

STROMBERG-CARLSON
LIGHTWAVE SYSTEMS

FUNDAMENTALS OF LIGHTWAVE TRANSMISSION

Par.	CONTENTS	Page	Fig.	ILLUSTRATIONS (Cont)	Page
1.	Introduction	1	15.	One of Many Lightwave Cable Configurations	17
2.	Related Information	1	16.	Tightly Bound Lightwave Cable	17
3.	Introduction to Lightwave Transmission	1	17.	Loosely Bound Lightwave Cable	17
3.01	Advantages of Lightwave Systems	1	18.	Cutaway View of Jewelled-Ferrule Type Single-Fiber Connector	18
3.02	Elements of a Lightwave Link	2	19.	Typical Tube Splice	18
4.	Lightwave Cable	12	20.	Variations of the Groove Splice	19
4.01	Construction	12	21.	Example of Three-Rod Splicing Device	20
4.02	Connectors	15			
4.03	Splicing	15			
Appendix 1	Glossary of Lightwave Terms	A1			

TABLE

Fig.	ILLUSTRATIONS	Page	No.		Page
1.	Size Comparison - Copper Cable Versus Lightwave Cable	3	1.	Comparison of Light Source Characteristics	7
2.	Typical Two-Way Lightwave Link	4	1.	INTRODUCTION	
3.	Conversion from Electrical Signals to Light	5	1.01	This section is an introduction to the fundamental techniques of lightwave transmission. It examines the advantages of lightwave systems over copper or other types of transmission systems and describes the elements of a lightwave link. Terms that are commonly used in discussions of lightwave systems are defined in the glossary in Appendix 1.	
4.	Emission Profiles of Possible Light Sources	6	2.	RELATED INFORMATION	
5.	Basic Types of Optical Fibers	8	2.01	A Sales and Instructional Literature Index of latest available publications can be obtained from your Stromberg-Carlson sales representative or from Publications Services, Stromberg-Carlson Corporation, 400 Rinehart Road, Lake Mary, Florida 32746.	
6.	Cone of Acceptance	10			
7.	Propagation of Light in Step-Index Fiber	10	3.	INTRODUCTION TO LIGHTWAVE TRANSMISSION	
8.	Propagation of Light in Graded-Index Fiber	11	3.01	Advantages.	
9.	Propagation of Light in Single-Mode Fiber	11		Lightwave transmission is the transmission of information via a lightwave carrier that is propagated	
10.	Conversion from Light to Electrical Signals	12			
11.	Simplified Block Diagram of Optical Repeater	13			
12.	Double Crucible, Direct-Melt Process	13			
13.	Inside Vapor-Phase Oxidation (IVPO) Method of Producing Glass-Fiber Preform	14			
14.	Glass Fiber Drawing and Jacketing Process	16			

COPYRIGHT® 1983 STROMBERG-CARLSON CORPORATION. ALL RIGHTS RESERVED. This document or parts thereof may not be reproduced in any form without the express written permission of Stromberg-Carlson Corporation.

This document is issued to provide information only and (unless specifically agreed to the contrary by Stromberg-Carlson in writing) is not to form part of any order or contract or be regarded as a representation relating to the products or services concerned. The information in this document is subject to change without notice.

through light-guides (optical fibers) made of glass or plastic. A lightwave system is an attractive alternative to copper or microwave for transmission systems that connect to digital telephone switching systems. Lightwave systems provide advantages today in cost, performance, installation, maintenance, and security. And these advantages will become greater as technology advances and production of lightwave cables and terminating equipment increases.

a. Cost.

Lightwave systems are demonstrating an increasing cost advantage over conventional copper transmission systems. While the cost of copper continues to rise, the cost of lightwave cable and terminal equipment continues to fall. Beyond this, the greater spacing between regenerators (repeaters) in a lightwave system means less money must be spent on regenerators, associated structures, and power provisions. In addition, the higher traffic capacity of lightwave systems yields higher revenue.

b. Performance.

1. Because light is used as the carrier, lightwave systems exhibit definite performance advantages over copper and microwave transmission systems. The broader useful bandwidth and higher frequencies of light propagated through optical fibers allow higher data rates and the multiplexing of many channels onto one fiber. With the low-loss fibers that are now available, signal attenuation is lower than in copper cables. This means that, whereas copper systems require regenerators every 1 to 2 miles, lightwave systems require repeaters only every 15 to 50 miles, depending on the grade of cable and type of light source and detector used. And because lightwave systems use completely enclosed light guides, signals transmitted through them are unaffected by the atmospheric conditions that can disrupt microwave transmissions.

2. Because optical fibers are dielectric rather than conducting, lightwave systems offer still other performance advantages. They are immune to electromagnetic interference (EMI) from lightning or inductive fields and to radio frequency interference (RFI) from radio stations or radar. They also do not

radiate electromagnetic emissions. Therefore, crosstalk between fibers in the same cable cannot occur.

c. Installation.

Greatly reduced size and weight (fig. 1) make lightwave cables easier and less expensive to store, install, and maintain. Fewer persons and lighter equipment are required to handle lightwave cables. Where equipment already exists for transporting, laying, or pulling copper cable, the same equipment can be used for lightwave cable.

d. Maintenance.

Lightwave systems require less preventive and corrective maintenance because they require fewer regenerators (repeaters) and associated structures and power provisions. Also, because they are dielectric, lightwave cables are less prone to service-interrupting damage from lightning.

e. Security.

Communications on lightwave cables are more secure than on copper cables because optical fibers do not radiate electromagnetic emissions as do copper cables. Unauthorized access to signals on a lightwave cable can be gained only by breaking into the cable. Even then, sophisticated sensing equipment is required to decode the lightpulse signal. Moreover, the intrusion is detected quickly because of the increased signal attenuation the intrusion causes.

3.02 Elements of a Lightwave Link.

a. Components.

A typical one-way lightwave link converts a stream of digital electrical signals into pulses of light, transmits the light pulses to a destination, and then converts the light pulses back into digital electrical signals. Three basic components accomplish this: a light source, a light detector, and an optical fiber that carries the light pulses from the source to the detector. In a carrier system that transmits several channels of data, a multiplexer at the transmitting end and a demultiplexer at the receiving end also are required. Depending on the type of light source, fiber, and light detector used and the distance spanned by the link, one or more regenerators may be required to amplify the light signals being

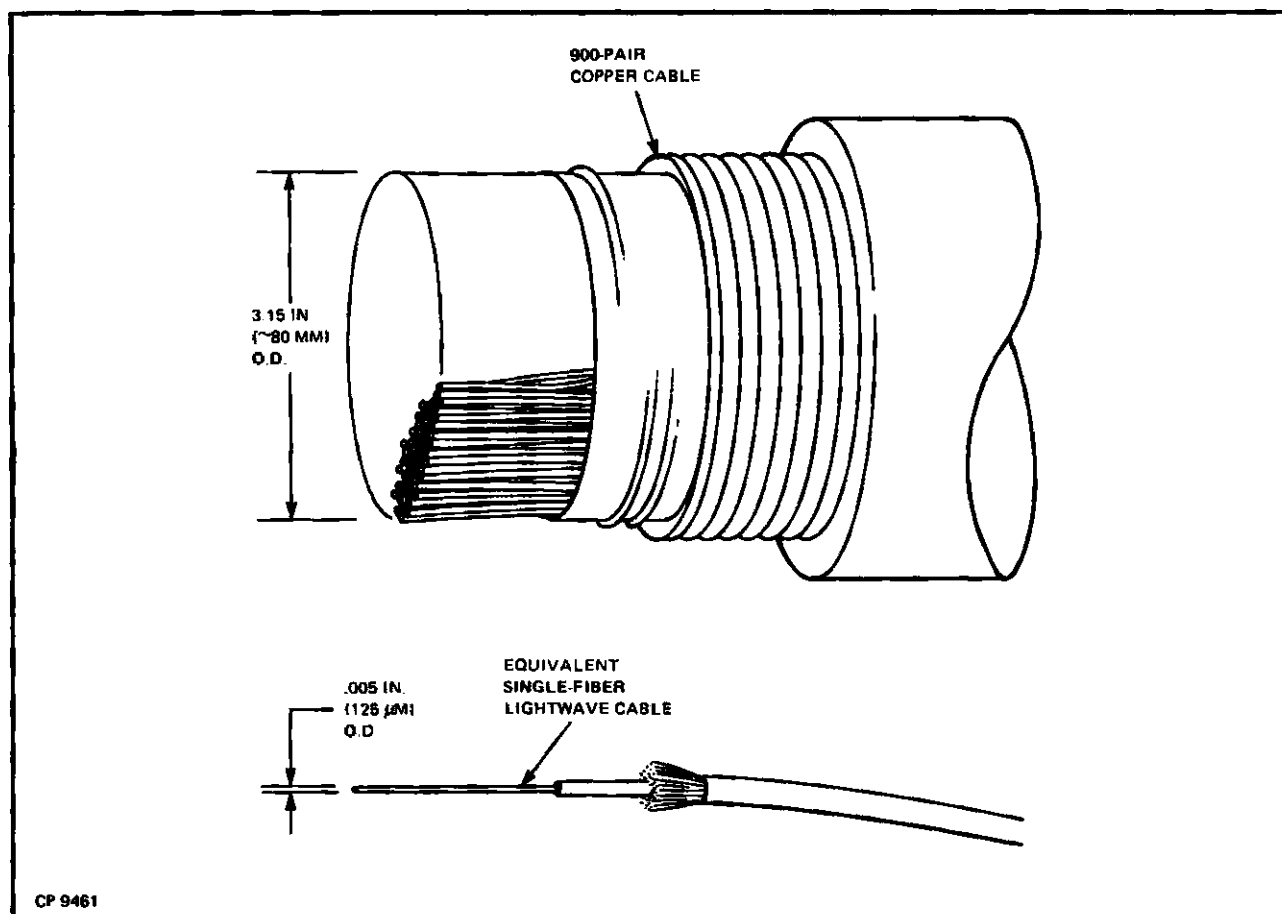


Figure 1. Size Comparison - Copper Cable Versus Lightwave Cable

transmitted. And, as figure 2 illustrates, for full-duplex operation one set of these components must be provided for each direction of transmission.

b. Conversion From Electrical Signals to Light.

1. Digital electrical signals to be transmitted over a lightwave link are converted to light by the light source. Either an injection laser diode (ILD) or one of several types of light-emitting diodes (LED) can serve as the light source. Each bit of the digital electrical signal is applied to a driver circuit (fig. 3), which then provides a stimulating pulse of current to the light source. Reacting to the current from the driver, the light source emits a pulse of light, which is launched into the end of the optical fiber.

2. Because the optical fiber has a very small diameter, the light source also must be correspondingly small. Several types of semiconductor light sources meet this requirement. These are:

- a) Conventional surface-emitting LED.
 - b) High-radiance (also known as Burrus-design) LED.
 - c) Edge-emitting LED.
 - d) Injection laser diode.
3. These light sources differ in how well they exhibit the characteristics by which a good source is selected. A good source should:
- a) Have a narrow emission profile (the pattern and divergence of light rays emitted).
 - b) Have a small emitting surface (smaller than the area of the core of the optical fiber).
 - c) Produce a bright light.

