CORNING

Fiber-Optic Technology Tutorial

Definition

Fiber-optic communications is based on the principle that light in a glass medium can carry information over longer distances than electrical signals can carry in a copper or coaxial medium. The glass purity of today's fiber, combined with improved system electronics, enables fiber to transmit digitized light signals well beyond 100 km (60 miles) without amplification. With few transmission losses, low interference, and high bandwidth potential, optical fiber is an almost ideal transmission medium.

Overview

The advantages provided by optical fiber systems are the result of a continuous stream of product innovations and process improvements. As the requirements and emerging opportunities of optical fiber systems are better understood, fiber is improved to address them. This tutorial provides an extensive overview of the history, construction, operation, and benefits of optical fiber, with particular emphasis on outside vapor deposition (OVD) process.

Topics

1. From Theory to Practical Application: A Quick History

An important principle in physics became the theoretical foundation for optical fiber communications: light in a glass medium can carry more information over longer distances than electrical signals can carry in a copper or coaxial medium.

The first challenge undertaken by scientists was to develop a glass so pure that one percent of the light would be retained at the end of one kilometer (km), the existing unrepeatered transmission distance for copper-based telephone systems. In terms of attenuation, this one percent of light retention translated to twenty decibels per kilometer (dB per km) glass material.

Glass researchers all over the world worked on the challenge in the 1960s, but the breakthrough came in 1970, when Corning scientists Drs. Robert Maurer, Donald Keck, and Peter Schultz created a fiber with a measured attenuation of less than 20 dB per km. It was the purest glass ever made.

The three scientists' work is recognized as the discovery that led the way to the commercialization of optical fiber technology. Since then, the technology has advanced tremendously in terms of performance, quality, consistency, and applications.

Working closely with customers has made it possible for scientists to understand what modifications are required, to improve the product accordingly through design and manufacturing, and to develop industry-wide standards for fiber.

The commitment to optical fiber technology has spanned more than twenty years and continues today with the endeavor to determine how fiber is currently used and how it can meet the challenges of future applications. As a result of research and development efforts to improve fiber, a high level of glass purity has been achieved. Today, fiber's optical performance is approaching the theoretical limits of silica-based glass materials. This purity, combined with improved system electronics, enables fiber to transmit digitized light signals well beyond 100 km (more than 60 miles) without amplification. When compared with early attenuation levels of 20 dB per km, today's achievable levels of 0.35 dB per km at 1310 nanometers (nm) and 0.25 dB per km at 1550 nm, testify to the incredible drive for improvement.

2. How Fiber Works

The operation of an optical fiber is based on the principle of total internal reflection. Light reflects (bounces back) or refracts (alters its course while penetrating a different medium), depending on the angle at which it strikes a surface. This occurs because different interfaces between materials refract light in different ways.

One way of thinking about this concept is to envision a person looking at a lake. By looking down at a steep angle, the person will see fish, rocks, vegetation, or whatever is below the surface of the water, assuming that the water is relatively clear and calm. However, by casting a glance farther out, thus making the angle of sight less steep, the individual is likely to see a reflection of trees or other objects on an opposite shore. Because air and water have different indices of refraction, the angle at which a person looks into or across the water influences the image seen.

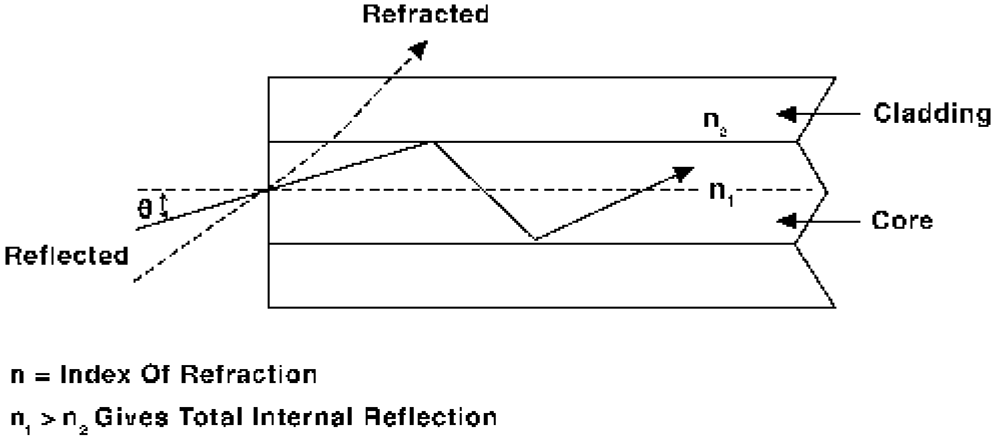
This principle is at the heart of how optical fiber works. Lightwaves are guided through the core of the optical fiber in much the same way that radio frequency (RF) signals are guided through coaxial cable. The lightwaves are guided to the other end of the fiber by being reflected within the core. Controlling the angle at which the light waves are transmitted makes it possible to control how efficiently they reach their destination. The composition of the cladding glass relative to the core glass determines the fiber's ability to refract light. The difference in the index of refraction of the core and the cladding causes most of the transmitted light to bounce off the cladding glass and stay within the core. In this way, the fiber core acts as a waveguide for the transmitted light.

