Introductory Fiber Optics Tutorial

Overview

Fiber optics is the technology of using glass-based waveguides to transport information from one point to another in the form of light.

A basic fiber optic system consists of a transmitting device which generates the light signal; an optical fiber cable which carries the light; and a receiver which accepts the light signal. The information (voice, data, or video) is encoded into electrical signals. At the light source, these electrical signals are converted into either digital or analog light signals. Once the signals are converted to light, they travel down the fiber until they reach a detector which changes the light signals back into electrical signals. Finally, the electrical signals are decoded into information in the form of voice, data, and/or video.

Fiber optic cables have many advantages:

- Cables can be all dielectric, no electromagnetic interference
- Low loss allows long links without a repeater
- Universal medium – video, data or voice applications
- Small, lightweight cables make handling and installation easy
- Virtually unlimited bandwidth or information carrying capacity

Optical fiber can carry more data at faster rates for longer distances than copper and coax. When an optimum architecture is deployed, fiber optic networks are inherently future-proof for building outside plant infrastructure.

Principles of Optical Waveguides

This section provides a description of optical waveguides, principles of operation and performance parameters used to characterize optical fiber.

Optical Waveguides

Fiber consists of a glass core and cladding area (the waveguide) covered by a protective acrylate coating. The core is the central region of an optical fiber through which light is transmitted. The cladding is the outer layer of the fiber. The core and cladding are manufactured together and cannot be separated from one another, but they each have their own chemical and optical properties. The core is silica doped with germanium. The cladding is pure silica glass.

The glass waveguide is protected by a coating, typically acrylate, applied during the manufacturing process to provide physical and environmental robustness for the fiber. The coating sizes can vary but the standard sizes are 250 µm, typically found in loose tube cables, or 900 µm typically found in tight-buffered indoor cables.

Principles of Operation

The following terms characterize an optical fiber's basic principles of operation: index of refraction, acceptance cone, and total internal reflection.

Index of Refraction

Index of refraction is a comparison between the speed of light in a medium and the speed of light in a vacuum (how fast the light travels through the material compared to its speed through a vacuum). The larger the index of refraction, the slower light travels in that medium (here, the optical fiber). When light passes from a medium of one index of refraction to another medium with a different index of refraction, the path will be refracted or reflected, depending on the angle of incidence.

Acceptance Cone/Numerical Aperture

To be carried through the core of the fiber, light must strike the end of the fiber within an imaginary "acceptance cone." The acceptance cone defines the maximum angle from the fiber's centerline at which light can be projected into the fiber core, without being lost. The acceptance cone is quantified by the Numerical Aperture (NA), the larger the NA, the larger the acceptance cone and the easier it is to launch light into the fiber.

Total Internal Reflection

Total Internal Reflection is the reflection that occurs when a light ray traveling in one material hits a different material at a glancing angle and reflects back into the original material with very little loss of light. Since the core and cladding are constructed from different compositions of glass, light entering the core is confined to the boundaries of the core because it reflects back whenever it reaches the cladding. Looking out over a calm lake and seeing the distant landscape reflected in the lake (like a mirror) is an example of the principle of total internal reflection.

Performance Parameters

System performance can be influenced by the optical fiber as well as the active electronic equipment characteristics. Performance of the entire system is what matters so both fiber and active equipment characteristics should be considered. The following terms define the performance parameters of fiber: wavelength, frequency, attenuation, and bandwidth.

Wavelength

Wavelength is a characteristic of light and is measured in nanometers. In the visible spectrum, wavelength can be described as the color of the light. Typical wavelengths for fiber optic use are 850 nm, 13010 nm, 1550 nm all of which are invisible to the naked eye. Visible light ranges from 700 nm (red) to 400 nm (violet).

Attenuation

Attenuation is the loss of optical power as light travels down the fiber. A fiber with low attenuation allows more light to reach the receiver after a given length of fiber, than one with high attenuation. Overall attenuation (end-to-end) for a system is measured in decibels (dB); attenuation for the fiber itself is specified as loss per length (dB/km). Attenuation is generally placed in two categories — intrinsic or extrinsic.

> **Intrinsic attenuation** occurs due to properties inherent to the fiber, such as its physical and chemical composition. The atomic structure of the glass, as well as chemicals added to or found in the silica, can cause light to be absorbed or scattered. In either case, optical power is being lost due to effects within the fiber itself. Optical fibers use very pure silica and high-quality additives (to engineer the glass' characteristics); impurities have been minimized, bringing today's fibers close to the theoretical minimum attenuation.
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> **Extrinsic attenuation** can be caused by two external sources: macrobending or microbending. A macrobend is a large-scale bend that is visible, such as a bent or kinked cable. A microbend is a small-scale distortion, such as pressure on the fiber from an over-tightened cable tie. Microbending is very localized and may not always be visible.

