FIBER OPTIC FUNDAMENTALS 2

THE NATURE OF LIGHT

In order to understand some of the more complex components used in modern, high-performance, fiber optic transmission systems, one should have a good understanding of the nature of light. Many of light's properties are not obvious in our everyday lives, yet these properties are vital to the success of many modern fiber optic components. An important characteristic of light is the fact that light acts like a wave. (It can also act like a particle, but that is not pertinent to this discussion.) Light travels as an oscillating wave of electric and magnetic fields. As a result, two phenomena affect the behavior of light: interference and polarization, both important fundamentals in understanding and designing modern fiber optic components.

Interference

Interference forms the basis of many modern fiber optic components, including fiber Bragg gratings, optical filters built directly into the fiber; lithium niobate modulators, used to modulate the laser or LED externally rather than by internal circuitry; and many types of bulk filters, devices used in wavelength-division multiplexing.

In Figure 2.1, the top two curves represent two light waves traveling along the same path. The figure illustrates only the electrical fields. The distance between the crests or troughs of the waves is the light's wavelength. This is analogous to color or frequency in later discussions. The two light waves shown are also "in phase." This means the peaks and the valleys of the two waveforms are perfectly aligned. When two light waves have the same wavelength and are in phase, they add together to produce a wave with the sum of the amplitudes of the input waves. This is known as constructive interference.

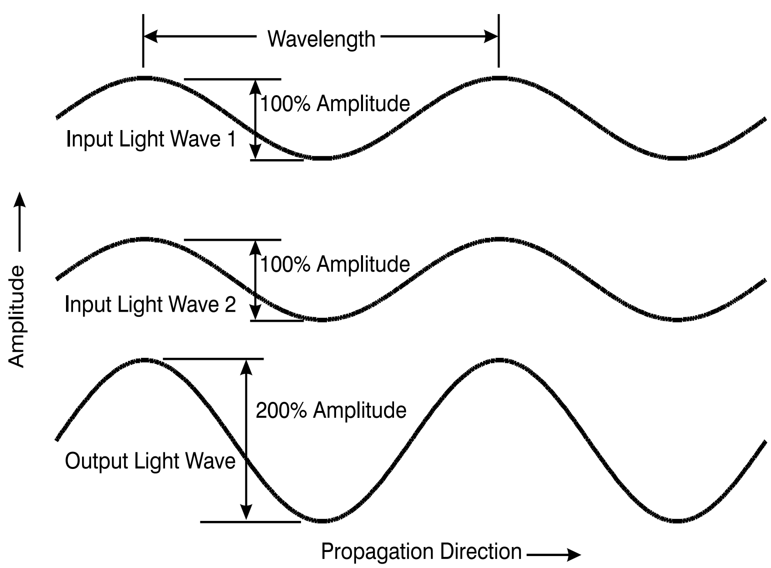


Figure 2.1: Constructive Interference

Figure 2.2 illustrates destructive interference, showing two light waves with the same wavelength but now "out of phase." The light waves shifted so that the peak on the first light wave aligns with the valley in the second light wave. In this case, the two input light waves almost cancel each other out, resulting in a very small output light wave.

