to choose from a full range of high-quality products for splicing and connecting lightwave media optimized for various applications.

A review of the designs and performance of AT&T splices and connectors is presented.

### Splicing

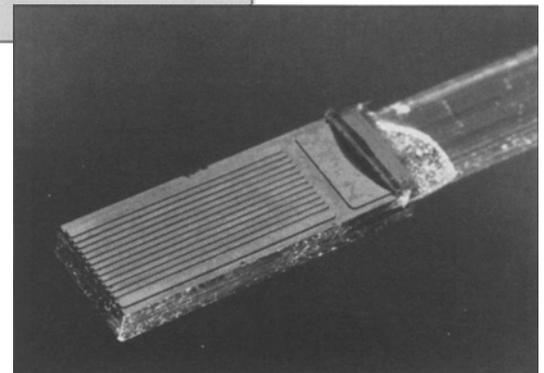
The two fundamental approaches to splicing optical fibers are fusion welding and mechanical joining. Both methods require three basic steps:



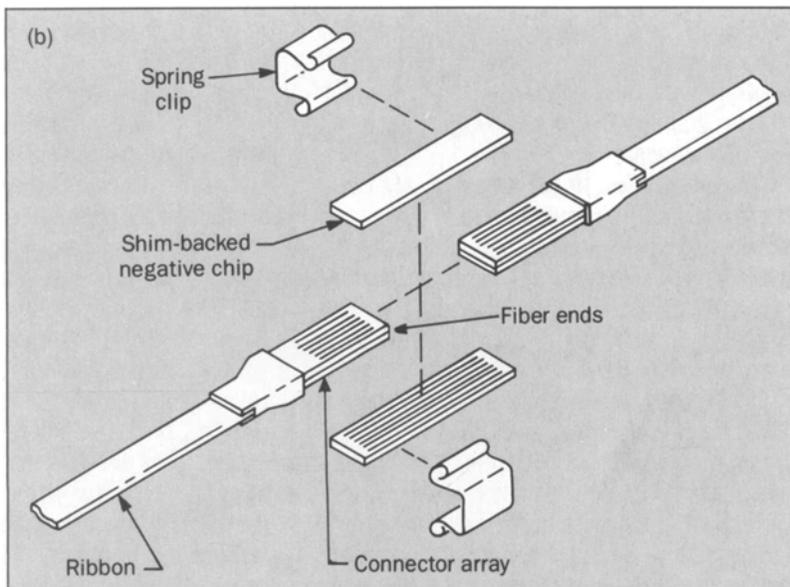
**Figure 1. (a) Light ribbon array connector. (b) Silicon chip array splice schematic.**

1. Fiber end preparation
2. Alignment of the fibers
3. Retention of the fibers in the aligned position.

Arc fusion is used by many for splicing optical fibers. In this method, the fiber ends are cleaved and aligned, and the ends are melted and fused to retain the alignment. In single-mode fusion, the fibers are aligned with x-y micropositioners that are driven with a feedback signal to peak the transmission of the splice. Despite automated alignment and fusion processes in the newer machines, the quality of the splices is still sensitive to small variations in the execution of the three basic steps and to unfavorable environmental conditions. Average field-splicing times vary greatly, from 15 to 40 minutes per splice, due mostly to environmental effects.



To achieve average splice losses of 0.1 to 0.25 dB with fusion in the field, resplicing is frequently required to eliminate high-loss splices. Fusion splices are physically the smallest and when properly made have extremely stable loss over a wide temperature range. However, for field splices of terrestrial cables, the size of a fiber splice is usually of little con-



sequence because the size of a cable splice is dictated by the minimum bend radius of the fibers, not the size of the fiber splice.

To prevent fiber breakage due to static fatigue and excess loss at long wavelengths, the minimum bend radius for depressed-cladding fibers is  $1\frac{1}{2}$  inches. For matched-cladding fiber designs, the minimum bend radius must be substantially larger to avoid excessive loss at long wavelengths (1550 nm).

In mechanical splices, the ground and polished ends are aligned and butted together with a matching gel or adhesive between the ends. Alignment is maintained mechanically. Some designs combine and simplify the three basic operations of end preparation, alignment, and retention to achieve increases in performance and productivity. Reflections from the fiber end faces can be made small enough that they do not interfere with the most sophisti-

cated transmission systems by using proper index matching gels or adhesives. The remaining small reflections are an aid in analyzing faults along a fiber route with an optical time domain reflectometer.

During the evolution of lightwave technology, AT&T developed reliable, high production, craft friendly, and long-term stable mechanical splices that are matched to the application. To this end, the first lightguide cables were designed with flat linear arrays (ribbons) of 12 fibers.<sup>1,2</sup> These cables were very receptive to splicing en masse (12 fibers at a time) with an array splice<sup>3</sup> that could be partially assembled in the factory. The array splice has application for both MIM and SM as discussed below. For individual fiber splicing, the fibers are placed in glass-ferrule supports that are easier to handle, grind, polish, and align than bare fibers. The ferrule supports,

the matching gels, and the alignment-retention structures are chosen to be environmentally compatible with the fiber. This is essential for long-term stability over wide temperature and humidity changes.

**Array Splices.** In the array splice, 12 fibers of a ribbon are sandwiched in the grooves of two precisely etched silicon chips (Figure 1). The sandwich is held together with epoxy, and the end faces of the fibers and array are polished flat and perpendicular to the array. The arrays are placed on the cable in the factory. In the field, two mating arrays are butted and aligned with two negative chips that mate with the grooves on the outside of the arrays to form a splice as shown in Figure 1b. The alignment is maintained with mechanical springs. A matching gel placed between the arrays maintains low and stable loss over a wide range of temperature and humidity.

The array splice was introduced in 1979 for MM applications. Over half a million splices have been made in the field with an outstanding reliability record; no splice failures have been reported. The MM splice loss averages 0.15 dB with a standard deviation of 0.15 dB. Field productivity is higher and installed cost is lower than corresponding measures for individual fiber splicing. An array splice (12 fibers) can be joined and tested in the field in 5 to 10 minutes.

The high productivity and low splicing cost stimulated interest in the array splice for SM applications. This would have been a wishful thought in 1980, but better dimensional control of the silicon chips and fibers have made SM array splicing feasible.<sup>4</sup>

The loss distribution of splices made in the laboratory is close to that of splices made in the field.<sup>5</sup> Average loss is about 0.35 dB with a