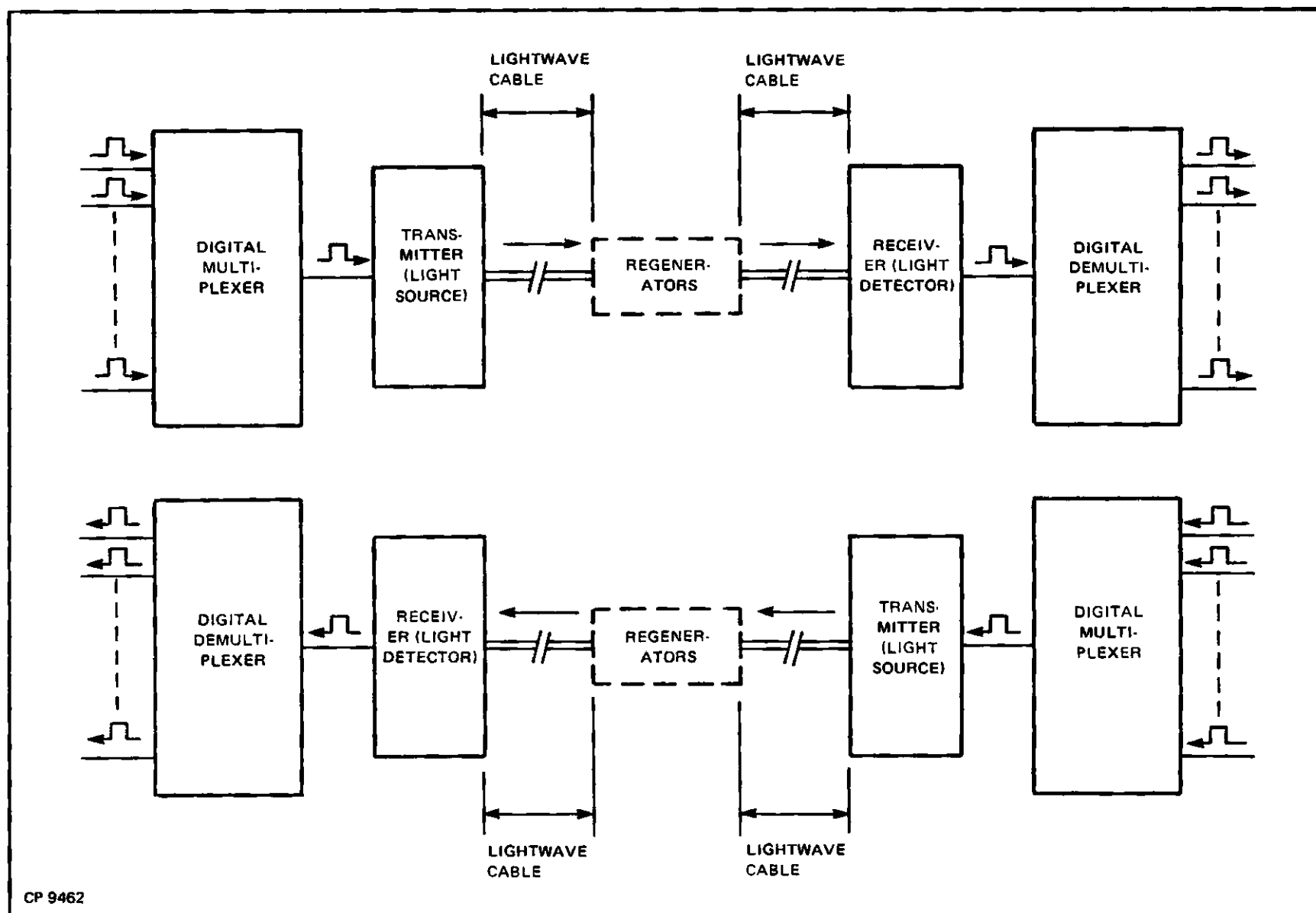


Figure 2. Typical Two-Way Lightwave Link

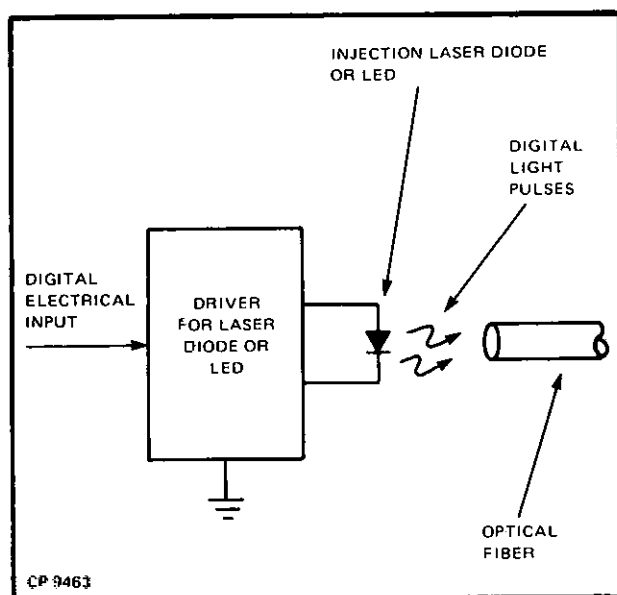


Figure 3. Conversion from Electrical Signals to Light

d) Produce light of a narrow bandwidth (as close to monochromatic as possible to reduce material dispersion, i.e., the broadening of a pulse of light because of the different propagation delays of the different wavelengths that constitute the pulse).

e) Couple efficiently to the optical fiber (so that a minimum of light is lost outside the coupling).

f) Respond very quickly to high-frequency modulation of input signals.

g) Give reliable performance over many years of operation.

h) Require few, if any, special drive and protection considerations.

i) Be inexpensive.

4. Figure 4 illustrates the differences in emission profiles among the possible light sources. Table 1 compares the characteristics of these sources.

c. Propagation of Light Through Optical Fiber.

1. Light is transmitted through an optical fiber because of the refractive and reflective properties of light and because of the structure of the fiber. As

a mode (ray) of light passes from a material of a certain density into another material of lower density, the light mode is refracted (bent) forward. This refracting of the light results from the difference in the speed of the light mode in the materials of different density. As the angle of incidence of the light mode with the juncture between the two materials becomes shallower and shallower, the refracting of the mode becomes greater and greater, and the refracted mode approaches a parallel with the juncture. When the angle of incidence becomes sufficiently shallow, the mode no longer leaves the denser material but is reflected back into it. This angle at which reflection of the light mode begins is called the critical angle. Thus, any light mode approaching the juncture between the two materials at any angle equal to or shallower than the critical angle is reflected totally back into the denser material.

2. For any transparent material, an index of how much the material refracts light is related to how fast light travels through the material. The index of refraction (n) for the material is the ratio of the velocity of light (V) through a vacuum to the velocity of light through the material:

$$n = \frac{V_{\text{vacuum}}}{V_{\text{material}}}$$

Since light travels more slowly in denser materials than in less dense materials, the denser material also has a higher index of refraction.

3. Optical fibers are constructed to take advantage of the refractive and reflective properties of light. Such fibers consist of a core of glass of a certain index of refraction (n_1), surrounded by a cladding of glass or plastic of a lower index of refraction (n_2). An outer jacket encloses the fiber to protect it from abrasion and to prevent light from radiating into adjacent fibers.

4. Two types of optical fibers are commonly used to transmit digital data: multimode fibers and single-mode fibers (fig. 5). Multimode fibers have a core with a diameter that is large (typically, 50-60 μm) relative to that of the cladding (typically, 125 μm). The resulting large cross-sectional area of the core accepts multiple modes (rays) of light,

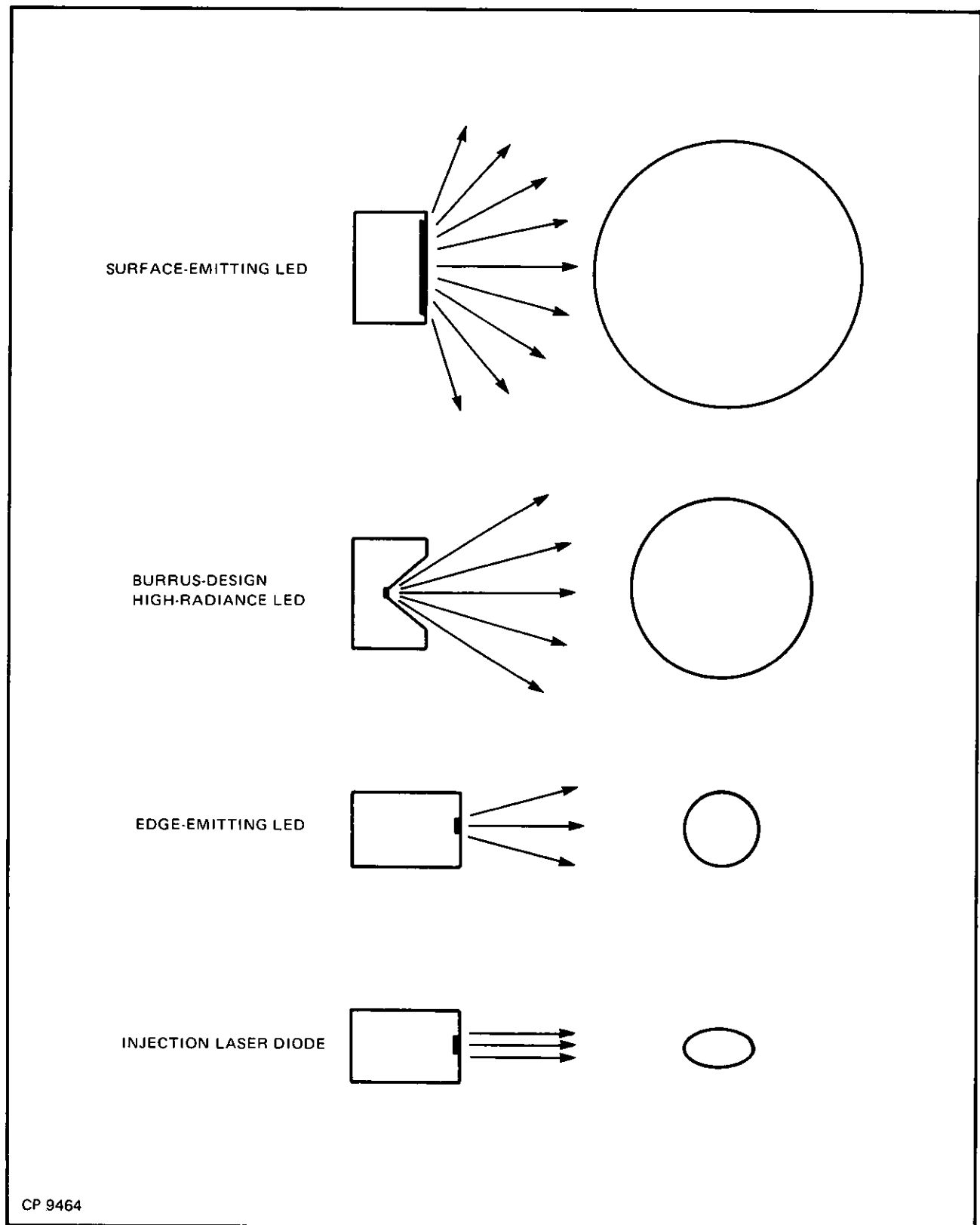


Figure 4. Emission Profiles of Possible Light Sources

Table 1. Comparison of Light Source Characteristics

CHARACTERISTIC	CONVENTIONAL SURFACE- EMITTING LED	BURRUS- DESIGN LED	EDGE EMITTING LED	INJECTION LASER DIODE
Emission Profile	Poor	Fair	Good	Excellent
Size of Emitting Surface	Poor	Excellent	Excellent	Excellent
Brightness	Fair	Good	Good	Excellent
Output Bandwidth	Fair	Good	Fair	Excellent
Efficiency of Source/Fiber Coupling	Poor	Good	Good	Excellent
Modulation Rate	Good	Good	Good	Excellent
Reliability/Life	Excellent	Excellent	Excellent	Fair
Simplicity of Drive Circuitry	Excellent	Excellent	Excellent	Fair
Cost	Excellent	Good	Excellent	Fair

entering the fiber at different angles. Single-mode fibers have a core with a diameter that is small (typically, 2-10 μm) relative to that of the cladding. The small cross-sectional area that results allows effectively only a single mode of light to enter the core, parallel with the center-line of the core.

5. Additionally, there are two types of multimode fibers: step-index and graded-index. In step-index fibers, the index of refraction is uniform across the radius of the core and then steps down sharply at the juncture between the core and the cladding. In a graded-index fiber, the index of refraction decreases along the radius from the center of the core to the juncture between the core and the cladding.

