Basics of Fiber Optics

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Fiber optics, which is the science of light transmission through very fine glass or plastic fibers, continues to be used in more and more applications due to its inherent advantages over copper conductors. The purpose of this article is to provide the non-technical reader with an overview of these advantages, as well as the properties and applications of fiber optics.

I. Advantages

Fiber optics has many advantages over copper wire (see Table 1) including:

- **Increased bandwidth:** The high signal bandwidth of optical fibers provides significantly greater information carrying capacity. Typical bandwidths for multimode (MM) fibers are between 200 and 600MHz-km and >10GHz-km for single mode (SM) fibers. Typical values for electrical conductors are 10 to 25MHz-km.

- **Electromagnetic/Radio Frequency Interference Immunity:** Optical fibers are immune to electromagnetic interference and emit no radiation.

- **Decreased cost, size and weight:** Compared to copper conductors of equivalent signal carrying capacity, fiber optic cables are easier to install, require less duct space, weigh 10 to 15 times less and cost less than copper.

- **Lower loss:** Optical fiber has lower attenuation (loss of signal intensity) than copper conductors, allowing longer cable runs and fewer repeaters.

- **No sparks or shorts:** Fiber optics do not emit sparks or cause short circuits, which is important in explosive gas or flammable environments.

- **Security:** Since fiber optic systems do not emit RF signals, they are difficult to tap into without being detected.

- **Grounding:** Fiber optic cables do not have any metal conductors; consequently, they do not pose the shock hazards inherent in copper cables.

- **Electrical Isolation:** Fiber optics allow transmission between two points without regard to the electrical potential between them.

	Coaxial Cable	Fiber Optic Cable (MM)	Fiber Optic Cable (SM)
Representative distance bandwidth products	100 MHz km	500 MHz km	100,000+ MHz km
Attenuation/km @ 1 GHz	>45 dB	1 dB	0.2 dB
Cable cost ($/m)	$$$$$$$$$	$	$
Cable diameter (in.)	1	1/8	1/8
Data security	Low	Excellent	Excellent
EMI immunity	OK	Excellent	Excellent

Table 1: Advantages of Fiber Optics over Copper

II. Fiber Optic Link Components

In order to comprehend how fiber optic applications work, it is important to understand the components of a fiber optic link. Simplistically, there are four main components in a fiber optic link (Figure 1).

- Optical Transmitter
- Optical Fiber/Cable
- Connectors
- Optical Receiver

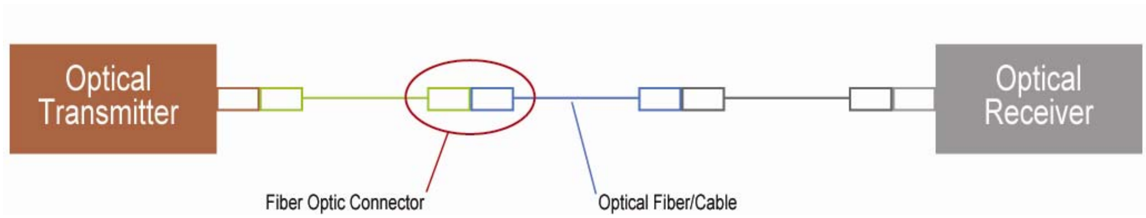

Figure 1: Simple Fiber Optic Link

II.1 Transmitter

The transmitter converts the electrical signals to optical. A transmitter contains a light source such as a Light Emitting Diode (LED) or a Laser (Light Amplification by Stimulated Emission of Radiation) diode, or a Vertical Cavity Surface Emitting Laser (VCSEL).

LED: Is used in multimode applications and has the largest spectral width that carries the least amount of bandwidth.

VCSEL: Is also used in multimode applications with a narrower spectral width that can carry more bandwidth than the LED.

LASER: Has the smallest spectral width, carries the most bandwidth, and is used in singlemode applications.

These sources produce light at certain wavelengths depending upon the materials from which they are made. Most fiber optic sources use wavelengths in the infrared band, specifically 850nm (1nm=10^{-9}m), 1300nm and 1550nm. For reference, visible light operates in the 400-700nm range (see Figure 2).