The Design of Fiber

Core and Cladding

An optical fiber consists of two different types of highly pure, solid glass to form the core and cladding. A protective acrylate coating (see *Figure 1*) then surrounds the cladding. In some cases, the protective coating may be a dual layer.

Figure 1. Core and Cladding

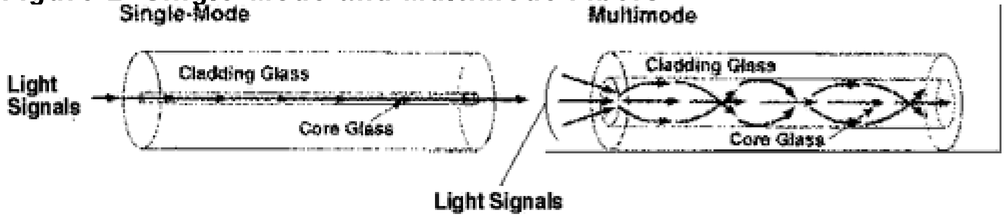


A protective coating is applied to the glass fiber as the final step in the manufacturing process. This coating protects the glass from dust and scratches that can affect fiber strength. This protective coating can be comprised of two layers: a soft inner layer that cushions the fiber and allows the coating to be stripped from the glass mechanically and a harder outer layer that protects the fiber during handling, particularly the cabling and installation/termination processes.

Single-Mode and Multimode Fibers

There are two general categories of optical fiber: single mode and multimode (see *Figure 2*).

Figure 2. Single-Mode and Multimode Fibers



Multimode fiber was the first type of fiber to be commercialized. It has a much larger core than single-mode fiber, allowing hundreds of rays or modes of light to propagate through the fiber simultaneously. Additionally, the larger core diameter of multimode fiber facilitates the use of lower-cost optical transmitters and connectors.

Single-mode fiber, on the other hand, has a much smaller core that allows only one mode of light at a time to propagate through the core. While it might appear that multimode fibers have higher capacity, in fact the opposite is true. Single-mode fibers are designed to maintain the integrity of each optical signal over longer distances, allowing more information to be transmitted.

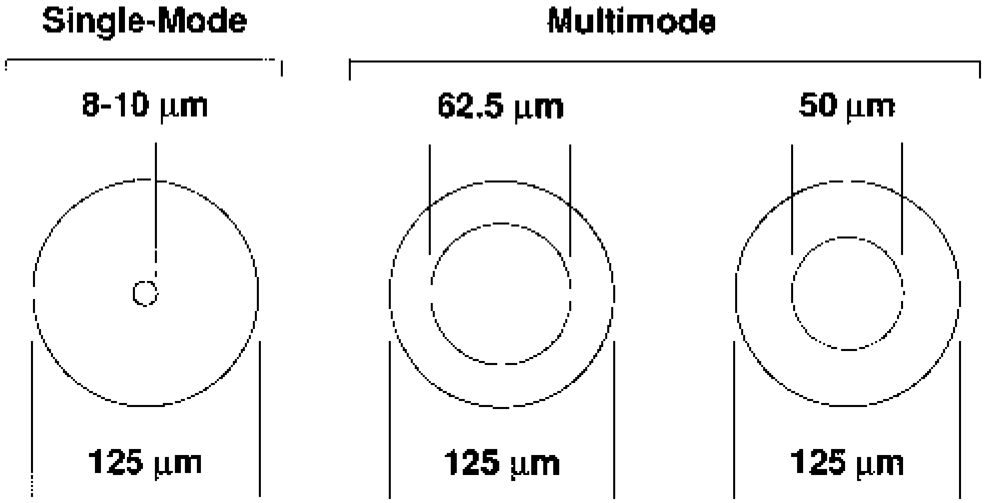
Its tremendous information-carrying capacity and low intrinsic loss have made single-mode fiber the ideal transmission medium for a multitude of applications. Multimode fiber is used primarily in systems with short transmission distances (under 2 km), such as premises communications and private data networks.

Optical Fiber Sizes

The international standard outer cladding diameter of most single-mode optical fibers is 125 microns (µm) for the glass and 245 µm for the coating. This standard is important because it ensures compatibility among connectors, splices, and tools used throughout the industry.

Standard single-mode fibers are manufactured with a small core size, approximately 8 to 10 µm in diameter. Multimode fibers, with core sizes of 50 to 100 µm in diameter, are used for specific applications, such as short-distance transmission of data. With its greater information-carrying capacity and lower intrinsic loss, single-mode fiber is typically used for longer-distance and higher-bandwidth applications (see *Figure 3*).