Bandwidth and Dispersion

Bandwidth is the amount of information that a system can carry such that each pulse of light is still distinguishable by the receiver. Although not a linear relationship, the longer the fiber, the lower the overall bandwidth for that system. Bandwidth for multimode fiber is measured in MHz•km. For single-mode fiber the bandwidth is often stated as "virtually unlimited." However, there are practical considerations that affect how light propagates

through fiber and how the information carrying capacity is impacted.
Dispersion refers to the spreading of a light pulse over time, with the result that adjacent pulses begin to blend and become non-distinguishable as the dispersion increases. Dispersion effects compound as system length increases, and generally, high-speed systems are more susceptible than low speed systems. Ultimately, the amount of dispersion in a fiber limits its bandwidth.

Dispersion can be classified into two main groups: modal and chromatic. Multimode fiber experiences modal dispersion because the multiple modes (paths) that conduct a light pulse are of varying lengths. A single light pulse actually shares the multiple modes in its journey through a fiber. Traveling at a given speed through varying path lengths means that some of the light pulse arrives behind other parts. For this reason, multimode communication fibers are made with a graded index of refraction in the core so that the longer paths travel faster than the shorter ones, making the light pulse arrive "together," minimizing modal dispersion.

In single-mode fiber, there is only one mode; therefore, modal dispersion does not exist. However, a laser pulse contains not a single wavelength, but a small range of wavelengths (or colors) of light. Different wavelengths travel at different speeds in the fiber. Therefore a pulse that contains energy at several wavelengths will "stretch out" as it travels through the fiber because some of the wavelengths move faster than others. At the extreme, adjacent pulses blend and become unreadable. In addition, a small amount of energy travels outside the core, in the edge of the cladding, where the index is lower and the speed is faster. These effects can be engineered so that they balance out to zero dispersion at a given operating wavelength – the zero-dispersion wavelength. Dispersion is measured in picoseconds per nanometer per kilometer or ps/(nm•km); this unit gives the pulse spreading (time shift) for each nm change in wavelength and for each km of system length.

Fiber Types

There are two basic fiber types: single-mode and multimode. Both act as transmission mediums for light, but operate in different ways with different characteristics and applications.

Once light enters an optical fiber, it travels down the fiber in a stable path called a mode. When a single pulse of light enters the fiber, it actually travels in one or more modes. Under ideal conditions, it will emerge from the fiber as a single pulse. The key difference between multimode and single-mode fiber is the core size. As core size is reduced there is a point at which only one mode remains, no matter how much smaller the core is made.

Single-mode fiber allows only one mode of light to travel within the fiber. The core size is approximately 8.3 µm. Single-mode fibers are used in applications where low signal loss and high data rates are required, such as access and long distance applications.

Multimode fiber allows for more than one mode of light to travel in the fiber. Common core sizes are 50, 62.5, or 100 µm. Multimode fiber is better suited for short distance applications. Multimode can be used with inexpensive connectors and LED transmitters making the total system cost lower.

Cable Types

There are two distinct optical fiber cable designs: loose tube cables and tight-buffered cables.

Loose tube cables were originally designed for outdoor environments and interbuilding campus backbone applications, but today there are also indoor (flame-retardant) versions available. The loose tube cable design provides stable and highly reliable optical transmission characteristics over a wide temperature range and offers very high fiber density (many fibers in a small cable diameter). The loose tube design also ensures long cable life by isolating the fibers from mechanical stresses. Loose tube cables are available in single-fiber and ribbon fiber designs. Single-fiber cables contain one or more buffer tubes with typically two to 12 individual fibers per tube. Ribbon cables contain one or more large buffer tubes with one or a stack of ribbons (typically 12 fibers each). Ribbon designs provide the highest fiber density and permit economical mass fusion splicing (12 at a time vs. a single fiber at a time). Either ribbon or single-fiber loose tube cables may be used in a feeder network, but loose tube cables are best where a portion of the fibers will be accessed at many points along the route. A single buffer tube may be accessed, while the remaining tubes are left unopened in a closure.

Tight-buffered cables are designed primarily for indoor environments, such as building backbones, horizontal applications, patch cords and equipment cables. Tight-buffered cables are more sensitive to temperature extremes and standard indoor products are not usually rated for long-term UV exposure (sunlight). The outside jacket is typically yellow for single-mode cables and orange for multimode cables. Tight-buffered cables are available for plenum or riser use. Tight-buffered cable assemblies, such as pigtails and patch cords, can be used inside of cabinets and closures that are placed outdoors, since these are protected environments.

Hardware

Hardware encompasses a wide range of equipment racks, splice and connector housings, cable management accessories, patch panels, cabinets, closures and pedestals as well as bothpassive and controlled environment vaults. Hardware has several functions from protection, connectivity, storage, management, and flexibility.

In particular for closures, there are sealed and breathable devices. Above-grade applications can either use sealed or "breathable" closures. Breathable means water-resistant and ventilated, but not waterproofed. Below grade applications require sealed closures to prevent ingress of moisture and humidity.

There are two types of connection schemes: cross-connection and interconnection. In cross-connection, all incoming cables are terminated in patch panels and connectivity is provided using patch cords to configure the links. Interconnection involves terminating one cable in the back of a patch panel and plugging pigtails from a second cable into the front of the same patch panel.

Network points that serve many subscribers will typically be cabinets for ease of fiber management and re-entry. Network points that serve only a few subscribers will typically be a smaller enclosure/closure.