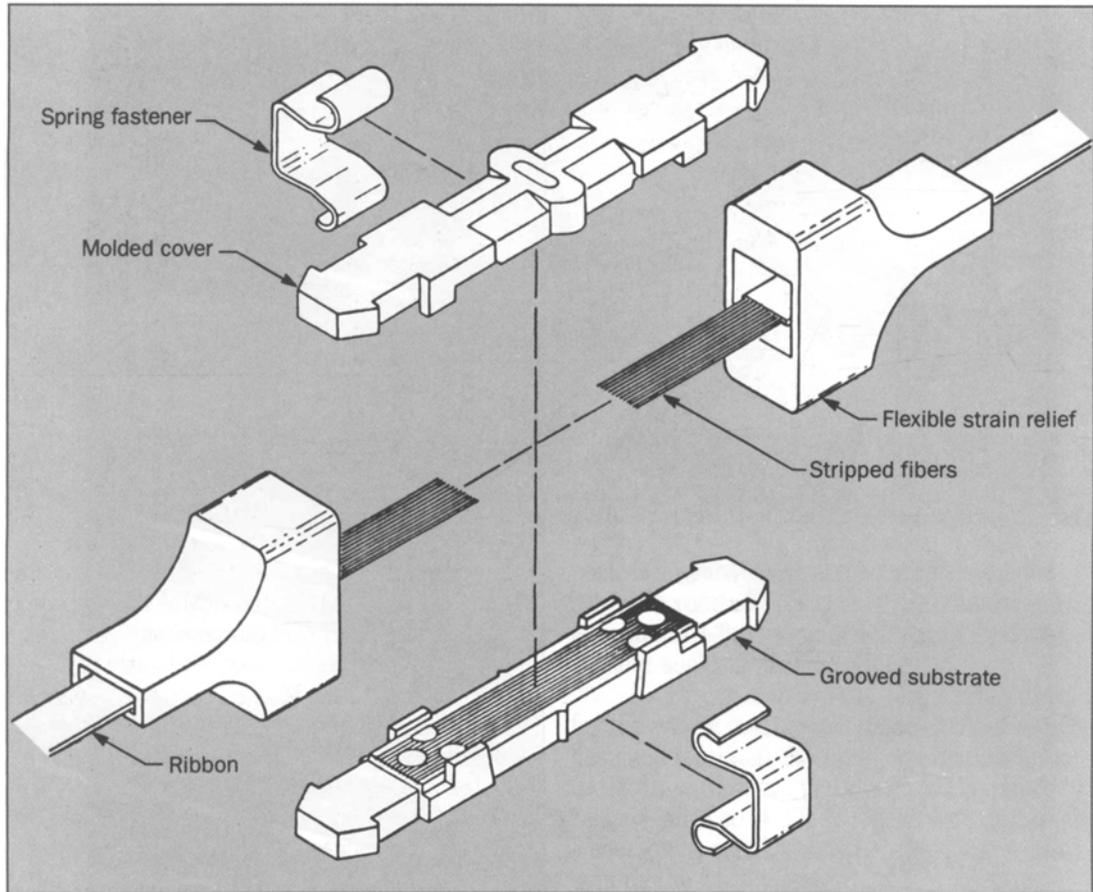
standard deviation of about 0.3 dB. The similarity of the two distributions indicates consistency between lab and field results.

Besides showing that the technology is transferable to the field, consistency between laboratory and field results indicates that the method is insensitive to craft skills and environmental conditions during splicing.

**Rapid Ribbon Splicing.** While factory-installed arrays yield the fastest field splice, fabrication of the entire splice in the field, which includes placing the fibers in the arrays, takes about 2 hours for the first splice and nearly 1 hour to complete each additional splice. This is still a very reasonable time and is as fast or faster than most individual splicing methods. However, 2 hours is a long time to restore the first pair of fibers of a damaged cable that is carrying service, even if six pairs of fibers are repaired at the same time. This shortcoming of the array splice for rapid restoration stimulated the development of the rapid ribbon splice, a field method for splicing a 12-fiber ribbon in 20 to 30 minutes.<sup>6</sup> Note, this is about the average time required for splicing one fiber with arc fusion.

In the rapid ribbon splice, all 24 fibers of a splice are ground and polished simultaneously. Then a portion of the ribbon is removed, and the bare fibers are placed into a grooved substrate with the ends butted as shown in Figure 2. The continuous grooves of the substrate align the fibers, and a matching gel is placed between the fiber ends to reduce the splice loss and reflections. A molded cover is placed over the fibers and secured with spring fasteners to retain the alignment. Only simple hand tools, a vacuum pump, and a fixture with a low-power microscope are required to make the splice. The rapid ribbon splicing operations

**Figure 2. Rapid ribbon splice.**



are easy and craft friendly.

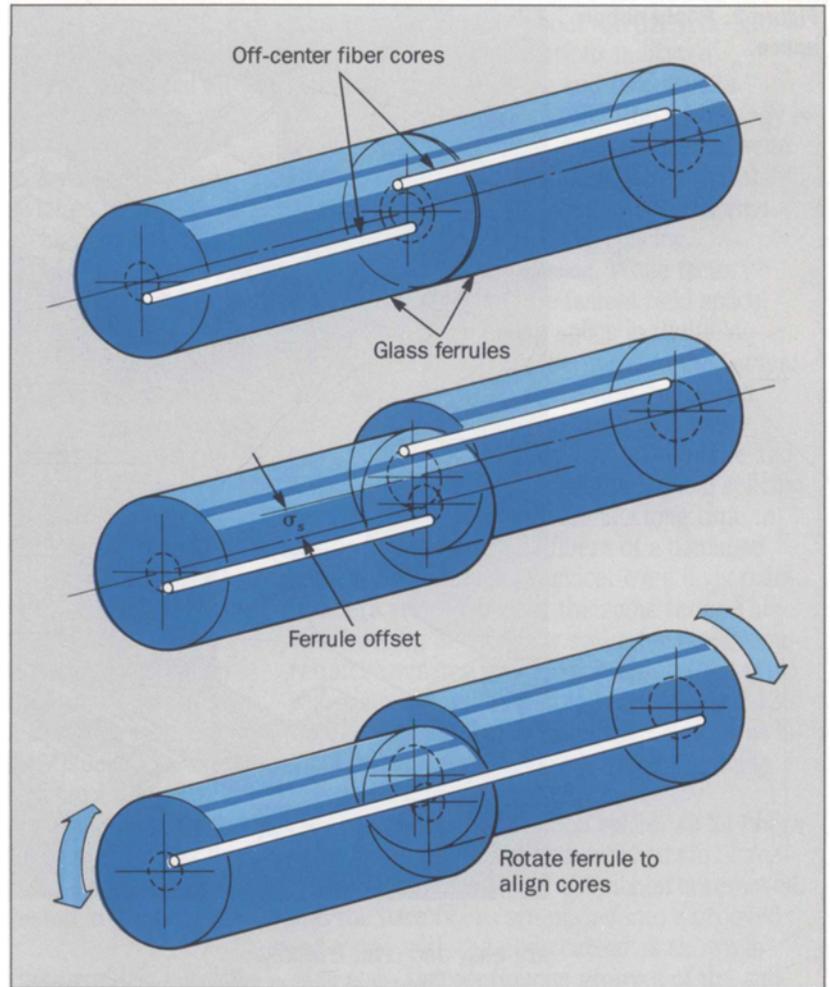
The rapid ribbon splice was first developed for multimode fibers, but it has since been enhanced so that SM fibers can be spliced as well.<sup>7</sup> Like the array splice, the field loss data tracks the laboratory loss data very well.

Average splice loss is about 0.35 dB with a standard deviation of about 0.3 dB. The splices are very stable; added loss over a temperature cycle from  $-40^{\circ}\text{F}$  to  $170^{\circ}\text{F}$  is less than

0.05 dB with no residual loss after cycling.

While the rapid ribbon splice design objective was to develop a quick temporary repair splice, the completed design surpasses the objectives and is a permanent splice that has application in new installations. It is particularly suited for LANs, building distribution systems (BDS), service drop cables, and other uses where factory-installed arrays are impractical. In these applications, it is difficult

**Figure 3. Principle of operation of the rotary splice.**



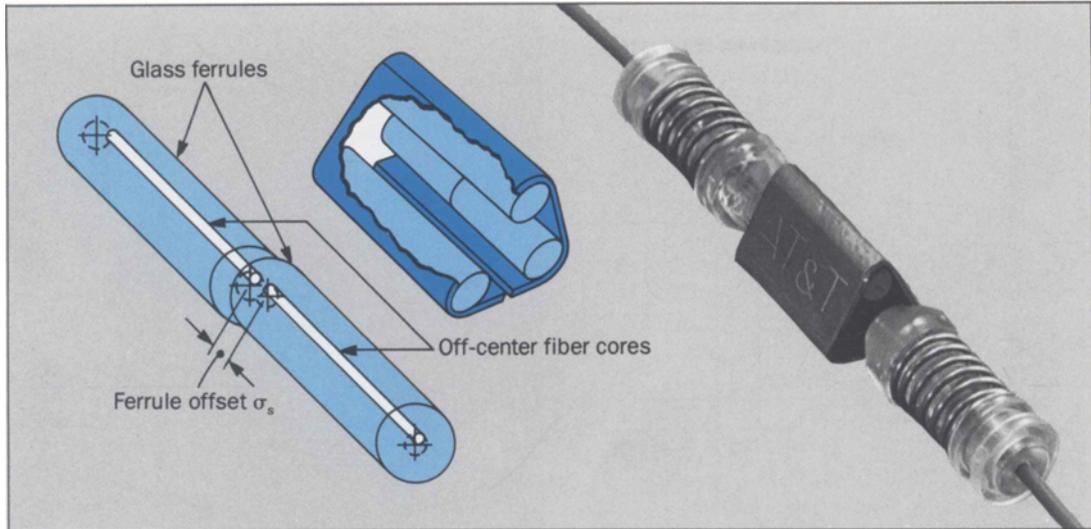
to determine the exact length of the cables, and the installations do not provide slack storage consistent with preterminated ends.