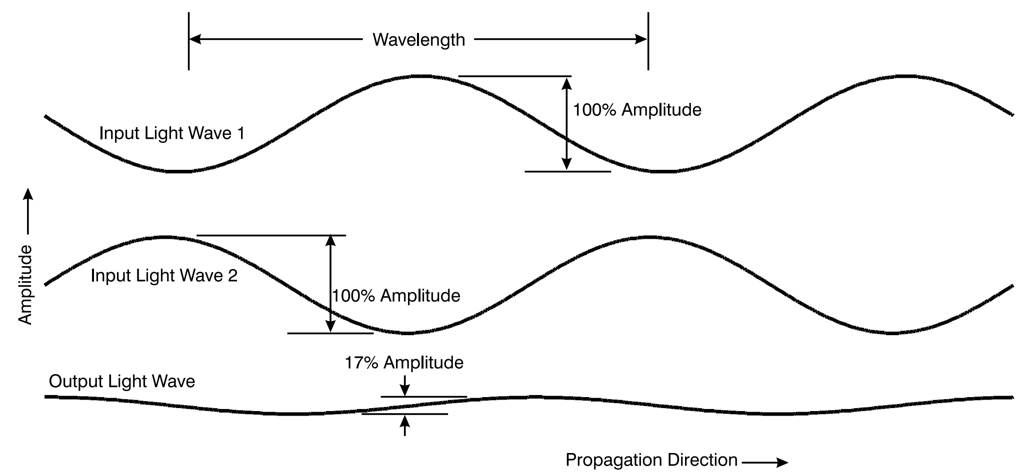


Figure 2.2: Destructive Interference

What causes interference in real systems? It usually occurs when a light wave combines with a delayed version of the same light wave. This principle governs lithium niobate modulators. Lithium niobate is an optically transparent crystal with the ability to change the delay of light in response to a change in an applied electric field. See Chapter 7 for a complete description of these modulators.

Polarization

Light waves travel along two planes separated by 90°. Figure 2.3 shows a polarized light wave traveling along the X axis. It consists of two components; the component labeled E represents the varying electric field and is known as the E-vector. The component labeled B represents the varying magnetic field and is known as the B-vector. This light wave shown is said to be vertically polarized because the E-vector is along the vertical axis. By convention, whichever axis the E-vector lies on is the plane of polarization. An unpolarized light wave would be a jumble of horizontally and vertically polarized light waves traveling together.

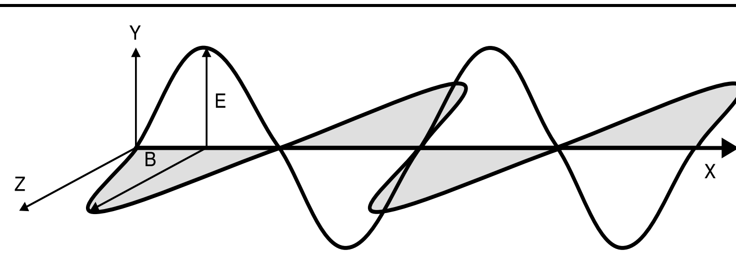


Figure 2.3: Light Waves Showing E and B Vectors

Polarized sunglasses most commonly make use of this principle. Their design allows the passage of only one polarization of light. Most reflected light has a horizontal polarization. The lens in the polarized sunglasses is vertically polarized, so it blocks the horizontally polarized reflection.

The Electromagnetic Spectrum

Light is organized into what is know as the electromagnetic spectrum. In this scheme, light refers to more than the portion of the electromagnetic spectrum that is visible to the human eye. The electromagnetic spectrum is composed of visible and near-infrared light like that transmitted by fiber, and all other wavelengths used to transmit signals such as AM and FM radio and television. Figure 2.4 illustrates the electromagnetic spectrum. As one can see, only a very small part of the spectrum is perceived by the human eye as light.