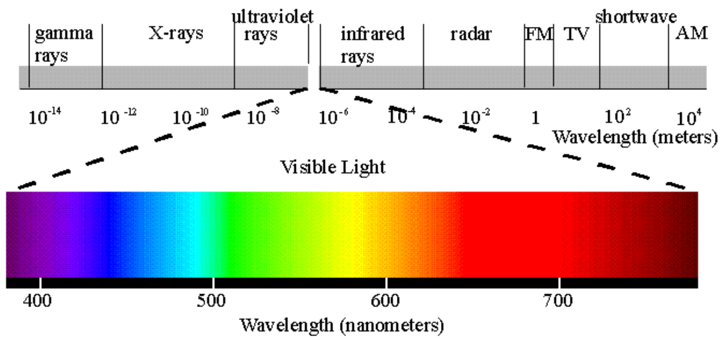

Figure 2: Electromagnetic Spectrum

II.2 Optical Fiber/Cable

In this section, we discuss the structure and properties of an optical fiber, how it guides light, and how it is cabled for protection.

An optical fiber is made of 3 concentric layers (see Figure 3):

- Core: This central section, made of silica or doped silica, is the light transmitting region of the fiber.
- Cladding: This is the first layer around the core. It is also made of silica, but not the same composition as the core. This creates an optical waveguide which confines the light in the core by total internal reflection at the core-cladding interface.
- Coating: The coating is the first non-optical layer around the cladding. The coating typically consists of one or more layers of polymer that protect the silica structure against physical or environmental damage. The coating is stripped off when the fiber is connectorized or fusion spliced.

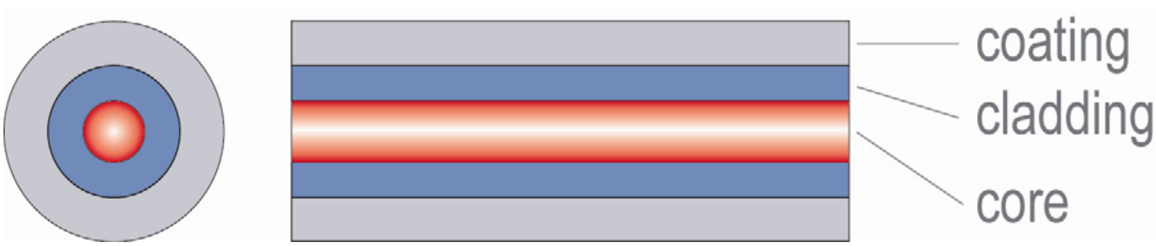

Figure 3: Optical Fiber Construction

- Buffer (not pictured): The buffer is an important feature of the fiber. It is 900 microns and helps protect the fiber from breaking during installation and termination and is located outside of the coating.

The light is "guided" down (see Figure 4) the core of the fiber by the optical "cladding" which has a lower refractive index (the ratio of the velocity of light in a vacuum to its velocity in a specified medium) that traps light in the core through "total internal reflection."

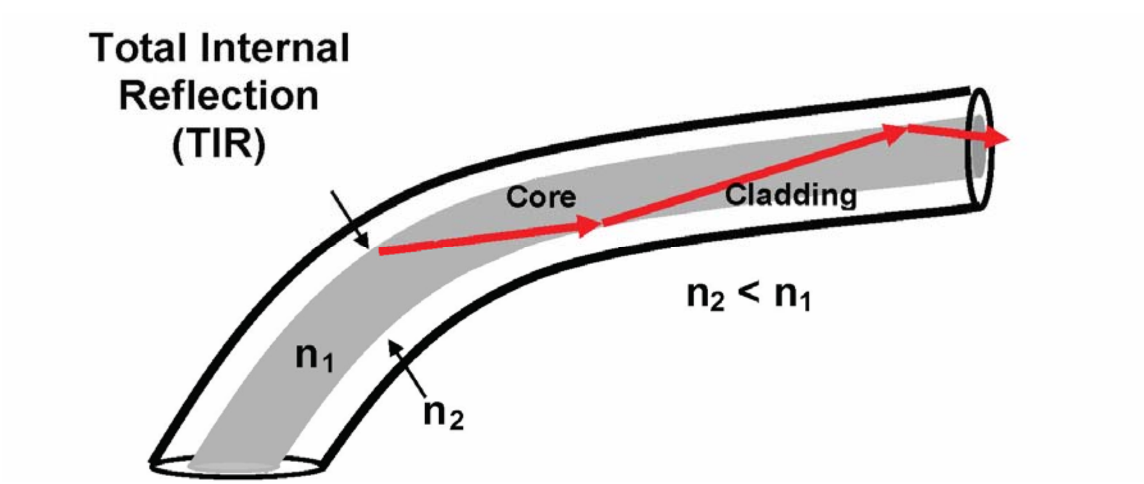

Figure 4: Diagram showing Total Internal Reflection

In fiber optic communications, single mode and multimode fiber constructions are used depending on the application. In multimode fiber (Figure 5), light travels through the fiber following different light paths called "modes." In single mode fiber, only one mode is propagated "straight" through the fiber (Figure 6).