**Individual-Fiber Splices.** AT&T's individual-fiber splices use glass capillary tubes to provide robust, easy-to-handle terminations for individual fibers in much the same way as sili-

con chips do for multiple fibers.

Accuracies and tolerances of glass tubes combined with careful mechanical design allow MM and SM fibers to be spliced with average splice losses of 0.20 dB without using any test equipment. Active alignment allows tuning of rotary SM splices to less than 0.05 dB

**Figure 4. Alignment sleeve for rotary mechanical splice.**



even when splicing is done in the field.

The MM mechanical splice was the first glass tube splice.<sup>8</sup> MM fibers are terminated in glass-tube assemblies using ultraviolet-curable cement, and the ends are ground and polished. Each ferrule is inserted in opposite ends of a cylindrical alignment sleeve and index matched with the same gel used with silicon chip arrays. Splice losses average 0.2 dB with no tuning or can be tuned to below 0.1 dB by active alignment. Losses are acceptable for MM fibers but not for SM fibers.

To achieve SM splice losses of 0.05 dB requires core alignment to within 0.4  $\mu\text{m}$ . The rotary mechanical splice<sup>9</sup> consistently achieves such alignment with no precision positioners of any kind.

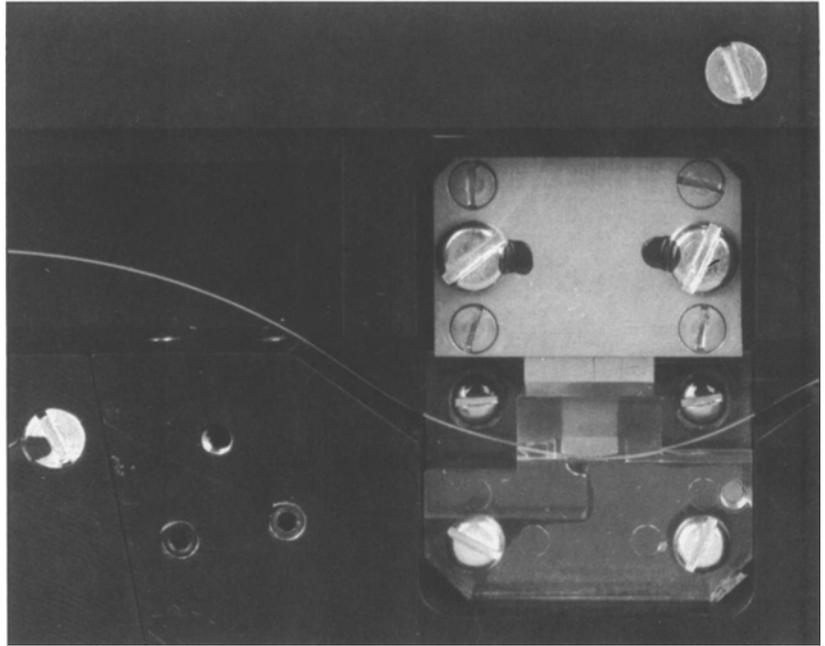
The principle of operation for the rotary mechanical splice is shown in Figure 3. Each fiber is mounted slightly off center in a glass ferrule, and the two ferrules are offset relative to each other so that two positions of

perfect alignment are available when the ferrules are rotated. The rotary mechanical splice is manually adjusted to one of these positions without sophisticated positioners.

Figure 4 shows the alignment sleeve for the rotary mechanical splice. This sleeve is designed to obtain extremely stable splice loss (0.02 dB variation) over a wide temperature range ( $-40^\circ\text{F}$  to  $+170^\circ\text{F}$ ) with no residual loss. Three-point contact with the glass tubes that contain the fiber ensures a stable, balanced geometry. By using glass rods in the alignment sleeve, mechanical and thermal properties of the rods and tubes are closely matched to those of the fiber. The same matching gel used in arrays and other mechanical splices is used to couple the light optically from one fiber to the other without Fresnel reflections. This soft gel expands or contracts as needed to offset slight differences in the thermal or mechanical properties of assembly components.

Although array splicing and rapid rib-

**Figure 5. Microbend local-injection unit.**



bon splicing are highly productive techniques for groups of 12 fibers, the rotary splice is the most quickly assembled high-performance individual-fiber mechanical splice available. Productivity is typically 10 minutes per splice including termination, tuning, testing, and splice storage. This splicing technique also achieves consistent performance; i.e., splice losses in the field with minimally trained craft almost exactly match laboratory results with highly trained operators. Systems can be better optimized because consistent splice performance is assured.

An enhanced, second-generation rotary splice—called the prealigned rotary (PAR) SM splice—achieves low loss (0.20 dB) without tuning. Splicing procedures and tolerances of the glass tubes have been optimized to

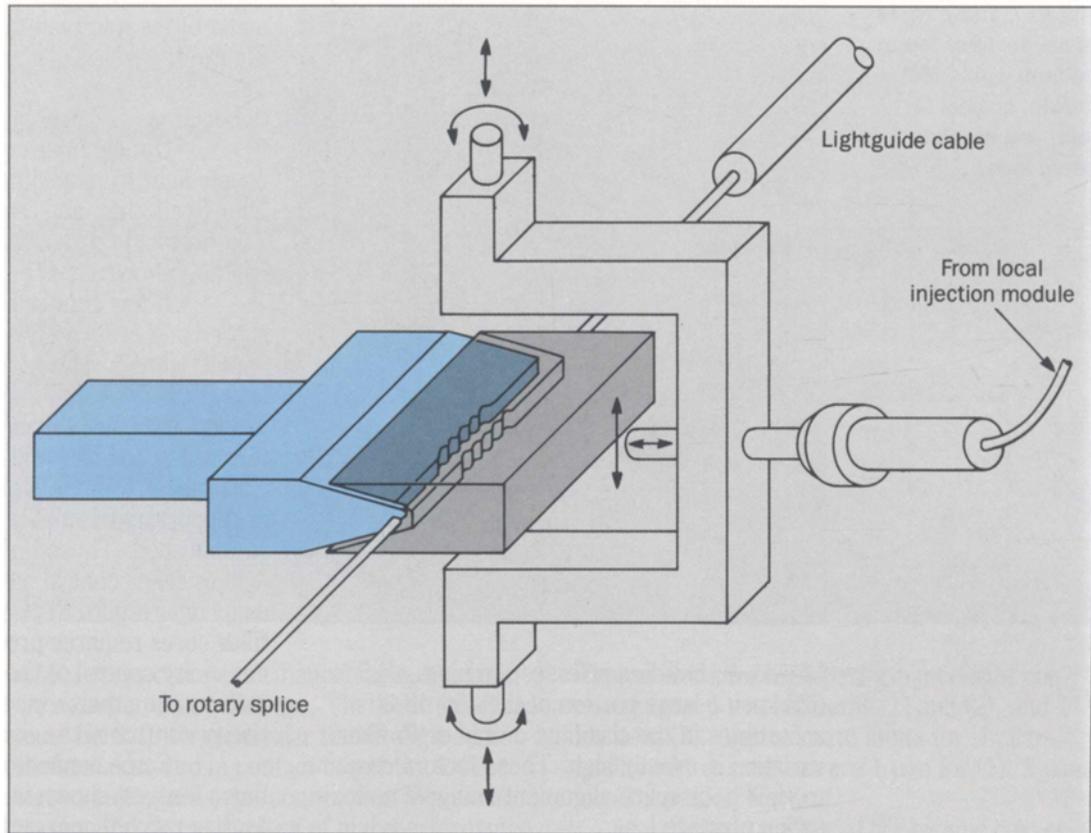
achieve these results; however, the splice can be optionally tuned to values below 0.05 dB with active alignment. The three largest offset-producing effects in glass-tube SM splices are:

- Eccentricities in the bore of the glass tubes
- Oversize diameter of the bore
- Eccentricities in the core of the fiber.

