1. General. Optical fibers are hair-thin strands of ultra-pure glass (or slightly larger strands of plastic), and are used for the transmission of signals. Unlike most signaling methods, optical fiber transmits light, rather than electricity.

Pulses or waves of light can be used in the same ways as pulses or waves of electricity and magnetism to transfer data from one place to another. Because of the transmission characteristics of light through optical fiber, it is in many ways superior to using electricity through conductors, offering less loss, less signal distortion, and allowing higher bandwidth transmission over longer distances than other media.

The current importance of optical fiber data transmission is difficult to overestimate. Not only has optical fiber become essential to long-distance telephone transmissions, but it is becoming increasingly important for all other forms of data transmission, such as CATV distribution, connecting cell phone towers, municipal traffic networks, security systems in buildings, airports, and the backbones of local area networks (LANs).

Use of optical fiber for the transmission of cable television signals is gaining quickly, and is in fact the standard distribution means for almost everything except the coaxial cable drops into businesses and residences, and, of course, interior wiring.

Computer networks are quickly exceeding the capacity of copper conductors, and are beginning to change over from copper to fiber. The newest computer networks are specifying optical fiber transmission, simply because the standards groups are uncertain that there will be a workable copper transmission method. [Desktop (horizontal) connections may transition from copper to wireless for mobility.]

THE ADVANTAGES OF FIBER OPTICS

A well-designed system of fiber optics as a communications medium offers four primary advantages over traditional electrical systems:

2. Performance. Optical fiber cables have a much greater bandwidth capacity than wire. This allows for high-volume, high-speed data transfer. Data transmission of optical fiber can easily reach speeds of hundreds of gigabits per second, far higher than copper communications cables.

NOTE: The terms “bits per second” and “hertz” can be confusing. One bit per second and one Hertz are rough equivalents, and are sometimes used interchangeably.
The term *Hertz* comes from the electrical and electronics industry. *Bit* comes from the digital computer industry. Because of this, electrical and electronic manufacturers, such as cable makers, will more often use *Hertz*, while computer industry people will use *bits per second*. When applied to the transmission characteristics of copper cables, *Hertz* is a fine term; but when discussion signals are transmitted from place to place, *bits per second* is better.

Because of the intricacies of computer technology, there is a slight technical difference between bits per second and Hertz; but again, the terms are so close to equivalent that there is little reason to “nit-pick” over interchangeable use.

3. **Electrical immunity.** Optical fiber cable is nonmetallic. Because of this, it can neither emit nor pick up electromagnetic interference (EMI) or radio frequency interference (RFI); both being problematic with metal wires. Cross talk between cables does not exist. Additionally, fiber optics (the term fiber optics has long been applied to the use of optical fiber in general) have no grounding or shorting problems. This is also an important feature when installing communications wiring in hazardous environments. Optical fiber cabling causes no sparking or excessive heat, even when broken.

4. **Small size and low weight.** Optical fiber cable weighs approximately one ninth the weight of coaxial cable and is also physically smaller. In order to carry 24 telephone conversations, telephone companies must use two pairs of copper wire. By using optical fiber cable rather than copper, one pair of cables can carry hundreds of thousands of conversations.

5. **Security.** Electronic bugging generally depends on electromagnetic monitoring. Because optical fibers carry light rather than electricity, they are immune to bugging. In order for bugs to be used on optical fiber cables, the cables must be physically tapped; this is easily detectable as the signal is diminished and error rates increase.

**APPLICATIONS**

Because of the advantages mentioned above, optical fiber is slowly becoming the standard method of data transfer. It is commonly found in the following applications:

- All long distance telephone lines
- All trans-oceanic telephone lines
- All Internet backbones, long-haul and trans-oceanic
- Local telephone lines
- Connections to cell phone towers
- Local Internet lines
- Cable television distribution
- Computer network backbones
- Computer network horizontal runs
- Closed-circuit television
- Electronic newsgathering
THE NATURE OF LIGHT

To understand the use of optical fibers, it is first necessary to understand the nature of light itself. Light is to optical fiber what electricity is to conductors.

Light is essentially a series of electromagnetic waves, with a few properties of particles added. When being described as a particle, light is often referred to as a stream of photons, moving from one place to another. A photon is considered to be very similar to an electron, and can be abstractly described as a primary particle of light, just as an electron may be described as a basic particle of electricity. As applied to optical fiber transmission, the particle characteristics of light are generally of lesser importance than the wave characteristics. Nonetheless, you should be aware of this dual nature (wave and particle) of light. A precise explanation of these characteristics would enter the realms of quantum physics, and is beyond the scope of this text.

The first characteristic of light that presents itself to us is color. Some light is red, some blue, some other colors. After years of research, it was discovered that each color of light has its own wavelength; or in other words, its own frequency (measured in cycles per second, or Hertz). For instance, waves of red light have a lower frequency than blue light, and green is in-between. Our eyes perceive different frequencies of light waves much like radios tune into different frequencies of radio waves. But rather than specifying light by its frequency, we signify the color by the wavelength of the light. So, a certain wavelength of light means a certain color of light. We measure wavelengths in nanometers (billionths of a meter). For example, a deep red light would have a wavelength of about 600 nm.

Wavelength and frequency really signify the same thing, and can be interchanged by using a mathematic formula. As wavelength decreases, the frequency increases. We specify wavelength for this work rather than frequency, since it is generally easier to use, and it is used in virtually all of scientific literature.

INVISIBLE LIGHT

Our eyes are perfectly tuned for the light of our sun. The sun puts out certain wavelengths of light, which our eyes pick up very well. There are, however, other wavelengths of light, and some of those are beyond our visual range. In other words, our eyes have limits, and beyond those limits we are blind. This is like a radio that can pick up the AM and FM bands, but not the shortwave bands. The shortwave signals are out there waiting, but your receiver cannot tune in to them.

You have no doubt heard of infrared light; it is the type of light that television remote control units use. These light waves are useful, but we cannot see them. It is this type of light that we use for optical signals.

It would be handy if we could use visible light in optical fibers, but it simply doesn’t work well. The characteristics of the glass used in optical fibers are such that they transmit certain wavelengths (colors) of light better than others. In particular, the wavelengths of 850 nm, 1300 nm, and 1550 nm are transmitted with a minimum of loss. These wavelengths are just outside of our visual spectrum, in the infrared range.
Some of the more common terms used to describe optical fiber are a “light tube” or a “conduit for light.” These terms have led a lot of people to think that there is some type of hole in the middle of an optical fiber. This is not the case.

None the less, optical fiber does function as a “tube” or “conduit” for light. Light does flow down the center of a fiber (the core) like water flows through a pipe. As you can see in Fig. 11.1, there are three concentric layers to an optical fiber.

1. Light pulses only through the glass core of the fiber.
2. The cladding (which is a different type of glass) serves as a barrier to keep the light within the core, functioning much like a mirrored surface.
3. The coating has nothing to do with light transmission, and is used only for mechanical strength and protection.

Light is kept to the core of the fiber, and flows though the core as water would flow through a tube. We could even say that the fiber is a “virtual” tube. The light stays in the center of the fiber, not because there is a physical opening there, but because the cladding glass reflects any escaping light back to the core.

These “light tubes” are very thin strands of ultra-pure glass. The dimensions of typical fibers are as follow:

- **Core**: 8–62.5 μm (a micron is one millionth of a meter)
- **Cladding**: 125 μm (outer diameter, so the cladding thickness over a 62.5 μm core would be \((125 - 62.5) \div 2 = 31.25 \mu m\))
- **Coating**: 250 μm (also the outer diameter)

The dimensions shown above are diameters. The core is one density of glass, the cladding is a second grade of glass, and the coating is an acrylate plastic.

6. **Cabling.** In order to suitably protect our glass fibers, we package them in cabling. It is a misconception that fiber cables are fragile.

   Actual fiber itself (not the cable, but only the thin fiber) is a concern; but this concern is more from twisting than from bending and pulling. Optical fiber is surprisingly flexible, and will not break easily like sheet glass. It actually has several times the sheering strength of steel; but, being so thin, it can be broken. Torsion is a concern. When optical fibers are both twisted and pulled, they tend to develop microcracks, which inhibit light transmission and distort the light signal.
Fiber cables, however, are not at all fragile. In fact they are often more durable than copper communication cables. Optical cables encase the glass fibers in several layers of protection, as is shown in Fig. 11.2.

The first protective layer is the coating that we mentioned earlier. The next layer of protection is a buffer layer. The buffer is typically extruded over the coating to further increase the strength of the single fibers. This buffer can be of either a loose tube or tight tube design. Most datacom cables are made using either one of these two constructions. A third type, the ribbon cable, is frequently used in the telecommunications work, and may be used for datacom applications in the future; it uses a modified type of tight buffering.

A tight tube, or tight buffer, is a layer of plastic extruded directly on to the bare fiber. This is nearly identical to the way plastic insulation is extruded over copper conductors to make insulated building wire; but this is obviously much thinner.

A loose tube is simply a paper or plastic tube—like a thin drinking straw—into which are inserted several optical fibers. Each of these fibers will have a very thin layer of plastic extruded over them, primarily for color-coding and to add a little bit of strength. If you think of threads inside of a drinking straw, you will have a reasonable understanding of how the loose tube protection scheme works. The tubes isolate the fibers from the outside world. They are free to move around inside of the tubes, which bear the external stresses.

After the buffer layer, the cable contains a strength member. Most commonly, the strength member is Kevlar fabric, the material that bulletproof vests are made from. The strength member not only protects the fiber, but also is used to carry the tensions of pulling the cable. (You can never ever pull the fibers themselves.)

After the strength member finally comes the outer jacket of the cable, which is typically some type of polyethylene or PVC. The exact type of nonmetallic jacketing will determine which suffix will apply to the cable designation, as covered in Sec. 40. In many cases, however, there will be additional stiffening members which also increase the cable’s strength and durability.

7. Fiber connectors. As the fiber optic field began to develop, one of the biggest mechanical problem that existed was permanently fixing the fibers at their ends. Since they have such as small diameter, they must be held rigidly in place and accurately aligned, in order to mate with other fibers, light sources, or light detectors. The first fiber connectors were difficult to install. They used a variety of glues, ovens, and long, difficult polishing methods.

Terminating fibers (termination involves installing a connector and polishing the face of the fiber) can now be done within half the previous time, and the process continues to improve.
8. Splices. While fiber connectors are used to make nonpermanent connections at the ends of fibers, splices are used to join ends of fiber to each other permanently. There are two primary ways this is done: by fusion, that is, by melting the pieces of glass together; and by mechanical means. The critical factors in splicing are the following:

1. That the fiber joint passes light without loss.
2. That the joint is mechanically secure; that is, that it will not be easily broken.

9. Testing. When installing a fiber system (the whole system of optical fibers is often called a cable plant, an old telephone industry term), it must be tested, to ensure that it will properly perform. The purpose of testing is to make sure that light will pass through the system properly. The main types of optical testing used in the field are the following:

- **Continuity testing.** This is a simple visible light test. Its purpose is to make sure that the fibers in your cables are continuous; that is, that they are not broken. This is done with a modified type of flashlight device and the naked eye, and takes only a few minutes to perform.

- **Power testing.** This is to accurately measure the quality of optical fiber links. A calibrated light source puts infrared light into one end of the fiber, and a calibrated meter measures the light arriving at the other end of the fiber. The loss of light in the fiber is measured in decibels.