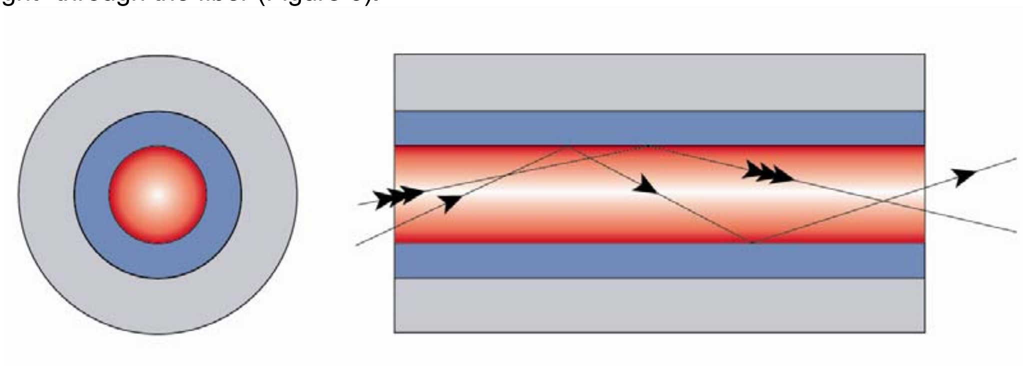

Figure 5: Multimode Fiber Light Propagation

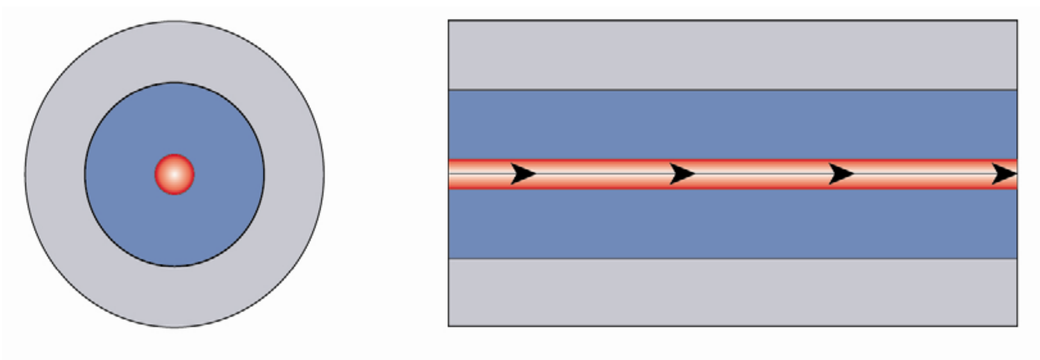

Figure 6: Single Mode Fiber Light Propagation

Typical multimode fibers have a core diameter/cladding diameter ratio of 50 microns/125 microns (10^{-6} meters) and 62.5/125 (although 100/140 and other sizes are sometimes used depending on the application). Single mode fibers have a core/cladding ratio of 9/125 at wavelengths of 1300nm and 1550nm.

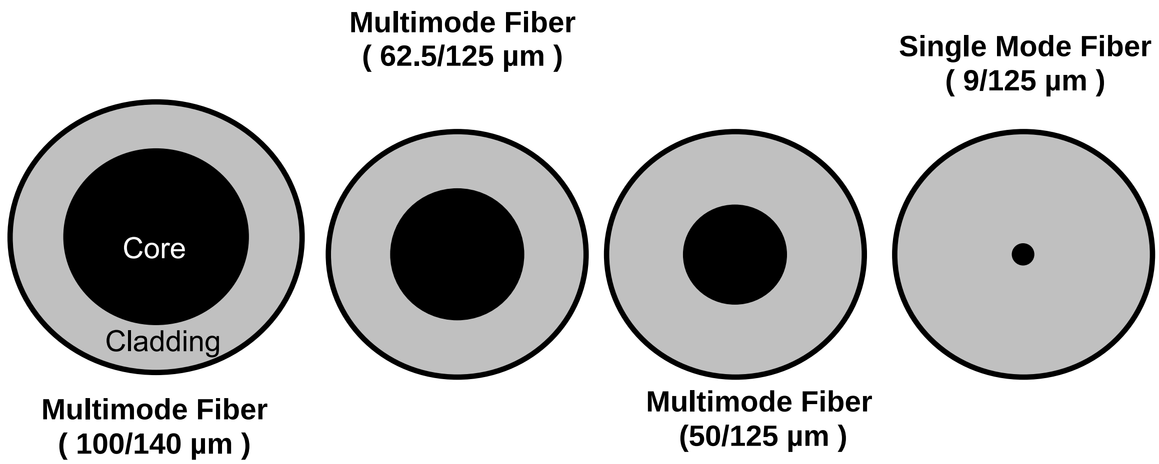

Figure 7: Popular Optical Fiber Core/Cladding Diameter Ratios

Light is gradually attenuated when it travels through fiber. The attenuation value is expressed in dB/km (decibel per kilometer). Attenuation is a function of the wavelength (λ) of the light. Figure 8 shows the attenuation as a function of the wavelength.