Figure 3. Optical Fiber Sizes



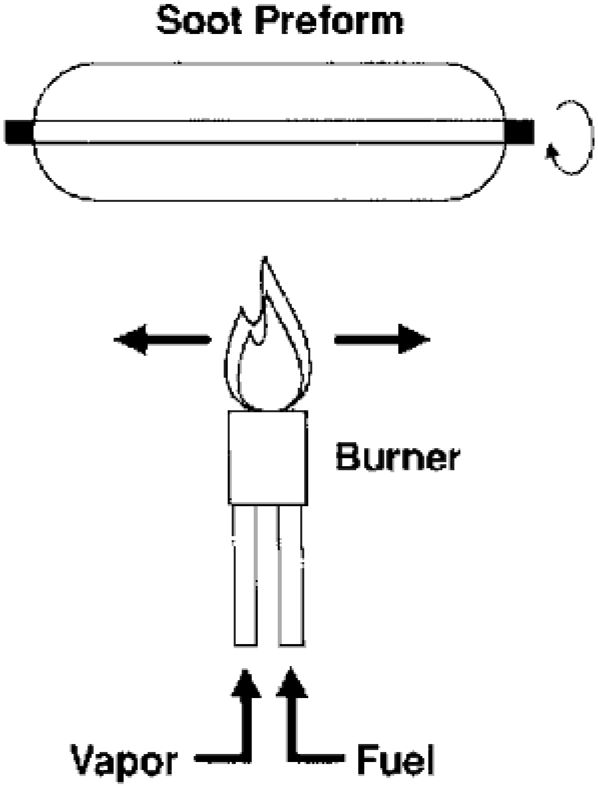
3. OVD Process

Optical fiber manufacturing consists of three primary steps: laydown, consolidation, and draw.

Laydown

In the laydown step, a soot preform is made from ultrapure vapors as they travel through a traversing burner and react in the flame to form fine soot particles of silica and germania (see *Figure 4*).

Figure 4. OVD Laydown Process



The OVD process is distinguished by the method of depositing the soot. These particles are deposited on the surface of a rotating target rod. The core material is deposited first, followed by the pure silica cladding. As both core and cladding raw materials are vapor-deposited, the entire preform is extremely pure.

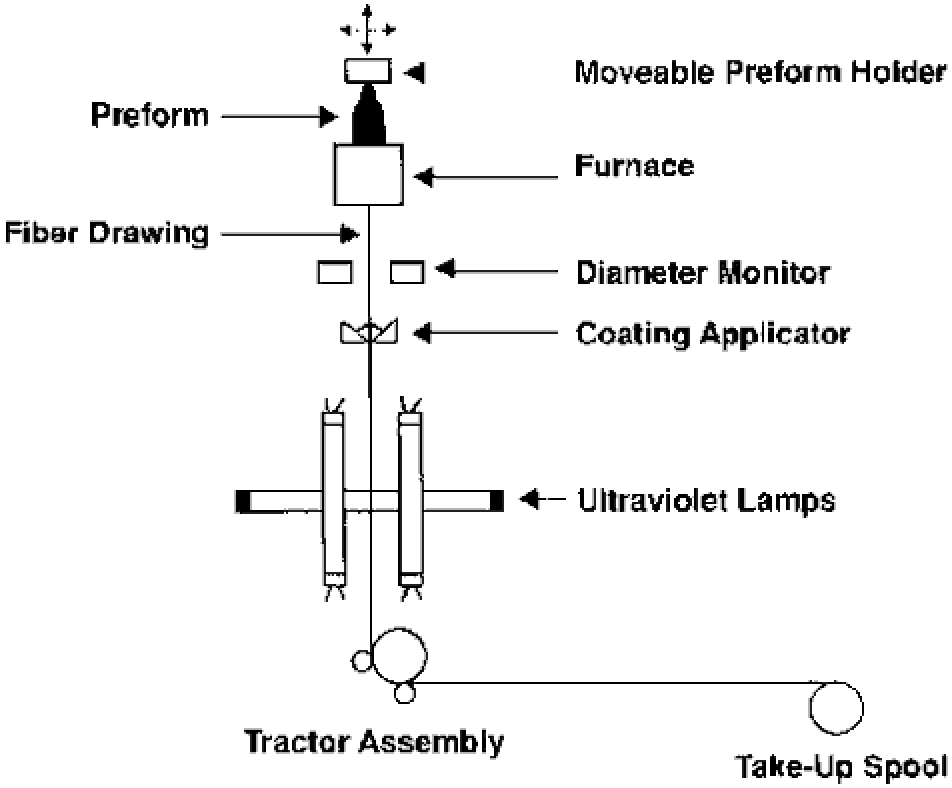
Consolidation

When deposition is complete, the target rod is removed from the center of the porous preform, and the preform is placed into a consolidation furnace. During the consolidation process, the water vapor is removed from the preform. This high-temperature consolidation step sinters the preform into a solid, dense, and transparent glass. The hole left by the target rod disappears completely; there is no hole in the finished fiber.

