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Fiber Optic Essentials

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Preface

The development of optical fiber technology for communication networks, medical applications, and other areas represents a unique confluence of the physics, electronics, and mechanical engineering disciplines. Its history extends back to the earliest uses of light and mirrors by ancient civilizations, including many false starts (the so-called "lost generation" described in Jeff Hect's book, *City of Light*), under-appreciated discoveries, and success stories. Today, the amount of optical fiber installed worldwide is equivalent to over 70 round trips to the moon, and this technology has matured to serve as the backbone of the Internet, the global telecommunications infrastructure, and the basis of exciting new developments in illumination, imaging, sensing, and control that were scarcely imagined when the laser was first developed in the early 1960s.

As this field has grown, many new practitioners with an established background in physics or electrical engineering have begun to work in some branch of the optical fiber field. Service technicians accustomed to working with copper cables have been asked to retrain themselves and understand the basics of optical cable installation. There are a growing number of non-traditional workers, including technical marketers, patent lawyers, and others who are attempting to transition into this area. And of course, many new students have begun to study this field as well. Understanding the fundamentals of fiber optics is essential for both the application designer and the basic researcher, and there are many good comprehensive references available, some of which extend to multiple volumes with thousands of pages. Clearly, entire books can and have been written on the topics of lasers, fiber manufacturing, and related areas. However, in working with both students and professionals who have recently entered this field, we have found a need for a much simpler introduction to the field. In this book, we have attempted to provide an overview of the field suitable for those with some technical or practical background that would allow a more rapid, accessible grasp of the material. We began with the assumption that chapters should be as short as possible, with minimal use of equations and no derivations. Condensing an entire book's worth of material into such a chapter is not an easy task, and we have needed to use a good deal of judgment in determining which topics to include and which to leave out. In this, we have tried to let practical applications rather than theoretical considerations be our guide. For example, we make only a passing reference to Maxwell's equations and do not use them to derive any results. This is not because we fail to appreciate the importance and elegance of these expressions; on the contrary, we would not be able to do them justice in the limited space allowed, and instead have left this topic open for readers who may wish to pursue it. Likewise, we offer only a brief nod to semiconductor materials engineering before describing its application to lasers and light emitting diodes (LEDs). The interested reader may refer to the many references provided on these and other topics, while bearing in mind that the guiding purpose of this book is to provide a high level overview for the general practitioner in this field.

We have also included some unique features which are not commonly found in handbooks of this type. Many prospective readers have asked us for a guide to understanding the bewildering number of acronyms and jargon in this field; accordingly, we provide an extensive list of definitions in the appendix which will hopefully make it easier for others to read in more detail about this field. We have provided a brief timeline of significant developments in the field, extending the excellent work done by others into the present day. Similarly, there is a chapter on basic facts about fiber optic technology which will hopefully be both interesting and informative to the casual reader, and offer some perspective on how this technology is applied to affect our daily lives. Along the same lines, we have included chapters on medical and other applications of fiber optics, something not often found in fiber handbooks. Overall, we hope this book strikes a balance between technical detail and reduction to engineering practice that will make it a useful source for many people in this area.

An undertaking such as this book would not be possible without a supportive staff at our publisher and the understanding of our families to whom we extend our deepest gratitude. This book is dedicated to our daughters, Anne and Rebecca, without whose inspiration and delight in math and science it would not have been possible. We also gratefully acknowledge the support of Dr. and Mrs. Lawrence Sher, Mrs. Helen DeCusatis, and the memory of Mr. Casimer DeCusatis, Sr.

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Poughkeepsie, New York, June 2005

Contents

Chapter 1 | Fiber, Cables, and Connectors

Every fiber optic system has three basic components—a **source**, a **fiber**, and a **receiver**. Each of these components will be discussed in more detail in the following chapters; for now, we provide a brief overview of each one and describe how they work together.

All types of fiber optic systems require a light source; for applications such as medical imaging or architectural lighting, this source can be any type of conventional light bulb. The optical fiber serves as a light guide in this case; its purpose is simply to convey light from the source to a desired destination. In optical communications systems, the source of light used is called a **transmitter**. There are several different types of transmitters, including light emitting diodes (LEDs) and various types of lasers. Their purpose is to convert an electrical signal into an optical signal which can be carried by the fiber. This process is called **modulating** the source of light. For example, imagine a flashlight being switched on and off very quickly; the pattern of optical pulses forms a signal which carries information, similar to the way a telegraph or Morse code system operates. Turning a light source on and off in this way is called **direct modulation** or **digital modulation**. The light can also be adjusted to different levels of brightness or intensity, rather than simply being turned on and off, this is called **analog modulation**. Some types of light sources cannot be easily turned on or off; in this case, the light source may be left on all the time, and another device called an **external modulator** is used to switch the beam on and off (imagine a window shutter placed in front of a flashlight). The simplest type of modulation involves changing the intensity or brightness of the light; this is known as **amplitude modulation** (similar to AM radio systems). It is also possible to modulate other properties of the light, such as its phase, frequency, or even polarization; however, these are not as commonly used in communication systems.