- **OTDR testing.** The OTDR is a piece of equipment properly called an optical time domain reflectometer. This device uses light backscattering to analyze fibers. In essence, the OTDR takes a snapshot of the fiber’s optical characteristics. It sends a high powered pulses into the fiber and measures the light scattered back toward the instrument. The OTDR can be used to locate fiber breaks, splices and connectors, as well as to measure loss. However, the OTDR method of loss measurement may not give the same value for loss as a source and power meter, due to the different methods of measuring loss. In addition, the OTDR gives a graphic display of the status of the fiber being tested. Another advantage is that it requires access to only one end of the fiber.

As useful as the OTDR is, however, it is not necessary in the majority of situations. A power meter and source are used to test the loss of fiber optic cable, simulating the way the fibers are used, and measuring the light lost from one end of the cable to the other. In addition, OTDRs are quite expensive. Even when they are necessary, many installers prefer to rent them, rather than to purchase them.

10. Basic optical terminology

- **Attenuation.** Attenuation is the weakening of an optical signal as it passes through a fiber. Attenuation is signal loss. Attenuation in an optical fiber is a result of two factors, absorption and scattering. Absorption is caused by the absorption of the light and its conversion to heat by molecules in the glass. Primary absorbers are residual deposits of chemicals that are used in the manufacturing process to modify the characteristics of the glass. This absorption occurs at definite wavelengths (the wavelength of light signifies its color and its place in the electromagnetic spectrum). This absorption is determined by the elements in the glass, and is most pronounced at the wavelengths around 1000 nm (nanometers), 1400 nm, and above 1600 nm. Scattering occurs when light collides with individual atoms in the glass, and is knocked off its original course. This is the primary cause of attenuation.
Fiber optic systems transmit in the “windows” created between the absorption bands at 850 nm, 1300 nm, and 1550 nm wavelengths, for which lasers and detectors can be easily made.

**Networks.** To communicate between several pieces of equipment (for example, between 20 different computers in an office), they must all be connected together. To do this, we must do two things:

1. Develop a logical method of connecting them. Should we tie them all to a central point? Should we connect them in a loop? Or just a direct link?
2. Provide a definite protocol for communicating. If the machines do not “talk to each other” in some type of order, the whole system will collapse in a jumble of signals that the machines can neither separate nor interpret.

There have been many types of networks developed, each with their own strengths and weaknesses. The many network names you have probably heard, such as Ethernet, 10base T, FDDI, ATM, and Token Ring are simply different methods of connecting computers together.

**Bandwidth.** Bandwidth is the range of signal frequencies or bit rate at which a fiber system can operate. In essence, it is a measure of the amount of signal that can be put through a fiber. Higher bandwidth means more data per second; lower bandwidth means less signal.

**Dispersion.** There are two especially confusing terms that you will come across in optical fiber literature. They are *chromatic dispersion* and *modal dispersion*. In both of these terms, *dispersion* refers to the spreading of light pulses until they overlap one another, and the data signal is distorted and lost. *Chromatic* refers to color, and *modal* primarily refers to the light’s path. Thus we can state in simple terms that:

\[
\text{Chromatic dispersion} = \text{Signal distortion due to color} \\
\text{Modal dispersion} = \text{Signal distortion due to path}
\]

Note that dispersion is not a *loss* of light; it is a *distortion* of the signal. Thus, dispersion and attenuation are two different and unrelated problems: Attenuation is a loss of light; dispersion is a distortion of the light signals.

---

11. **Total internal reflection.** Optical fibers function well for signal transmission because of the principle of *total internal reflection*.

When light goes from one material to another of a different density (in scientific terms, this difference in density is called *index of refraction*), the light’s path will bend. This is what causes the illusion of a stick bending when it is stuck into water. When the light bends at a certain angle (and this angle is different for different types and densities of materials), all of it is reflected, and none passes through the boundary between the two materials.

This phenomenon is used to bend the light at the core/cladding boundary of the fiber, and trap the light in the core. By choosing the material differences between the core and cladding, one can select the angle of light at which total internal reflection occurs.

This angle defines a primary fiber specification, the *numerical aperture* of a fiber, which is also abbreviated as NA.

12. **Numerical aperture.** The numerical aperture (NA) designates the angle called *the angle of acceptance*—the angle beyond which the light rays injected into an optical fiber are no longer guided, and will pass through the core/clad boundary and be lost.
Fibers with higher NAs will accept a wider range of light paths (the technical term for paths is modes). Because there are so many modes, the signal will be distorted. So, a fiber with a higher NA will cause increased signal distortion, and will be able to carry less signal. We may then say that high-NA fibers have less bandwidth, and that low-NA fibers have greater bandwidth.

13. Index of refraction. The index of refraction of a material is the ratio of the speed of light in vacuum to that in the material. In other words, the index of refraction is a measure of how much light slows down after it enters the material. Since light has its highest speed in a vacuum (approximately 300,000 kilometers per second), and since light slows down whenever it enters any medium, (water, plastic, glass, crystal, oil, etc.), the index of refraction of any material is greater than one.

For example, the index of refraction in a vacuum is 1, that of glass and plastic optical fibers is around 1.5, and water has an index of refraction of around 1.3. You can see from this that the light signals sent through an optical fiber travel at considerably less than the “speed of light” as most people think of it. The much-stated speed of light (again, 300,000 kilometers per second) is the speed of light in a vacuum—not the speed of light in all materials.

14. Pulse spreading (dispersion). We have previously discussed signal distortion, saying that it comes from two primary causes—the colors of light sent through the fiber (chromatic dispersion), and the paths that light takes as it moves through the fiber (modal dispersion). Both of these reasons for distortion have the same final effect—to distort the signal by pulse spreading.

Pulse spreading is illustrated in Fig. 11.3. Notice that the digital signal sent into the fiber is square. As the signal travels down the fiber, it is distorted, and begins to spread.

Pulse spreading is not a loss of light—just as much light is leaving the fiber as entered it. The light signals, however, are distorted. If the pulses spread too much, they will be unintelligible to the receiver, and the communication will be ineffective.

One at a time, we will now explain why both color and path cause this pulse spreading.

15. Chromatic dispersion. Chromatic dispersion (pulse spreading due to the colors of light sent through the fiber), occurs because of one fact: Different colors of light (which we also call different wavelengths of light) travel at different speeds in an optical fiber.
For example, if two different wavelengths (colors) of light are sent into a long fiber at the same time, one of them will reach the far end before the other will—they will not reach the end at the same time.

You can see from this example that the time difference between the two different wavelengths arriving at the end of the long fiber would tend to spread a data pulse. This causes the pulse spreading that is shown in Fig. 11.3.

Because of chromatic dispersion, it is important to use light sources that put out a very narrow range of colors. Unfortunately, a technology of building affordable, single-color light sources has not yet been developed. Our current light sources put out a range of wavelengths (colors), not a single wavelength.

The newer lasers are the best of our light sources, and put out a reasonably small range of wavelengths. Even though these lasers are more expensive than light emitting diode (LED) light sources, they are often used because they cause far less chromatic dispersion. The LED sources are used only for shorter runs where higher chromatic dispersion is manageable.

Good laser sources are said to have a narrow spectral bandwidth, putting out light within a 1 nm range. So, the light output from a 1550 nm laser will be within a range of 1549.5 and 1550.5 nm.

LED sources, on the other hand, are said to have a broad spectral bandwidth. Many LEDs have a spectral bandwidth of 20 nm. So, the light output from an 850 nm LED would be between 840 and 860 nm.

16. Modal dispersion. (A factor in multimode fiber only.) Modal dispersion (pulse spreading due to the paths of light sent through the fiber), occurs because some paths through a fiber are more direct than others. Look at Fig. 11.4, and you will see this illustrated.

In Fig. 11.4, one of the light rays go right down the middle of the fiber, another enters the fiber at a rather severe angle, and must bounce from side to side, all the way through the fiber.

You can see how the light ray that goes down the middle of the fiber has a significantly shorter path, and will reach the far end considerably sooner than the other ray of light will. Notice how different paths of light traveling through a fiber will reach the end at different times, and will cause a data pulse to spread.

Modal dispersion has been a major factor in determining the design of optical networks, and even in the design of fibers themselves.

17. Types of optical fibers. The three main types of optical fibers that are commonly used today are the following:

Single-mode fibers. A single-mode fiber allows only one light wave ray to be transmitted down the core. The core is extremely small, usually between 8 and 9 μm. Because of quantum mechanical effects, the light traveling in the very narrow core stays together in packets, rather than bouncing around the core of the fiber.
This tendency of the light in a narrow core to travel in packets is not because the core is small enough to allow only one photon at a time to pass through. Photons are many orders of magnitude smaller than the core. Rather, this effect is due to a relationship between the wavelength of the light and the core size. As stated above, this is a quantum mechanical effect, and a detailed explanation is beyond our scope in this text.

Thus single-mode fiber has an advantage over all other types in that it can handle far more signal, and over far greater distances.

**Multimode, graded-index fibers.** Graded-index fibers contain many layers of glass, each with a lower index of refraction as it moves outward from the center. Since light travels faster in the glass with lower indexes of refraction, the light waves refracted to the outside of the fiber are speeded up to match those traveling in the center. The result that this type of fiber allows for high speed data to be transmitted over a reasonably long distance. Multimode fibers are used with LED light sources, which are less expensive than the laser light sources which are used for single-mode. Graded index fibers come in core diameters of 50, 62.5, 85, and 100 μm. For a long time, 62.5 μm was the standard size, although 50 μm fiber is now being specified for Gigabit Ethernet networks.

**Multimode, step-index fibers.** Step-index fibers are used far less than the other types, having a far lower capacity. They have a relatively wide core, like multimode, graded-index fibers, but since they are not graded, the light put through them bounces wildly through the fiber, and exhibits high levels of modal dispersion (signal distortion due to path).

All three types of fiber are shown in Fig. 11.5.

![Multimode Step Index](image1)

![Multimode Graded Index](image2)

![Singlemode](image3)

**FIGURE 11.5** Multimode step-index fibers.

**18. Fiber sizing.** The size of an optical fiber is referred to by the outer diameter of its core and cladding. For example, a size given as 62.5/125 indicates a fiber which has a core of 62.5 μm and a cladding of 125 μm. The coating is not typically mentioned in the size, because it has no effect on the light-carrying characteristics of the fiber.
The core is the part of the fiber that actually carries the light pulses that are used for transferring data. This core may be made of either plastic or glass. The size of the core is important, as core sizes of joined fibers must match. Larger cores have greater total light-carrying capacity than smaller cores, but have less signal-carrying capacity than the smaller cores because they lead to far greater signal distortion. We may say that more photons can travel through a larger core, but they are not effective for transferring signals.

The cladding sets a boundary around the fiber so that light running into this boundary is reflected back into the cable. This keeps the light moving down the cable, keeping it from escaping. Claddings can be made of either glass or plastic, and always have a different density than that of the core. (If they did not have a different density [index of refraction], they could not reflect escaping light back into the core.)

As an example of this, imagine that you are standing next to a calm mountain lake. As you look across the lake, you can see a reflection of the mountains and trees on the far side. The lake works as a large mirror. As you move your eyes closer, eventually the reflection stops, and you can see through the surface of the water. Just in front of your feet, you can see fish swimming in the water. In this example, the water’s surface acts like the cladding of an optical fiber, with the air acting as the core. When the light reaching your eyes is of a shallow enough angle, the surface of the lake reflects all of it. But when the angle between your eyes and the water’s surface becomes too steep, the light passes through the surface, and is not reflected.