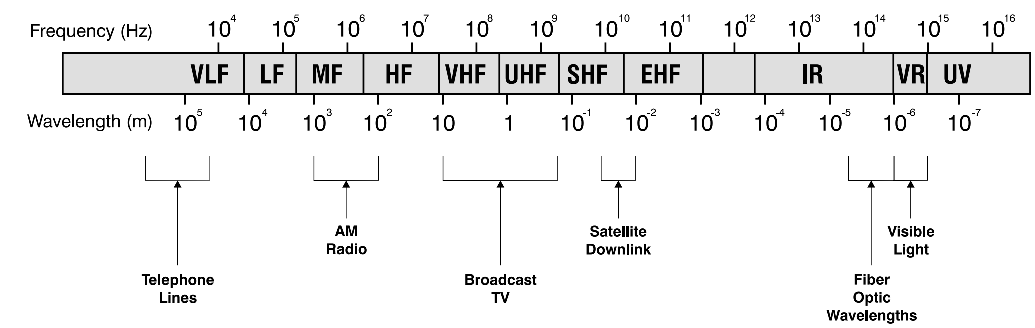


Figure 2.4: Electromagnetic Spectrum

Fiber optic wavelengths are measured in nanometers (the prefix nano meaning one-billionth) or microns (the prefix micro meaning one-millionth). Wavelengths for fiber optic applications can be broken into two main categories: near-infrared and visible. Visible light, as defined by the human eye, ranges in wavelengths from 400 to 700 nanometers (nm) and has very limited uses in fiber optic applications, due to the high optical loss. Near-infrared wavelengths range from 700 to 1,700 nanometers; these wavelengths are almost always used in modern fiber optic systems.

APPLYING LIGHT

Light signals have been used to communicate for as long as lighthouses have warned sailors away from treacherous shorelines. This application seems simplistic compared to today's possibilities. As countries continue to develop networks for global communication, fiber optics offers a method of transmission that allows for clearer, faster, more efficient communication than copper. A fiber optic communication system holds many advantages over a copper wire system. For example, while a simple two-strand wire can carry a low-speed signal over a long distance, it cannot send high-speed signals very far. Coaxial cables can better handle high-speed signals but still only over a relatively short distance. An advantage of copper cables, that fiber cannot duplicate, is the ability to transmit AC or DC power in addition to communication signals. Fiber optics holds a great advantage over copper media because it can handle high-speed signals over extended distances. Other advantages of fiber include:

Immunity from Electromagnetic (EM) Radiation and Lightning: Because the fiber itself is made from dielectric (nonconducting) materials, it is unaffected by EM radiation. The electronics required at the end of each fiber, however, are still susceptible and require shielding. Immunity from EM radiation and lightning was initially most important to the military. In terms of secure communications, fiber itself is not inherently secure, but it does not normally emit any EM radiation that can be readily detected. Immunity to EM radiation is important in modern aircraft designs that have composite skins; these nonconducting skins do not shield the electronics or wiring from EM fields or radiation. Lightning immunity is a key reason to use fiber optic devices in commercial security and intelligent transportation systems, because these systems are usually dispersed over a wide area making them susceptible to damage from lightning strikes and interference. Immunity from EM radiation is an important factor in choosing fiber to upgrade existing communication systems. The fiber can often be run in the same conduits that currently carry power lines, simplifying installation.

Lighter Weight: This feature refers to the optical fiber itself. In real world applications, copper cables can often be replaced by fiber optic cables that weigh at least ten times less. For long distances, a complete fiber optic system (optical fiber and cable, plus the supporting electronics) also has a significant weight advantage over copper systems. This is often not true for short systems, however, because fiber optic systems almost always require more elaborate, and thus larger and heavier electronics than copper systems.

Higher Bandwidth: Fiber has higher bandwidth than any alternative available. The CATV industry in the past required amplifiers every thousand feet or so on their supertrunks when copper cable was used. This is due to the limited bandwidth of the copper cable. A modern fiber optic system can carry the same signals with similar or superior signal quality for 50 miles or more without needing intermediate amplification (repeaters). Even at that, most modern fiber optic communication systems use less than a few percent of fiber's inherent bandwidth.

Better Signal Quality: Because fiber is immune to EM interference, has lower loss per unit distance, and wider bandwidth, signal quality is usually substantially better compared to copper.

Lower Cost: This has to be qualified. Fiber certainly costs less for long distance applications. However, for signal transmission requirements over distances of a few feet, copper is cheaper and probably always will be. The cost of fiber itself is cheaper per unit distance than copper if bandwidth and transmission distance requirements are high; however, the cost of the electronics and electro-optics at the end of the fiber can be substantial. The price of copper is such today that for very long distance links, converting to a fiber optic system can often be completely paid for by the salvage value of the removed copper. Fiber and copper systems can be compared by finding a break-even distance. At distances shorter than the break-even distance, copper is cheaper and vice versa. In the mid 1980's the break-even distance was 10 km or more. Today, the break-even distance is often less than 100 meters. Most of this gain has come from the reduced cost of fiber optic systems and components. Some of the gain is also due to the fact that the cost of copper has increased over the same period of time.