The PAR splice almost totally eliminates the offsets that result from the first two of these mechanisms, leaving only the fiber core eccentricity. Stability is the same as in the standard rotary splice and productivity is improved by a factor of 2 (5 minutes total assembly time).

**Local Injection Detection.** Both fusion and mechanical splices often use active alignment to minimize offsets. Although far-end transmission monitoring has been used in the field, it is a cumbersome technique compared to the con-

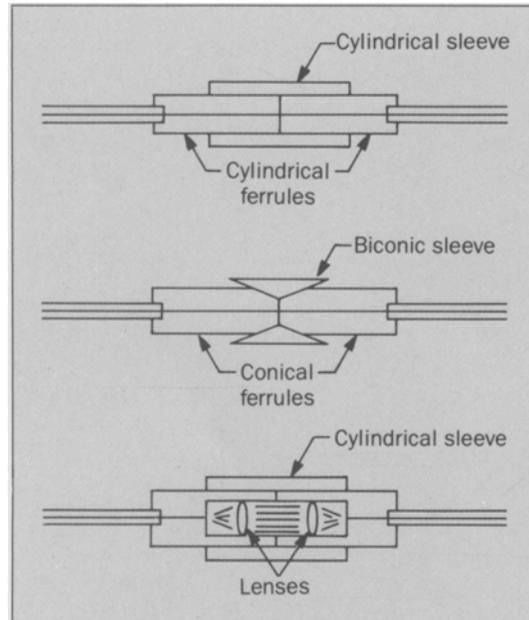
**Figure 6. Schematic of microbend region.**



venience of local light detection. Local detection can be done by sensing the light transmitted through the splice or sensing the light lost at the splice. The sensitivity of local loss detection is 200 times greater than the sensitivity of local transmission. This increased sensitivity is used in the rotary splice to achieve extremely accurate alignment and accompanying low loss. Because local loss detection equipment can be easily calibrated, accurate splice-loss measurements can also be accomplished with this technique.

There are two fundamental processes used to inject or couple light into the core of a single-mode fiber: microbending and macrobending. These bends couple light from the fundamental  $LP_{01}$  mode to the  $LP_{11}$  leaky mode and vice-versa. Conventionally, light from a 0.8- to 0.9- $\mu\text{m}$  LED source is focused on to a relatively small radius (1 to 5 mm) macrobend to inject typically -50 dBm or less light into the fiber. Although this technique will work satisfactorily with transmission detection, most fibers are not single-mode at 0.8 to 0.9  $\mu\text{m}$ .

**Figure 7. Three types of connectors. Top to bottom: cylindrical ferrule, conical ferrule, and expanded-beam lens.**



Moreover, bending stresses are high—125 to 625 kpsi; a large portion of the  $-50$  dBm is sometimes in the cladding; and fiber-to-fiber variation is usually high. These factors combine to yield poor splice alignment and give no indication of splice loss.

Local light injection using short-period, small-amplitude microbends<sup>10</sup> has several advantages:

1. The modulated  $1.3\text{-}\mu\text{m}$  laser source excites the single-mode fiber properly.
2. Greater than  $-35$  dBm can be injected almost totally in the core.
3. Bending stresses are less than 50 kpsi.
4. Fiber-to-fiber variation is low.
5. The technique is compatible with local loss-detection techniques.

A photograph of a microbend local-injection unit is shown in Figure 5, and a sche-

matic of the microbend region itself appears in Figure 6.

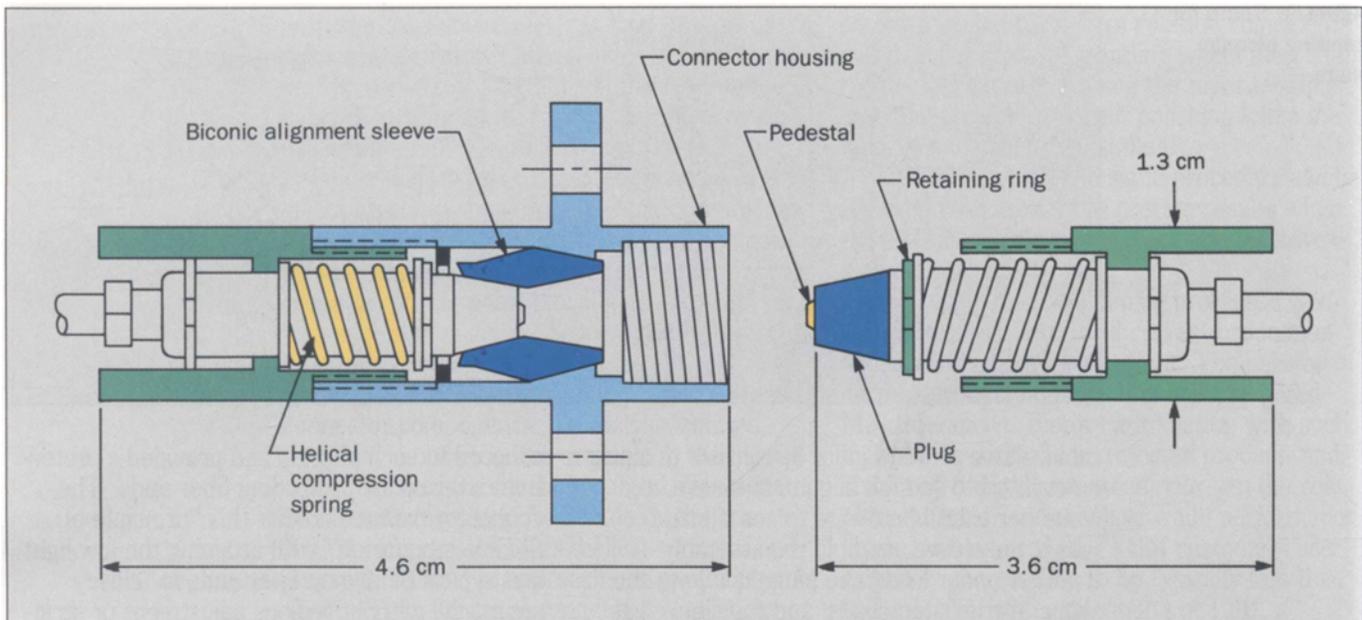
### Connectors

Optical fiber connectors are used to couple light from a source to fiber, from one fiber to another, and from fiber to a detector. The first and third are special applications and will not be discussed here.

A few connectors use bare fibers with scored and broken ends, but by far the most popular configuration for optical fiber connectors is the precision-aligned butt joint with ground and polished ends. Most butt connectors use secondary and tertiary alignment. This means the fibers are positioned and held in supporting ferrules as the ends are ground and polished. These ferrules, which are usually cylindrical or conical, are then aligned in sleeve couplings (Figure 7). Good alignment of the fiber cores requires precise diameter and concentricity control of the cylindrical ferrule and sleeve, and precise taper length and concentricity control of the conical parts.