6. All modes of light that are to be transmitted through an optical fiber must enter the core of the fiber within a theoretical cone of acceptance (fig. 6). The half-angle Θ of this cone is related to the theoretical light-gathering ability of the fiber, or numerical aperture (NA), by the equation $\text{NA} = n_0 \sin \Theta$, where n_0 is the index of refraction of the

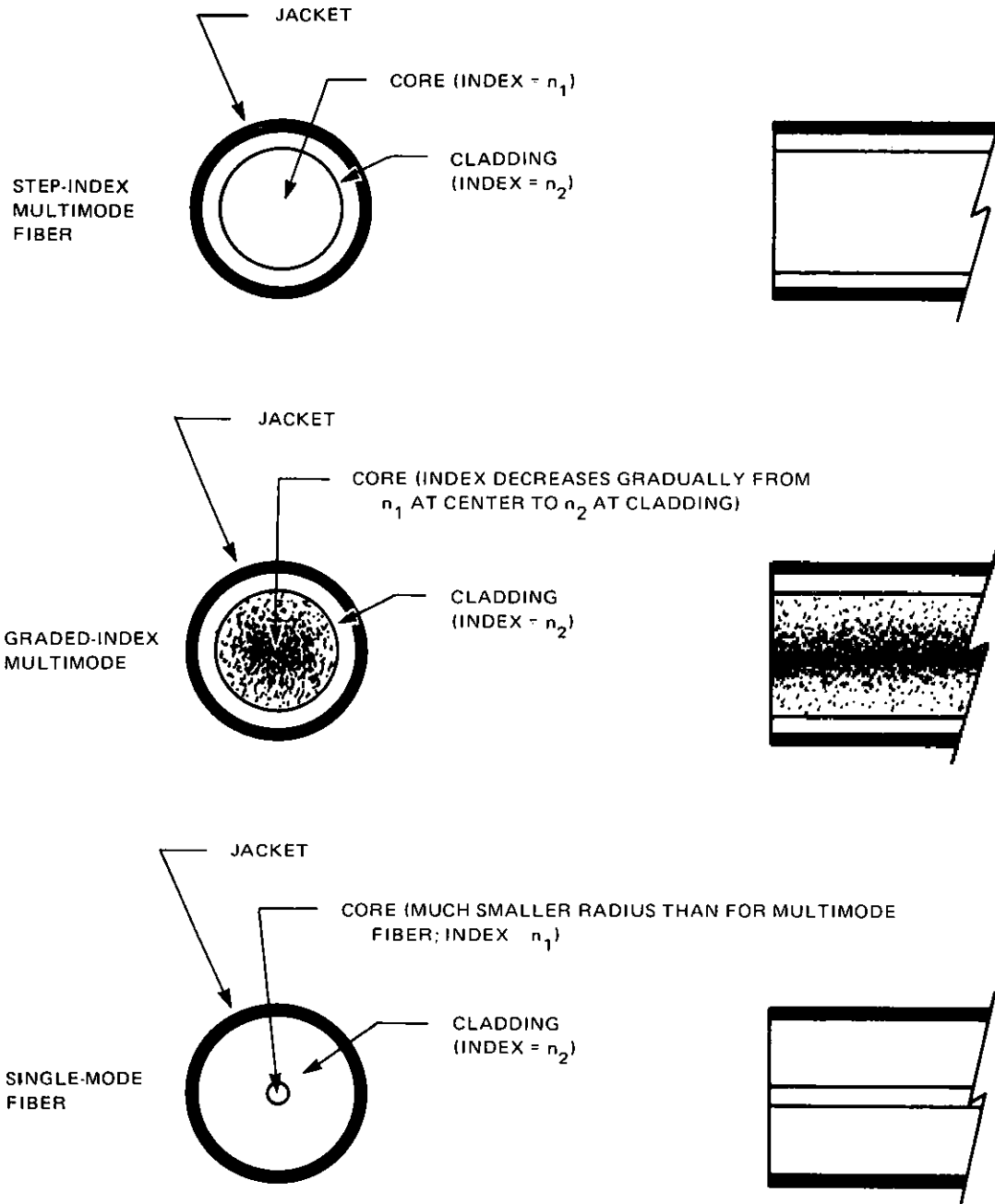
medium from which light enters the fiber ($n_0 = 1.00$ for air). In turn, the numerical aperture can be determined by the relationship

$$\text{NA} = \sqrt{n_1^2 - n_2^2}$$

where n_1 is the index of refraction of the core (for a graded-index fiber, n_1 is the index of refraction at the center of the core) and n_2 is the index of refraction of the cladding. Combining these expressions, the half-angle of the cone of acceptance can be determined using the equation

$$\Theta = \text{ARCSIN} \sqrt{\frac{n_1^2 - n_2^2}{n_0^2}}$$

7. For example, if the respective indexes of refraction for a given fiber are $n_1 = 1.48$ and $n_2 = 1.46$ (values commonly found in actual fibers), the cone half-angle is calculated as follows:



CP 9465

Figure 5. Basic Types of Optical Fibers

$$\theta = \text{ARCSIN} \sqrt{\frac{(1.48)^2 - (1.46)^2}{1.00}}$$

$$= \text{ARCSIN } 0.242487$$

$$= 14.03^\circ$$

Any light mode entering the core of the fiber within the cone defined by this half-angle is confined inside the core by total reflection off the core/cladding juncture and is propagated by a series of such reflections to the distant end of the fiber.

8. Figure 7 illustrates how light is propagated through a step-index multimode fiber. A light mode that enters the core on a parallel with the center-line of the core (mode A, fig. 7) travels straight through the core to the distant end of the fiber (assuming the fiber has no bends). Any light mode that enters the core at an angle that is within the cone of acceptance (mode B, fig. 7) travels into the core at that angle until it encounters the juncture between the core and the cladding. Then the mode is reflected back toward the other side of the core at the same angle (angle of incidence) at which it struck the core/cladding juncture. Through such repeated reflections the light mode is propagated to the distant end of the fiber. Any light modes that enter the core from outside the cone of acceptance (mode C, fig. 7) pass through the juncture and are trapped and dispersed in the cladding.

9. A limitation in data-carrying ability is inherent in a step-index multimode fiber. Multiple modes of light radiating from the same source at different angles take varying amounts of time to travel to the distant end of the fiber. This is because some modes travel directly or almost directly through the fiber along the shortest path while other modes reflect off the sides and across the core many times, following much longer paths to the distant end of the fiber. This situation, called modal dispersion, results in a pulse of light being much broader when it is detected than it was when it was generated. Because of the broadening of each pulse of light (representing a bit of data), modal dispersion limits the number of data bits that can be transmitted through a step-index multimode fiber in a given amount of time.

10. Graded-index multimode fibers are not so affected by modal dispersion as are step-index fibers. Because the index of refraction of the graded-index core decreases gradually from the center out to the cladding, any light mode that enters the core at an angle within the cone of acceptance (mode B, fig. 8) is refracted toward the center of the core. Each time the mode passes through the center and starts to travel toward the cladding it is refracted back toward the center. Thus, light modes that enter the core at an angle travel a shorter distance through a graded-index fiber than those that reflect off the core/cladding juncture in a step-index fiber. This means that all the modes of a pulse of light launched into a graded index fiber arrive at the distant end more nearly at the same time than in a step-index fiber, resulting in less broadening of each pulse. Consequently, more bits of data can be transmitted in the same amount of time through a graded-index fiber than through a step-index fiber.

11. Modal dispersion is eliminated in a single-mode fiber, because the diameter of the core is so small that it effectively accepts only one mode of light (mode A, fig. 9). This single mode must be launched perpendicular to the face of the core. Any other mode that enters the fiber goes into the cladding and is dispersed there (mode B, fig. 9). Because only a single mode of light from each pulse is propagated through the core of a single-mode fiber, each pulse is nearly the same width when it is detected as when it is generated. The only pulse broadening that occurs results from material dispersion, which occurs because different wavelengths of light travel at different speeds through the fiber. (This type of dispersion exists in all types of optical fibers.) Therefore, more data bits can be transmitted in a certain amount of time through a single-mode fiber than through either type of multimode fiber.

d. Conversion From Light to Electrical Signals.

1. At the receiving end of an optical fiber, an optical detector converts the pulses of light into electrical signals (fig. 10). Either a PIN photodiode or an avalanche photodiode in the detector converts each light pulse into one bit of digital data, which is amplified and applied to interfaced digital circuitry.