Easily Upgraded: The limitation of fiber optic systems today, and for many years to come, is the electronics and electro-optics used on each end of the fiber. The fiber itself usually has much more transmission capability, especially higher bandwidth, than is being utilized. Once fiber is installed, particularly a single-mode fiber, advances in electronics and electro-optics can be readily incorporated using the installed fiber.

Ease of Installation: Many newcomers to fiber optics are often concerned about glass being very brittle and prone to breakage. In fact, glass is many times stronger than steel, and optical fibers are so small that they are very flexible. A good quality fiber optic cable incorporates strain relief materials as well as bend limiters that make the cable very hardy. Copper coax, is in fact, much more fragile than a fiber optic cable. Copper coax cables are prone to kinks and deformities that will permanently degrade the performance of the cable. Glass however, will not deform or kink. Thus, it can usually take much more abuse than copper.

TYPICAL FIBER OPTIC COMMUNICATIONS SYSTEM

Modern fiber optic transmission systems can be extraordinarily complex as the data rates, channel counts, and transmission distances increase. However, the basic principles behind fiber optic transmission are relatively simple. As shown in Figure 2.5, fiber optic links contain three basic elements: the transmitter (Tx) that allows for data input and outputs an optical signal, the optical fiber that carries the data, and the receiver (Rx) that decodes the optical signal to output the data.

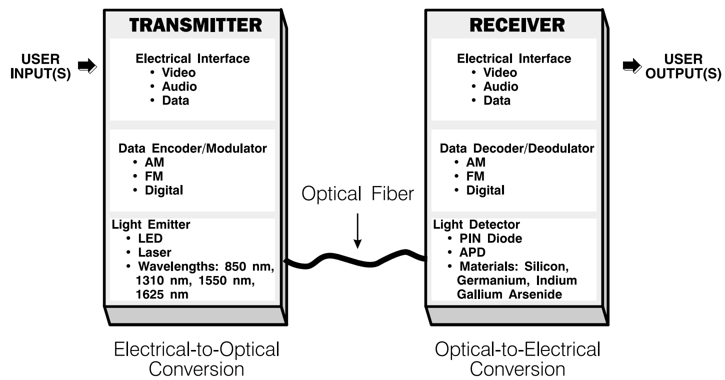


Figure 2.5: Elements of a Fiber Optic Link

The transmitter in Figure 2.5 uses an electrical interface, either video, audio, data, or other forms of input, to encode the user's information through modulation. Three forms of modulation are typically used: amplitude modulation (AM), frequency modulation (FM), and digital modulation. The electrical output of the modulator is usually transformed into light either by means of a light-emitting diode (LED) or a laser diode (LD). The wavelengths of these light sources range from 780 nm to 1625 nm for most fiber optic applications.

The receiver in Figure 2.5 decodes the light signal back into electrical signals. Two types of light detectors are typically used: the PIN photodiode or the avalanche photodiode (APD). Typically, these detectors are made from silicon (Si), indium gallium arsenide (InGaAs), or germanium (Ge). The detected and amplified electrical signal is then sent through a data decoder or demodulator that converts the electrical signals back into video, audio, data, or other forms of user input.

The next level of complexity for fiber optic transmission systems involved the addition of multiple wavelengths of light on each fiber. Each wavelength of light is a distinct "color" that can be combined for transmission and subsequently separated out at the receiver end by using various optical filters. This technique is referred to as wavelength-division multiplexing (WDM). Wavelength is usually denoted by the Greek symbol, lambda or λ, in fiber optic systems. Often the λ symbols have subscripted numbers denoting different wavelengths, e.g., λ_1. Figure 2.6 shows a basic WDM system transmitting two wavelengths in the same direction on the fiber.