Some connectors use an expanded-beam lens, as shown in Figure 7. This connector has relaxed concentricity requirements, but this is offset by more stringent angular requirements. Because the ends can be sealed with glass disks, the connector is less susceptible to damage during multiple reconnects, and its performance is less sensitive to debris. This has made the expanded-beam connector attractive for some applications in dirty environments. But to date, it has not been successful in capturing a sizable market and will not be discussed further here.

Connectors generally have greater loss than splices because they are not tuned, and matching gels are not ordinarily used. Further-



**Figure 8. Biconic connector.**

more, connector performance can suffer from wear and end-face damage. The fiber end faces must be flat, perpendicular to the alignment-surface axis, and in contact to get the lowest loss in a dry, butt-joint connection. With contacting end faces, the loss of high-performance MM and SM connectors is typically 0.3 to 0.5 dB. These figures will increase by about 0.3 dB from Fresnel reflections if there is an air gap between the fiber ends.

Other connector contributions to loss that may be discussed without specifying the shape of alignment surfaces are:

1. Eccentricity between bore and alignment-surface axes
2. Diametral clearance between the largest bore and smallest fiber
3. Angular misalignment between bore and alignment-surface axes.

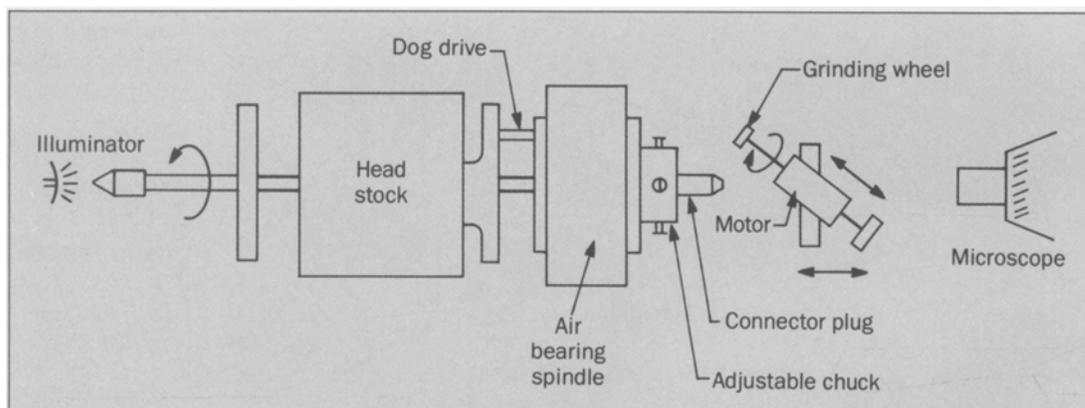
Typical limits for high-performance MM connectors are 5  $\mu\text{m}$  for items (1) and (2), and  $1^\circ$  for item (3). Approximate limits for similar-quality SM connectors are 1  $\mu\text{m}$  for (1), 2  $\mu\text{m}$  for (2), and  $1/2^\circ$  for (3).

Several million AT&T biconic connectors are in use today in both MM and SM systems, and several companies, in addition to AT&T, now make the biconic connector. Ruggedized multiple-fiber connectors have been designed for military applications that incorporate the biconic connector.

AT&T and many other manufacturers throughout the world also offer cylindrical connector designs. These are currently being introduced in simplex and duplex configurations for local area networks.

**Biconic Connector.** In simple description, the biconic connector for single-fiber lightguide

**Figure 9. Setup for grinding biconic plugs.**



cable, illustrated in Figure 8, consists of a plug on each cable end, an alignment sleeve, and some peripheral hardware to contain and mount the sleeve and hold the assembly together under load. The plug ends have the shape of truncated cones, and the sleeve has two corresponding internal tapers. Ideally, the transfer-molded plugs, fiber cores, and both tapers in the alignment sleeve have a common axis.

The initial design of the connector was based on the observation that transverse offset of fiber ends contributes about 20 times more loss in a lightguide connection than longitudinal end separation of the same amount. A taper was chosen for the aligning surface so that lot-to-lot isotropic shrinkage variations in nominally identical molding materials would not manifest themselves in transverse offset but in the less critical end separation.<sup>11</sup> A taper also provides for relatively easy backplane insertion and low abrasion.

Anticipated variations in end separation were accommodated in the 1977 Atlanta MM Fiber System Experiment through elastic contact of index-matching cushions that

adhered to each plug tip and provided a protective covering for protruding fiber ends. The connector patent<sup>12</sup> credits this "principle of flexible interfacing" with attaining the low light loss typical of aligned fiber ends in "close approach" without tedious adjustment or stringent end-separation tolerances. The alignment sleeves used in the Atlanta Experiment were machined from brass. After the Atlanta Experiment, a lapping and polishing procedure was adopted, which produced fiber ends that were flush with the body of the silica-filled epoxy plug and permitted precise adjustment of the taper length. From the plug material, Bell Laboratories developed a transfer-molded biconic sleeve whose dimensions could be held more closely than those of machined sleeves. Eccentricities were less, and tighter control on the length parameter allowed nominal separation between fiber ends to be reduced to 25  $\mu\text{m}$ . Reported mean loss and standard deviations, obtained without the index-matching cushions, suggested that some connections must have had contacting plug ends.<sup>13</sup>

In 1980, Bell Laboratories reported mean connector losses of just over 0.20 dB

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with standard deviations less than 0.10 dB by purposely selecting plug and sleeve lengths to ensure contact of plug ends in the assembled connector. Impressive figures like these drove the evolution of specifications of the two crucial dimensions—plug taper length and sleeve ball separation—in a direction that corresponds to contacting plugs. Given the reality that reasonable manufacturing tolerances were essential, it was geometrically obvious that the biconic design could not achieve seated alignment and contacting plug ends in all connections without some compliance in the connector components. An analysis showed that this compliance was available in the elastic deformation of the meshing conical alignment surfaces as the plugs are seated by the controlled compression of the helical spring. The plugs were found to approach one another by about 25  $\mu\text{m}$  during seating if the cone angles differed slightly to dispose alignment to begin at the plug ends and promote the necessary deformation by intensifying the contact stresses between the plug and sleeve.

The MM biconic connector set a new industry standard for precision molding,<sup>14</sup> and AT&T's initial strategy for connecting SM fibers was to use the MM biconic production for suitable ultraprecise connector components. However, it became apparent in the early 1980s that this scheme would not meet the rapidly increasing demand for SM connectors, and production plans to grind MM biconic plugs to meet SM concentricity requirements were implemented.

In this operation, a slightly oversized biconic connector is held in the rotating jaws of a grinder as shown in Figure 9, and microscopic observation of the illuminated bore dictates the plane and angular adjustments nec-