Coatings are typically multiple layers of ultraviolet curable acrylate plastic. This is necessary to add strength to the fiber, to protect it, and to absorb shock. These coatings are between 25 and 100 μm thick. (One micron is equal to one millionth of a meter. For comparison purposes, a sheet of paper has a thickness of approximately 25 μm.) Coatings can be stripped from the fiber (and must be for terminating) either mechanically or chemically, depending on what type of plastic is used.

19. Manufacturing fiber. Manufacturing optical fiber is a very difficult and complex process. In general, the process entails three parts:

1. The manufacture of a preform, which is a cylinder of glass that the optical fiber will be made from. They are generally about three feet long and an inch wide. The preform has a physical make up identical to the final fiber, including both core and cladding, except that it is much wider and shorter.

2. Pulling the fiber. The preform is heated very precisely, and a thin strand of glass is pulled off of one end. The diameter of this strand is controlled very carefully through variances in heating and pulling tension. This strand is the optical fiber, containing both the core and cladding.

3. Cooling, coating, winding. Once the fiber is pulled off the preform, it must be carefully and slowly cooled, covered with the final coating, and wound on to reels.

There are three methods currently used to fabricate moderate to low loss waveguide fibers: modified chemical vapor deposition (MCVD), outside vapor deposition (OVD), and vapor axial deposition (VAD).

Modified chemical vapor deposition. MCVD begins with a hollow glass preform, approximately 3 ft long and 1 in. in diameter, and is placed in a horizontal or vertical lathe and spun rapidly. A computer-controlled mixture of gases is passed through the inside of the tube. On the outside of the tube, a heat source (oxygen/hydrogen torch) passes up and down.
Each pass of the heat source fuses a small amount of the precipitated gas mixture to the surface of the tube. Most of the gas is vaporized silicon dioxide (glass), but there are carefully controlled remounts of impurities (dopants) which cause changes in the index of refraction of the glass. As the torch moves and the preform spins, a layer of glass is formed inside the hollow preform. The dopant (mixture of gases) can be changed for each layer so that the index may be varied across the diameter.

After sufficient layers are built up, the tube is collapsed into a solid glass rod, which is the preform. It is now a scale model of the desired fiber, but much shorter and thicker.

The preform is then taken to the drawing tower, where it is pulled into a length of fiber up to 10 kilometers long.

**Outside vapor deposition.** This method utilizes a glass target rod which is placed in a chamber and spun rapidly on a lathe. A computer-controlled mixture of gases is then passed between the target rod and the heat source. On each pass of the heat source, a small amount of the gas reacts and fuses to the outer surface of the rod, resulting in what is referred to as “soot” on the preform, although it is certainly nothing like creosote and charcoal on the inside of a chimney. After enough layers are built up, the target rod is removed and the remaining soot preform is collapsed into a solid rod. The preform is then taken to the tower and pulled into fiber.

**Vapor axial deposition.** This process utilizes a very short glass target rod which is suspended by one end. A computer-controlled mixture of gases is applied between the end of the rod and the heat source. The heat source is slowly backed off as the preform lengthens due to the soot build-up caused by gases reacting to the heat and fusing to the end of the rod. After sufficient length is formed, the target rod is removed from the end, leaving the soot preform.

The preform is then taken to the drawing tower to be heated and pulled into the required fiber length.

**20. Fiber coatings.** After the fiber is pulled, a protective coating is applied very quickly after the formation of the hair-thin fiber. The coating is necessary to provide mechanical protection and prevent the ingress of water into any fiber surface cracks. The coating typically is made up of two parts: a soft inner coating, and a harder outer coating. The overall coating thickness varies between 62.5 and 187.5 μm, depending on fiber applications.

These coatings are typically strippable by mechanical means, and must be removed before fibers can be spliced or fitted with connectors.

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Core/cladding diameter (m)</th>
<th>Attenuation (dB-km)</th>
<th>Bandwidth (MHz-km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>850 nm</td>
<td>1300 nm</td>
</tr>
<tr>
<td>Step index</td>
<td>200/240</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Multimode</td>
<td>50/125</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Graded index</td>
<td>62.5/125</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>85/125</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>100/140</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Single-mode</td>
<td>8–9/125</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Plastic 1 mm</td>
<td>(1 dB/m 665 nm)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
21. A brief history of optical fiber.  The idea of the optical fiber dates back to the nineteenth century in England, where a man named Tyndall developed a “light fountain” based on the phenomenon of internal reflection.

In 1881 William Wheeler, a Concord, Massachusetts engineer, applied for a patent that illustrates the transport of light by means of a light conductor. This patent describes an indoor lighting system intended to substitute for the incandescent bulbs which Edison had just invented. The system uses light emitted by a powerful electrical arc that is distributed to each of the rooms in a building by means of optical conductors.

In 1934, AT&T engineer Norman R. French devised the first optical transmission system, followed by RCA’s Kell and Sziklai. The RCA patent described today’s photonic transmission systems in some detail.

The principle of an optical fiber was described in 1957, first in England by Hopkins and Kapany, who described the first fibroscope in a paper published in the journal *Nature*, then in the United States by American Optical Corp.’s R&D Manager, Brian O’Brien, who patented a bundle of optical fibers used for image transport.

The invention of the laser revived the researchers interest in optical communications and Charles K. Kao and George Hockham, of STL (Standard Telecommunications Laboratories), were the first to demonstrate that long distance transmissions via optical fibers were possible.

In 1970, three Corning Glass Works researchers, R. Maurer, D. Keck, and P. Schultz, made practical long distance transmission possible by producing an optical fiber with 20 dB/km attenuation.

The key dates in the history of optical fiber signal transmission are the following:

1880 A. G. Bell’s Photophone
1881 W. Wheeler’s patent for a light conducting guide
1934 N. R. French’s patent for a partly optical transmission system
1950 R. D. Kell & G. C. Sziklai’s patent for an optical transmission system
1957 B. O’Brien’s patent for a fiber bundle
1957 Articles in the journal *Nature* on fiber bundles and a fibroscope
1961 Invention of the laser
1966 C. Kao & G. A. Hockham: long distance optical transmissions

22. Data transmission.  Optical data transmission (the method of sending data through optical fiber cables) is illustrated in Fig. 11.6. This drawing shows a telephone conversation traveling over optical fiber cabling. The voice is first transformed by the telephone into an electrical signal. This signal is then scanned by a digital encoder, which reduces the signal into binary code (a series of offs and ons). The driver, which activates
the LED or laser light source, transmits the on as bursts of light and the off as the absence of a light pulse. The light travels through the optical fiber cable until it is received at its destination, amplified, and fed into a digital decoder. The decoder translates the digital signal back into the original electrical signal. And finally, the telephone changes the electrical signal back into sound.

Transmitters and decoders are the devices which change electricity into light pulses, and change light pulses back into electrical pulses.

23. Simplex and duplex transmission. Optical transmissions are called simplex, half-duplex, or full-duplex based on their method of transmission. Both simplex and half-duplex systems use only one fiber to communicate, and are less expensive to build.

The simplex method transmits in only one direction, while the half-duplex system can send signals in both directions, but not both directions at the same time. Half-duplex is similar to a two-way radio in its operation. The terminal electronics must act as both a receiver and transmitter and are, appropriately, called transceivers.

The full-duplex system, on the other hand, uses two fibers to communicate. This way one fiber is always available to transmit from point A to point B while the other fiber is transmitting from B to A. Therefore, both ends of a full-duplex system have both transmitters and receivers. Because of this, you must be careful not to mix them up during installation by reversing the transmit and receive fibers. Sometimes the fibers are color coded, or they may have some other identifying feature such as a ridge marking one fiber on duplex cables. In any case, be careful to not reverse the two fibers when installing connectors on the ends.

24. Units of measurements. The magnitudes involved in transmission through optical fibers lead to submultiples and multiples of units to be widely used: decibel, micrometer, megabit, and so on.

Generally, all dimensions of an optical fiber are expressed in micrometers (μm), which is one millionth of a meter. Of course, millimeter (mm) is used for large diameter fibers.

The wavelengths of light are also expressed in micrometers, or nanometers (nm), which are billionths of a meter.

Transmission parameters such as rates (bit/s) or bandwidth (Hz-km) are expressed in multiples such as kilo, mega, or giga. And the terabit (trillions of bits per second) may soon be the reference for transmission rates in telecommunication networks.

Energy losses and attenuations are only expressed in decibel.

25. Frequency and wavelength. Wavelength (an inverse function of frequency) is just one way of describing the speed of vibration of these photons emitted from a light source. The speed of any wave phenomenon is always the wavelength (λ) multiplied by the frequency (f). Light as a form of electromagnetic radiation has a speed (usually stated as “c”) of $3.0 \times 10^8$ m/sec in a vacuum, very nearly that speed in air and perhaps $\frac{1}{3}$ less in a glass fiber. Thus, for light $c = \lambda f$. For example, $10,000,000,000,000$ Hz ($10^15$ Hz) would correspond to a wavelength of about $3.0 \times 10^{-6}$ m or 30 nanometers (nm) in air, which is in the ultraviolet range. Our eyes recognize wavelengths from about 390 nm to 770 nm as different colors running from violet to red. There are thousands of other wavelengths we do not see. Our eyes and brains are not tuned to receive them.

Different frequencies of light have different characteristics of loss (attenuation) through glass. Because of these loss characteristics, engineers have chosen 850, 1310, and 1550 nm as the first, second, and third windows of fiber transmission. Since we can’t see these three wavelengths, we can’t tell, with the naked eye, if their transmitters are operating.
26. Decibel-watt conversion. In optics, all energy and power levels, and all losses or attenuations, are expressed in decibels rather than in Watts. The reason is simple: all transmission calculations and measurements on a fiber are almost always made as comparisons against a reference: received power compared to emitted power, energy in versus energy out (energy lost in a connection), and so on.

Generally, energy levels (emission, reception, etc.) are expressed in dBm. This signifies that the reference level of 0 dBm corresponds to 1 milliwatt (mW) of power.

Generally, power losses or gains (attenuation in a fiber, loss in a connector, etc.) are expressed in dBm.

The unit dBm is used for very low levels, in the microwatt level.

A decibel is simply one tenth of a Bel (the name given in honor of Alexander Graham Bell), which is a difference of an order of magnitude (10 times) in the intensity of any event. That number is inconveniently large, so we use decibels instead. It is important to bear in mind that this is a logarithmic relationship. One half of a Bel increase is not half again the original number (1.5 ×); it is 10^{0.5} times the original number or about 3.2 ×. Using decibels, a half Bel increase is a 5 dB increase, thus a positive 5 dB change reflects a multiplier of 3.2. Because the logarithm of 2 (using base 10) is about 0.3, decibel measurement works as follows: a difference of 3 dB equals a doubling or halving of power.

A 3 dB gain in power means that the optical power has been doubled. A 6 dB (3 + 3) gain means that the power has been doubled, and then squared, equaling four times the original power. A 9 dB gain (3 + 3 + 3 dB) is an eightfold (the original doubling cubed) increase in power, and a 12 dB [(3 + 3) + (3 + 3)] gain is about 16 times the original power level. This is the original squared result squared again, or restated as the original doubling raised to the fourth power of the original power level. The resulting number makes sense when you consider that 10 dB = 1.0 Bel, defined in terms of a tenfold change. A 3 dB loss of power means that the power has been cut in half. A 6 dB loss means that the power has been cut in half, then cut in half again, equaling one-fourth of the original power. If you have a scientific calculator (or the one built into most computer operating systems) simply hit the inversion (usually “INV”) key (or set the check box), type in the increase or decrease in Bels (dB × 0.1) and hit the “log” button, and the result will be the multiplying factor from the original power level.