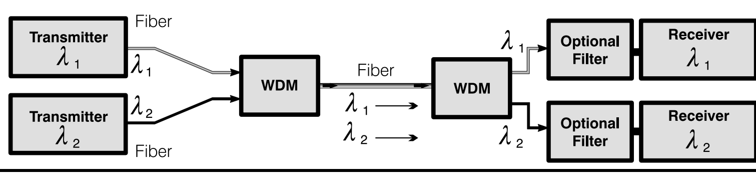


Figure 2.6: Basic WDM System

As the load from Internet traffic increased, WDM systems evolved into systems that could carry a multitude of wavelengths (colors). These systems were called dense wavelength-division multiplexing (DWDM) systems. Erbium-doped fiber amplifiers (EDFA) made DWDM systems practical. The EDFA allowed the multitude of wavelengths on the fiber to be boosted simultaneously, making the systems very economical. Early systems carried four to eight wavelengths and then later, sixteen. The increase in capacity per fiber was dramatic but still insufficient to handle the exponentially growing Internet traffic load. Figure 2.7 shows a simple four wavelength DWDM fiber optic transmission system. An EDFA is included to increase the possible transmission distance.

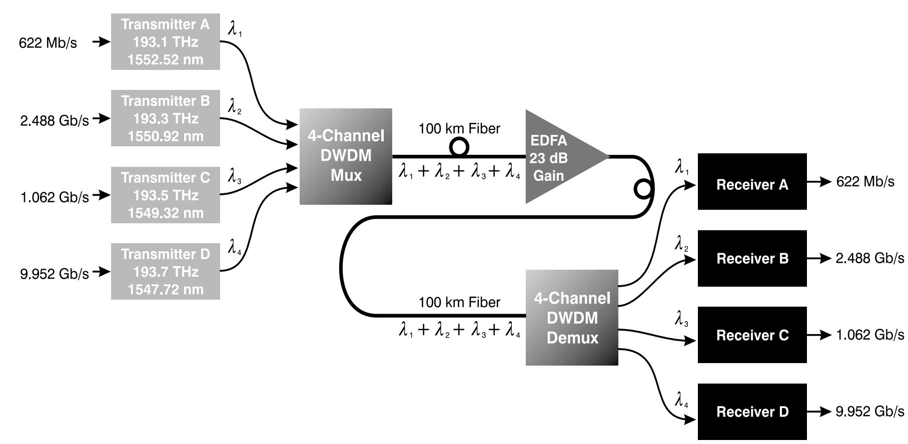


Figure 2.7: Basic Four Channel DWDM System

Figure 2.8 shows many key elements associated with a modern fiber optic transmission system such as external modulators, forward error correction, solitons, and Raman amplifiers. These more advanced concepts will be discussed fully in chapters 7, 9, and 14 of this book.