CO/HE hardware will typically be equipment racks, connector and splice housings, and coupler shelves to manage a greater number of subscribers.

Selecting the appropriate hardware will depend on the physical network point, number of subscribers, installation method (connectors or splicing) and the location (aerial, above grade, or below grade.)

Connectorization

Connectorization involves installing a connector on the end of a fiber and allows the fiber to be connected, disconnected, and reconnected without the use of any special tools for the convenience of managing and configuring a network.

There are two types of connectors: single-fiber and multi-fiber connectors.
The most common single-fiber connectors are ST® compatible, SC and FC. The most common multi-fiber connectors today are SC/Duplex, MT-RJ, LC and MTP®. The SC/Duplex, MT-RJ, and LC connectors are all two-fiber connectors. The SC/Duplex

and LC connectors use two ferrules (essentially two connectors) held together by a clip for handling as a single unit. MT-RJ connectors use a single ferrule and have a locking mechanism similar to a copper RJ-45 connector. The MTP® is a ribbon connector, available in single ferrules accommodating up to 12 fibers.

Termination Techniques
There are three common termination techniques for optical fibers:

- Pigtail splicing
- Preconnectorized cable assemblies
- Field connectorization

Pigtail Splicing is a termination technique where one end of the cable is already terminated with factory-installed connectors. The non-terminated end is fusion-spliced to the cable to be terminated. Pigtail assemblies are available in a variety of cable and connector types, custom lengths and fiber counts. Pigtail splicing requires splicing hardware – splice housing, splice trays, and heat-shrink protectors

Preconnectorized Assemblies are assemblies with both ends already terminated with factory-installed connectors. These assemblies are available in a variety of cable and connector types, custom lengths, and fiber counts.

Prestubbed hardware is also available, in which the preconnectorized assembly is already mounted in the back of the connector housing/ patch panel – one need only mount the hardware in a rack and pull the other end of the cable. Special pulling grips are available to protect the connectors during pulling. When using preconnectorized assemblies, it is necessary to carefully engineer the cable length and, if pulling a terminated end through a conduit, make certain that the conduit is large enough to accommodate the pulling grip.

Field Connectorization is the direct installation of a fiber optic connector in the field. Connector advancements have made field connectorization fast and easy. Both epoxy/polish and no-epoxy/no-polish field-installable connectors are available. The no-epoxy/no-polish type requires the least complex and lowest cost tools and can be taught in a minimum of time compared to polish types. Attenuation and reflectance is comparable to factory terminated connectors.

Photonics: Splitters, Couplers, and WDM Devices

The term "photonics," as used here, refers to passive devices that manage light. The most common photonic device in passive optical networks today is the optical splitter (also called a coupler). Splitters divide the light from one fiber among two or more output fibers. In access networks, the splitter outputs are usually equal in power level and ratios may range from 1 x 2 to 1 x 32. Unequal (usually custom) outputs are also available for use where the splitter will feed downstream links of very different lengths or secondary splitters of different ratios. Attenuation through a splitter depends primarily on the split ratio (a 1 x 2 is about 3 dB, a 1 x 4 is about 6 dB, etc.) plus a small amount inherent to the devices (and any splicing).

Wavelength Division Multiplexing (WDM) devices allow a single fiber to carry multiple wavelengths by combining or separating individual wavelengths.

Concatenated Splitters are built by splicing 1 x 2 splitters to each other to achieve an overall split ratio. For example, three 1 x 2's can be spliced together to get a 1 x 4 split. 1 x 2 devices are available in equal splits as well as splits ranging from 99/1% to 45/55%. Custom non-equal split ratios are usually built by concatenating the right combination of these 1 x 2 devices.

Planar Splitters are built on a single chip with input and output fibers attached to the chip.

Testing

Testing of any installed cabling system is crucial to ensuring the overall integrity and long-term performance of the network. Proper testing also maximizes the system's longevity, minimizes downtime and maintenance and facilities system upgrades or reconfigurations. It is important to test the system after installation to ensure the specifications are met and to document the system performance. When troubleshooting is necessary, testing can determine whether a problem is in the cable plant or the electronics by checking power levels at key points. If there is an issue with the cabling, testing can determine the magnitude and location of a fault.

Use of connectorization (instead of splicing) at key locations can allow for easy troubleshooting by creating convenient test points. This is especially important in splitter-based networks because it is difficult to test through splitters. While attenuation measurements (with a power meter and light source) can be made through a splitter, an Optical Time Domain Reflectometer (OTDR) will produce very limited information through splitters. Being able to temporarily disconnect a fiber from a splitter input or output allows the OTDR to be used for finding the distance to a fault.

For fiber optic systems, the primary field test parameter is attenuation. Attenuation measures optical power loss between cable termination points. System loss measurements should always be less than the link-loss budget calculated in the design. The OTDR can also measure distance to points of loss as well as faults (or simply the far end). The OTDR works much like radar by sending out pulses of light and then looking for backscatter and reflections that return to the OTDR. Using the speed of light and the time interval for the reflections, the distance to splices, connector and end points can be measured.