A loss of 3 dB in optical power is equivalent to a 50% loss. For example, 1 milliwatt of power in, and 0.5 milliwatt of power out.

A 6 dB loss would equally a 75% loss. (1 milliwatt in, 0.25 milliwatt out.)

27. Active and passive components. The two primary classifications of optical components are active components and passive components. Active components are elements in an optical transmission line that somehow convert electrical energy into optical energy or optical energy to electrical energy. Typical active components include light sources (light emitting diodes, laser diodes) and detectors (photodiodes, phototransistors.). Optical components whose operation also requires electrical energy, such as active couplers or optical amplifiers, also belong to this category.

Passive components are elements whose function in an optical link is not to convert electricity into light and vice versa. Passive components would include all the components used in a link, except the active components (optical emitters, receivers, and amplifiers), such as connectors, splices, terminal blocks, couplers, and the like. Mechanical elements such as the protective casings of joints or cable heads are also classified as passive components.

28. Materials used for active components. Silicon, germanium, gallium arsenide, indium phosphide are semiconductor materials used in active optical components.
Silicon and germanium are used for photodiodes only. Gallium arsenide and gallium aluminum arsenide are reserved for emitters. InGaAs and InGaAsP (indium gallium arsenide and indium gallium arsenide phosphide) are general purpose materials with very good emission and reception characteristics.

The abbreviations we use for these materials are the following:

Silicon Si
Germanium Ge
Gallium Ga
Aluminum Al
Arsenide As
Indium In
Phosphide P

29. LED light sources. LEDs are the most widespread emitters. Their operating principle is simple: a voltage is applied to a semiconductor made of two electrically opposed regions, generating a current flow through the diode. The P region (the positively biased semiconductor region) is doped so that it lacks electrons with respect to the basic material, thus creating what are called “holes”—places where electrons are missing. The N region (the negatively biased semiconductor region) is inversely doped, thus creating free electrons. When a voltage is applied to the diode, the electrons and the holes move toward the junction between the two regions where they combine by emitting photons, the essential particles of light.

30. Types of LEDs. There are three types of LEDs that are commonly used for optical fiber work. The first two are the surface emission diodes and transverse emission diodes. The fundamental difference between these two types of diodes lies in the emission surface, which is much smaller in transverse emission diodes. The photons generated by current flowing between the two P and N regions are confined in the junction, which has a very small thickness. Therefore, light is emitted on one side of the diode.

The third LED type is the Burrus diode (after the name of Charles A. Burrus, of AT&T Bell Laboratories), in which an optical fiber gathers the emitted light. Therefore, the characteristics of this diode are directivity and a high coupling rate.

Following are several commonly used LEDs:

- GaAs, GaAlAs LEDs: 820–850 nm transmission systems on multimode fibers
- GaAsP LED: plastic optical fibers, visible infrared (665 nm)
- InGaAsP LED: 1330 nm transmission systems on multimode fibers

31. Semiconductor lasers. Semiconductor lasers provide a higher power and a better directivity than LEDs. These characteristics are inherent to their different design although they use the same principle of photon emission by electron excitation. When an electron moves from one energy level to a lower level, it emits a photon. This is called “spontaneous emission,” and can be controlled and triggered by a photon hitting the electron, which then emits a photon with the same wavelength as the first one. This
Light Amplification by Stimulated Emission of Radiation, which is the Laser effect. Vertical-cavity, surface-emitting lasers (VCSELs) are used a great deal in optical fiber systems.

The Laser effect (defined as an “emission of a strong light energy with a high directivity”) is obtained when several conditions are met:

1. The number of high energy level particles must be greater than that of lower level particles. If it is not so, lower level particles absorb the light energy emitted by the photons.
2. These photons must remain confined in a resonator so that amplification can be ensured. A resonant cavity is therefore made of two mirrors, one reflecting the light and the other one letting the beam thus created through.

Laser diodes are made of a semiconductor crystal, one side of which is coated by a reflective layer (to form the reflecting mirror) while the emission side is left bare.

Most of the semiconductor materials used for LEDs cannot be used for lasers, such as LEDs emitting in the visible range. In contrast, the materials used for lasers can also be used for LEDs. (A laser diode is capable of operating as an LED.)

The laser effect in a semiconductor is triggered above a given threshold, when the initial stimulation has produced enough photons for the process to be maintained and amplified. Below this threshold, the laser diode functions as a light emitting diode. Beyond this value, a small increase in the control current will generate a very high increase in the emitted power.

At the end of the manufacturing line, all the laser diodes that do not meet the qualification criteria for lasers are regarded as LEDs and used as such.

32. Typical laser diodes. Here are some commonly used lasers:

- Multimode Lasers: Classical Laser Diodes (LDs), called Perot-Fabry, for 1300 nm transmission systems on conventional single-mode fibers, and 1550 nm transmission systems on dispersion-shifted single-mode fibers.
- Single-mode Lasers: Monochromatic LDs, called DFB for 1550 nm transmission systems on conventional single-mode fibers.

33. Emission spectrums. The first criterion of choice of an optical emitter (LED or laser) is its wavelength, which influences the attenuation in the link. The second criterion is its spectral bandwidth, which influences signal distortion (chromatic dispersion). The emitter is not monochromatic; it scatters a light energy centered around its nominal wavelength (the wavelength for which is specified). The spectrum of emission of laser diodes is much narrower than that of light emitting diodes. Chromatic dispersion is therefore much lower with a laser than with an LED.

The emission wavelength is dependent the materials used to manufacture the light source. The spectral bandwidth is dependent on the structure of the emitter.

34. Configurations of emissions. When an optical emitter, LED or laser, is driven by an analog signal, the light energy which it generates varies continuously depending on the variations of this signal. In the case of a digital signal, the energy is modulated according to the pulses.
In other words, whatever configuration of signal goes in will be the signal configuration that goes out.

**TABLE 11.2** Optical Power Levels of Fiber Optic Communication Systems

<table>
<thead>
<tr>
<th>Network type</th>
<th>Wavelength, nm</th>
<th>Power range, dBm</th>
<th>Power range, W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telecom</td>
<td>1300, 1550</td>
<td>+3 to −45 dBm</td>
<td>50 nanowatts to 2 milliwatts</td>
</tr>
<tr>
<td>Datacom</td>
<td>665, 790, 850, 1300</td>
<td>−10 to −30 dBm</td>
<td>1 to 100 microwatts</td>
</tr>
<tr>
<td>CATV</td>
<td>1300, 1550</td>
<td>+10 to −6 dBm</td>
<td>250 microwatts to 10 milliwatts</td>
</tr>
</tbody>
</table>

35. **Photodiodes.** The light detectors used for optical transmission are semiconductor photodiodes. The operation of these photodetectors is the opposite of LEDs. When a voltage is applied across the diode, the electrons and the holes migrate out of the junction zone between the P and N regions. The empty zone thus created blocks the current flowing through the diode. When the diode is illuminated, electron-hole pairs are formed and current flows again in proportion to the light energy received.

The detector sensitivity at a determined wavelength is dependent on the selected materials.

36. **Characteristics of optical receivers.** Phototransistors are not used in optical communication systems because their pulse response time is too great for today’s transmission rates. The detectors most frequently used are PIN devices and avalanche photodiodes (APD). “PIN” refers to P-intrinsic-N, the empty zone between the P and N regions of a semiconductor that is doped so that current flow is faster when it is illuminated.

Here are common optical receivers along with their common uses:

- PIN-FET diodes (combining a PIN photodiode and a field effect transistor): used in numerous applications due to their low cost (integrated electronics)
- PN photodiodes: used for low rate transmission systems
- PIN photodiodes: used for high rate transmission systems, low reception levels
- Phototransistors: used for low cost sensors, economical data transmission systems
- Photodarlingtons: used for low cost sensors, economical low rate applications
- Avalanche photodiodes (APD): used for very low reception levels
- Photoreceivers with built-in photodiode and preamplifier (Pin-FET): used for medium rate applications

37. **Coupling the source to the fiber.** The injection of the light energy into the fiber is one of the essential points in optical transmission.

The source power varies from about 10 μW for LEDs to a few tens of milliwatts for semiconductor lasers. The emitted energy is not integrally injected into the fiber; rather, it is dependent on the emission angle of the source (10 to 20° for lasers, much wider for LEDs). The alignment of the source and of the fiber and of the emitting area is also important.

Therefore, the coupling of the emitter and of the fiber, also called *injection*, must be performed with the utmost care.
38. Passive components. Following are descriptions of the most common passive optical components:

**Couplers.** Today, couplers are widely used in optical transmission systems. Couplers are essentially T connections, which split a branch off of a continuous fiber.

Local area networks are one typical application, where each piece of equipment (computer, printer, etc.) is connected to the network via a coupler, which is an optical T branch, functioning the same as those used to send electronic signals used with coaxial cables.

**Typical coupler topologies.** The typical configurations of passive couplers are the *star* and the *tee*.

Tee couplers are made of two fibers, one main fiber which passes through it, and one branch fiber. The energy carried by the first fiber is divided at the branching point into two portions that are not necessarily equal: 50/50 couplers are available, but 25/75, 10/90 couplers, and other configurations are available as well.

The star coupler has more than 3 input/outputs (sometimes abbreviated as *I/Os*). The light entering through one or several fibers is mixed in the coupler and exits via the other fibers.

Tee or star couplers are available in numerous models and applications, including:

- Star couplers (2-way to 2-way, 4-way-to-4-way, etc.). These are used in local area networks, dispatching networks, sensors, instrumentation.
- T or X couplers, used in local area networks, dispatching networks, sensors, and for instrumentation.
- **Mux-Demux** (Multiplexer-Demultiplexer) couplers. These are used in telecommunications, videocommunications, instrumentation, and for sensors.

**Splitters.** The splitter, or directional coupler, is so called because it can separate the energy only in one transmission direction. In the other direction, it can become a multiplexer (putting light sources together).

The two-directional coupler is used to divide the energy in both directions.

39. Wavelength division multiplexing. Wavelength division multiplexing (WDM) is the process of sending several signals with different wavelengths in both directions through the same fiber. This can be done as long as there is a gap between each wavelength that is sufficient to prevent any mixing of the pulses. This gap need not be large; in fact, gaps in the range of tenths of a nanometer are common.

Wavelength division multiplexing systems use couplers to group the signals on the same fiber. On the other end of the line, when the signals are received, couplers are used to dispatch the signals to their respective devices.

The same coupler may be a *multiplexer* (which puts several light sources together) or a *demultiplexer* (which divides one light source into many) according to the fibers used at the input and at the output.

40. Types of optical cables, by cable composition; by NEC classification.

The physical construction of optical cables for system functions is not governed by any agency. On the other hand, optical cables possess (assuming they are listed) NEC designations that are essential to understand in terms of fire resistance and in the context of a
building electrical system. This section covers both concepts, beginning with system functions and concluding with the NEC classifications. The final cable selection specification will combine both. It is up to the designer of the system to make sure that the cable selected will meet the application requirements. Five basic cable types have however emerged as de facto standards for a variety of applications:

**Simplex and zipcord.** One or two fibers, tight-buffered, Kevlar reinforced and jacketed. Used mostly for patch cord and backplane applications. See Fig. 11.7.