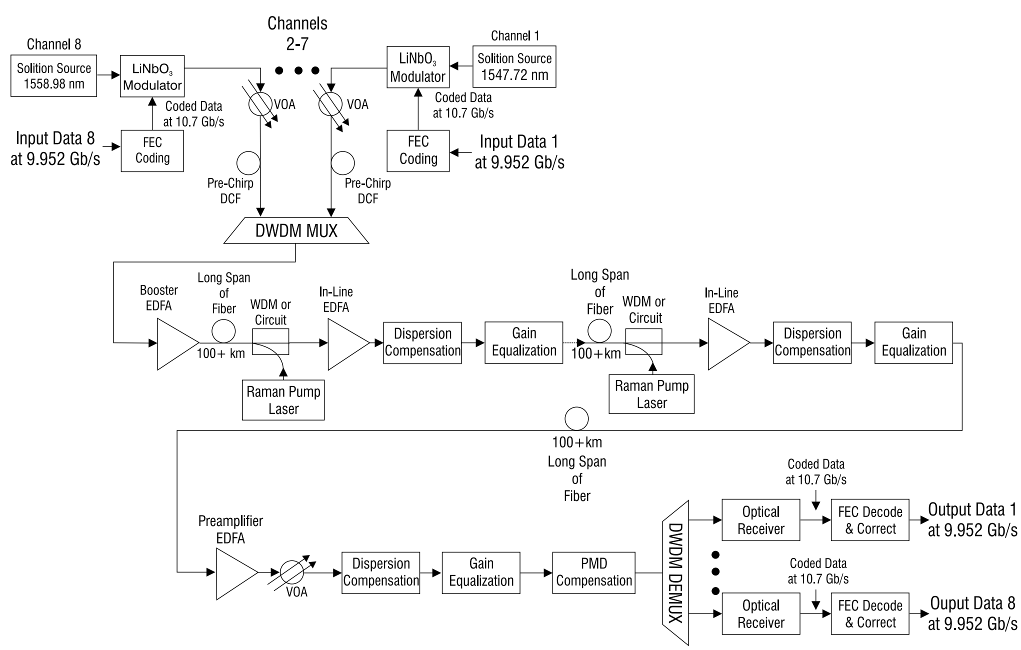


Figure 2.8: Modern DWDM Long-haul Communication System

In any transmission system, fiber provides a private pipeline that can carry huge amounts of data. Alternatives to fiber optics include over-the-air broadcast and hard-wired copper wires carrying electrons. Figure 2.9 explains these three schemes for transmitting information from one point to another.

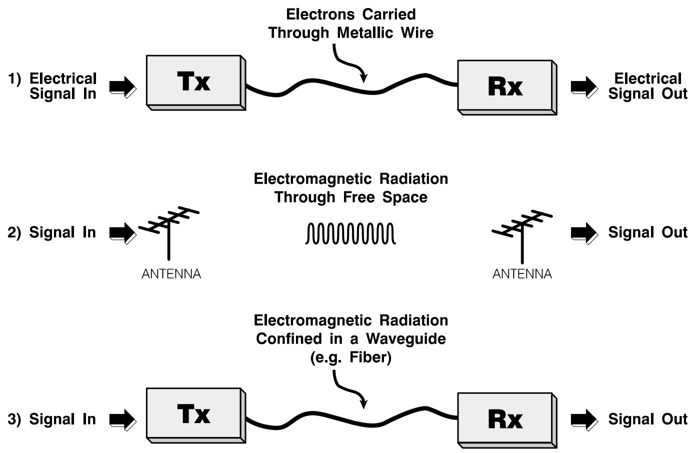


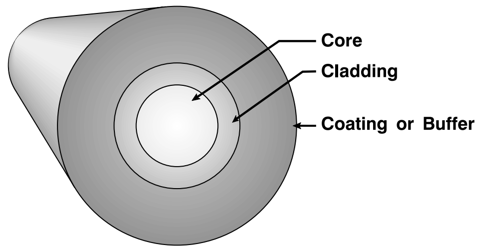
Figure 2.9: Transmission Schemes

Metallic transmission, the first scheme, uses a copper wire or coaxial cable to carry a modulated electrical signal containing information. This method allows for a limitless number of private channels (assuming you have that much copper cable), but each channel has limited information and distance capability due to the inherent characteristics of copper cable. The second scheme for moving information between two locations is free-space transmission. This is how radio signals and over-the-air TV signals are received. Free-space transmission has the advantage of providing very large bandwidth capability as well as long distance capability, but it does not provide a private channel. Also, the free-space spectrum is a finite, limited, and costly commodity. It cannot provide the millions of high-speed communication channels required by the global information age. The last scheme is waveguide transmission. This describes optical fiber transmission. A waveguide (optical fiber) confines the electromagnetic radiation (light) and moves it along a prescribed path. Optical fiber offers the best of both metallic and free-space transmission. It has the key advantage of metallic transmission, the ability to carry a signal from point A to point B without cluttering the limited free-space electromagnetic spectrum; however, fiber does not have the disadvantage of metallic transmission: very limited bandwidth and data rate.