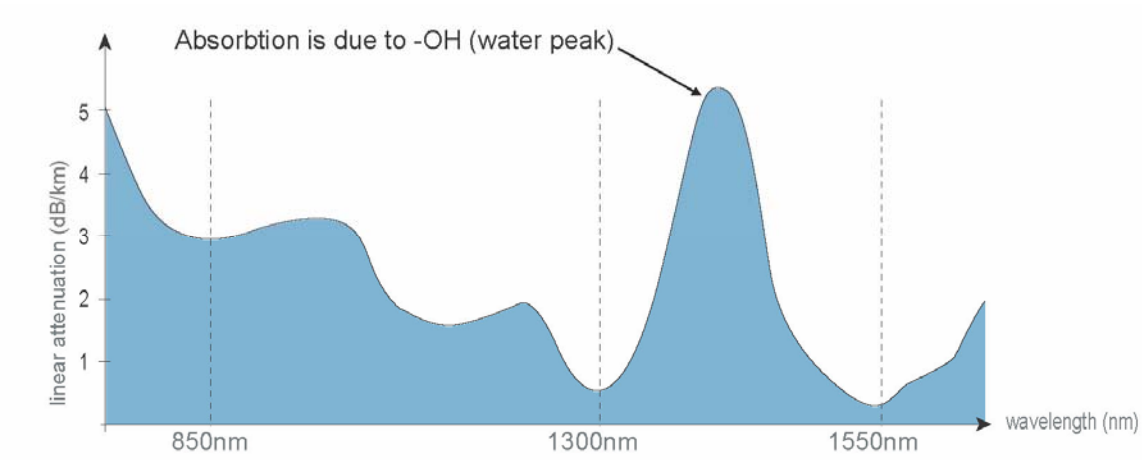

Figure 8: Attenuation vs. Wavelength of Optical Fiber

As discussed in Section II.1, the typical operating wavelengths are 850nm (nanometers) and 1300nm in multimode, and 1300nm or 1550nm in single mode. Note that there are natural "dips" in the attenuation graph at these wavelengths. For example, at an 850nm operating wavelength, there is 3dB attenuation after 1km propagation (according to the graph). 3dB of attenuation means that 50% of light has been lost.

Bandwidth is a measure of the data-carrying capacity of an optical fiber. It is expressed as the product of frequency and distance. For example, a fiber with a bandwidth of 500MHz-km (Megahertz kilometer) can transmit data at a rate of 500MHz along one kilometer of fiber. The bandwidth of single mode fibers is much higher than in multimode fibers. The main reason for the lower bandwidth in multimode fibers is modal dispersion.

In multimode fibers, information (ABC) is propagated in fiber according to N modes or paths (see Figure 9), as if it were "duplicated" N times (for example, in the diagram, the mode 3 path is longer than the mode 2 path, which are both longer than the mode 1 path). If information is too close, there is a risk of overlapping ("smearing") the information, and then it will not be recoverable at the end of the fiber. It is necessary to space the data sufficiently to avoid overlap, i.e., to limit the bandwidth.

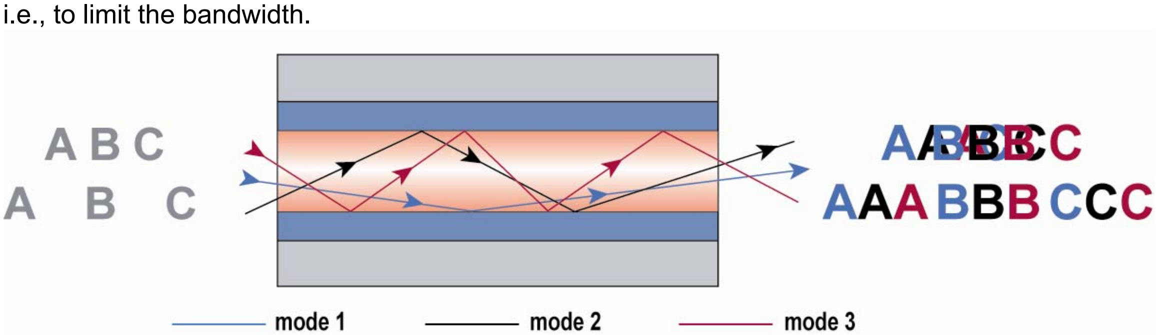

Figure 9: Modal Dispersion in Multimode Fibers

Modal dispersion can be alleviated to a large extent by grading the index of refraction from the middle of the core to the cladding (graded index fiber), thereby equalizing the paths (Figure 10).