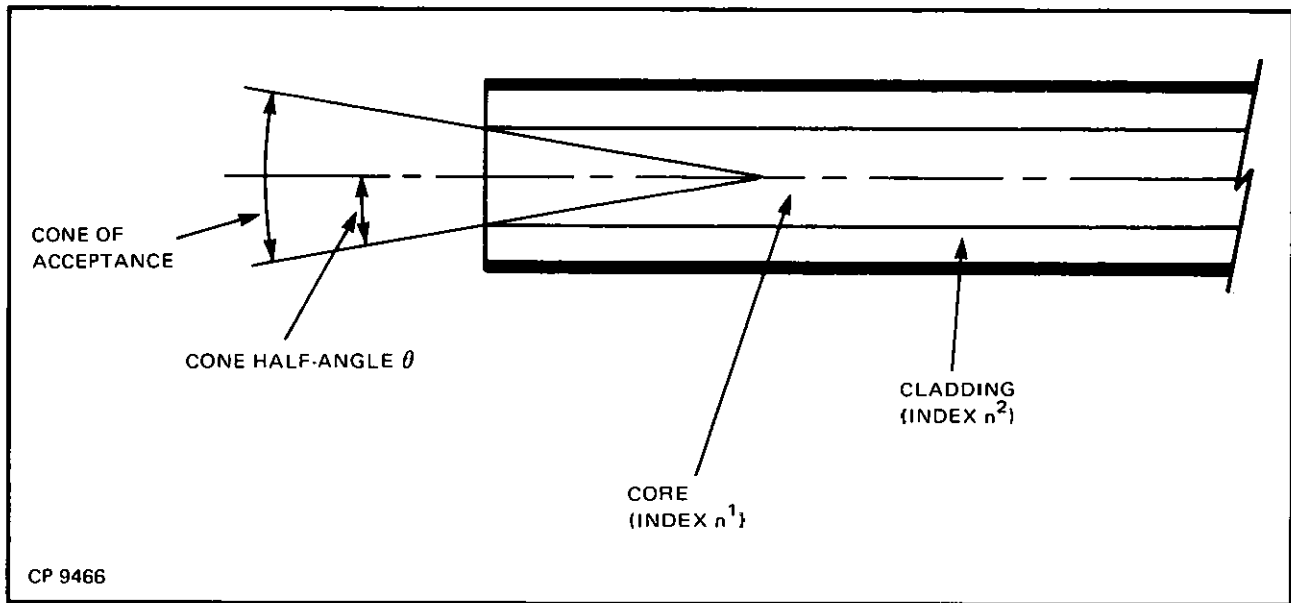


Figure 6. Cone of Acceptance

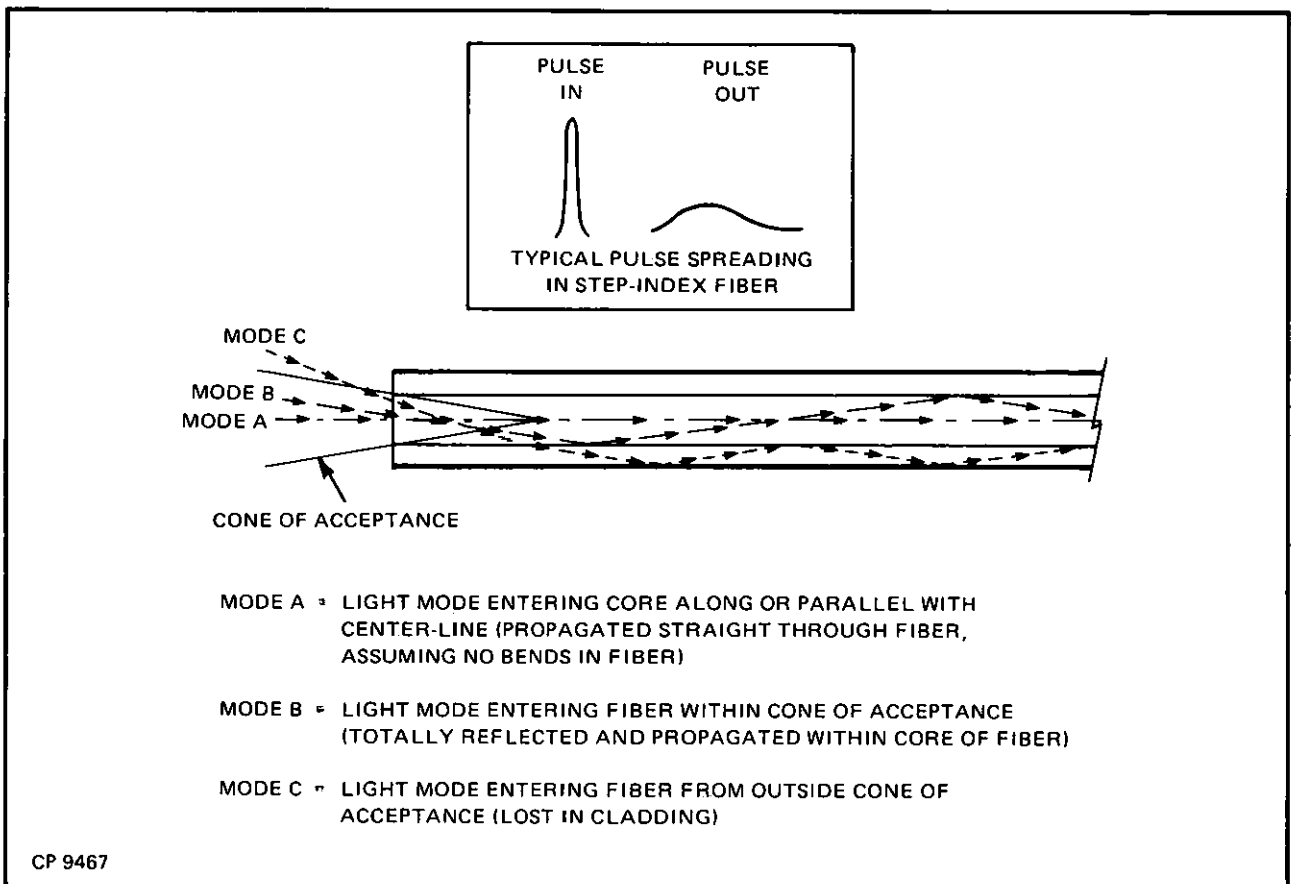


Figure 7. Propagation of Light in Step-Index Fiber

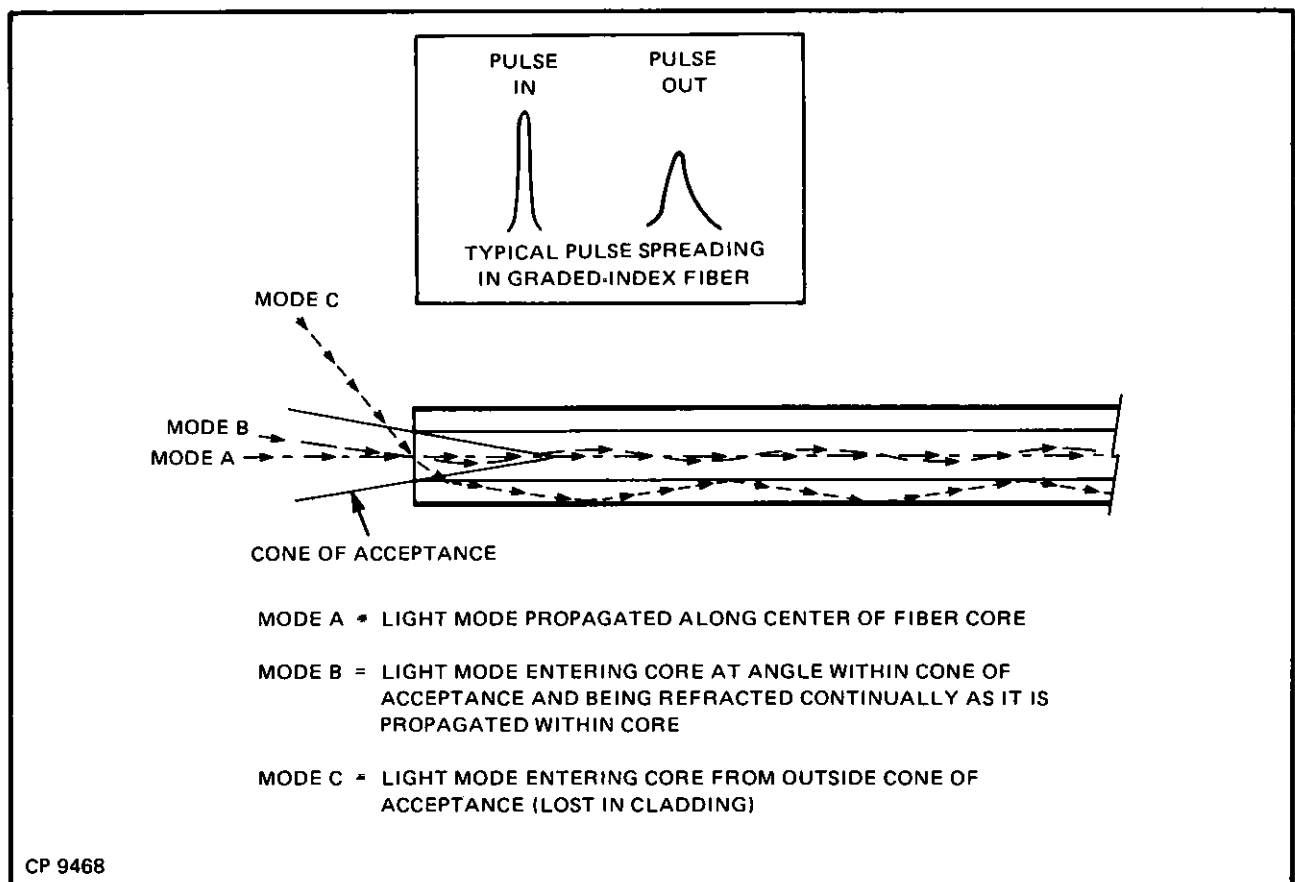


Figure 8. Propagation of Light in Graded-Index Fiber

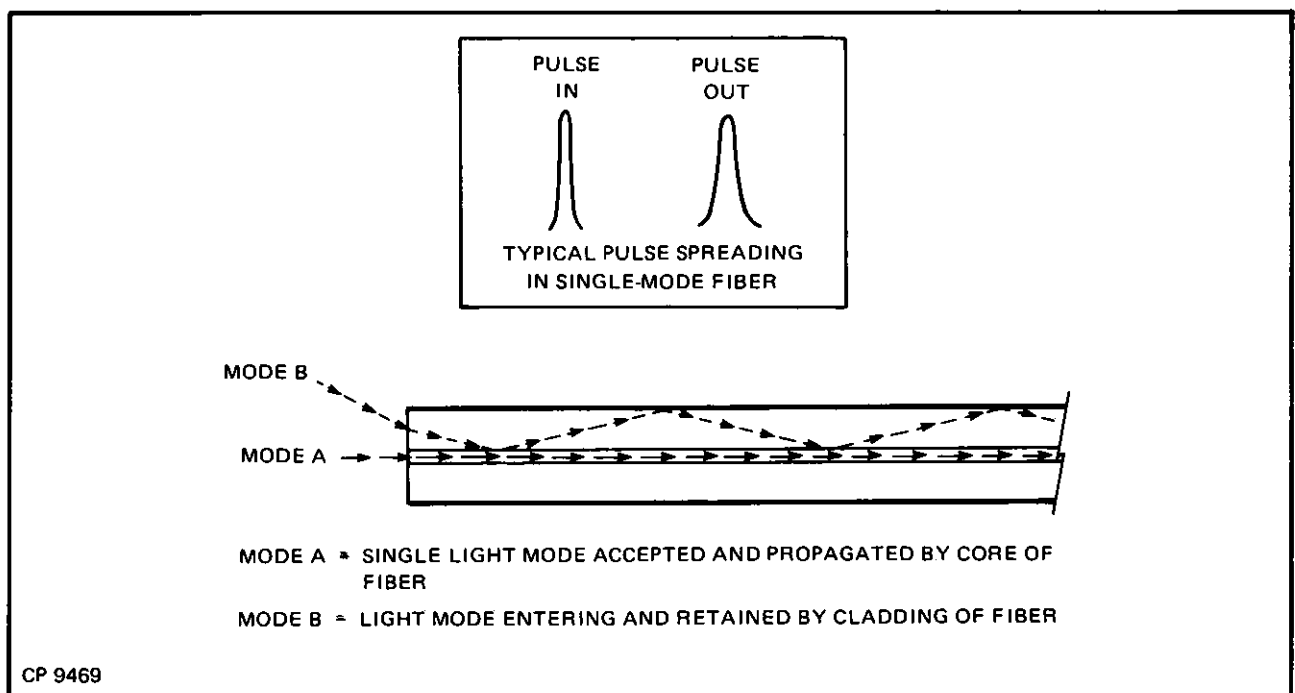


Figure 9. Propagation of Light in Single-Mode Fiber

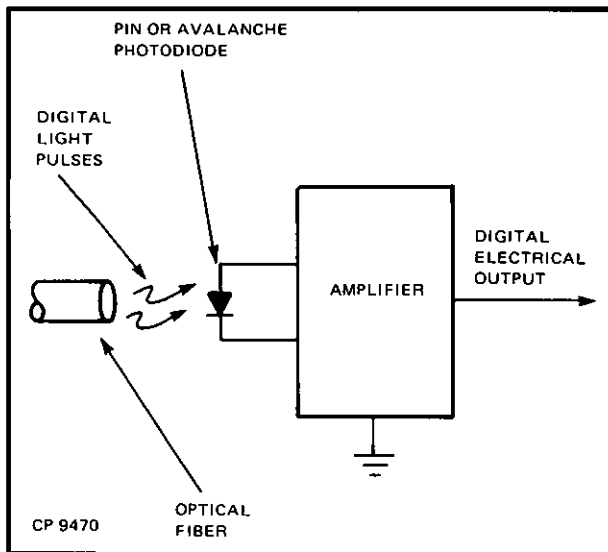


Figure 10. Conversion from Light to Electrical Signals

2. The PIN photodiode is the less expensive and the simpler of the two types of photodiodes used in optical detectors. However, it generates less current in relation to the amount of light detected than the avalanche photodiode. To compensate for this, the PIN photodiode can be combined in a hybrid package with a field effect transistor (FET) amplifier to form a PINFET receiver. Such a receiver offers excellent sensitivity, with low noise.

3. The avalanche photodiode produces much more current with respect to the amount of light it detects, because it has an inherent gain or amplifying capability. However, this type of photodiode also requires a much higher bias voltage and additional circuitry for automatic gain control (AGC). In addition, the avalanche photodiode is more expensive than the PIN photodiode.

e. Boosting the Signal.

Depending on the characteristics of the source, optical fiber, and detector used, a lightwave link can extend from 15 to 50 miles (24 to 80 kilometers) before losses and dispersion seriously degrade the signal. But for longer links, one or more regenerators are required to boost the signal. As figure 11 illustrates, a regenerator converts the incoming light signals into a digital bit stream. The digital signals then are reshaped, amplified, and applied to an optical source. The optical source converts the renewed digital signal into light

pulses, which are launched into the outgoing optical fiber. Depending on what components are used in the rest of the link, the optical detector in the regenerator can be either a PIN photodiode or an avalanche photodiode. The source can be either a laser diode or a light-emitting diode (LED). Because two separate fibers are required for a bidirectional link, two regenerators (one for each fiber) are required at each point where the signal must be boosted.

4. LIGHTWAVE CABLE

4.01 Construction.

a. Optical Fiber.

1. Optical fiber is produced by heating the materials from which the fiber is to be made to a molten state and drawing a thin strand from the molten materials. The materials that constitute the core and the cladding of the fiber may be melted separately in concentric crucibles (fig. 12), and a single strand may be drawn from these crucibles to produce the fiber. This is called the direct-melt process. It has the advantage of being rapid and continuous, but it has the disadvantage of being easily contaminated with impurities.

2. Optical fiber also can be drawn from a previously formed glass blank (preform) heated in a drawing furnace. The preform can be produced in any of several ways, but the method that yields the purest preform and the best control and uniformity of index of refraction is chemical vapor deposition (CVD). During the CVD process, the materials that are to constitute the preform are vaporized and then directed toward a baiting surface inside a zone of high temperature. On entering the high-temperature zone, the vapor is oxidized into a soot that is deposited on the baiting surface. By controlling the ingredients that are vaporized, the composition of the soot that is accumulated on the baiting surface can be controlled.

3. A common CVD method of producing a glass preform is called inside vapor-phase oxidation (IVPO). In this process, the chemical vapors are directed into a silica baiting tube that is held between two rotating mandrels (fig. 13). A heating mechanism that can move laterally along the baiting