**Tightpack cables.** Also known as distribution style cables. Up to several tight-buffered fibers bundled under the same jacket with Kevlar reinforcement. Used for short, dry conduit runs, and riser and plenum applications. These cables are small in size, but because their fibers are not individually reinforced, these cables need to be terminated inside a patch panel or junction box. See Fig. 11.8.

**Breakout cables.** These cables are made of several simplex units, cabled together. This is a strong, rugged design, and is larger and more expensive than the tightpack cables. It is suitable for conduit runs, and riser and plenum applications. Because each fiber is

---

**FIGURE 11.7** Simplex and zip-cord optical cable.
individually reinforced, this design allows for a strong termination to connectors and can be brought directly to a computer backplane. See Fig. 11.9.

**Loose-tube cables.** These are composed of several fibers cabled together, providing a small, high fiber count cable. This type of cable is ideal for outside plant trunking applications. Depending on the actual construction, it can be used in conduits, strung overhead, or buried directly into the ground. See Fig. 11.10.
Hybrid or composite cables. There is a lot of confusion over these terms, especially since effective with the 1993 edition, the NEC switched its terminology from hybrid to composite.

Under the new terminology, a composite cable is one that contains a number of copper conductors properly jacketed and sheathed depending on the application, and in the same cable assembly as the optical fibers.

This situation is made all the more confusing since there is another type of cable that was formerly called composite. This type of cable contains only optical fibers, but which have two different types of fibers: multimode and single-mode.

Remember that there is confusion over these terms, with some people using them interchangeably. At this point the proper terminology is the following:

- A composite cable is a fiber/copper cable.
- A hybrid cable is a fiber/fiber cable.

Conductive and nonconductive cables. The NEC adds definitions for optical fiber cable types for its own purposes, which have nothing to do with cable performance in terms of signal transmission, and everything to do with how the cables interface with the electrical system. For example, a tightpack cable assembly, defined above, might be a conductive or nonconductive cable depending on internal construction, or theoretically even a composite cable if made up with copper in addition to the fiber. Since the NEC permits some optical fiber cables but not others to run in industrial cable trays next to medium-voltage (over 600V) power conductors, the importance of these distinctions to the installing electrician is clear. Specifically:

- A conductive cable is one with noncurrent-carrying conductive members such as metallic strength members, metallic vapor barriers, or metallic armor or sheath.
- A nonconductive cable is one with no metallic members and no electrically conductive materials.

Fire resistance of optical fiber cables. The NEC has an additional classification system for optical fiber cables, which also has nothing to do with signal transmission but has everything to do with how the cables will perform under fire conditions, particularly with respect to the likelihood that they will add a dangerous amount of fuel and transmit fire from one place to another. As in the case of other power-limited circuits (see Div. 9 Sec. 485) a hierarchy has been created as evidenced by a required cable marking, although in this case it only has three instead of four layers because residential occupancies have no special allowances. Specifically, optical fiber cables must be listed as compliant with one of the following designations:

- General purpose cable with no suffix, or a suffix “G” is generally suitable for all locations except as covered below whether concealed or exposed. The marking will begin with “OF” for optical fiber, then add a conductive element designation (either “C” for conductive or “N” for nonconductive) and conclude with no suffix or a “G” depending on which test protocol it was tested to. A “no suffix” cable may not have been tested to a certain Canadian standard and could be restricted in certain applications within the Canadian market.
- Riser cable is the next better grade of cable, and it can be used in risers from floor to floor. The marking also begins “OF,” followed by “C” or “N” and finish with an “R.”
- Plenum cable is the highest grade, and it can be used in plenum cavities used for environmental air such as above a suspended ceiling that connects to the intake of a large air handler. It will have the same markings as for riser cable except the final marking will be a “P.”

Better cables in this hierarchy can always substitute for poorer cables, and nonconductive cables can always substitute for conductive cables within the same location rating, as shown in NEC Table 770.154(E). For example, OFNP can substitute for OFNR, which can
substitute for OFCR or it could substitute for OFNG or OFN, and the like. Any listed cable is also permitted in a more restricted location than its nominal marking would indicate if it is pulled into another wiring method that would be permitted for the location. For example, the interior of a plenum-cavity suspended ceiling normally requires OFNP or OFCP grade fiber, but even OFN or OFC can be pulled into a steel raceway system in that location, such as EMT and steel boxes in accordance with NEC 300.22(C).

Unlisted cables cannot be used in buildings generally, but they can be used for outside plant. They are limited to the first 15 m (50 ft) from their “point of entrance,” and they cannot be used in a riser or plenum cavity. The point of entrance can, if necessary, be artificially extended into the building through the use of appropriately grounded rigid or intermediate metal conduit; if these wiring methods extend from the point where the outside plant enters the facility to an enclosure, then the point of entrance will be the downstream enclosure.

Optical fiber Raceways are commonly referred to as “innerduct” because they will often be pulled into large underground conduits to segment groups of fiber optic cables and provide them with a low-friction surface for insertion. They are also widely used as a raceway within buildings that is easily installed because it comes in coils that can be bent by hand. They are closely related to electrical nonmetallic tubing, a power wiring method covered in Div. 9, Sec. 27. They must be listed, and their allowable locations are the same as for optical fiber cables with comparable markings.

41. Connectors and splices. Connecting and splicing optical fibers is one of the more labor-intensive parts of the installation process. Pulling the cables into place is relatively easy, and other parts of the installation are comparably simple. But connecting these glass fibers correctly requires time, special tools, and specific skills.

All fiber joints must meet two criteria. They must be:

1. Mechanically strong: Fiber connections must be capable of withstanding moderate to severe pulling and bending tests.
2. Optically sound with low loss: Since the purpose of fiber is to transmit light, the fiber joint must transmit as much light power as possible with as little loss and back reflection as can be designed into the joint.

Fiber connections fall generally into two categories: the permanent or fixed joint which uses a fiber splice, and the nonfixed joint which uses a fiber optic connector.

Splices are used as a permanent connection. Typical uses include reel ends, for pigtail vault splices and at distribution breakouts. The criteria for good fiber splices are low loss and high mechanical strength. Additional considerations are expense per splice and possible reusability of the splice itself.

Fiber optic connectors are used as a termination for inside cables, outside cables as they terminate in a central office, for interfaces between terminals on LANs, for patch panels, and for terminations into transmitters and receivers.

Whether one joins fibers using splices or connectors, one negative aspect is always common to both methods—signal loss. This loss of light power at fiber connections is called attenuation, and is measured in decibels.

42. Attenuation. Attenuation is the loss of signal or light intensity as it travels through an optical fiber transmission system. Some losses occur in the fiber itself and others at fiber joints. Measurement of attenuation (loss) is made in decibels (dB).

Attenuation in the optical fiber itself usually occurs as a result of absorption, reflection, diffusion, scattering, or dispersion of the photon packets within the fiber. However, losses also occur at splices and connections.
The factors which cause attenuation in an optical fiber system can be broken into two categories: those being intrinsic losses (losses coming from built-in characteristics) and extrinsic losses (losses from external factors). Intrinsic losses occur from factors over which the installer has very little control and are generally caused by engineering design or manufacturing flaws. The following is a list of the more prominent intrinsic losses:

1. **Core eccentricity (core off-center)**
   - Caused by the center of the core and the center of the cladding not being precisely the same center. This results in an overlap or underlap of fiber cores at a splice point.

2. **Core ellipticity (oval shape)**
   - A departure from circularity. A very small variation in the roundness of a fiber core can affect the total system loss.

3. **Numerical aperture (NA) mismatch**

4. **Core diameter mismatch**

Extrinsic losses on the other hand are caused by the mechanics of the connection itself. Frequent causes of extrinsic loss attenuation at splicing points include:

1. **Misalignment of fiber ends** caused by improper insertion techniques into splices and connectors.

2. **Bad cleaves and poor polishing techniques** resulting in poor end face quality.

3. **Inadvertent air spaces** between fibers at a splice or connection which has not been corrected with index matching gel or liquid.

4. **Contamination** caused by dirt, wiping tissue, cotton swabs, shirt sleeves, or airborne dust particles.

In the case of fiber connectors, single-mode allowable connector losses range from 0.05 to 0.5 dB per connector (0.1 to 1.0 dB per connection) with a return loss typically less than -30 dB. Multimode connectors have a nominal connector loss of 0.06 to 0.7 dB per connector (0.12 to 1.4 dB per connection) with a return loss less than -25 dB being typical.

**TABLE 11.3**

<table>
<thead>
<tr>
<th>Receiving fiber</th>
<th>Transmitting fiber</th>
<th>Connection Losses (Excess Loss in dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50/125</td>
<td>62.5/125</td>
<td>14-16</td>
</tr>
<tr>
<td>62.5/125</td>
<td>85/125</td>
<td>30-4-16</td>
</tr>
<tr>
<td>43/100</td>
<td>10/140</td>
<td>2-14-16</td>
</tr>
</tbody>
</table>

**Back reflection.** Another type of loss is back reflection (or reflectance) and is measured in return loss. As the light travels through the fiber, passing through splices and connections, some of the light is reflected by fiber end faces at those points. This is shown in Fig. 11.11. Typical allowable back reflectance losses are less than -20 dB for single-mode fibers. Connectors have a nominal back reflectance loss of less than -10 dB.

Typical allowable back reflectance losses for single-mode fibers are as follows:

- -10 dB for connector
- 0.0 to 0.25 dB for connectors
- 0.0 to 0.25 dB for connectors
- 0.0 to 0.25 dB for connectors
- 0.0 to 0.25 dB for connectors

When testing from the large core into the small core, back reflection can be significant, while testing from the small core into the large core, back reflection is much more marginal. Generally, a return of -40 dB or better is required to ensure proper system operation.

**Back reflection.** Another type of loss is back reflection (or reflectance) and is measured in return loss. As the light travels through the fiber, passing through splices and connections, some of the light is reflected by fiber end faces at those points. This is shown in Fig. 11.11. Typical allowable back reflectance losses are less than -20 dB for single-mode fibers. Connectors have a nominal back reflectance loss of less than -10 dB.

Typical allowable back reflectance losses for single-mode fibers are as follows:

- -10 dB for connector
- 0.0 to 0.25 dB for connectors
- 0.0 to 0.25 dB for connectors
- 0.0 to 0.25 dB for connectors
- 0.0 to 0.25 dB for connectors

Back reflection (or reflectance) is a departure from circularity. A very small variation in the roundness of a fiber core can affect the total system loss. When testing from the large core into the small core, back reflection can be significant, while testing from the small core into the large core, back reflection is much more marginal. Generally, a return of -40 dB or better is required to ensure proper system operation.

**Back reflection.** Another type of loss is back reflection (or reflectance) and is measured in return loss. As the light travels through the fiber, passing through splices and connections, some of the light is reflected by fiber end faces at those points. This is shown in Fig. 11.11. Typical allowable back reflectance losses are less than -20 dB for single-mode fibers. Connectors have a nominal back reflectance loss of less than -10 dB.

Typical allowable back reflectance losses for single-mode fibers are as follows:

- -10 dB for connector
- 0.0 to 0.25 dB for connectors
- 0.0 to 0.25 dB for connectors
- 0.0 to 0.25 dB for connectors
- 0.0 to 0.25 dB for connectors

When testing from the large core into the small core, back reflection can be significant, while testing from the small core into the large core, back reflection is much more marginal. Generally, a return of -40 dB or better is required to ensure proper system operation.