In a step index fiber, the index of refraction changes abruptly from the core to the cladding. To help reduce modal dispersion, fiber manufacturers created graded-index fiber. Graded-index fiber has an index of refraction which gradually increases as it progresses to the center of the core. Light travels slower as the index of refraction increases. Thus, a light path propagating directly down the center of the fiber has the shortest path but will arrive at the receiver at the same time as light that took a longer path due to the graded-index of the fiber.

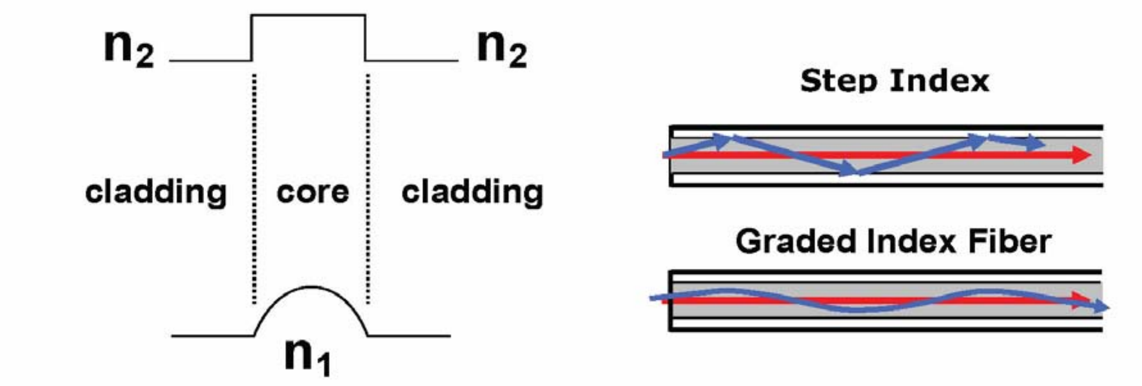

Figure 10: Graded Index in Multimode Fibers

Of course, modal dispersion is not an issue in single mode fiber because only a single mode is propagated (Figure 11).

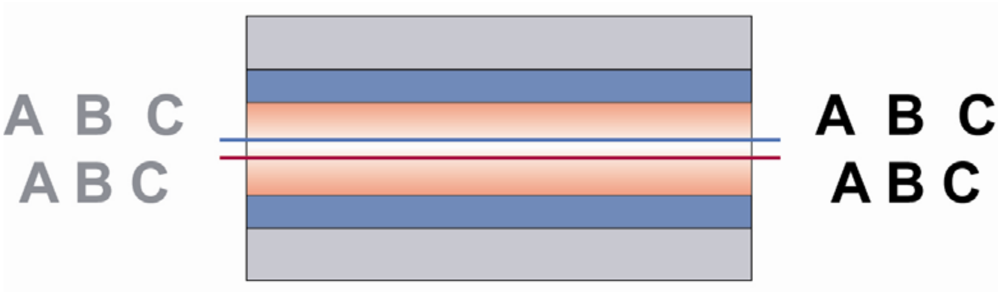

Figure 11: Single Mode Propagation

Unfortunately, the optical fiber construction shown in Figure 3 is fragile. Thus, for most applications, the fiber must be made into a cable. There are many ways to construct a cable (tight buffer, loose tube, gel filled, distribution, breakout, etc). However, in our single fiber cable example (see Figure 12), the 250 micron coating is jacketed with a 900 micron buffer and built into a 3.0mm outer sheath cable with aramid yarn (Kevlar™) as a strength member. As a typical example, Figure 13 portrays a cable with multiple optical fibers.