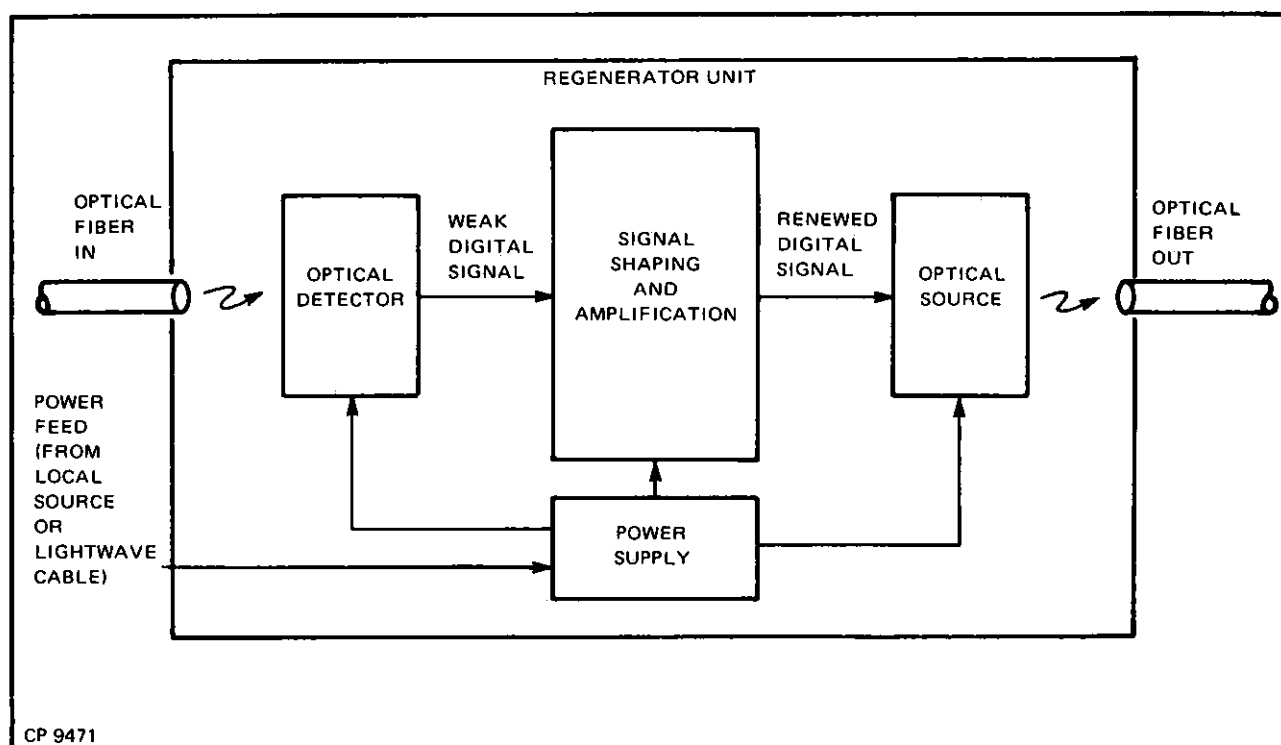


Figure 11. Simplified Block Diagram of Optical Repeater

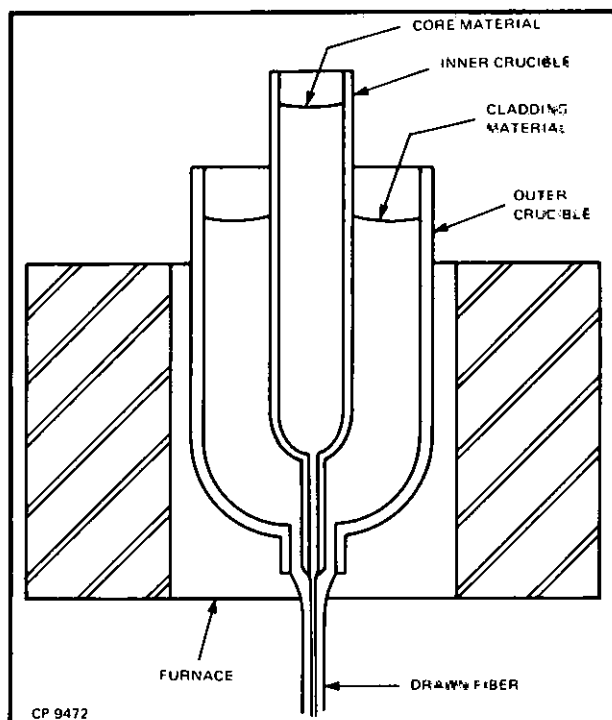


Figure 12. Double Crucible, Direct-Melt Process

tube is positioned at the end of the tube into which the vapors are injected. On entering the heated zone (approximately 1500 °C) inside the tube, the vapors oxidize into soot and are deposited uniformly on the inside surface of the tube. As the heating mechanism moves toward the other end of the tube, the soot deposit is extended until a uniform layer of the soot covers the entire inside surface. Then the heating mechanism moves quickly back to the starting position and begins another pass along the baiting tube. Any unoxidized vapors and undeposited soot are exhausted from the far end of the baiting tube. Each time the heating mechanism passes along the length of the tube, another layer of soot is deposited.

4. The ratio of the ingredients in the soot (corresponding to the ratio of the ingredients in the vapor) determines the index of refraction of the fiber that eventually will be drawn from the preform. To produce a preform for a graded-index fiber, a sufficient number of layers of a given ratio

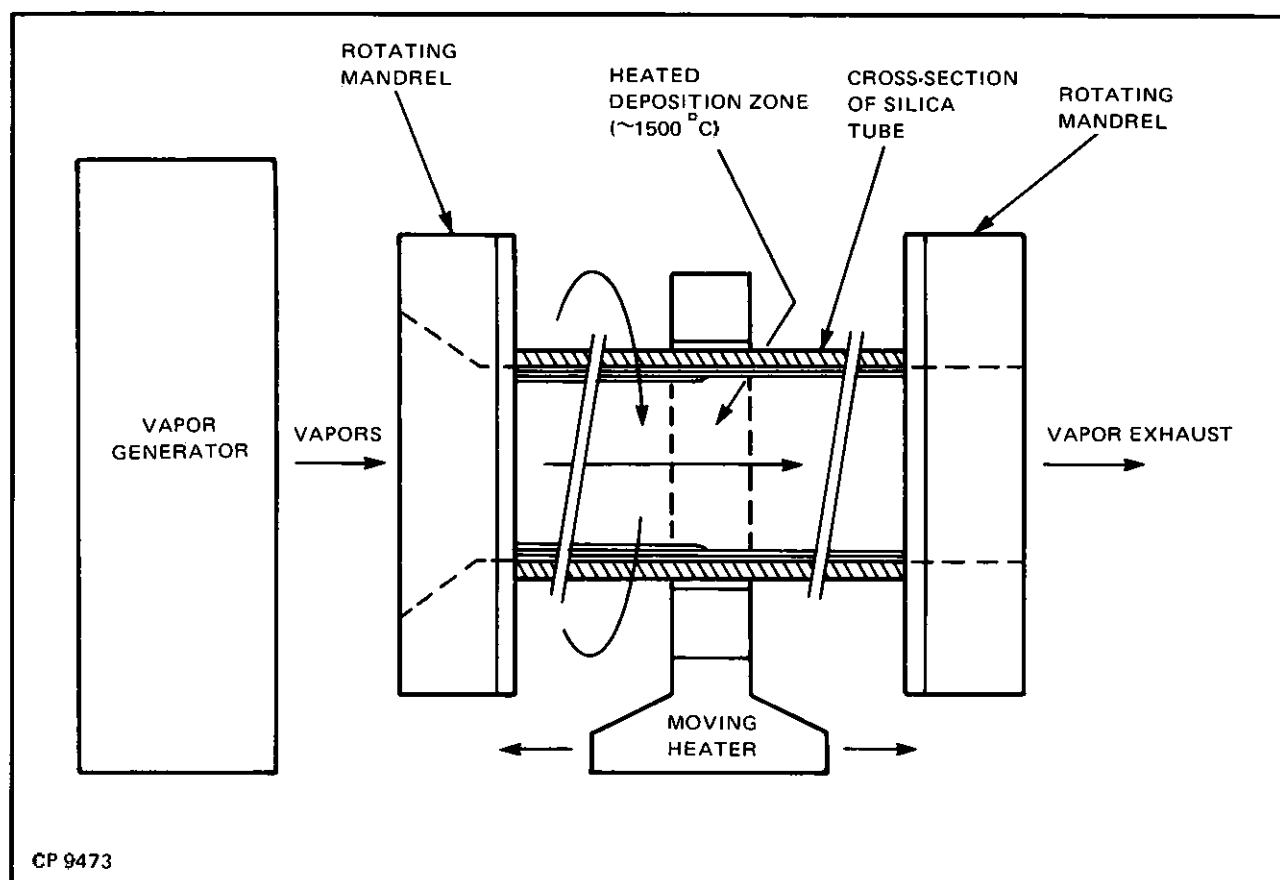


Figure 13. Inside Vapor-Phase Oxidation (IVPO) Method of Producing Glass-Fiber Preform

are built up to produce the portion of the preform that will become the cladding in the finished fiber. After that, for each successive layer, the ratio of ingredients is altered slightly to produce a layer of soot that corresponds to a certain grading of refractive index in the graded-index core of the finished fiber. This process is repeated until the baiting tube is nearly filled, leaving only a small hole in the center, running the length of the tube.

5. Then, to complete the manufacture of the preform, the heating mechanism is passed along the tube again, but at a higher temperature (approximately 1900 °C). This sinters the soot deposit; surface tension increases in the outer layer of soot to collapse the inner layers inward, closing the center hole and shrinking the preform from the baiting tube. The completed preform then is ready for drawing.

6. Another CVD type of preform manufacture is called outside vapor-phase oxidation (OVPO). Two OVPO methods currently are in use. The first is similar to the IVPO method described in preceding paragraphs. However, the baiting surface is a rod instead of a tube, and the vapors are converted to soot by burning them in torches. The resulting soot is deposited in layers on the rod by passing the torches back and forth along the rod. When sufficient layers have been built up, the baiting rod is removed and sufficient heat is applied to sinter the preform, closing the central hole left by the baiting rod. A disadvantage of this process is that the preform can be contaminated easily because the process is not enclosed.

7. The other OVPO method of making a preform is called axial deposition. For this method, the torches are arranged so that the soot that is to

become the core of the fiber is directed axially at the end of a circular baiting surface. As a column of core soot is built up on this surface, other burners arranged perpendicular to the core column produce cladding soot that is deposited on the core column. With this method, preforms of any length can be produced rapidly and continuously.

8. A preform is converted into optical fiber by the drawing process illustrated in figure 14. The preform is inserted into a mechanism that feeds it gradually into a heater. This heater raises the temperature of the end of the preform to more than 2000 °C, converting it to molten glass. A strand of molten glass is pulled from the preform and fed through a diameter monitor, a jacketing extruder, and a jacketing dryer. Finally, the strand is attached to a drawing drum, which begins drawing the fiber.

9. A regulator senses the temperature in the preform heater and regulates the power to the heater to maintain the proper melting temperature. The diameter monitor senses any irregularity in the diameter of the fiber being drawn. If an irregularity occurs, the drive speed control speeds up or slows down either the preform-feeder drive or the drawing-drum drive. The ratio of the speed of the preform feeder to that of the drawing drum is the same as the ratio of the diameter of the drawn fiber to that of the preform.

10. The jacketing extruder applies the coating that protects the optical fiber from abrasion or other damage to the cladding surface. A drying furnace hardens the jacketing before the completed fiber is wound onto the drawing drum.

b. Cable Assembly.

1. In telephone transmission applications, several optical fibers are assembled into a cable. The assembly requirements of such a cable are similar to those of a conventional copper cable, with some exceptions. For example, although coated with a jacketing, optical fibers require more isolation from the stresses, abrasion, and bending that occur inside a cable during handling and installing of the cable. It is essential that the fibers be isolated from the tensile stresses that are imposed on the cable

while it is being pulled through ducting or when suspended in an aerial installation. Moreover, provisions may be required for a separate supervisory communication path or for regenerator power feed through the cable.

2. Many different cable designs are available to satisfy these special requirements. Most have a strength member of some kind to absorb the tensile stresses, and some include copper leads or pairs for order wire, supervisory, and power feed requirements (fig. 15). In some lightwave cables, the fibers are encased in relatively thick plastic jackets and bound tightly inside a protective inner cable sheath or jacket (fig. 16). In other cable configurations, the fibers are fed loosely through hollow plastic buffer tubes that isolate the fibers from all other components in the cable and provide additional protection from stretching due to tensile stress (fig 17). Aside from these special components, lightwave cables are constructed in the same way as conventional copper cables, with fillers, cushions, and an external sheath.

4.02 Connectors.

Connectors for lightwave cables are available in a variety of types. Some are designed to connect multiple-fiber cables, whereas others are designed for single-fiber cables. All types of connectors must achieve precise alignment of the ends of the optical fibers that are being joined. One type of single-fiber connector is illustrated in figure 18. It is a jewelled-ferrule type, which uses a sprung alignment cage to line up precisely the ferrules that terminate the fiber ends that are to be joined. Other connector types may use alignment rods or V-grooves to accomplish this purpose.

4.03 Splicing.

a. Fiber Preparation.