**Back reflection.** Another type of loss is back reflection (or reflectance) and is measured in return loss. As the light travels through the fiber, passing through splices and connections, some of the light is reflected by fiber end faces at those points. This is shown in Fig. 11.11. Typical allowable back reflectance losses are less than -20 dB for single-mode fibers. Connectors have a nominal back reflectance loss of less than -10 dB.

Typical allowable back reflectance losses for single-mode fibers are as follows:

- -10 dB for connector
- 0.0 to 0.25 dB for connectors
- 0.0 to 0.25 dB for connectors
- 0.0 to 0.25 dB for connectors
- 0.0 to 0.25 dB for connectors

When testing from the large core into the small core, back reflection can be significant, while testing from the small core into the large core, back reflection is much more marginal. Generally, a return of -40 dB or better is required to ensure proper system operation.
Connectors. Remember that connectors are used as terminating fixtures for temporary nonfixed joints. As such, they are made to be “plugged-in” and disconnected several or many times. Since no one connector is ideal for every possible situation, a wide variety of connector styles and types have been developed over the short life of fiber communications. We can classify connectors by assigning them into five major categories:

1. Resilient ferrule
2. Rigid ferrule
3. Grooved plate hybrids
4. Expanded beam
5. Rotary

Examples of these types of connectors can be seen in Figs. 11.12 and 11.13. Connector compatibility exists between the same types from different manufacturers. Adapters are generally available in either sleeve connectors or patch cords to allow coupling of different types of connectors. Although no single connector is best for every application, listed below are the currently popular connectors found in many different types for various applications.
Although not compatible with all other connectors, most ferrule types that use a 2.5 mm ferrule allow a loose fit for temporary testing. For example, by lightly inserting the ferrule of an ST into an FC coupler, a fast (but not always recommended) test can be made for continuity.

45. Cable termination and connector installation. Before the installation of connectors onto a fiber cable, a breakout kit may have to be installed. This procedure will not be necessary on breakout cables having 2 mm buffered fibers, but will be required on 250, 500, or 900 μm tight buffer cables. The break out kit consists of 2 mm buffer tubing over 900 μm inner tubing. The bare fibers are inserted into these buffer tubes to provide handling protection and strength when mounted onto connectors.

Installing a fiber connector onto a pigtail or unbuffered fiber is a widely varied process. The four most common ways of accomplishing this task are:

1. Epoxy glue with oven cure then polish
2. Hot melt preglued then polish
3. Cleave and crimp, no polish
4. Prepolished splice

The epoxy glue method is the oldest, and is still widely used today. This process involves filling the connector with a mixed two-part epoxy. The prepared and cleaned fiber is then inserted into the connector. After curing the epoxy in an oven for the proper time (10 to 40 minutes) the fiber is scribed and cleaved nearly flush with the end of the connector, and polished with a succession of finer and finer lapping papers. Typical polish papers start at 3 μm and go as fine as 0.3 μm grit.

The Hot Melt (trademark of 3M Co.) uses a preloaded connector. The connector is placed into an oven to soften the glue and allow insertion of the prepared fiber. After cooling, the scribe and polish process is the same as the previously described polish process.

Cleave and crimp connectors, on the other hand, do not need a polish procedure. The connector already has a polished ferrule tip and requires only the insertion of a properly cleaved fiber to butt against the internal fiber “stub.” Once in place, the fiber connector is crimped to hold the fiber in place.

Each mounting method has its advantages and disadvantages, varying from ease of installation to cost per connector to performance qualities.

46. Choosing a fiber connector. With all of the myriad selections of connector types, styles, and physical characteristics available on the market, choosing the specific connector for your job is often a mystifying task. One important criteria is connector...
performance. When selecting a connector, comparisons of performance are generally based on the following criteria:

- Insertion loss: Usually 0.10 to 1.0 dB per connection.
- Return loss (back reflection, reflectance): Varies from $-20$ (air gap like a SMA) to $-60$ dB (the best APC angle polished connectors)
- Repeatability of connection: Usually specified at thousands of times.

Also, your choice of fiber connector may also depend upon such things as single-mode or multimode fiber, and the type of mounting.

The accessibility of the fiber to casual users may cause you to anticipate rough handling. In this case, gripping strength of the connector becomes important to avoid pull-outs by users. Gripping points of the connector may include the fiber itself, the primary plastic buffer coating (tight buffer), the loose tube buffer, the cable strength members (Kevlar), and/or the cable jacket itself.

Another additional reason for choosing a particular type of connector is the type of equipment already purchased or currently in use. If, for instance, you are adding to an existing system already equipped with ST connectors, one should continue to use ST connectors to ensure compatibility system-wide. If you are using previously purchased electronics with Biconic connectors installed, then that will be your choice, unless you wish to change all of the connections in the equipment.

47. Terminating single-mode fibers. Terminating single-mode cables generally uses a combination of connector installation and splicing. Since the single-mode connector has very fine tolerances, they are generally terminated in a manufacturing lab. (The critical factors are loss and reflectance.) In a laboratory setting, fiber insertion and physical contact polishing can be controlled precisely. Complete cable assemblies with connectors on both ends are made and tested, since testing a cable with two ends is easier than with bare fiber on one end.

In the field, the assemblies are cut in half and spliced onto the installed backbone cables. Although the splice adds some additional loss and cost, the overall method provides a higher yield and better connection at lower cost than trying to control the termination process in the field.

48. Breakout kits. Breakout kits are a simple box (into which a cable enters), fitted with semirigid tubes, through which the individual fibers exit. The tubes provide mechanical protection for the unprotected fibers, which will usually run from the breakout point to individual connectors or splices.

This procedure is not necessary on “breakout cables” having 2 mm buffered fibers, but will be required on 250, 500, or 900 μm tight buffer cables. The breakout kit consists of 2 mm buffer tubing over 900 μm inner tubing. The bare fibers are inserted into these buffer tubes to provide handling protection and strength when mounted onto connectors. These tubes are frequently referred to as furcation tubing.

49. Splices. The two basic categories of splices are fusion and mechanical. Generally speaking, splices offer a lower return loss, lower attenuation, and are physically stronger than connectors. Also, splices are usually less expensive than connectors (two connectors being required to equal one splice), they require less labor, constitute a smaller joint for
inclusion into splice closures, offer a better hermetic seal than connectors, and allow either individual or mass splicing.

The type of splice chosen is usually determined by:

**Type of fiber.** Most single-mode fiber is fusion-spliced because of its lower loss and better return loss performance. Multimode fiber, with its complicated core structure, does not always fusion splice easily, so mechanical splices can give equal performance at a lower overall cost. (Some experienced installers, however, regularly fusion-splice graded index fibers with good results.)

**Attenuation including return loss.** New fusion splicers give incredibly low loss when used properly, while a properly terminated connector can approach the loss of a mechanical splice.

**Physical durability.** The “welding” process used in the fusion splice gives higher strength and greater durability.

**Ease of installation.** A fully automated fusion splicer is very expensive, but makes the splicing a one-button process. Partly automated fusion splicers are less expensive, but require more effort to use. Mechanical splicing types vary, but are usually easier to use than connector kits.

**Cost per splice.** In the case of fusion splicing, the most common type of splicing for single-mode fiber in new work, the initial capital investment is generally much greater than the cost for mechanical splicing. A fusion splicing machine is a several thousand dollar investment. However, very low loss can be achieved (sometimes 0 dB), and fusion splices show almost no back reflection at all. An additional benefit of fusion splicing is that the mechanical tensile strength of the fiber remains near that of the original fiber (50 to 75,000 psi).

50. **Fusion splicing.** Fusion splicing uses an electric arc to ionize the space between prepared fibers to eliminate air, and to heat the fibers to proper temperature (2000°F). The fibers are then fed in as semiliquids, and meld together. The previously removed plastic coating is replaced with a plastic sleeve or other protective device. The perfect fusion splice results in a single fiber rather than two fibers having been joined. One drawback to fusion splicing is that it generally must be performed in a controlled environment, such as a splicing van or trailer, and should not be done in open spaces because of dust and other contamination.

Fusion splicing in manholes is prohibited because of the explosive gases which are frequently found in such locations, and because of the electric arc generated during this process.

Due to the “welding” process, it is sometimes necessary to modify the fusion parameters to suit particular types of fibers, especially if it is necessary to fuse two different fibers (fibers from two different manufacturers, or fibers with different core/cladding structures).

A fusion splicer is shown in Fig. 11.14.

51. **Mechanical splicing.** Mechanical splicing is quick and easy for restoration, its major use, and is sometimes used for new construction. It does not require a controlled environment other than a reasonable level of dust control. The strength of a mechanical splice is better than most connectors, although fusion splices are stronger. Back reflection and loss vary dramatically from one type of splice to another.

Equipment investment for specific splicing kits are far less expensive than for fusion splicers. Splices are either glued, crimped, or faced. Mechanical splices all must use some type of index matching gel or liquid which is subject to contamination and aging. Those splices which require adhesive glue can become outdated as the glue ages.
Mechanical splices use either a V groove or tube type design to obtain fiber alignment. The V groove is probably the oldest and still most popular method especially for multifiber splicing of ribbon cable. This type of splice is either crimped or snapped to hold the fibers in place.

Tubular splices on the other hand may rely on glue or crimping to hold the fibers together, while a small tube inside which the fibers are inserted causes alignment to occur.

Faced type of splices are very much like miniaturized connectors using ferrules and a polishing process.

Completed splices, whether fusion or mechanical, are placed into splicing trays that are designed to accommodate the particular type of splice in use. Splicing trays then fit into splice organizers, and in turn into a splice closure.

A mechanical splice is shown in Fig. 11.15.

52. **Hand tools and supplies.** No job can be completed without the correct tools, and fiber splicing and connectorizing are no exception. Hand tools can be purchased as a prepackaged tool kit or on an individual basis as needed. At a minimum, to complete most fiber optic operations, the following will be needed:

- Cleaning fluid and rags (or an approved cable cleaner).
- Buffer tube cutter.
- Reagent grade, isopropyl alcohol in nonspill bottle or presoaked pads.
Canned air.
Tape: masking and “Scotch” invisible.
Coating stripper
Cleaver or scribe.
Microscope or cleave checker.
Splicing method (fusion or mechanical) determines specific tooling needs.
Connectorization method determines specific tool kit (if required).
Fusion splicer (optional).
OTDR (optional, rentable).
Splicing van or trailer (nice to have an organized workplace, especially for outside plant work).
Power meter (for measuring optical power or loss).
LED or laser light source (to inject a test signal for loss).
Visible light source (for tracing cables).
Fiberoptic talkset to communicate over the fiber. Alternatives are walkie-talkies and cellular phones.
Termination kits (these may be made by purchasing tools individually rather than in a kit form). Sometimes the splicing or connectorization kits will contain too many small insignificant tools which you may already own. Once you determine the needed tools, you can purchase only those tools.

53. **Fiber optic safety.** Optical fibers are generally considered safe, due to the fact they carry no electricity, and therefore cannot cause fires like electrical wiring. Nonetheless, fiber is not entirely safe, and does pose certain risks to installers.

The first, though less serious, type of fiber danger is due to the light the fiber transmits; in particular, light put out by the lasers that drive some of these systems (CATV, Dense Wavelength Division Multiplexing). The various types of light sources used by common fiber systems was shown in Sec. 31, along with the wavelength of light used and power level. This table shows that while the power levels of all these systems are relatively low, the highest go up to about 10 milliwatts. While this may not sound like a lot of wattage (especially compared to several-hundred watt lamps), bear in mind that all of this light may be pumped through a fiber that is only 9 millionths of a meter (μm) in diameter. Even at these low...
levels, that can be a fairly high level of watts per square centimeter. Remember the trick of starting a fire with a magnifying glass, and be in mind that light is able to do damage.