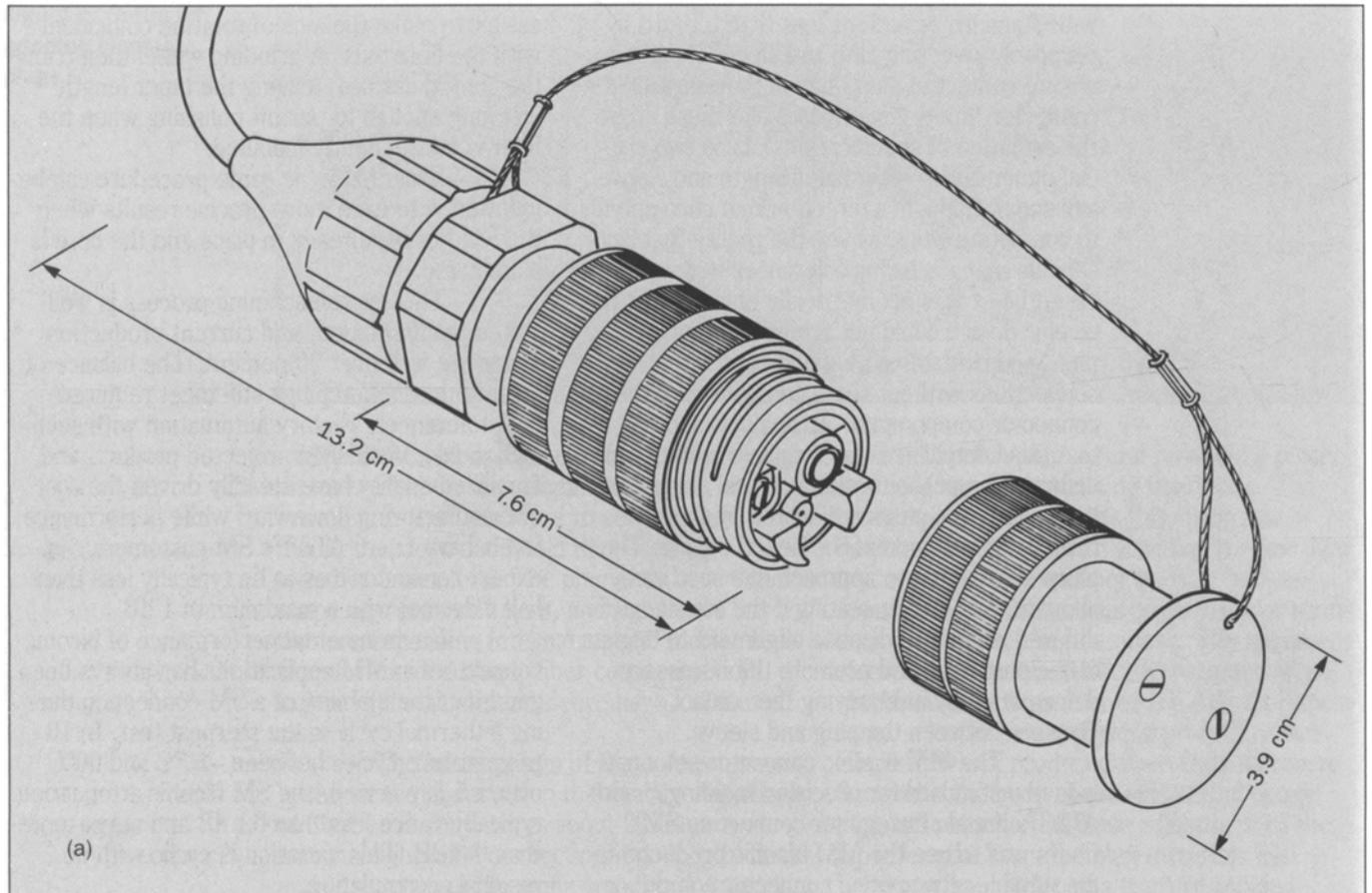
essary to make the axis of rotation coincident with the bore axis. A grinding wheel then trims the conical surface, leaving the taper length just long enough to permit polishing when the fiber is subsequently installed.

Essentially the same procedure can be followed with even more precise results when the SM fiber is already in place and the core is illuminated.<sup>15</sup>

This micromachining process is well-suited to automation, and current production yields are well over 90 percent. The balance of current production plugs still meet required MM tolerances. Factory automation with such high yields, virtually no rejected product, and stabilized quality have steadily driven the cost of manufacturing downward while performance levels have risen. AT&T's SM customers can expect connector loss to be typically less than half a decibel with a maximum of 1 dB.

Environmental performance of biconic connectors in MM applications has always been good, but the stability of a SM connection during a thermal cycle is the sternest test. In 10 temperature cycles between  $-20^{\circ}\text{C}$  and  $60^{\circ}\text{C}$  over a 5-day period, the SM biconic attenuation typically varies less than 0.1 dB and never more than 0.3 dB. This variation is cyclic with no residual accumulation.

The biconic connector has also recently found an MM military application. The tactical fiber optic cable assembly (TFOCA) connector shown in Figure 10a with its lanyard-attached dust cover was developed by AT&T during 1985 under contract to the U.S. Army Communications Electronic Command. It is a hermaphroditic duplex embodiment of the biconic connector ruggedized to meet stringent military requirements. The development included design of the sleeve retainer visible in

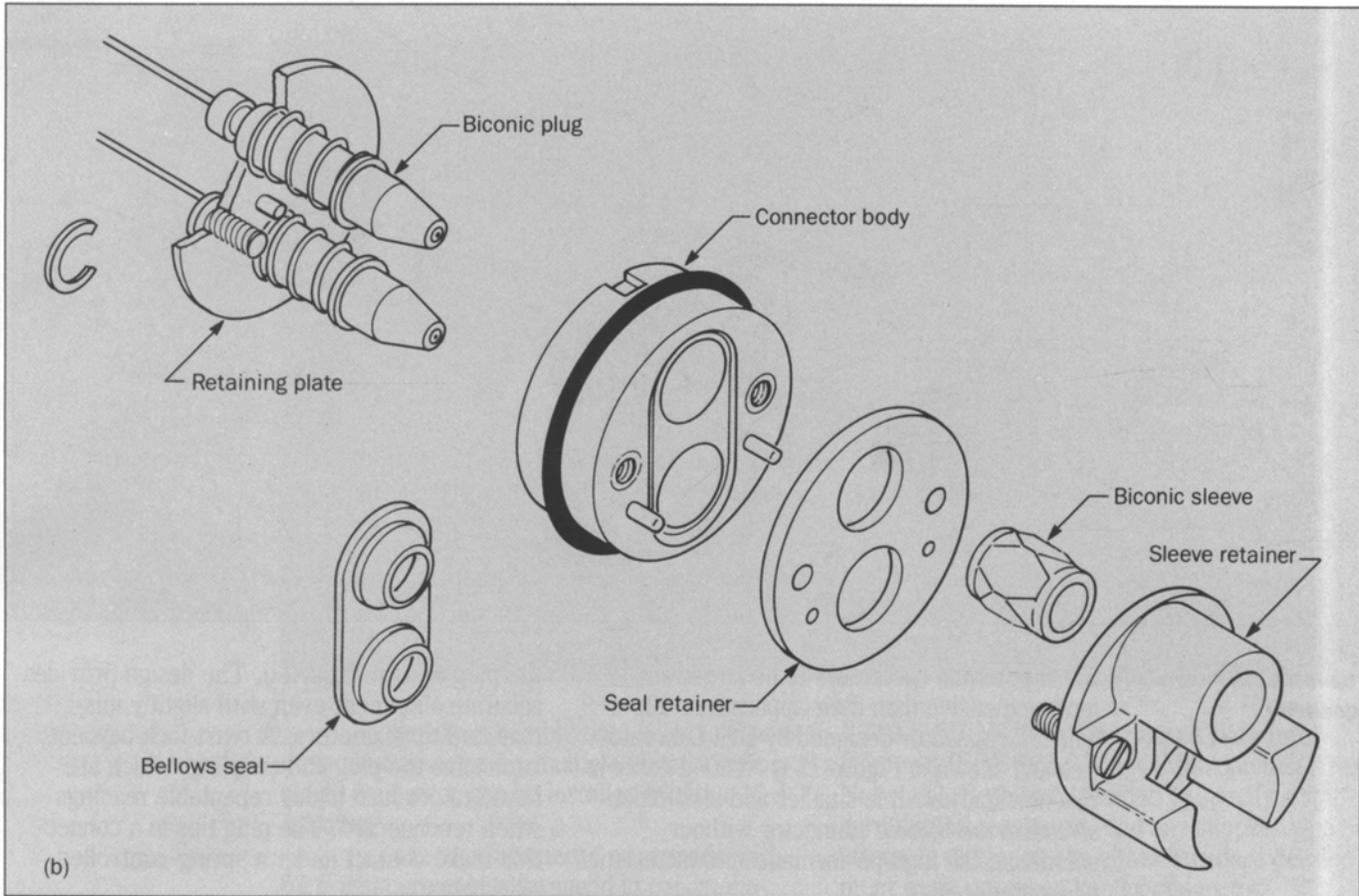


**Figure 10. Tactical fiber optic cable assembly. (a) Connector with dust cover. (b) Exploded view.**

Figure 10b at the forward end of an exploded view of the connector-insert assembly. It is removable to allow cleaning of the biconic alignment surfaces, provides the hermaphroditic geometry, and furnishes impact protection for an otherwise exposed biconic plug. The TFOCA connector is completely sealed against casual water entry when it is mated or when the hermaphroditic dust cover is in place. The confirming test requirement was a 24-hour

immersion in 2 meters of water.