Before two lengths of optical fiber can be spliced together, the ends of the fiber must be made as flat and as free of burrs and irregularities as possible. This is to reduce the light losses that result from such imperfections. One way to prepare the end of a fiber is to fit a lapping fixture to the end of the fiber and grind the end until it is smooth and flat. An easier way is to score the surface of the fiber at a point a few inches from the end and then pull the end until the fiber

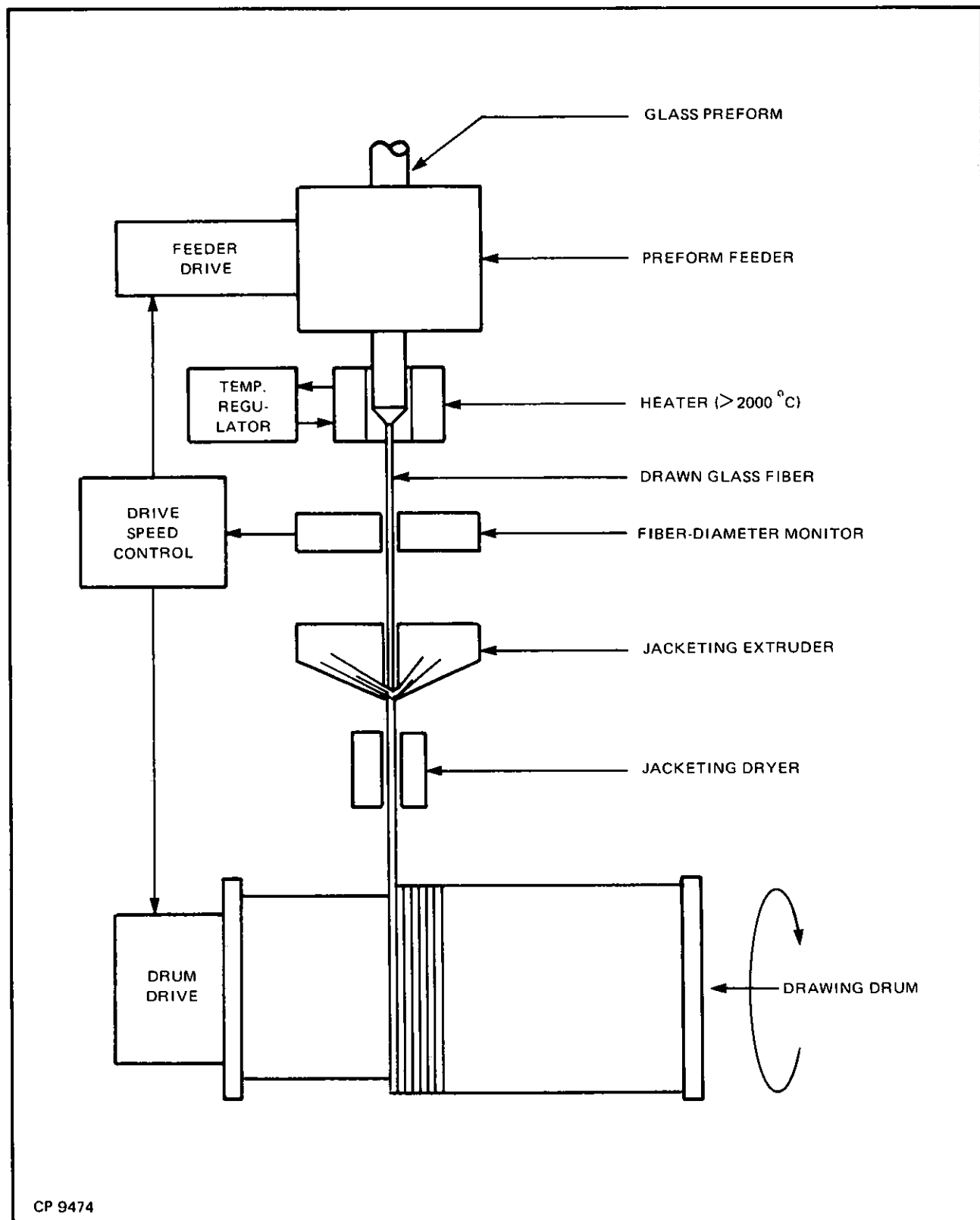


Figure 14. Glass Fiber Drawing and Jacketing Process

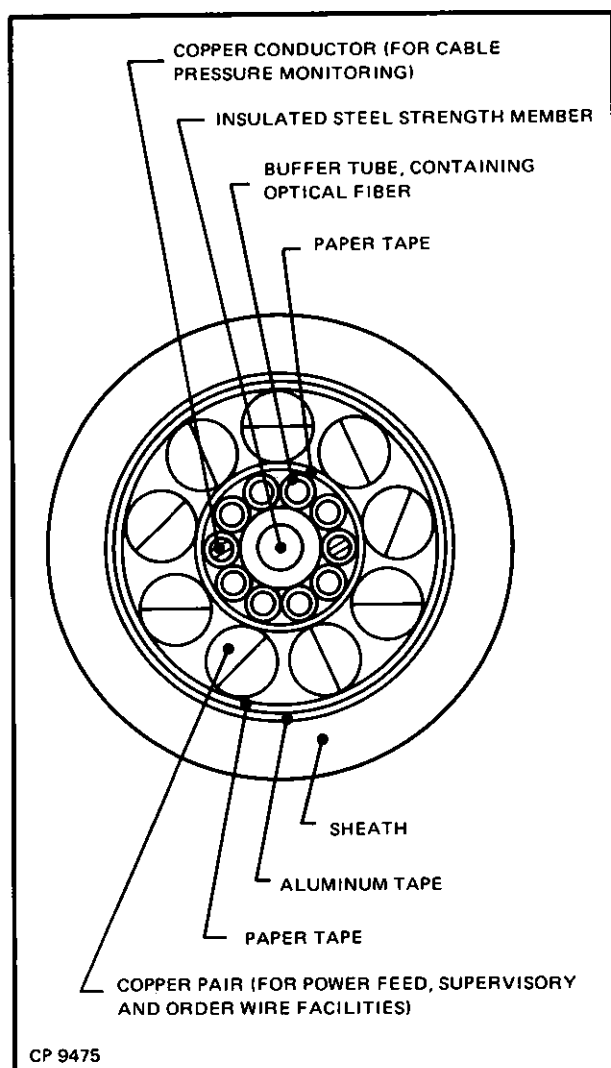


Figure 15. One of Many Lightwave Cable Configurations

breaks at the score mark. The resulting break is of sufficient quality that it generally requires no further preparation for splicing.

b. Mechanical Splices.

Numerous mechanical splicing techniques are available, but they fall generally into one of three groups: tube splices, groove splices, and alignment-rod splices. Tube splices use glass, plastic, metal, or heat-shrinkable tubes (fig. 19) with the inside diameter sufficiently small to encase the fiber ends and hold them in alignment. Groove splices (fig. 20) use two intersecting surfaces to confine and align the two fibers to be joined. Various means are used to hold the fibers against the intersection of the surfaces. Alignment-rod

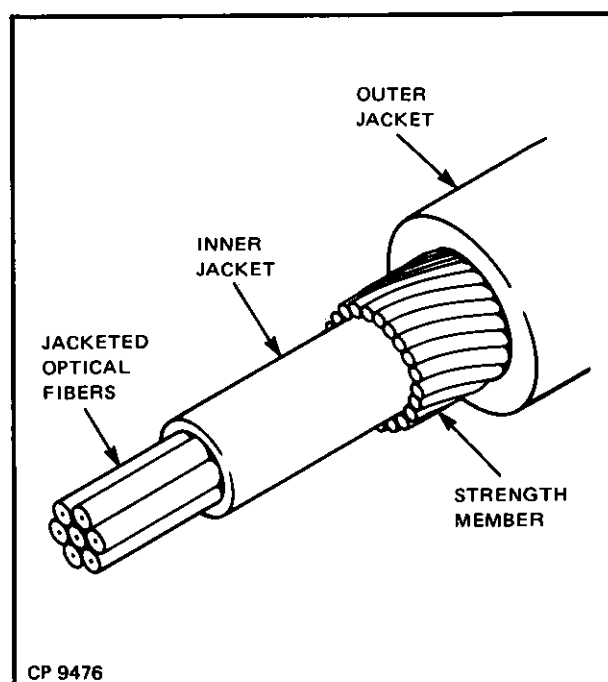


Figure 16. Tightly Bound Lightwave Cable

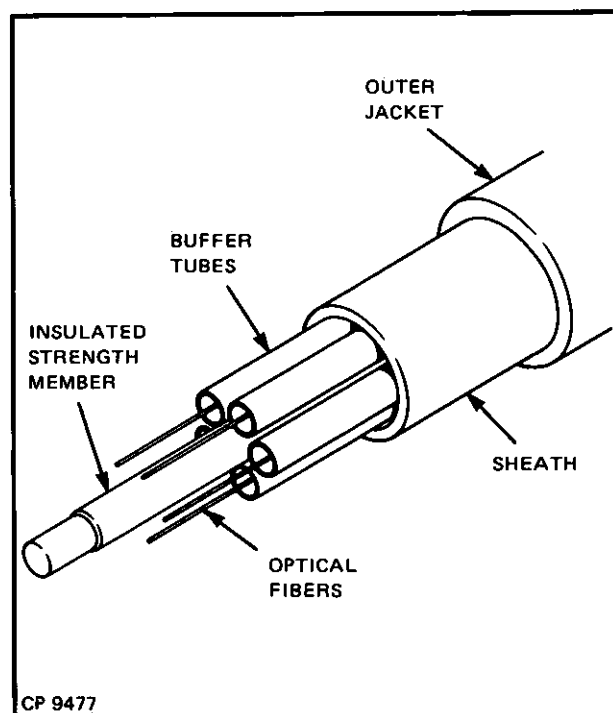


Figure 17. Loosely Bound Lightwave Cable

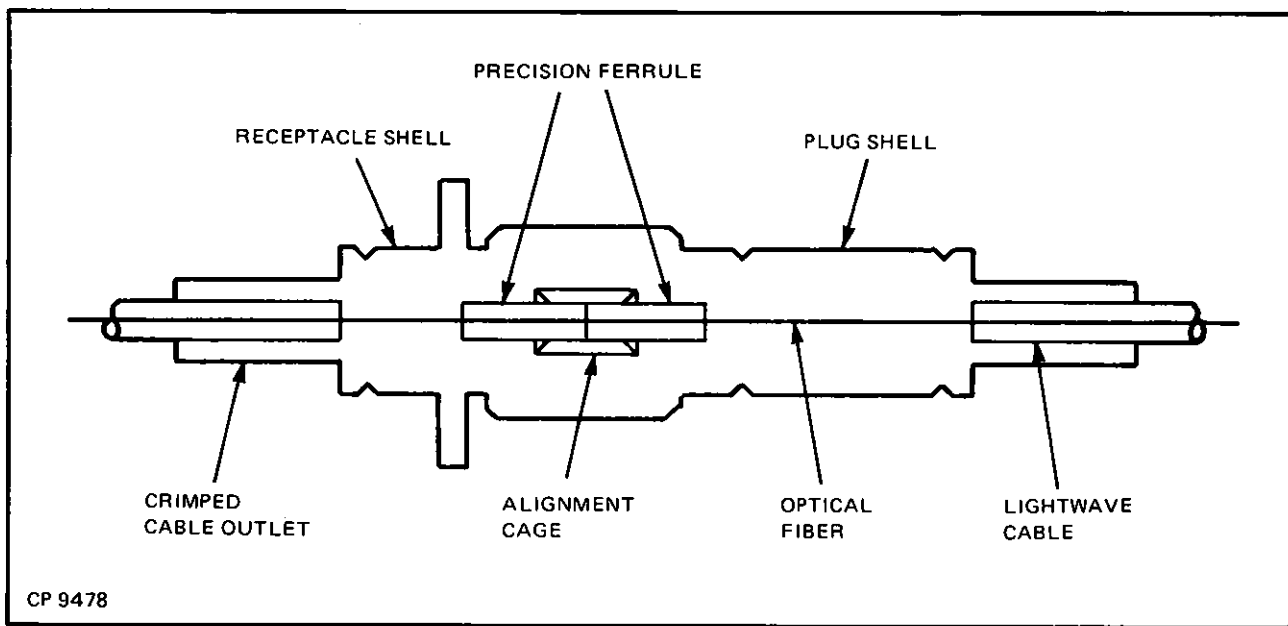


Figure 18. Cutaway View of Jewelled-Ferrule Type Single-Fiber Connector

splices (fig. 21) use three or more steel rods, pins, or cylinders to apply aligning forces to the joined ends of the fibers. With most of these techniques, epoxy is injected into the splice to cement the fibers in place and match the refractive index of each fiber to that of the other.

c. Fused Splices.

Lower light losses are achieved with fused splices than with mechanical splices. This is because the separation between the two fiber ends, which introduces reflective losses, is eliminated. In fusing fibers, the jacketing is stripped away and the two fiber ends are carefully aligned in a jig. Then the fiber ends are heated to a molten state. After the ends fuse, cool, and harden, a protective jacketing is installed around the splice.