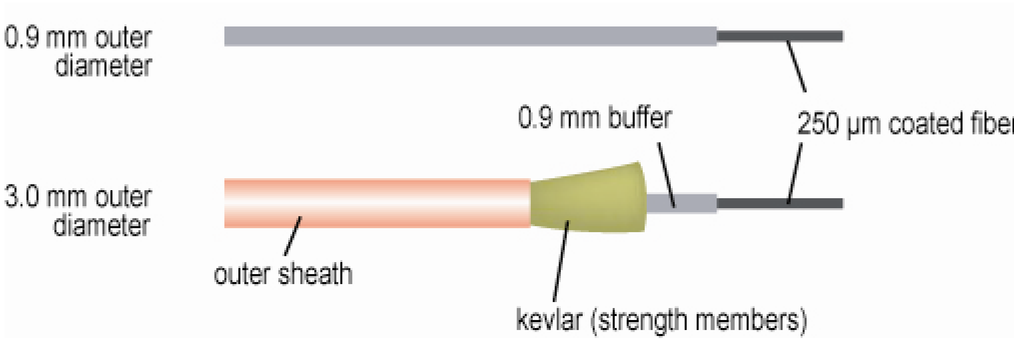

Figure 12: Construction of a Single Fiber Cable

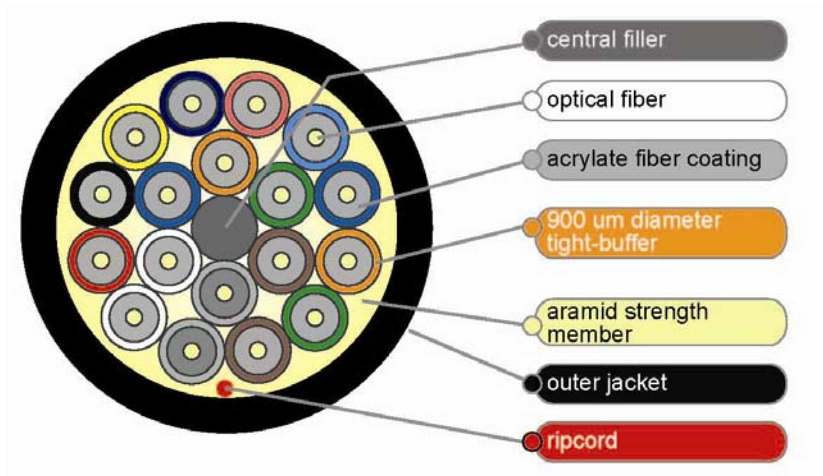

Figure 13: Example of the Construction of a Multi- Fiber Cable

II.3 Connectivity

Fiber optic links require a method to connect the transmitter to the fiber optic cable and the fiber optic cable to the receiver. In general, there are two methods to link optical fibers together.

II.3.1 Fusion Splice

The first method is called a fusion splice. This operation consists of directly linking two fibers by welding with an electric arc or a fusion splicer (see Figure 14). The advantages of this approach are that the linking method is fast and simple and there is very little insertion loss (the loss of light generated by a connection is called Insertion Loss [IL]). The disadvantages are that the link is relatively fragile, is permanent, and the initial cost (of the fusion splicer) is high.

Figure 14: Fiber-optic Fusion Splicer

II.3.2 Connectors

The second method involves the uses of fiber optic connectors. A connector terminates the optical fiber inside a ceramic ferrule, using epoxy to hold the fiber in place. The connectors can be mated and unmated at any time. The advantages of this approach are that the connection is robust, the connector can be chosen according to the application, and the connector can be connected and disconnected hundreds or even thousands of time without damaging the connectors. The disadvantages of this approach are that the connectorization takes longer than fusion splicing, requires special tools, and the insertion loss can be higher when compared with fusion splicing.

There are two types of fiber optic connectors: physical contact and expanded beam.

II.3.2.1 Physical Contact Connectors

Physical contact connectors utilize fiber in a tightly toleranced ceramic ferrule. This allows easy handling of the fiber and protects it from damage. The principle of physical contact connectors involves the direct contact of polished fibers within two ceramic ferrules. The ferrules are aligned using a ceramic alignment sleeve (see Figure 15). Insertion loss is a function of the alignment accuracy and the polish quality. There are springs behind the ferrule to ensure that the two ferrules are in constant contact even in high vibration and shock environments.

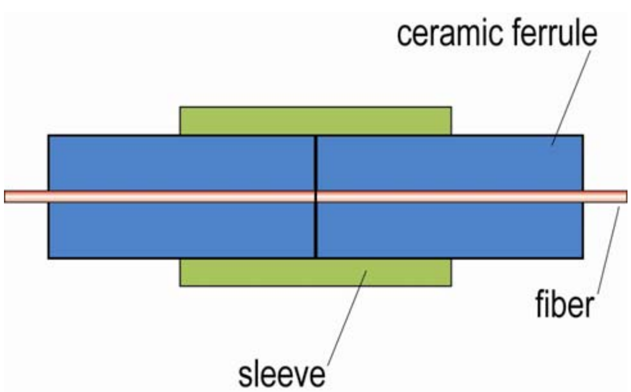

Figure 15: Physical Contact

Physical contact connectors are the most common type of fiber optic connection. They are rugged, repeatable, easy to clean, cost-effective, and perform well. In addition, for physical contact connectors, the insertion loss is generally low (approximately 0.3dB). There are many types of fiber optic connectors used in various applications. The most popular single fiber connectors are (see Figure 16):

- FC-Ferrule Connector: Although the FC connector is being replaced in many applications (telecom and datacom) by LC and SC connectors, it is still used in measurement equipment. The connector has a screw threading and is keyed allowing the ferrule to be angle polished providing low backreflection (light is reflected back to the transmitter, most often at the connector interface due to an index of refraction change).