FIBER OPTIC COMPONENTS

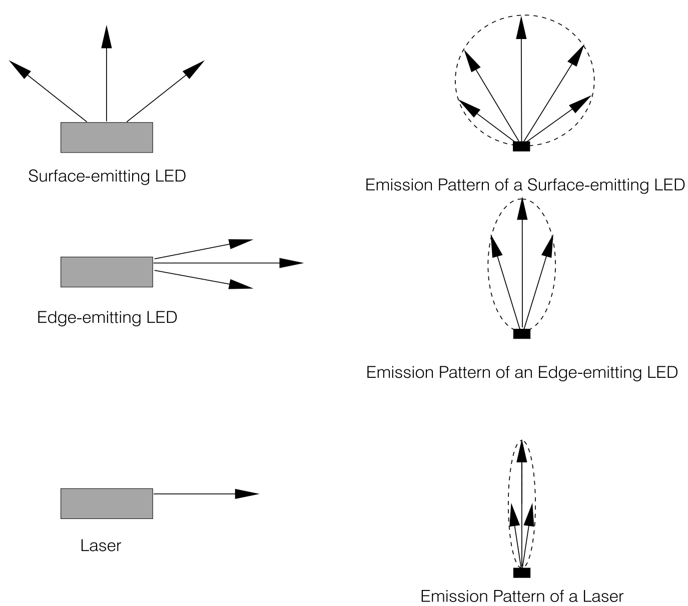
Optical Fiber: Optical fibers are extremely thin strands of ultra-pure glass designed to transmit light signals from a transmitter to a receiver. These signals represent electrical signals that include, in any combination, video, audio, or data information. Figure 2.10 shows the general cross-section of an optical fiber. The fiber consists of three main regions. The center of the fiber is the core. This part of the fiber actually carries the light. It ranges in diameter from 9 microns (μm) to 100 microns in the most commonly used fibers. The next region, the cladding, surrounds the core and confines the light in the core. The cladding typically has a diameter of 125 microns. A key design feature of all optical fibers is that the refractive index of the core is higher than the refractive index of the cladding. Both the core and cladding are usually doped glass materials. The outer region of the optical fiber is called the coating or buffer. The buffer, typically a plastic material, provides protection and preserves the strength of the glass fiber. Usual diameters for the buffer are 250 microns, 500 microns, and 900 microns. Optical fiber is discussed extensively in Chapter 3.

Figure 2.10: Cross-section of an Optical Fiber



Light Emitters: The two types of light sources used in fiber optics are light-emitting diodes (LED's) and laser diodes (LD's). LED's may be surface-emitting or edge-emitting sources. The surface-emitting LED (SLED) emits light over a very wide angle. This type of light source is often called a Lambertian emitter because of the nature of the emission pattern. This broad emission angle is attractive for use as an indicating LED because of the wide viewing angle, but is a detriment for fiber optic uses. Because the emitting angle is so large, it is difficult to focus more than a small amount of the total light output into the fiber core. The key advantage of surface-emitting LED's is their low cost, making these light emitters the dominant type in use. The second type of light emitter is the edge-emitting LED (ELED). This LED type has a much narrower angle of light emission and also has a smaller emitting area. This allows a larger percentage of the total light output to be focused into the fiber core. ELED's are also generally faster than their surface-emitting cousins. The disadvantage of ELED's is that they are very temperature sensitive compared to SLED's. The last light emitter type is the laser diode. A laser has a very narrow emission angle, and the emitting spot is very small, usually only a few microns in diameter. Because of the small emission angle and emitting spot, a very high percentage, often more than 50%, of the output light can be focused into the fiber core. The laser diode is the fastest of these three emitter types. Figure 2.11 illustrates the emission patterns of these sources.

Figure 2.11: Sources and Emission Patterns



Many characteristics are considered when making the decision to use LED's or LD's in fiber optic systems. Some basic considerations include center wavelength, spectral width (the full range of wavelengths around the center wavelength, often called the FWHM, Full Width Half Maximum), and optical output power of the light source. The spectral width is important as larger values bring with them an increased possibility of dispersion problems, limiting bandwidth. The optical output power of the light source is also important in that it must be neither too weak nor too strong. A weak source will not provide enough power to transmit a light signal through a usable length of optical fiber, while a source that is too strong could cause distortion of the signal by overloading the receiver. These and other light source characteristics will be explored at length in Chapter 5.