The Draw

The finished glass preform is placed in a draw tower and drawn into a continuous strand of glass fiber (see *Figure 5*).

Figure 5. Optical Fiber Drawing Process



First, the glass blank is lowered into the top of the draw furnace. The tip of the blank is heated until a piece of molten glass, called a gob, begins to fall from the blank—much like hot taffy. It pulls behind it a thin strand of glass, the beginning of an optical fiber.

The gob is cut off, and the fine fiber strand is threaded into a tractor assembly. Then, as the diameter is monitored, the assembly speeds up or slows down to control the size of the fiber's diameter precisely.

The fiber progresses through a laser-based on-line monitor that measures the diameter hundreds of times per second to ensure specified outside diameter. Next, the primary and secondary coatings are applied and cured, using ultraviolet lamps.

At the bottom of the draw, the fiber is wound on spools for further processing. Fiber on these spools is proof-tested to ensure the strength of each fiber, cut to length, and measured for performance of relevant optical and geometrical parameters. With a unique identification number that encodes all relevant manufacturing data (including raw materials and manufacturing equipment), each fiber reel is placed into protective shipping containers. Finally, the fiber is prepared for shipment to customers worldwide.

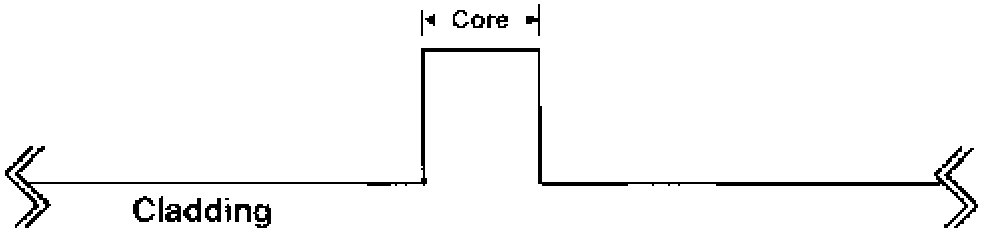
4. OVD Benefits

The benefits of fiber produced by the patented OVD process include enhanced reliability, lower attenuation, and solid geometrical and optical consistency.

Matched-Clad Fiber Consistency

Fibers are made of a core and cladding glass, each with slightly different compositions. The manufacturing process determines the relationship between those two glasses. The OVD process produces matched-clad fiber, the single-mode fiber design that allows for the most consistent fiber (see *Figure 6*).

Figure 6. Matched-Clad Fiber Design

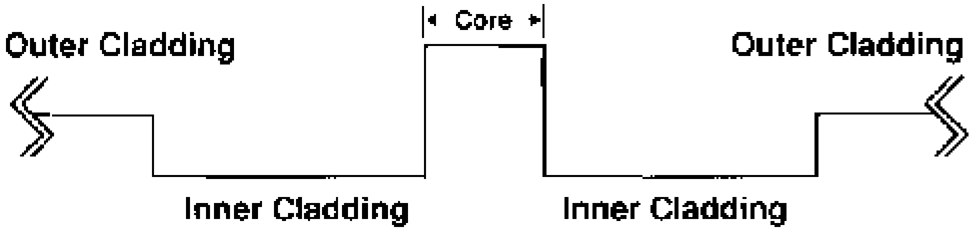


The OVD process produces well-controlled fiber profiles and geometry, both of which lead to a more consistent fiber. Fiber-to-fiber consistency is especially important when fibers from different manufacturing periods are united to form an optical system.

Depressed-Clad Fiber Profile

The inside vapor deposition (IVD) or modified chemical vapor deposition (MCVD) process produces what is called depressed-clad fiber because of the shape of its refractive index profile.

Figure 7. Depressed-Clad Fiber Design



Depressed-clad fibers are made with two different cladding glasses that form an inner and an outer cladding region. The inner cladding region adjacent to the fiber core has an index of refraction that is lower than that of pure silica, while the outer cladding has an index equal to that of pure silica. This depressed region is typically a design requirement as a result of using the IVD process.

Questions of Strength

One common misconception about optical fiber is that it must be fragile because it is made of glass. In fact, research, theoretical analysis, and practical experience prove that the opposite is true. While traditional bulk glass is brittle, the ultrapure glass of optical fibers exhibits both high tensile strength and extreme durability.

How strong is fiber? Figures like 600 or 800 thousand pounds per square inch are often cited, far more than copper's capability of 100 pounds per square inch. That figure refers to the ultimate tensile-breaking strength of fiber produced today. This is fiber's real, rather than theoretical, strength, which is 2 million pounds per square inch.

ABCs of Fiber Strength

The actual strength of optical fiber is determined by the depth of inherent microscopic flaws on its surface. These microscopic flaws exist in any fiber. As in a length of chain, the weakest link (or, in fiber's case, the deepest flaw) determines the ultimate strength of the entire length of fiber.