You will also notice from this that almost all of these wavelengths are at 800 nm (nanometers, or billionths of meters) or higher. These are all infrared light, which our eyes do not see. Hazardous situations can arise when untrained people pick up a live fiber, and look directly into it. They see no light, and therefore assume no danger. In these situations, damage can be done to an unsuspecting person’s retina. This is especially hazardous when inspecting fiber ends with a microscope, since the microscope will focus nearly all of the light directly into the eye. Serious damage can result from this.

Do not, however, confuse looking into a live fiber with performing continuity checks. One of the better fiber testing tools is called a visual tracer. Essentially, a visual tracer is a visible light that you shine down the fiber. You then use your eye to trace the fiber through its course to its end.

The tracer itself can be a flashlight, a specially modified flashlight, or even a microscope that will hold the fiber in place steadily, and couple an adequate amount of power into the fiber. The better tracers are special test sources that use a bright red LED source. The power levels of all visual tracers are too low to cause eye damage, so you do not have to be concerned with them. Besides, they are visible, and you can tell that you are looking at a light source.

For single-mode cables, a more powerful tool is sometimes used, called a visual fault locator (VFL). These use red lasers with enough power to actually show breaks in the fiber through the jacket of the fiber. They are stronger than simple fiber tracers, but still not powerful enough to do bodily damage.

There is a special film card that can be used to identify live fibers by eye. This small card converts the infrared light to visual light. By using it, you can tell quickly and easily whether a fiber is live or not.

All this being said, the odds of going blind by looking into the broken end of an optical fiber are virtually nil. It is possible for someone to be injured by mishandling optical fibers, but only under certain circumstances. Those circumstances are usually the following:

1. The light source must be high-powered. Only the more powerful lasers are strong enough to cause injury.
2. The beam of light exiting the fiber must be narrow. Do you remember the old trick of starting a fire with sunlight and a magnifying glass? Just as in that case, the light from a fiber must be very tightly focused to cause harm. This is why broken fibers do not cause harm. Broken ends of glass fiber are erratic, and scatter the light that passes through them. This light is nowhere near focused enough to cause damage to the eye.

All of this is not to say that looking into the end of a properly polished fiber cannot be a problem. Since a polished fiber end will not diffuse the light that flows through it, the potential for injury with such fibers exists.

A far more serious safety concern is the fibers themselves. Fibers are pieces of glass. And like all glass, they can cut and injure us.

Because of this, handling fiber requires considerable care. First of all, you must be very careful when handling open fibers, that is, fibers that are not contained in a cable. (Modern optical fiber cables are very safe, and pose no danger to the installer. It is when the cables are opened up that hazards like these start.) If you were to accidentally jab yourself with one of these open fibers, you could easily end up with a painful sliver. But what is worse is that this sliver may not be visible! Remember that these slivers are made of transparent glass, and can be very difficult to see.

Jabbing yourself with a fiber is not, however, the biggest glass hazard. The really dangerous situation is when fibers are stripped, trimmed, and cut. These operations result in short, nearly microscopic pieces of glass lying around a work area. These are short, thin,
invisible needles. If they are left lying around in a busy work area, it is almost inevitable that someone will end up touching or handling them. As sharp and thin as these glass shards are, they will easily penetrate the skin. And unlike a wood sliver, these glass slivers will not degrade inside the skin.

These cut pieces of fiber are dangerous. In order to avoid this hazard, a technician working with fibers should make generous use of masking tape (or any other type of tape) to catch the fiber pieces. Some technicians wrap the tape around a few fingers, sticky side out. This catches the fibers as soon as they are cut. Plenty of sticky side out tape should be kept at the work area, and the entire area should be blotted frequently with tape to pick up stray pieces. Also, this tape must be handled carefully. When the pickup operation is complete, the tape should be folded upon itself and carefully disposed of. This tape should never be left lying open, or wadded up and thrown on the floor. Remember, fibers are insidious, since they are very difficult to see, especially when you are not expecting them to be present. If you sit on some of these cut pieces, you won’t forget ever again.

Pieces of fiber should be placed in bottles with screw lids (or other type of secure container) as soon as they are trimmed from cables, typically during the terminating procedure.

As mentioned earlier, one of fiber’s better-known characteristics is that it carries no electricity, and is therefore not a fire hazard. That does not, however, mean that optical fiber cables cannot be a fire hazard in a building.

Optical cables must be installed according to their fire safety characteristics, if they are to result in a safe installation, as covered in Sec. 40. In addition, proper fire stops must be used when they (like any cable) pass through any fire-rated partition, such that the required fire separation of the partition is maintained. In addition, any abandoned optical fiber cables (defined as not terminated at equipment other than a connector and not identified for future use with a tag) must be removed. The tag must have sufficient durability for the use at its location.

Regardless of the overall safety of optical fiber, optical cable installations carry many of the same risks as copper cables.

Installers need to pay special attention to long outdoor runs of cables with metal components. (Many outdoor cables have metal strength members or other metal components.) These long pieces of metal can have significant voltages induced into them from lightning strikes in the area. Contact with these pieces can be dangerous. While these metal cable components are required to be grounded in all buildings, this may not always be done out of doors. You should ground any metal cable components before handling them.

Working near power conductors is often required in fiber optic installations. This, as always, is a serious hazard. There are three types of optical cables (see Sec. 40 for NEC definitions of cable types), each with their own system separation rules, as follows:

a. Composite optical fiber cables containing nonpower-limited control or power circuits are only permitted to be used where the optical fiber and the nonpower-limited components are functionally associated. However, once a composite cable qualifies for use under this criterion, it may be used in the same raceway or cable tray as nonpower-limited wiring conductors, and these cables may enter other wiring enclosures for termination or other purposes. In industrial occupancies only, with qualified maintenance and supervision, composite cables are even permitted with the power conductor operating at medium voltage (over 600V).

b. Conductive optical fiber cables are not permitted in the same raceway or cable tray as nonpower-limited wiring of any kind.

c. Nonconductive optical fiber cables are permitted within a common raceway or the same cable tray as nonpower-limited wiring of any kind operating at 600V or less. If the nonconductive fiber cables are functionally associated with the nonpower-limited wiring, the cables are permitted in nonpower-limited wiring enclosures. Nonconductive optical fiber cables are also permitted in common wiring enclosures where installed in
a factory- or field-assembled control center. In industrial occupancies only, with qualified maintenance and supervision, nonconductive optical fiber cables are also permitted with the power conductors operating at medium voltage (over 600V).

d. **With power-limited circuits.** Optical fiber cables are permitted without limitation as to being either conductive or nonconductive, and are permitted to be part of a composite cable with, and to run in the same wiring raceways, cable trays, and other enclosures with copper wiring that is part of a power-limited system. Specifically, optical fiber cabling is permitted with a Class 2 or Class 3 system per NEC Article 725 (See Div. 9 Sec. 481 to 489.), or a power-limited fire alarm system per NEC Article 760, or a communications system as covered in NEC Article 800, or a CATV system covered in NEC Article 820, or a network-powered broadband communications system having a low-power source as defined by the applicable parameters in NEC Table 830.15.

Where these requirements specify a separation between optical fiber cabling of any type and electrical power or control circuits of any type, those separation requirements can be met by providing a permanent or listed barrier between the systems. This can be accomplished in cable tray or surface raceway systems by using barriers compatible with the tray or surface raceway, and in an enclosure by either arranging a fixed and grounded permanent barrier or by enclosing the optical fiber cables in a grounded raceway as required. For example, flexible metal conduit is often used within a nonpower-limited enclosure to extend either the nonpower-limited source wiring or the power-limited or optical fiber cabling from the entry point to a termination point where system separation no longer needed to be maintained.

54. **Testing.** Testing fiber optic components and systems requires making several basic measurements. The most common measurement parameters are shown in the following table. Optical power, required for measuring source power, receiver power and loss or attenuation, is the most important parameter, and is required for almost every optical link. Backscatter and wavelength measurements are the next most important, and bandwidth or dispersion are very rarely performed in the field. Measurement or inspection of geometrical parameters of fiber are essential for fiber manufacturers only.

<table>
<thead>
<tr>
<th>Test parameter</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Power (Source Output, Receiver Signal Level)</td>
<td>Fiber Optic Power Meter</td>
</tr>
<tr>
<td>Attenuation or Loss of Fibers, Cables, and Connectors</td>
<td>FO Power Meter and Source, Test Kit or OLTS (optical loss test set)</td>
</tr>
<tr>
<td>Source Wavelength</td>
<td>FO Spectrum Analyzer</td>
</tr>
<tr>
<td>Backscatter (Loss, Length, Fault Location)</td>
<td>Optical Time Domain Reflectometer (OTDR)</td>
</tr>
<tr>
<td>Fault Location</td>
<td>OTDR, Visual Cable Fault Locator</td>
</tr>
<tr>
<td>Bandwidth/Dispersion (Modal &amp; Chromatic)</td>
<td>Bandwidth Tester or Simulation Software</td>
</tr>
</tbody>
</table>

55. **Power meter testing.** Fiber optic power meters measure the average optical power emanating from an optical fiber and are used for measuring power levels and, when used with a compatible source, for loss testing. They typically consist of a solid state detector, signal conditioning circuitry, and a digital display of power. To interface to the large variety of fiber optic connectors in use, some form of removable connector adapter is usually provided.
Power meters are calibrated to read in milliwatts, microwatts and/or dBm (this refers to the decibel to one milliwatt; thus a dBm reading refers to how many dBs the power level is from one milliwatt). Some meters offer a relative dB scale also, useful for laboratory loss measurements.

Although most fiber optic power and loss measurements are made in the range of 0 dBm to $\pm 50$ dBm, some power meters offer much wider ranges. For testing analog CATV systems or fiber amplifiers, special meters with extended high power ranges are used. Optical power meters have a typical measurement uncertainty of $+/- 5\%$.

56. **Visual cable tracers and fault locators.** The most common fault with fiber optic systems is poor connections. Since the light used in systems is not visible, visual inspections will not tell you whether or not the transmitter is operating. This problem can be overcome by injecting the light from a visible source, such as a LED or incandescent light bulb. By doing so, you can visually trace the fiber from transmitter to receiver, and verify that the light is traveling the correct course. The test instruments that are used to inject visible light are called visual fault locators.

If a powerful enough visible light, such as a HeNe (Helium-Neon) or visible diode laser is injected into the fiber, high loss points can be made visible. This method will work on buffered fiber and even jacketed single fiber cable if the jacket is not opaque to the visible light. The yellow jacket of single-mode fiber and the orange of multimode fiber will usually pass the visible light. Most other cable colors, especially black and gray, will not work with this technique, nor will most multifiber cables. However, many cable breaks, macrobending losses caused by kinks in the fiber, bad splices, and the like can be detected visually.

Since the loss in the fiber is quite high at visible wavelengths, on the order of 9 to 15 dB/km, this instrument has a short range, typically 3 to 5 km, which is more than enough for virtually all indoor installations.

57. **Microscopes.** Generally the first test performed once the fibers are pulled into place is a visual inspection with a microscope. This is done when preparing fiber ends for termination.

The microscopes used for testing fibers have stages which are modified to hold the fiber or connector in the field of view. Fiber optic inspection microscopes vary in magnification from 30 to 800 power, with 30 to 100 power being the most widely used range. Cleaved fibers are usually viewed from the side, to see breakover and lip. Connectors are viewed end-on, or at a small angle, to find polishing defects such as scratches.