- LC-Lucent Connector: LC connectors are supplanting SC connectors because of their smaller size and excellent panel packing density and push-pull design. They are also used extensively on small form-factor pluggable transceivers.

- SC-Subscriber Connector: SC connectors also offer a push-pull design (which reduces the possibility of end-face damage when connecting) and provide good packing density. They are still used in datacom and telecom applications.

- ST-Straight Tip Connector: ST connectors are engaged with a bayonet lock which is engaged by pushing and twisting the connector. The bayonet interlock maintains the spring-loaded force between the two fiber cores.

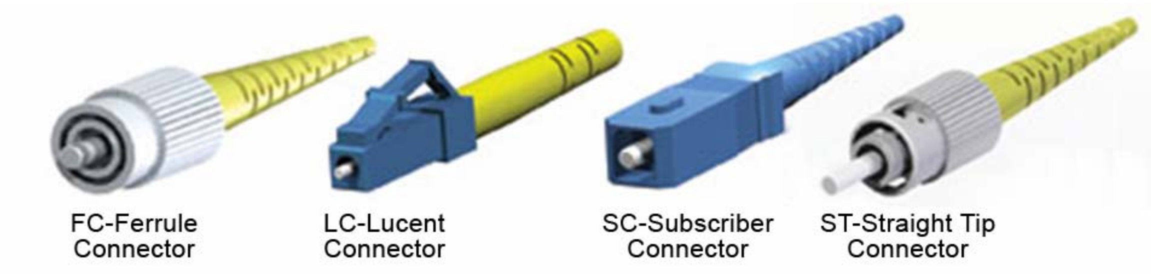

Figure 16: Popular Single Fiber Connectors

These physical contact connectors perform well against particle contaminates (dust, mud, etc) and are usually less sensitive to liquid contaminates (water or oil). The physical contact pushes liquid out of the way and the liquid does not degrade the connection. Physical contact connectors are cleaned by wiping the ferrule with a clean cloth or wipe, spraying with a cleaner or washing with water.

It is also common to provide multiple fibers in a single connector. An example is the MPO (Multiple Fiber Push-On/Pull-Off-see Figure 17) connector which supports 12 fibers in a single ferrule. Another example is the TFOCA-II® connector which provides 4 or 12 fiber optic channels for harsh environment fiber-optic applications (see Figure 18).

Figure 17: MPO Multi-fiber Connector

Figure 18: AFSI TFOCA-II® Connector

II.3.2.2 Expanded Beam Technology

The other connector technology is expanded beam, which consists of placing a lens at the exit of each fiber to widen and collimate the light. In this configuration, there is an air gap between the two optical fibers/lens assemblies (see Figure 19).

The mechanical interface between the connectors must be precise. Dust and dirt must not interfere with the alignment of the optical elements. Expanded beam connectors are less susceptible to particle contaminates such as dirt and dust but they perform poorly with liquids or film on the lenses. They can also be very difficult to terminate in the field.

The loss generated by an expanded beam connection is more than that of a physical contact connector due to the lenses, mechanical alignment and sometimes protective windows (approximately 0.8 to 2.5dB typical).

This type of connector performs well against particle contamination on the lens because the beam is expanded to a much larger size than the beam that comes directly from a fiber. However, any liquid or film (such as a fingerprint) on a lens creates significant loss in an expanded beam connector. Expanded beam connectors are also very sensitive to alignment of the lenses. Connectors must always be tightly coupled and kept clean on the mating surface in order to work properly. Cleaning an expanded beam connector must be done with care because any liquid (water, alcohol or another cleaner) that is trapped inside the connector may migrate to the surface of the lens, causing an unacceptable increase in insertion loss.