The OVD process offers a significant benefit in the area of fiber strength. Because OVD does not start with a bulk-glass or externally manufactured rube, every millimeter of the fiber is made from the ultrapure vapor-deposition process and contains fewer surface flaws.

Many fiber manufacturers tensile-load, or proof-test, fiber after production. This process eliminates the largest flaws, thereby ensuring a strength level to specification.

Life Expectancy

Fiber is designed and manufactured to provide a lifetime service of twenty years or more, provided it is cabled and installed according to recommended procedures. Life expectancy can be extrapolated from many tests. These test results, along with theoretical analysis, support the prediction of long service life. Environmental issues are also important to consider when evaluating a fiber's mechanical performance.

Bending Parameters

Optical fiber cable is easy to install because of its light weight, small size, and flexibility. Nevertheless, some people new to fiber express concern over the precautions required to avoid too-tight bends, which can cause loss of light or premature fiber breakage.

Experience and testing show that bare fiber can be safely looped with bend diameters as small as two inches, the recognized industry standard for minimum-bend diameter. Splice trays and other fiber-handling equipment, such as racks, are designed to prevent fiber-installation errors.

5. Fiber Geometry: A Key Factor in Splicing and System Performance

As greater volumes of fiber in higher-fiber-count cables are installed, system engineers are becoming increasingly conscious of the impact of splicing on their systems. Splice yields and losses have a profound impact on the quality of system performance and the cost of installation.

Glass geometry, the physical dimensions of an optical fiber, has been shown to be a primary contributor to splice loss and splice yield. Early on, one company recognized the benefits provided by tightly controlled fiber geometry and has steadily invested in continuous improvement in this area. Its tightly controlled manufacturing process helps engineers reduce systems costs and yet remain within the industry's low maximum splice-loss requirement.

Fiber that exhibits tightly controlled geometry tolerances will not only be easier and faster to splice but will also reduce the need for testing by ensuring predictable, high-quality splice performance. This is particularly true when fibers are spliced by passive, mechanical, or fusion techniques for both single fibers and fiber ribbons. In addition, tight geometry tolerances lead to the additional benefit of flexibility in equipment choice.

The benefits of tighter geometry tolerances can be significant. In today's fiber-intensive architectures, it is estimated that splicing and testing can account for more than 30 percent of the total labor costs of system installation.

Fiber Geometry Parameters

The three fiber geometry parameters that have the greatest impact on splicing performance are the following:

- **cladding diameter**—the outside diameter of the cladding glass region

- **core/clad concentricity (or core-to-cladding offset)**—how well the core is centered in the cladding glass region

- **fiber curl**—the amount of curvature over a fixed length of fiber

These parameters are determined and controlled during the fiber-manufacturing process. As fiber is cut and spliced according to needs dictated by each individual system, it is important to be able to count on consistent geometry along the entire length of the fiber and not to rely solely on measurements made only at the end of the fiber.

Cladding Diameter

Cladding diameter tolerances control the outer diameter of the fiber, with tighter tolerances ensuring that fibers are almost exactly the same size. During splicing, inconsistent cladding diameters can cause cores to be misaligned where the fibers join, leading to higher losses.

Cladding diameter tolerances are controlled by the drawing rate. Some manufacturers are able to control the tolerance of the cladding to a level of 125.0 ±1.0 µm. Once the cladding diameter tolerance is tightened to this level, core/clad concentricity becomes the single largest geometry contributor to splice loss.

Core/Clad Concentricity

Tighter core/clad concentricity tolerances help ensure that the fiber core is centered in relation to the cladding. This reduces the chance of ending up with cores that do not match up precisely when two fibers are spliced together. A core that is precisely centered in the fiber yields lower-loss splices more often.

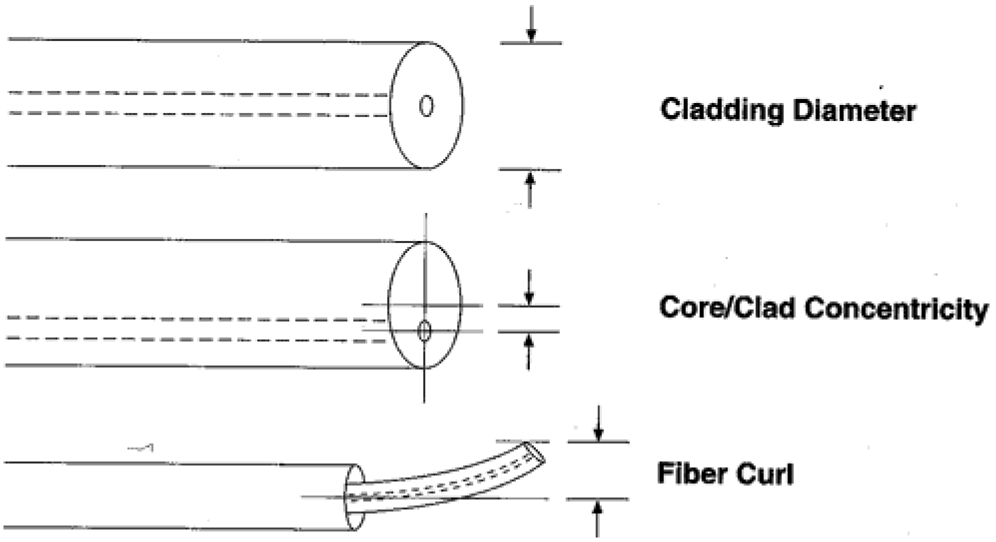
Core/clad concentricity is determined during the first stages of the manufacturing process, when the fiber design and resulting characteristics are created. During these laydown and consolidation processes, the dopant chemicals that make up the fiber must be deposited with precise control and symmetry to maintain consistent core/clad concentricity performance throughout the entire length of fiber.