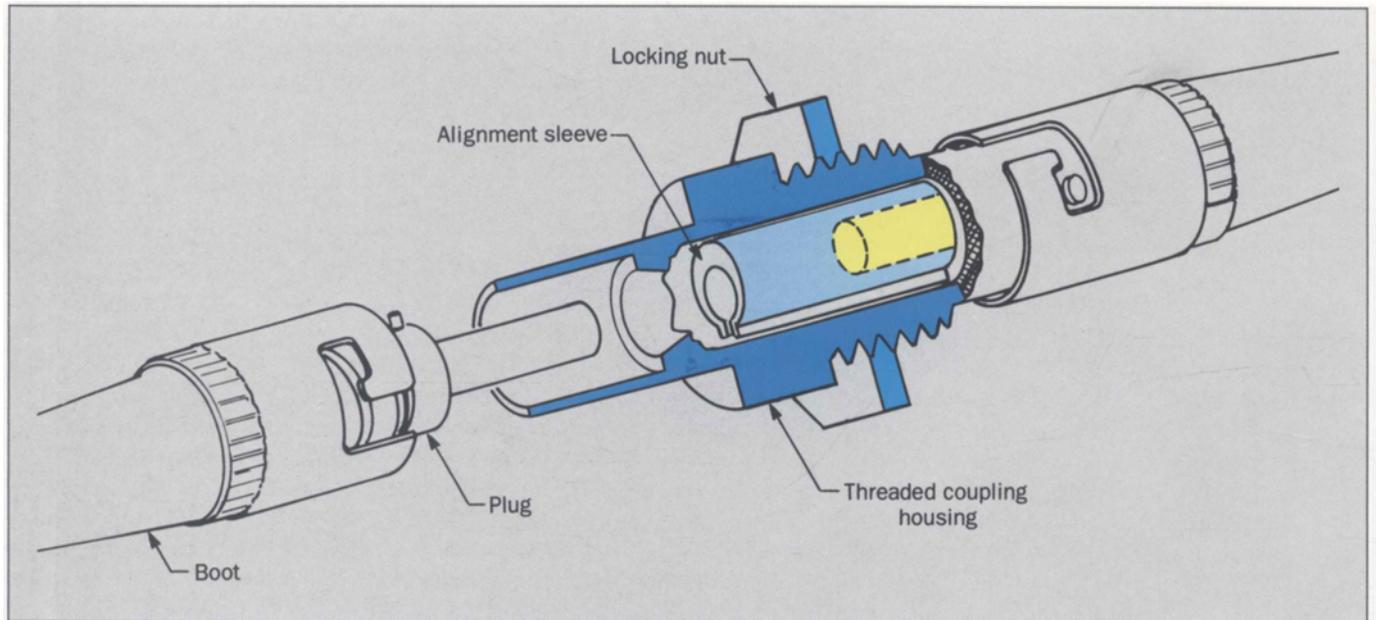
The development contract specified a battery of more or less typical connector tests, but two of these are novel enough to mention here. The first of these was the mud test. In this test, the unprotected connector was used to scoop a generous quantity of mud following an initial optical-loss baseline measurement. The connector was then cleaned using only tap water and a cloth. In many repeated demon-



strations, the maximum observed change in attenuation was 0.05 dB. The second test specifies that the connector be able to sustain a 400-pound cable tension with no mechanical or optical degradation. This was done without epoxy, crimping, or the use of any special tools by capturing the cable's aramid-yarn strength members between locking steel tapers that tighten under tension. The design exceeded expectations; the mean tensile failure load was

999 pounds, well above specification.

**ST® Connector.** A market is opening up for short-haul, connector-intensive applications calling for a small, low-cost multimode connector. Such applications include fiber distribution of wideband services within large buildings and development of fiber-based local area networks. In spite of the biconic connector's previously discussed attributes and track record, it is perceived among these nonradi-



**Figure 11. ST® series connector.**

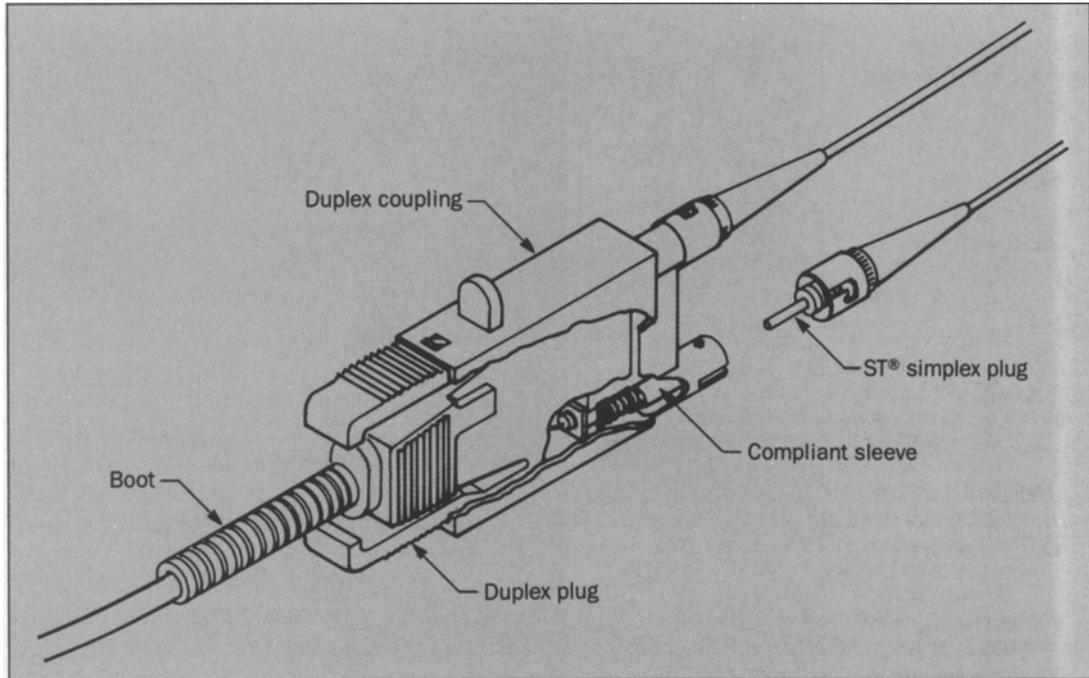
tional potential customers to be larger and more expensive than their applications allow. The ST connector designed by Bell Laboratories and shown in Figure 11 is AT&T's entry in this new market. It is smaller and less expensive than the biconic connector without sacrificing the high-performance characteristics of its predecessor.

The connector is directly compatible with AT&T's 50- and 200-Mb/s optical data links and, like the biconic, can be applied in the factory or terminated in the field. It consists of two identical robust plugs with cylindrical ceramic tips that are aligned by a uniquely configured split sleeve in four available housings. The sleeve is a patented<sup>16</sup> molded part with a cross section that is tailored to expand uniformly and exert a constant pressure when

the plug tips are inserted. The design provides accurate alignment even with slightly mismatched tip diameters. A twist-lock bayonet latch joins the plug and coupling, which are keyed to produce highly repeatable readings when reconnected. The plug tips in a connection make contact under a spring-controlled axial thrust.