Detectors: Detectors convert optical power into an electrical signal. These may be positive-intrinsic-negative (PIN) photodiodes or avalanche photodiodes (APD's). The basic difference between the two is that the APD provides a good deal of internal gain, simplifying the task of signal amplification. As is almost always the case with engineering trade-offs, with an advantage comes a disadvantage. APD's are more expensive and require extensive additional support electronics because of the need to provide a high-voltage bias supply that must be temperature compensated. PIN diodes, on the other hand, do not require this additional support circuitry and are very economical, but they require more complex amplifier stages. PIN detectors are by far the most economical option, which gives them the largest share of the market. APD's are becoming more important as data rates and span lengths increase. Light detectors are discussed in detail in Chapter 6.

Interconnection Devices: An interconnection device is any component or technique used to connect a fiber or a fiber optic component to another component or fiber. Interconnection devices provide both light junctions and mechanical junctions for interconnecting fiber optic systems. As light junctions, they provide outputs or inputs for signal sources. Mechanically, they hold the connections in place. Interconnection devices include connectors and splices. Some uses for interconnection devices are:

- Interfaces between local area networks and devices
- Patch panels
- Portable military communication links
- Network-to-terminal connections
- Connections between recording equipment, cameras, and sound equipment in portable studios

Interconnection devices are treated in detail in Chapter 8.

In addition to these fiber optic components, this guide will discuss active devices for optical amplification (Chapter 7), passive devices for WDM transmission and switches (Chapter 9), system design (Chapter 10), applications for optical fiber (Chapter 11), video transmission (Chapter 12), data transmission (Chapter 13), the theoretical and practical limitations of optical fiber (Chapter 14), testing and measurement techniques (Chapter 15), and the future of the fiber optics industry (Chapter 16).

SOME USEFUL TERMINOLOGY

A few more terms should be explained before this book proceeds any further, especially as the discussion on digital transmission evolves.

Bit: A bit is a single digit in a binary number system, either a zero or a one. (The base ten counting system that we use in our everyday lives is so called because each digit can be any value from zero to nine.) The binary number system and the bit are the basis of all modern computers, calculators and communication systems. The bit can be thought of as a type of Morse code where any symbol (e.g., a letter or number) may be represented by a series of dots and dashes, corresponding to a zero and a one in binary.

Data Rate: Data rate describes the rate at which symbols (letters or numbers), are used to transmit a message. A modern fiber optic system can easily transmit at a data rate of 10 Gbit/s. This means that 10 billion bits (zeroes or ones) move from point A to point B every second.

Digital Transmission: The process of moving bits from point A to point B is referred to as digital transmission.

Chapter Summary

- Because light acts like a wave in many instances, effects such as interference and polarization can impact modern fiber optic systems.
- Constructive interference adds to the light wave output, but destructive interference diminishes the light wave output.
- The electromagnetic spectrum includes all the wavelengths or colors of light, not just colors visible to the human eye.
- Fiber optic systems holds many advantages over conventional copper wire and coax cable systems, including EMI immunity, lighter weight, higher bandwidth, lower cost, and better signal quality.
- Fiber optic components transmit information by turning electronic signals into light and light signals back into electronic signals.
- Wavelengths of light used in fiber optic applications include near-infrared and visible.
- The three basic elements of a fiber optic link are the transmitter, the receiver, and the optical fiber.
- The most common transmission schemes are metallic transmission, free-space transmission, and waveguide transmission.
- Optical fibers are extremely thin strands of ultra-pure glass designed to transmit light signals from a transmitter to a receiver.
- The two types of light sources used in fiber optics are light-emitting diodes (LED’s) and laser diodes (LD’s).
- Two types of detectors associated with fiber optics are the PIN photodiode, and the avalanche photodiode (APD).
- An interconnection device is any component or technique used to connect a fiber or fiber optic component to another component or another fiber. These devices include connectors, splices, couplers, splitters, switches and wavelength-division multiplexers (WDM’s).

Selected References and Additional Reading

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