Fiber Curl

Fiber curl is the inherent curvature along a specific length of optical fiber that is exhibited to some degree by all fibers. It is a result of thermal stresses that occur during the manufacturing process. Therefore, these factors must be rigorously monitored and controlled during fiber manufacture. Tighter fiber-curl tolerances reduce the possibility that fiber cores will be misaligned during splicing, thereby impacting splice loss.

Typical mass fusion splicers use fixed v-grooves for fiber alignment, where the effect of fiber curl is most noticeable.

Figure 8. Cladding Diameter, Core/Clad Concentricity, and Fiber Curl



6. How to Choose Optical Fiber

Single-Mode Fiber Performance Characteristics

The key optical performance parameters for single-mode fibers are attenuation, dispersion, and mode-field diameter.

Optical fiber performance parameters can vary significantly among fibers from different manufacturers, in ways that can affect your system's performance. It is important to understand how to specify the fiber that best meets system requirements.

Attenuation

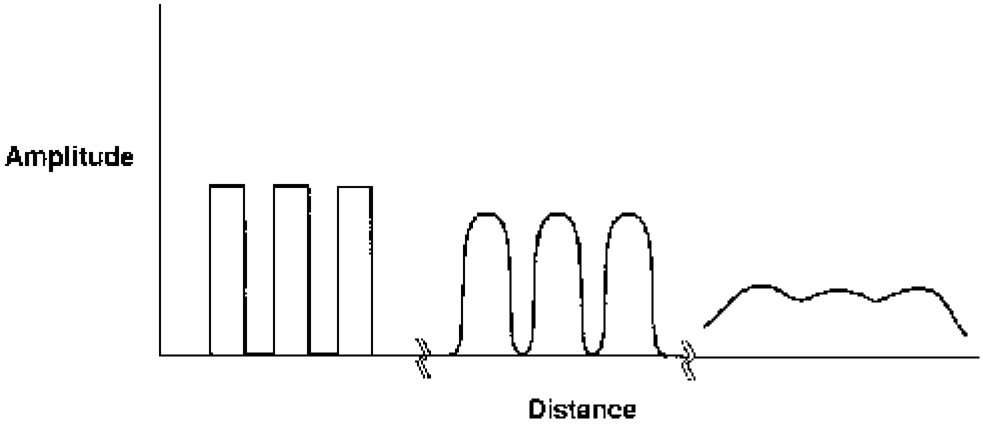
Attenuation is the reduction of signal strength or light power over the length of the light-carrying medium. Fiber attenuation is measured in decibels per kilometer (dB/km).

Optical fiber offers superior performance over other transmission media because it combines high bandwidth with low attenuation. This allows signals to be transmitted over longer distances while using fewer regenerators (amplifiers), reducing cost, and improving reliability.

Dispersion

Dispersion is the smearing or broadening of an optical signal that results from the many discrete wavelength components traveling at different rates (see *Figure 9*). In digital transmission, dispersion limits the maximum data rate or information-carrying capacity of a single-mode fiber link. In analog transmission, dispersion can cause a waveform to become significantly distorted and can result in unacceptable levels of composite second-order distortion (CSO).