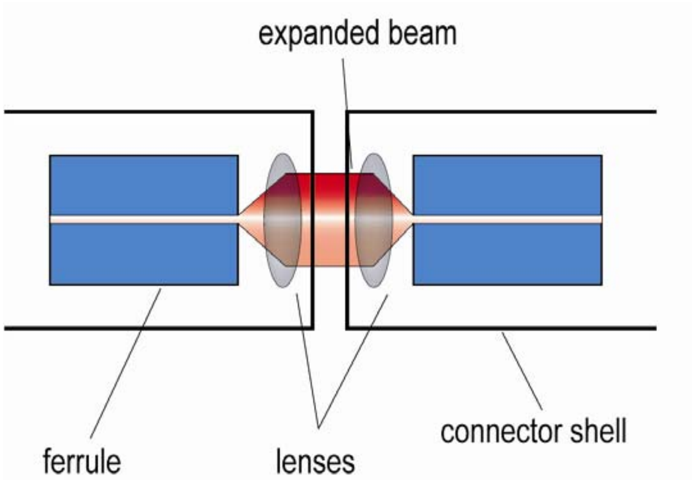

Figure 19: Expanded Beam Technology

II.4 Receiver

The last component of the fiber optic link is the optical receiver, which uses a photodiode to convert the optical signals into electrical. The two types of photodiodes used are: Positive Intrinsic Negative (PIN) and the Avalanche PhotoDiode (APD)

In a similar fashion as that of the laser transmitter, the photodiode will receive wavelengths depending on material composition (see Figure 20).

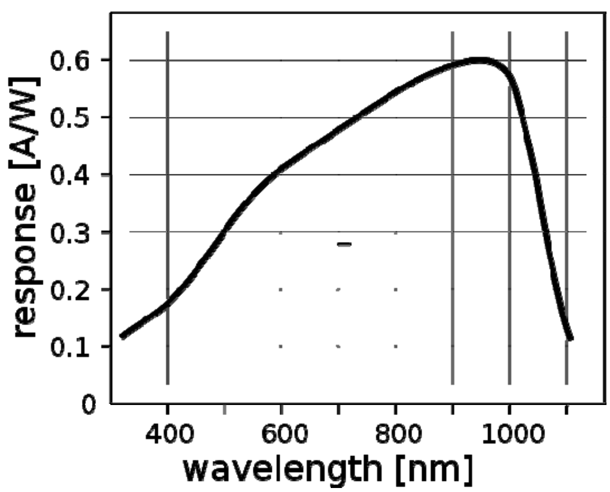

Figure 20: Responsivity of a Silicon Photodiode

III. Fiber Optic Applications

As discussed, fiber optics is used in myriad applications. Due to its low weight, high bandwidth capacity and immunity to electromagnetic and RF interference, fiber optics is used extensively in avionics on both military (see Figure 21) and commercial aircraft systems. Applications include radar links, video systems, sensor networks, and in-flight entertainment systems.

Figure 21: Military Aircraft

Fiber optics is also used for command, control, and telemetry in industrial applications wherever there are large electric motors. These motors generate large electromagnetic fields. Instead of using heavily shielded copper conductors, manufacturers use fiber optics to eliminate electromagnetic interference concerns. Examples include top drive control links for drilling rigs (Figure 22) and command and control for longwall mining systems.

Figure 22: Top Drive Control Link

Fiber optics is also used in data communications (see Figure 23) and telecommunications systems due to its ability to transmit high bandwidths over longer distances than copper conductors.

Figure 23: A Data Center using Fiber Optics

IV. Conclusion

Fiber optics provides many advantages over copper conductors including higher bandwidth, transmission of signals over longer distances, lower weight and cost and immunity from electromagnetic interference. These attributes make it the increasingly preferred medium for applications such as avionics, energy, mining, broadcast, and data/telecommunications.

About the Authors

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Brian Shirk, Product Manager: Brian has over 15 years of experience in the defense and telecommunications industries. He is responsible for training, tools, and termination kits across all product lines. Prior to joining AFSI, he held a variety of engineering positions in the telecommunications industry. Brian graduated from DeVry Institute with a Bachelor of Science in Electrical Engineering Technology.

Company Overview

Amphenol Fiber Systems International (AFSI), a division of Amphenol, provides reliable and innovative fiber optic interconnect solutions that withstand the harsh environments of military (ground systems, avionics, shipboard), energy, and broadcast applications. With nearly two decades in business, AFSI continues to maintain its position as a global leader in fiber optic interconnect components and systems such as termini, M28876, 38999 assemblies, MIL-ST, TFOCA and the TFOCA-II® connector, which AFSI developed and patented. AFSI has delivered millions of fiber optic connectors in more than 34 countries. Whenever there is a need for superior cost-effective fiber optic systems and products that will stand up to demanding operating environments, you can rely on AFSI for engineering know-how, top-quality products and expert technical support.

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