The fiber is secured in the plug with a specially developed heat-cured epoxy, and a combination of adhesive bonding and mechanical crimping is used to attach the plug to single-fiber cable. An elastic boot limits the bend radius of the cable at the connector entrance. A special tool kit allows an operator to assemble the connector in the field. Up to 12 connectors can be cured at once in the oven that is part of the tool kit.

**Figure 12. ST duplex connector.**



Average assembly time is about 6 minutes per connector for multiple installations; a single connector can be installed in about 15 minutes.

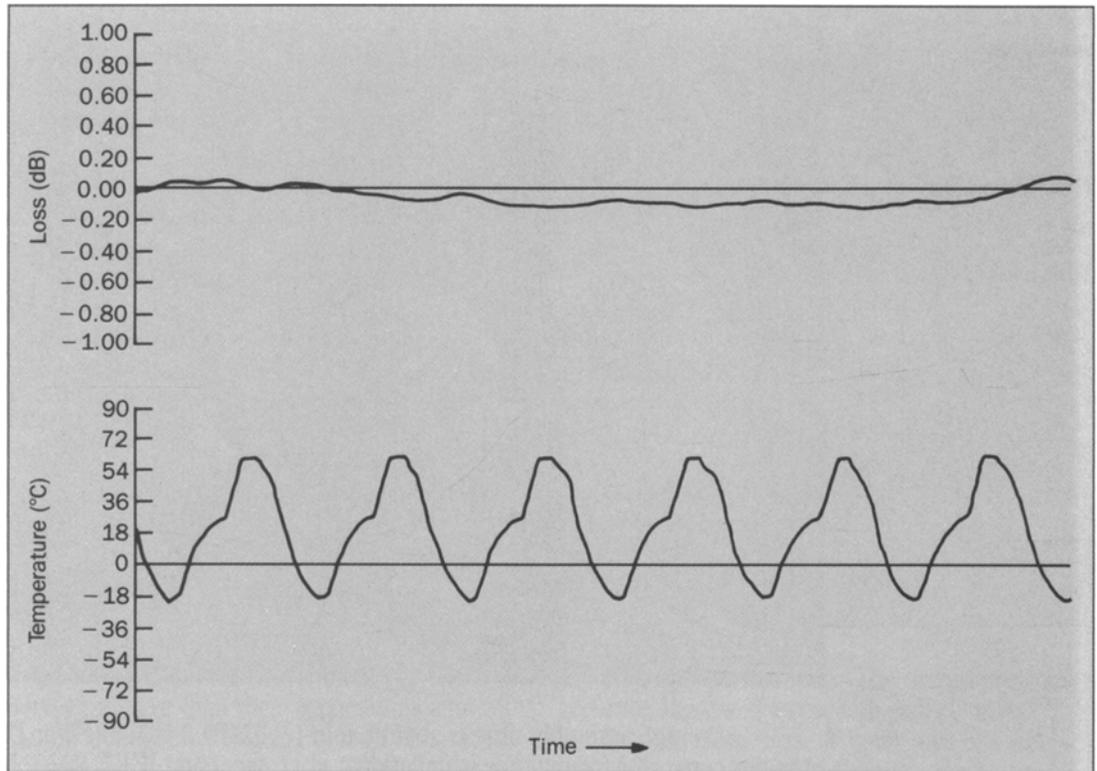
Loss measurements were made with 62.5- $\mu\text{m}$  core cables arranged in concatenations made of typical production cables and couplings. Concatenations of 10 jumpers of similar fiber were built incrementally to determine connection losses. From 260 random interconnections of 35 jumpers and 50 alignment sleeves, the mean loss and standard deviation were 0.22 and 0.15 dB, respectively.<sup>17,18</sup>

The two most active groups working on standards development for LANs are ANSI

X3T9.5 FDDI (Fiber Distributed Data Interface) and IEEE 802.6 MAN (Metropolitan Area Network). Both have decided to specify a standard duplex receptacle, and any supplier who attempts to respond to either standard development must provide a duplex connector.

Figure 12 shows AT&T's ST connector in its duplex configuration with a duplex-to-simplex coupling. The duplex plug is polarized and keyed to mate only with matching receptacles or couplings; the keying scheme may be changed in the field. The plug snaps into the receptacle or coupling and is released by depressing the clothespin latches. A spring-loaded bumper extends to protect the plug tips as the plug is removed. The ST duplex connec-

**Figure 13. Typical thermal cycle test data for the ST duplex connector.**



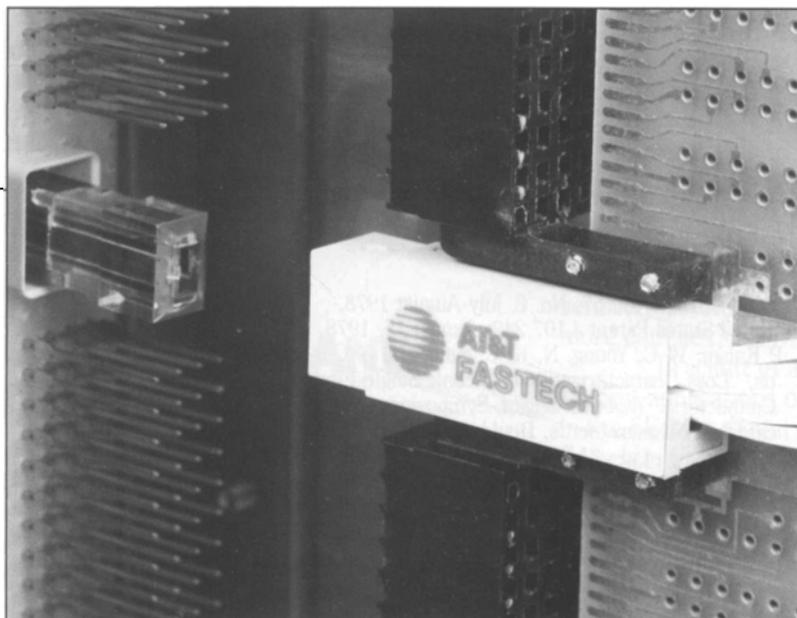
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tor uses an adaptation of the TFOCA military connector's cable-retention scheme; i.e., locking tapers capture the cable's aramid yarn. The optical performance of the connectors in duplex configuration approaches that of a single connector. A random concatenation of cables that yield 200 loss measurements has a mean loss of 0.28 dB and a standard deviation of 0.17 dB. The environmental performance of the ST duplex connector is equally impressive. Figure 13 shows typical loss variation in parallel with corresponding temperature variations ranging from  $-20^{\circ}\text{C}$  to  $60^{\circ}\text{C}$ .

A multifiber array connector (MAC)

has been developed by AT&T Bell Laboratories<sup>19</sup> for use with the Fastech<sup>®</sup> packaging system (Figure 14), as well as with other types of packaging systems. This connector allows designers to interconnect from 2 to 18 optical fibers through a backplane. The MAC is compact, with a maximum envelope of 0.5 by 0.6 by 2.26 inches, and requires a minimum circuit-pack spacing of 0.75 inch. It can be used to interconnect 50/125  $\mu\text{m}$  or 62.5/125  $\mu\text{m}$  multimode fiber. When 50/125  $\mu\text{m}$  multimode fiber is used, an average loss of 0.5 dB occurs, with 0.87  $\mu\text{m}$  wavelength and short launch and receive conditions. A single-mode version of

**Figure 14. Multifiber array connector for use with the Fastech® packaging system.**



the connector is under development with a projected average loss of 1 dB.

The MAC hardware consists of protective housings for the arrays (refer to Figures 1a and 1b) and a bend-radius limiter for ribbon jumpers. This hardware has alignment and mating features that automatically align and optically connect the arrays when a circuit pack is plugged into the backplane. The housings are constructed of flame-retardant molded plastic, and are designed for complete snap-fit assembly. This allows fanout or ribbon-jumper arrays to be removed and replaced without removing the housing from the backplane or the circuit pack. Fiber mismatch is prevented by keying the housing.

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