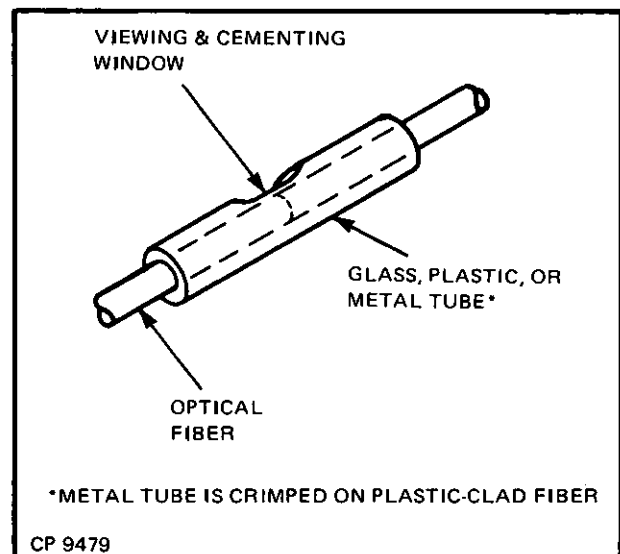


Figure 19. Typical Tube Splice

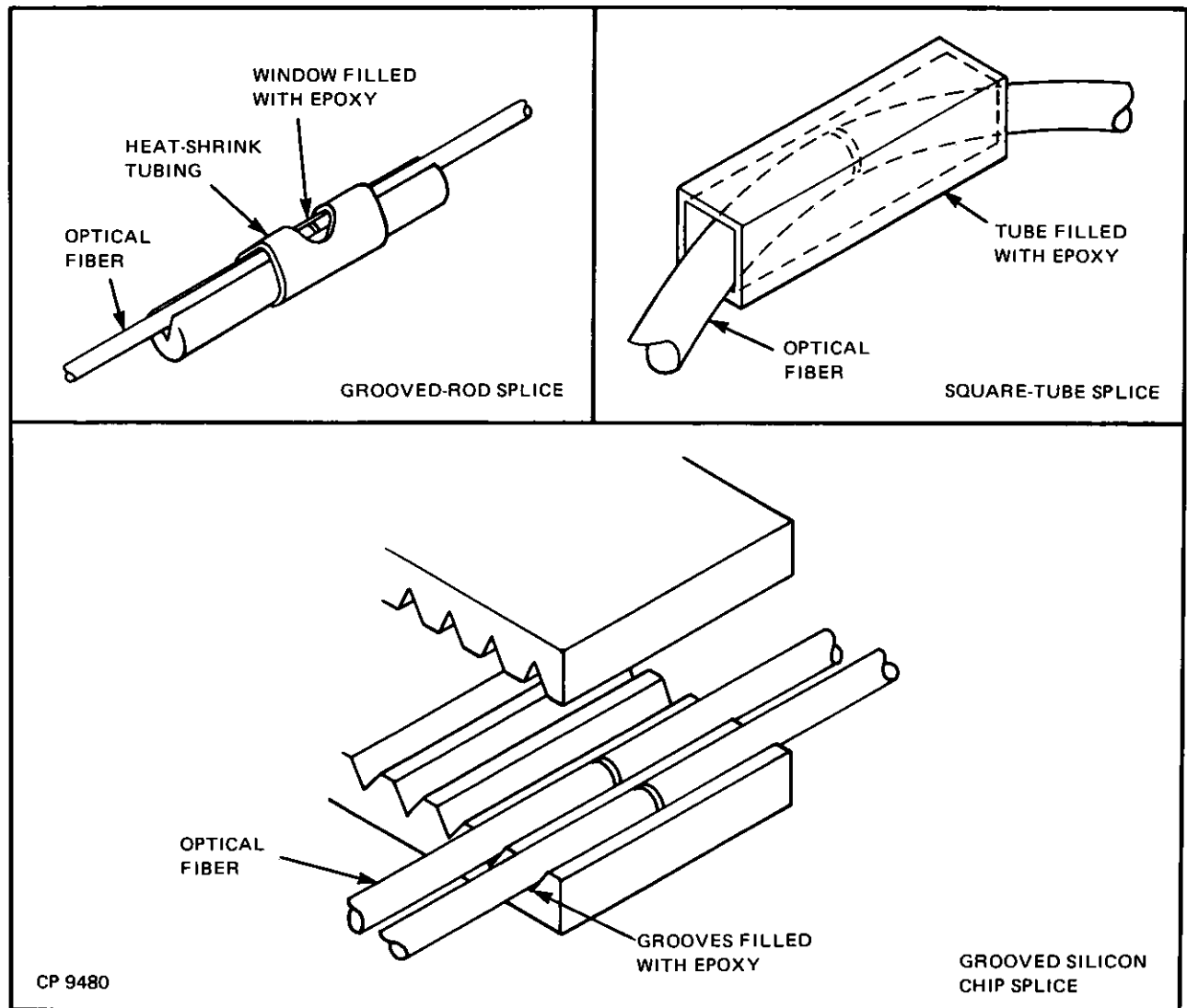


Figure 20. Variations of the Groove Splice

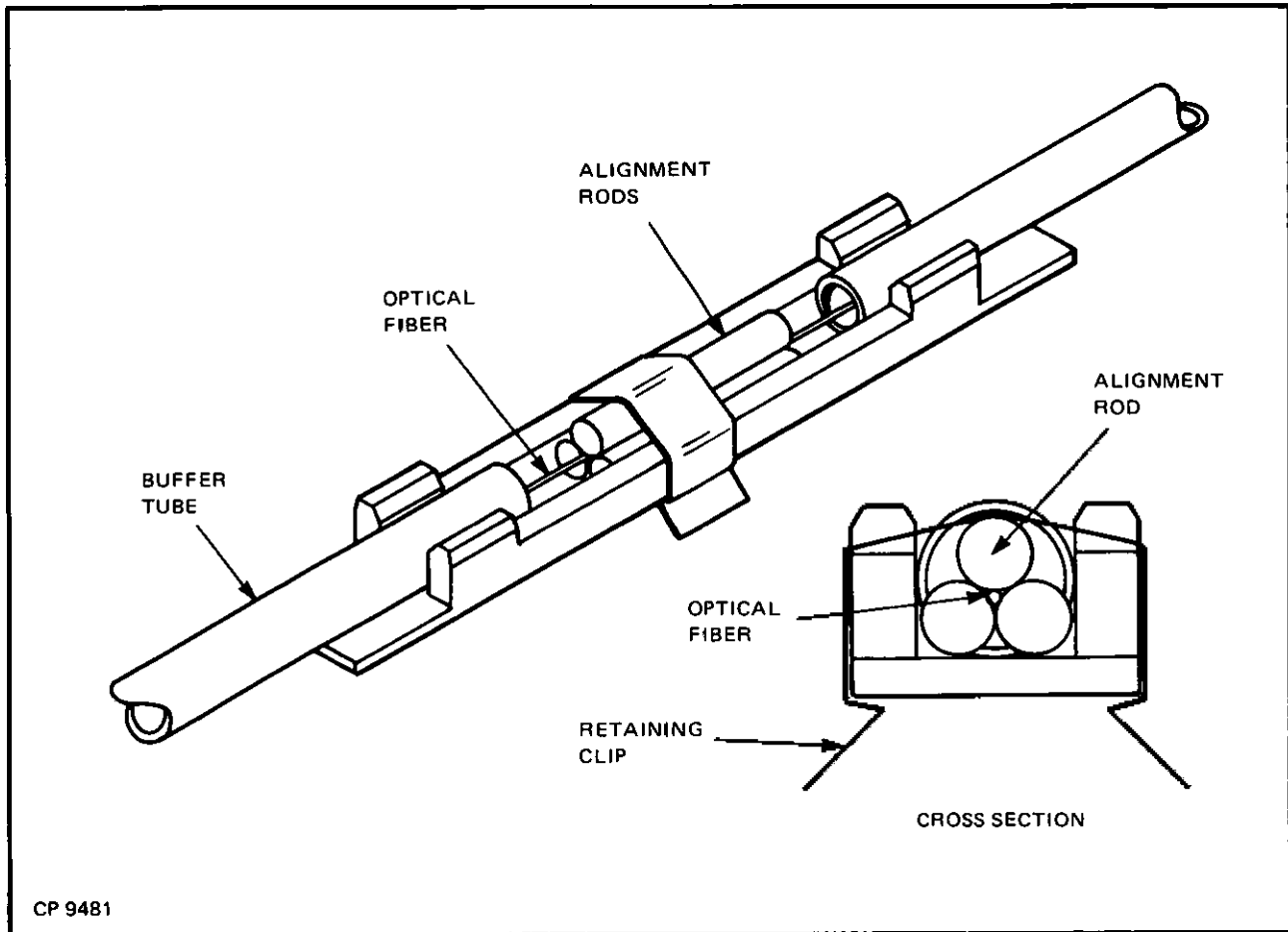


Figure 21. Example of Three-Rod Splicing Device

SECTION 45-001-01
Issue 1, November 1983
Appendix 1, November 1983

GLOSSARY OF LIGHTWAVE TERMS

ABSORPTION LOSS

Absorption and scattering of light in an optical fiber caused by traces of metallic elements and water in the glass of which the fiber is made.

ACCEPTANCE CONE

The cone defined by rotating the acceptance half-angle of an optical fiber about the center line of the fiber. Light entering the core outside the acceptance cone is lost into the cladding of the fiber.

ACCEPTANCE HALF-ANGLE

The maximum angle from the center line of an optical fiber, at which a ray of light entering the core of the fiber in a plane of the center line is propagated by total reflection off the core/cladding juncture. The acceptance half-angle is defined by:

$$\arcsin \sqrt{\frac{n_1^2 - n_2^2}{n_0^2}}$$

Where: n_0 = index of refraction of the medium from which the light enters the fiber.

n_1 = index of refraction of the core of the fiber.

n_2 = index of refraction of the cladding of the fiber.

BANDWIDTH

In lightwave systems, the number of bits of information per second that can be propagated by a unit length of optical fiber. The bandwidth of a fiber is limited by modal, material, and waveguide dispersion, which at maximum bandwidth cause the light pulses to spread and overlap so as to be no longer distinguishable.

BEND LOSS

Loss of light rays from the core into the cladding of a fiber that is bent beyond a critical radius of curvature. The rays that are lost are those that are just within the critical

A**ANGSTROM**

A unit of length, equal to 1×10^{-4} micron (3.9×10^{-9} inch), used to express wavelengths of light.

AREA LOSS

Loss of light rays (in dB) from the uncovered portion of the face of the core of an optical fiber that is joined to a smaller diameter core.

ATTENUATION

The loss in optical power (measured in decibels per kilometer) that results from absorption and scattering in an optical fiber.

AVALANCHE PHOTODIODE (APD)

A type of semiconductor light detector used in high-speed lightwave links, usually receiving light through a single-mode fiber from a laser diode source. The avalanche photodiode is named for the sudden chain-reaction flow of electrons that occurs across the barrier region of the diode after a very high reverse bias is applied.

AXIAL RAY

A ray of light that passes through an optical fiber on a parallel with the center line, without any internal reflection off the core/cladding juncture.

B

angle for total internal reflection in a straight section of the fiber.

BURRUS-DESIGN LED

A type of high-radiance light-emitting diode with a small, circular emitting surface recessed in a well etched into the substrate. The etched well eliminates substrate material that would otherwise absorb radiated light from the emitting surface. It also allows a lightwave pigtail to be installed close to the emitting surface to capture more of the radiated light.

CLADDING

The material that surrounds the core of an optical fiber. The cladding is usually of the same material as the core (glass or plastic), but of a slightly lower index of refraction so as to cause total internal reflection of light rays launched into the core. The cladding usually is covered by a protective coating called the jacketing.

COHERENT LIGHT

Light in which all waves are of the same frequency and in phase.

COLLIMATED BEAM

A beam of light in which the rays, or modes, are nearly or perfectly parallel.

CORE

The central portion of an optical fiber, through which light is propagated by total internal reflection off the core/cladding juncture. Total internal reflection of light occurs because the index of refraction of the core is higher than that of the cladding material that surrounds the core.

DARK CURRENT

A small amount of current generated spontaneously by a photodiode even though it is not detecting any light. Generation of dark current results from the inherent characteristics of the structure of the photodiode. Therefore, dark current is an unavoidable source of noise in an optical receiver.

DECIBLE (dB)

Unit used to express logarithmically the ratio between two values. It is used in lightwave systems to express the amount of optical power lost in a lightwave link. Some common loss values are:

- a. -5dB = 69% loss of power.
- b. -4dB = 60% loss of power.

C**COUPLING LENS**

A lens that focuses light from an optical source (such as a light-emitting diode) into an optical fiber or from one optical fiber into another (as in certain types of lightwave connectors).

COUPLING LOSS

Loss of optical power (expressed in dB) at points where the source or the detector is coupled to the fiber or where two fibers are coupled to each other. Coupling loss occurs from a combination of separation (gaps), lateral displacement, angular misalignment, or differences in refractive index between the coupled components.

CRITICAL ANGLE

The precise angle of incidence at or within which light rays striking the core/cladding juncture from inside the core of a fiber are reflected totally back into the core. Beyond the critical angle, light rays are partially or completely lost into the cladding.

D

- c. -3dB = 50% loss of power.
- d. -2dB = 37% loss of power.
- e. -1dB = 20% loss of power.
- f. -.5dB = 11% loss of power.
- g. -.2dB = 5% loss of power.
- h. 0dB = 0 loss of power.

DISPERSION

The spreading or broadening of a pulse of light as it traverses an optical fiber. Three different types of dispersion occur in optical fibers: material dispersion, modal dispersion, and waveguide dispersion.

E

F

FIBER OPTICS (FO)

Same as lightwave transmission.

FIBER OPTIC CABLE

Same as lightwave cable.

FLUX

In lightwave systems, rays of light energy radiated from an optical source.

FLUX BUDGET

The calculated amount of flux an optical source must generate to overcome the losses in the system and meet

the flux input requirements of the optical detector at the other end of the link.

FRESNEL REFLECTION LOSS

Loss of optical power in a lightwave link because of a juncture between the core of a fiber and another material of different refractive index (source, detector, air, fluid, or another coupled fiber). The loss occurs because some of the light is reflected from the juncture, back toward the source.