Photos showing fiber ends in various stages of polishing are shown in Fig. 11.16. A well-made connector will have a smooth, polished, scratch free finish, and the fiber will not show any signs of cracks or pistoning (where the fiber is either protruding from the end of the ferrule or pulling back into it).

The proper magnification for viewing connectors is generally accepted to be 30 to 100 power. Lower magnification, typical with a jeweler’s loupe or pocket magnifier, will not provide adequate resolution for judging the finish on the connector. Too high a magnification tends to make small, ignorable faults look worse than they really are. A better solution is to use medium magnification, but inspect the connector three ways:

1. By viewing directly at the end of the polished surface with side lighting
2. By viewing directly with side lighting and light transmitted through the core
3. By viewing at an angle with lighting from the opposite angle
Viewing directly with side lighting allows determining if the ferrule hole is of the proper size, the fiber is centered in the hole, and a proper amount of adhesive has been applied. Only the largest scratches will be visible this way, however. Adding light transmitted through the core will make cracks in the end of the fiber, caused by pressure or heat during the polish process, visible.

Viewing the end of the connector at an angle, while lighting it from the opposite side at approximately the same angle, will allow the best inspection for the quality of polish and possible scratches. The shadowing effect of angular viewing enhances the contrast of scratches against the mirror smooth polished surface of the glass.

One needs to be careful in inspecting connectors, however. The tendency is to be overly critical, especially at high magnification. Only defects over the fiber core are a problem. Chipping of the glass around the outside of the cladding is not unusual and will have no effect on the ability of the connector to couple light in the core. Likewise, scratches only on the cladding will not cause any loss problems.

58. **Continuity testing.** Continuity testing is the most fundamental fiber optic test. It is usually performed when the cable is delivered to the job site (and certainly before installation) to ensure that no damage has been done to the cable during shipment to the work site.

This testing is commonly done with a visible light source, which can be an incandescent lamp, HeNe laser at 633 nm or a LED or diode laser at 650 nm, a wavelength (that is, color) which can be seen by the eye. HeNe laser instruments are usually tuned to an output power level of just less than 1 mW, making them Class II lasers which do not have enough power to harm the eye, but do have enough power to be easily seen over about 4 km of fiber, and to even find fiber microbends or breaks by viewing the light shining from the break through the yellow or orange jacket used on most single fiber cables. In most cases, a high quality flashlight, shined directly into a good fiber end, works quite well.
59. **Insertion loss testing.** The most basic (and most commonly performed) fiber optic test is called an *Insertion Loss* test. Insertion loss is the loss caused by the insertion of a component such as a splice or connector in an optical fiber. Figures 11.17 and 11.18 display the basic method of insertion loss testing. These drawings show a single cable being tested. But in the field each fiber, from one end of the system to the other, is commonly tested this way. Since the power meter test set consists of two parts (the light source and the meter), one piece can be used at one end of the system, and another at the far end. The process usually includes the following parts:

1. The test set is referenced. This is done by connecting the two parts with a known good jumper, and setting the zero level on the meter.
2. The source is taken to one end of the links, the meter to the other.
3. Some type of communication link is established between the two ends (walkie-talkies, cell phones, talk sets, etc.).

![Single-end insertion loss test.](image1)

**FIGURE 11.17** Single-end insertion loss test.

![Double-end insertion loss test.](image2)

**FIGURE 11.18** Double-end insertion loss test.
4. Each fiber is tested, one after another, and the results are carefully recorded.

5. When required, each fiber segment of fiber (for example, from one patch panel to another) is tested separately.

6. Some systems may be tested in either directions. (Source at A, meter at B or Source at B, meter at A.)

Virtually all optical fiber systems are tested for end-to-end insertion loss to confirm that the required signal will be permitted to pass.

Loss is typically measured at 850 and 1300 nm wavelengths for multimode links. Single-mode fiber is always tested at 1300 nm, and may also be tested at 1550 nm.

60. Testing the installed fiber system. To thoroughly test the cable system, one needs to test it three times: before installation, each installed segment, and complete end-to-end loss.

One should test the cable on the reel for continuity before installing it, to insure no damage was done in shipment from the manufacturer to the job site. Since the cost of installation usually is high, often higher than the cost of materials, it only makes sense to ensure that one does not install bad cable. It is generally sufficient to just test continuity, since most fiber is installed without connectors and then terminated in place, and connectors are the most likely problem to be uncovered by testing for loss. After installation and termination, each segment of the cable plant should be tested individually as it is installed, to ensure each connector and cable is good. Finally, each end-to-end run (from equipment placed on the cable plant to equipment) should be tested as a final check.

For multimode fibers, testing is now usually done at both 850 and 1300 nm wavelengths (colors) using LED sources. This will prove the performance of the cable for every data-com system, and will meet the requirements of all network vendors. For single-mode fiber cables, testing is usually done at 1300 nm, but 1550 is sometimes required also. The 1550 nm testing will show that the cable can support wavelength division multiplexing (WDM) at 1300 and 1550 nm for future service expansion.

If cable system end-to-end loss exceeds total allowable loss, the best solution is to retest each segment of the cable plant separately, checking suspect cables each way, since the most likely problem is a single bad connector or splice. Bad connectors must then be repolished or replaced to bring the loss within acceptable ranges.

61. Optical time domain reflectometers. The optical time domain reflectometer (OTDR) is one of the most powerful types of optical fiber testers. It uses the phenomena of backscattered light to analyze fibers, find faults, and optimize splices. Any time light is sent through a fiber, a small amount of light is scattered backward to the source. If there is some type of fault or obstruction in the fiber, an unusually high amount of light will be scattered back. The OTDR operates by sending into the fiber a high powered pulse and then measuring the light scattered back toward the instrument.

If one assumes that the average amount of backscatter (called the backscatter coefficient) is constant, the OTDR can be used to measure loss as well as locate fiber breaks, splices, and connectors. In addition, the OTDR gives a graphic display of the status of the fiber being tested. And it offers another major advantage over the source/power meter in that it requires access to only one end of the fiber.

OTDR measurement is heavily dependent on the backscatter coefficient, which is a function of fiber scattering characteristics, core diameter, and numerical aperture. OTDRs must also be matched to the fibers being tested in both wavelength and fiber core diameter.
to provide accurate measurements. Thus many OTDRs have modular sources to allow substituting a proper source for the application.

While most OTDR applications involve finding faults in installed cables or checking splices, they are also very useful in inspecting fibers for manufacturing faults.

If a fiber has a splice or connector, an OTDR’s signal will be diminished as the pulse passes it, so the OTDR sees a reduction in power, indicating the light loss of the joined fibers. If the splice or connector reflects light, the OTDR will show the reflection as a spike above the backscattered signal. The OTDR can be calibrated to use this spike to measure optical return loss.

The end of the fiber will show as a deterioration of the backscatter signal into noise, if it is within the dynamic range of the OTDR. If the end of the fiber is cleaved or polished, one will also see a spike above the backscatter trace. This allows one to measure the total length of the fiber being tested.

Figure 11.19 shows a typical OTDR trace.

![Optical time domain reflectometer optical fiber ODTR trace test](image)

**FIGURE 11.19** Optical time domain reflectometer optical fiber ODTR trace test.

**62. The limitations of OTDR use.** With the OTDR, one can measure loss and distance. To use them effectively, it is necessary to understand their measurement limitations. The OTDR’s distance resolution is limited by the transmitted pulse width. As the OTDR sends out its pulse, crosstalk in the coupler inside the instrument and reflections from the first connector will saturate the receiver. The receiver will take some time to recover, causing a
nonlinearity in the baseline of the display. It may take the time equivalent to 100 meters before
the receiver recovers. It is common to use a long fiber cable called a pulse suppressor between
the OTDR and the cables being tested to allow the receiver to recover completely.

The OTDR also is limited by the pulse width in its ability to resolve two closely spaced
features. Long distance OTDRs may have a minimum resolution of a few hundred meters,
while short range OTDRs can resolve features several meters apart.

When measuring distance, the OTDR has two major sources of error not associated with
the instrument itself: the velocity of the light pulse in the fiber, and the amount of fiber in
the cable. The velocity of the pulse down the fiber is a function of the average index of
refraction of the glass. While this is fairly constant for most fiber types, it can vary by a few
percent. When making cable, it is necessary to have some excess fiber in the cable, to allow
the cable to stretch when pulled without stressing the fiber. This excess fiber is usually 1 to 2%.
Since the OTDR measures the length of the fiber, not the cable, it is necessary to subtract
1 to 2% from the measured length to get the likely cable length. This is very important if
one is using the OTDR to find a fault in an installed cable, to keep from looking too far away
from the OTDR to find the problem. This variable adds up to 10 to 20 meters per kilometer,
therefore it is not ignorable.

Accurate OTDR attenuation measurements depend on having a constant backscatter
coefficient. Unfortunately, this is often not the case. Fibers which have tapers in core size
are common, or variations in diameter are a result of variations in pulling speed as the
fiber is being made. A small change in diameter (1%) causes a larger change in cross sec-
tional area which directly affects the scattering coefficient, and can cause a large change
in attenuation (on the order of 0.1 dB). Thus fiber attenuation measured by OTDRs may
not be uniform along the fiber, and can produce significantly different losses in opposite
directions.

The first indication of OTDR problems for most users occurs when looking at a splice
and a “gain” is seen at the splice. Since passive fibers and splices cannot create light,
another phenomenon is obviously the cause. A “gainer” is an indication of the difference
of backscatter coefficients in the two fibers being spliced.

If an OTDR is used to measure the loss of a splice and the two fibers are identical, the
loss will be correct, since the scattering coefficient is the same for both fibers. This is
exactly what you see when breaking and splicing the same fiber, the normal way OTDRs
are demonstrated.

If the receiving fiber has a lower backscatter coefficient than the fiber before the splice,
the amount of light sent back to the OTDR will decrease after the splice, causing the OTDR
to indicate a larger splice loss than actual.

If one looks at this splice in the opposite direction, the effect will be reversed. The
amount of backscattered light will be larger after the splice and the loss shown on the OTDR
will be less than the actual splice loss. If this increase is larger than the loss in the splice, the
OTDR will show a gain at the splice, an obvious error. As many as one-third of all splices
will show a gain in one direction. The usual recommendation is to test with the OTDR in
both directions and average the reading, which has been shown to give measurements
accurate to about 0.01 dB.

63. **Noncommunication applications of optical fiber.** The optical fiber has first
been devised as a simple means to carry light from one point to another. A patent registered
by William Wheeler in 1881 describes a home lighting system using light conducting tubes.
A more recent patent describes a bundle of optical fibers used to carry images. Today, light
guide fibers are used in every technical and scientific sector, including surgery, industry,
fundamental research, avionics, automotive, and consumer.
The most common of these noncommunication applications are the following:

Light guides
Medical lasers
Public lighting and displays
Home lamps and Christmas tree lighting
Transmission of images
Medical imaging (endoscopy, etc.)
Sensors
Passage detectors for objects or people
Gyrosopes
Pressure sensors
Audio detectors

Fibroscopes are increasingly used in medicine and surgery, both in the detection and the eradication of abnormal formations. Fiber gyroscopes are found in modern aircraft. Optical sensors are legion, and are used in all industries. Lighting uses for optical fibers are increasing steadily. Image guide (faceplate), sensor, and lighting/indication are three major applications of fibers as light guides.