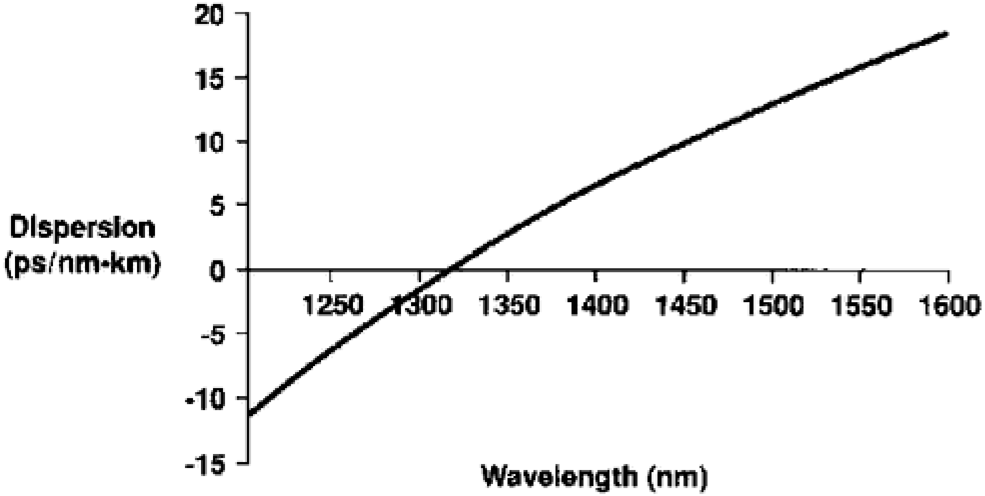
Figure 9. Signal Dispersion



Dispersion vs. Wavelength

Fiber dispersion varies with wavelength and is controlled by fiber design (see *Figure 10*). The wavelength at which dispersion equals zero is called the zero-dispersion wavelength. This is the wavelength at which fiber has its maximum information-carrying capacity. For standard single-mode fibers, this is in the region of 1310 nm.

Figure 10. Dispersion and Wavelength



Dispersion is expressed as the time increase in signal width (in picoseconds) per unit divided by the source spectral width (in nm) per unit times the length of fiber (in km).

Chromatic dispersion consists of two kinds of dispersion. Material dispersion refers to the pulse spreading caused by the specific composition of the glass. Waveguide dispersion is the pulse spreading that occurs as the light travels in both the core and the inner cladding glasses. The two types can be balanced to produce a wavelength of zero dispersion at 1310 nm.

Dispersion-Shifted Fiber

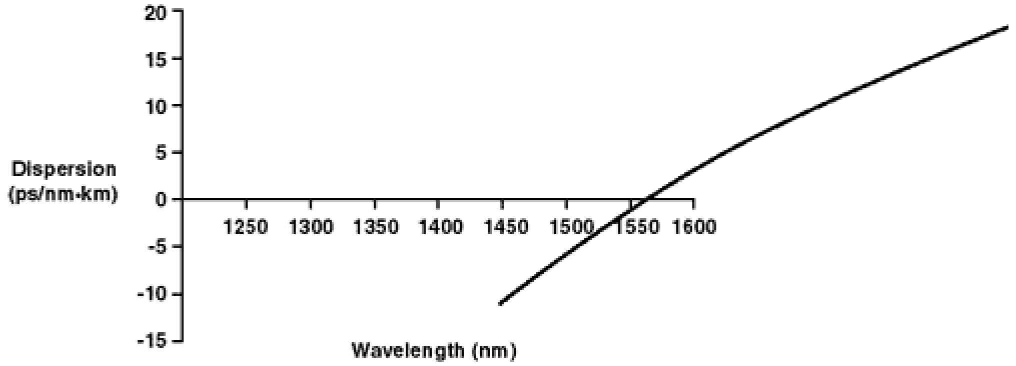
Optical fibers also can be manufactured to have the zero dispersion wavelength in the 1550 nm region, which coincides with fiber's lowest attenuation point. Dispersion-shifted fiber can allow for greater transmission capacity over longer distances than would be possible with standard single-mode fiber.

Transmission in the 1550 nm Window

Optical fibers also can be manufactured to have the zero dispersion wavelength in the 1550 nm region, which is also the point where silica-based fibers have inherently minimal attenuation. These fibers are referred to as nonzero dispersion-shifted fiber (NZDSF). This fiber is used primarily in applications that require both long-distance and high-capacity transmission rates.

For applications such as the interconnection of headends, delivery of programming to remote node sites, high-speed communication networks, and regional and metropolitan rings (used primarily for competitive access applications), NZDSF fiber can improve system reliability, increase capacity, and lower system costs (see *Figure 11*).

Figure 11. Wavelength and Dispersion



Mode-Field Diameter

Mode-field diameter (MFD) describes the size of the light-carrying portion of the fiber. This region includes the fiber core as well as a portion of the surrounding cladding glass. MFD is an important parameter for determining a fiber's resistance to bend-induced loss and can affect splice loss as well. MFD, rather than core diameter, is the functional parameter that determines optical performance when a fiber is coupled to a light source, connectorized, spliced, or bent. It is a function of wavelength, core diameter, and the refractive-index difference between the core and the cladding. These last two are fiber design and manufacturing parameters.

Cutoff Wavelength

Cutoff wavelength is the wavelength above which a single-mode fiber supports only one mode or ray of light. An optical fiber that is single-moded at a particular wavelength has two or more modes at wavelengths shorter than the cutoff wavelength.