G

GRADED-INDEX FIBER

Optical fiber containing core material that gradually decreases in refractive index from the center out to the juncture between the core and the cladding. This grading of the index of refraction causes light rays launched at angles into the core to be refracted continually back toward the center of the core. Such light rays oscillate about the center of the core as they are propagated through the fiber. Thus, they follow a shorter distance and thereby produce less spreading of the pulse of which they are a part than in a step-index fiber.

H

HIGH-ORDER MODE

A mode or ray of light that is propagated through the core of a fiber by reflecting internally at angles close to the critical angle.

INDEX MATCHING FLUID

A transparent fluid or cement with an index of refraction nearly the same as those of two fiber cores that are being coupled to each other. Index matching fluid reduces the fresnel reflection loss that occurs at the juncture between the two fibers.

INDEX OF REFRACTION (N)

The ratio of the velocity of light in a given medium to the velocity of light in a vacuum (or in air, since the difference is negligible). For example, the index of refraction for the core glass of a certain optical fiber is derived as follows:

$$N_{\text{core glass}} = \frac{V_{\text{vacuum}}}{V_{\text{core glass}}} = \frac{186,000 \text{ mi/sec}}{128,275 \text{ mi/sec}} = 1.45$$

INDEX PROFILE

The distribution of the refractive indexes of an optical fiber across the diameter of the cross section. For a step-index fiber, the index profile shows a sharp vertical step representing the abrupt change in index between the clad-

I

ding and the core. For a graded-index fiber, the index profile resembles a parabolic curve as it increases from the cladding to the center of the core and then drops off again to the cladding.

INFRARED

The range of wavelengths of light from 740 nanometers to 1 millimeter, invisible to the unaided eye. The most common wavelengths of light used as the carrier in light-wave systems - 850 nanometers and 1300 nanometers - are in the infrared region.

INJECTION LASER DIODE (ILD)

A semiconductor light source used in high-speed light-wave links. Laser diodes are edge-emitting devices that produce coherent light. Therefore, they can be used with optical fibers of smaller numerical aperture and spectral width than can conventional light-emitting diodes. However, they are more costly and more temperature-sensitive and require higher bias voltage than conventional light-emitting diodes.

J

K

L

LAMBERTIAN EMITTER

A type of light source that emits light uniformly over the entire surface. It appears equally bright when viewed from any angle.

LASER

A device that emits intense coherent light as a nearly collimated beam. "Laser" is an acronym for "Light Amplification by Stimulated Emission of Radiation".

LIGHT DETECTOR

A device that detects pulses of light and generates corresponding digital electrical pulses. In lightwave systems, the two common light detectors are the PIN photodiode and the avalanche photodiode.

LIGHT-EMITTING DIODE (LED)

A semiconductor light source that produces incoherent light. The most common types used in lightwave systems are the conventional surface-emitting LED, the edge-emitting LED, and the Burrus-design high-radiance LED.

LIGHT GUIDE

An optical fiber, or a bundle of such fibers, used to transmit light from a source to a detector.

LIGHT LEAKAGE LOSS

Loss of light rays from the core of an optical fiber into the cladding because of imperfections at the juncture between the core and the cladding.

LIGHT SOURCE

In telecommunications, a device that is driven by a digital electrical signal to produce corresponding light pulses for transmission through an optical fiber to a light detector. The two common types of light source are the injection laser diode (ILD) and the light-emitting diode (LED).

LIGHTWAVE CABLE

One or more optical fibers assembled into a cable along with the necessary strength members, protective wrappings or armor, supplementary copper conductors, and sheathing to satisfy the requirements of a specific application.

LIGHTWAVE TRANSMISSION

Transmission of information via lightwave carrier propagated through light-guides made of glass or plastic. In telecommunications, the information is transmitted in digital form, each bit represented by a discrete pulse of light.

LOSS BUDGET

The total allowable signal loss (in dB) in a lightwave link. The total loss from coupling, splicing, and dispersion must be low enough to meet the input requirements of the final optical receiver in the link.

LOW-ORDER MODE

A mode or ray of light that is propagated through the core of a fiber by reflecting internally at shallow angles (nearly parallel with the centerline of the fiber).

M

MATERIAL DISPERSION

- a. Broadening of a pulse of light, as it is propagated through an optical fiber, because of the naturally dispersive nature of a transparent medium. Two factors are responsible for material dispersion. The first is that the refractive index of a transparent medium (such as the core of an optical fiber) varies as a function of the wavelength of the light passing through it. Mathematically, this is expressed by the following relationship:

$$N = \frac{V_{\text{vacuum}}}{(f_{\text{medium}}) \times (L_{\text{medium}})}$$

Where: N = index of refraction of the transparent medium

V_{vacuum} = velocity of light in a vacuum

f_{medium} = frequency of light in the medium

L_{medium} = wavelength of light in the medium

- b. The other factor is that common light sources generate pulses of light of multiple wavelengths, not just one. Together, these factors mean that different wavelengths of a pulse of light undergo different amounts of refraction as they are propagated through a fiber. Thus, for the same pulse, some wavelengths are propagated faster than others, resulting in broadening of the pulse as it is detected at the receiver end.

MERIDIONAL RAY

A ray that is propagated through a fiber by internal reflection and that remains in a single plane that includes the axis of the fiber.

MICROBENDS

Microscopic distortions of an optical fiber caused by deformations in the structure in which the fiber is supported, such as a cable. Microbends cause scattering of light rays that strike them, contributing to the total optical power loss of the fiber.

MICRON

A unit of length equal to 1×10^{-6} meter (4×10^{-5} inch); sometimes called a micrometer.

MINIMUM BEND RADIUS

The minimum radius around which an optical fiber can be bent without breaking.

MODAL DISPERSION

Broadening of a pulse of light, as it is propagated through an optical fiber, because of differences in the paths followed by the rays constituting the pulse. Rays of the pulse that enter the core at steep angles (high-order rays) are reflected at steep angles throughout the fiber, taking more time to reach the receiver end than those rays that enter on or near a parallel with the axis of the fiber (low-order rays). Thus, the total pulse is broader when it is detected than when it is generated.

NANOMETER

A unit of length equal to 1×10^{-9} meter (4×10^{-8} inch), or 1×10^{-3} micron.

NUMERICAL APERTURE (NA)

A numerical expression representing the light-accepting ability of an optical fiber. The numerical aperture is equivalent to the sine of the acceptance half-angle of the fiber, and is calculated by the formula:

$$NA = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

OPTICAL ALIGNMENT

Positioning of the ends of two optical fibers in a connector or a splice so that the angular and side-to-side alignment and the amount of longitudinal separation between them produces the least amount of optical power loss.

OPTICAL BREAK

A carefully produced break in an optical fiber such that the resulting fiber end is flat, smooth, and perpendicular to the axis of the fiber. The most effective means of producing such a break is to score the external surface of the fiber and then pull in both directions from the score until the fiber breaks.

MODE

One of the many discrete paths by which light flux can be propagated through an optical fiber, according to solutions of Maxwell's equations for the propagation of electromagnetic waves in a cylindrical waveguide. Inside a fiber, a mode can be considered to be the equivalent of a ray of light.

MULTIMODE FIBER

An optical fiber with a relatively large core diameter, able to propagate more than one mode of light from an optical source.

N

Where: NA = numerical aperture

n_0 = index of refraction of the medium (air, index-matching fluid, etc.) in which the fiber end is immersed

n_1 = index of refraction of the fiber core

n_2 = index of refraction of the fiber cladding

NUMERICAL APERTURE LOSS

Same as area loss.

O**OPTICAL DETECTOR**

A device that detects light pulses from an optical fiber and generates corresponding electrical signals. The two common optical detectors in lightwave systems are the PIN photodiode and the avalanche photodiode.

OPTICAL EMITTER

Same as a light source.

OPTICAL FIBER

A dielectric (plastic or glass) waveguide used to transmit information in the form of modulated light from an optical source to an optical detector. Commonly used optical fibers consist of a transparent core of a given index of

refraction, surrounded by a transparent cladding of a slightly lower index of refraction. The fiber usually is coated with a plastic jacketing and is assembled into a cable.

OPTICAL RECEIVER

A device that converts light input signals from an optical transmitter into electrical output signals.

OPTICAL REGENERATOR

A device that receives attenuated optical signals, converts them to electrical signals, amplifies and conditions the electrical signals to a specified level and grade, and then converts the renewed electrical signals back to light for transmission through the next leg of a lightwave link.

PHOTODETECTOR

A device that detects light and, in response, generates electrical signals. In lightwave systems, the commonly used photodetectors are the PIN photodiode and the avalanche photodiode.

PIGTAIL

A short piece of optical fiber attached to an optical source or to an optical detector. The other end of the pigtail can be fitted with a connector or prepared for splicing. Pigtails allow sources and detectors to be connected to lightwave transmission systems without danger of disturbing the optical alignment at the source or the detector.

PIN PHOTODIODE

- a. A type of light detector that consists of three sandwiched layers of semiconductor materials. One of the outer layers (the P region) is doped with impurities that produce a net deficiency of electrons in the layer; holes present where electrons normally would constitute the equivalent of positive charges. The other

OPTICAL REPEATER

Same as an optical regenerator.

OPTICAL SOURCE

Same as a light source.

OPTICAL TRANSMITTER

A device that converts electrical input signals into light output signals for transmission to an optical receiver.

OPTICAL WAVEGUIDE

Same as optical fiber.

P

outer layer (the N region) is doped with impurities that produce a net excess of electrons in the layer, acting as negative charges. The central layer (the I region) is an intrinsic layer, i.e., a material with no dopants added. It contains equal numbers of holes and electrons.

- b. Photons striking the PIN photodiode are absorbed into the intrinsic layer, where they cause electron/hole pairs to form. These electron/hole pairs modulate the flow of current between the P and N regions that results from the bias voltage. As the number of photons striking the photodiode increases, the amount of bias current allowed to flow to the output of the photodiode increases. If no light is detected by the photodiode, only a minimal amount of current (dark current) is output due to spontaneous generation within the diode.

PULSE SPREADING

Same as dispersion.

Q

QUANTUM

A general term for a packet of radiant energy, having no mass, no electrical charge, and no magnetic field.

QUANTUM EFFICIENCY

Efficiency of a photodetector at a given wavelength and temperature. Quantum efficiency is stated in terms of electrons generated per photon incident on the photodetector.

R**RADIANCE**

Measure of optical power output by a surface-emitting optical source. Radiance is stated in watts per solid angle (steradian) per square centimeter of emitting surface.

RADIATION PATTERN

A curve showing the intensity of radiation of a source per output angle.

RAY

A path followed by radiated light, normal, or perpendicular, to the wavefront of the radiated light.

RECEIVER

Same as optical receiver.

RECEIVER SENSITIVITY

Measure of the optical power (in dBm) required by an optical receiver to achieve a certain performance level.

REFLECTANCE LOSS

Same as fresnel reflectance loss.

REFRACTIVE INDEX (N)

Same as index of refraction.

REGENERATOR

Same as optical regenerator.

REPEATER

Same as optical regenerator.

RESPONSIVITY

Measure of the performance of an optical detector, stated as the amount of signal current produced per optical flux incident on the detector.

S**SCATTERING LOSS**

Loss in an optical fiber caused by such irregularities in the fiber as undissolved particles, roughness in the juncture between the core and the cladding, and microscopic differences in refractive index.

SINGLE-MODE FIBER

An optical fiber with the core so small as to permit only one mode of light to be propagated through the fiber. Because of the limited numerical aperture of a single-mode fiber, a laser diode is required as the optical source.

SKEW RAY

A ray of light that is propagated through an optical fiber by total internal reflection, but which never passes through the axis of the fiber.

SOURCE OPTICAL POWER

Total optical power (in milliwatts) emitted by an optical source.

STEP-INDEX FIBER

Optical fiber containing core material of uniform refractive index and of large enough diameter to propagate many modes of light. The transparent cladding material that surrounds the core is of slightly lower refractive index, so that light modes are propagated through the fiber by total internal reflection off the juncture between the core and the cladding.

T**TENSILE STRENGTH**

The amount of pulling force required to break an optical fiber. Flaws in or damage to the surface of an optical fiber can reduce greatly the tensile strength of the fiber.

TOTAL INTERNAL REFLECTION

Total reflection of light modes inside the core of an optical fiber because of the difference in the refractive indexes of the core and the cladding of the fiber. Only those

light modes that strike the core/cladding juncture within a critical angle are reflected repeatedly back into the core and thus propagated to the end of the fiber. All other modes are partially or completely lost into the cladding of the fiber.

TRANSMITTER

Same as optical transmitter.

U

V

W

WAVEGUIDE

A guide that conveys single or multiple modes of electromagnetic radiation from a source to a detector.

WAVELENGTH DIVISION MULTIPLEXING

A method of channel multiplexing in which each channel is assigned to a specific wavelength (color) of the light

that is transmitted by a lightwave system. Channels are demultiplexed by filter circuits, in the receivers, that pass only the wavelengths for the channels to which they are assigned.

X

Y

Z