The effective cutoff wavelength of a fiber is dependent on the length of fiber and its deployment. The longer the fiber, the shorter the effective cutoff wavelength. Or, the smaller the bend radius of a loop of the fiber is, the shorter the effective cutoff wavelength will be.

Environmental Performance

While cable design and construction play a key role in environmental performance, optimum system performance requires the user to specify fiber that will operate without undue loss from microbending.

Microbends are small-scale perturbations along the fiber axis, the amplitude of which are on the order of microns. These distortions can cause light to leak out of a fiber. Microbending may be induced at very cold temperatures because the glass has a different coefficient of thermal expansion from the coating and cabling materials. At low temperatures, the coating and cable become more rigid and contract more than the glass. Consequently, enough load may be exerted on the glass to cause microbends. Coating, fiber ribbon, and cabling materials are selected by manufacturers to minimize loss due to microbending.

Specification Examples of Uncabled Fiber

To ensure that a cabled fiber provides the best performance for a specific application, it is important to work with an optical fiber–cable supplier to specify the fiber parameters just reviewed as well as the geometric characteristics that provide the consistency necessary for acceptable splicing and connectorizing.

Splicers and Connectors

As optical fiber moves closer to the customer, where cable lengths are shorter and cables have higher fiber counts, the need for joining fibers becomes greater. Splicing and connectorizing play a critical role both in the cost of installation and in system performance.

The object of splicing and connectorizing is to match, precisely, the core of one optical fiber with that of another in order to produce a smooth channel through which light signals can continue without alteration or interruption.

There are two ways that fibers are joined:

- splices, which form permanent connections between fibers in the system

- connectors, which provide remateable connections, typically at termination points

Fusion Splicing

Fusion splicing provides a fast, reliable, low-loss, fiber-to-fiber connection by creating a homogenous joint between the two fiber ends. The fibers are melted or fused together by heating the fiber ends, typically using an electric arc. Fusion splices provide the highest-quality joint with the lowest loss (in the range of 0.04 dB to 0.10 dB) and are practically nonreflective.

Mechanical Splicing

Mechanical splicing is an alternative method of making a permanent connection between fibers. In the past, the disadvantages of mechanical splicing have been slightly higher losses, less-reliable performance, and a cost associated with each splice. However, advances in the technology have significantly improved its performance. System operators typically use mechanical splicing for emergency restoration because it is fast, inexpensive, and easy.

Connectors

Connectors are used in applications where flexibility is required in routing an optical signal from lasers to receivers, wherever reconfiguration is necessary, and in terminating cables. These remateable connections simplify system reconfigurations to meet changing customer requirements.

Self-Test

1. A physics principle that became the theoretical foundation of optical fiber communications holds that ___________ in a __________ medium can carry more information over longer distances.

    a. light; coaxial

    b. electrical signals; glass

    c. light; glass

    d. electrical signals; copper

2. Single-mode fiber was the first type of fiber to be commercialized.

    a. true

    b. false

3. What are the three primary steps in the optical fiber manufacturing process?

    a. laydown, compilation, and draw

    b. assembly, consolidation, and pull

    c. laydown, consolidation, and draw

    d. assembly, compilation, and pull

4. Which of the following is not a characteristic of the fiber produced by the OVD process?
    a. less attenuation
    b. infinite flexibility
    c. exceptional strength
    d. fewer flaws
5. Fiber curl is exhibited by all fibers.
    a. true
    b. false
6. Attenuation is which of the following?
    a. the inherent curvature along a specific length of optical fiber
    b. the wavelength above which a single-mode fiber supports only one mode or ray of light
    c. the reduction of signal strength over the length of the light-carrying medium
    d. smearing an optical signal that results from the many discrete wavelength components traveling at different rates
7. Controlling the _____________ at which light waves are transmitted makes it possible to control how efficiently they reach their destination.
    a. speed
    b. angle
    c. time
    d. rate
8. Dispersion is which of the following?
    a. the inherent curvature along a specific length of optical fiber
    b. the wavelength above which a single-mode fiber supports only one mode or ray of light

c. the reduction of signal strength over the length of the light-carrying medium

d. smearing an optical signal that results from the many discrete wavelength components traveling at different rates

9. The longer the fiber is, the shorter the effective cutoff wavelength will be.

a. true

b. false

10. Mechanical splicing is the predominant choice of operators for joining fibers.

a. true

b. false

Correct Answers

1. A physics principle that became the theoretical foundation of optical fiber communications holds that ____________ in a ___________ medium can carry more information over longer distances.

a. light; coaxial

b. electrical signals; glass

c. light; glass

d. electrical signals; copper

See Topic 1.

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b. assembly, consolidation, and pull

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    See Topic 2.

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Acronym Guide

CNR
carrier-to-noise ratio

CSO
composite second-order distortion

IVD
inside vapor deposition

MCVD
modified chemical vapor deposition

MFD
mode-field diameter

NZDSF
nonzero dispersion-shifted fiber

OVD
outside vapor deposition

RF
radio frequency