The **fiber** is a thin strand of glass or plastic which connects the light source to its destination (in the case of a communication system, it connects the transmitter to the receiver). Of course, there are other ways to carry an optical signal without using fibers which are beyond the scope of this book. For example, another type of **optical waveguide** can be made by layering polymers or other materials on a printed circuit board; these waveguides work on the same basic principles as an optical fiber. If the distances are fairly short, light can simply be directed through free space. Some laptop computers come equipped with infrared communication links that operate in this manner, much like a television remote control. This approach can also be used between two buildings if they are not too far apart (imagine two telescopes or lenses aimed at each other, with a light source on one side and a detector or receiver on the other side). This requires a clear line of sight between the transmitter and the receiver, as well as good alignment so that the beam does not miss the receiver; bad weather conditions will also affect how well this system works. We will focus our attention on the type of fibers most commonly used for communications, medical applications, and other related systems. The fiber often has layers of protective coatings applied to strengthen it and form an **optical cable**, in the same way that copper wires are often coated with plastic. Just as electrical connectors are required to plug a cable into a socket, **optical connectors** and sockets are also needed. Both fiber and copper cables may also be **spliced** to increase the distance, although the process is more difficult for fiber than for most copper systems. Most fibers used today are made from extremely high purity glass, and require special fabrication processes. We will describe the standard **fabrication equipment** needed to manufacture these fibers, such as **fiber drawing**, **chemical vapor deposition**, and **molecular beam epitaxy**.

In medical and lighting applications, the light is delivered to its destination to provide illumination or some other function. In a communication system, the light is delivered to an optical **receiver**, which performs the opposite function of the transmitter; it converts optical signals back to electrical signals in a communication system. A receiver is composed of an optical **detector** (sometimes called a **photodetector**) and its associated electronics. After traveling through the various components of a fiber optic link, the signal we are trying to detect will be corrupted by different types of noise sources. The receiver must be designed to separate a signal from this noise as much as possible. A simple approach would be to amplify the signal, and devices called **repeaters** and **optical amplifiers** may be inserted at various points along the link for this purpose. They can be used to extend the range of the system; however, bear in mind that amplification cannot solve all our problems, since it often increases the power of both the signal and the noise. There are also some types of noise which cannot be overcome simply by increasing the signal strength (for example, timing jitter on the digital data bits in a communication system). In some applications a transmitter and receiver are packaged together, this is called a **transceiver**.

Communication systems may also use other devices such as **multiplexers**, which combine several signals over the same optical fiber. Different wavelengths, or colors of light, can be carried at the same time over the same fiber without interfering with each other. This is called **wavelength division multiplexing (WDM)**; in later chapters we will discuss this in more detail. Optical fibers are often interconnected to form large **networks** which may reach around the world. It is also necessary to test and repair these networks using special tools. There are many tests of fiber optic systems that can be done with standard laboratory equipment. However, there are several pieces of equipment specific to fiber optics. An example of this is an **optical time domain reflectometer (OTDR)** that can non-destructively measure the location of signal loss in a link.

Non-communications applications of fiber optics include **medical technology**, **illumination**, **sensors**, and **controls**. Their sources differ dramatically from optical communications systems. Instead of requiring conversion from an electronic to an optical signal, the initial signal is often optical. Medical applications such as **fiberscopes** can use optical fibers to reach inside of the human body and create a picture. The signal is imaged directly onto a bundle of fibers. Additional fibers provide light to illuminate the image. Optical fibers can also be used in surgery; medical conditions can be diagnosed using fluorescence effects, and surgery can be performed using high intensity guided laser light. Optical fibers are also used in transducers and bio-sensors used for the measurement and monitoring of temperature, blood pressure, blood flow, and oxygen saturation levels [1].

There are other, non-medical, applications of imaging, illumination, sensors, and controls. Just as fiber lasers can be used for surgery, higher power systems are used in manufacturing for welding metal. Fiberscopes are also used for security and law enforcement, as well as for examining air ducts in buildings or other hard-to-reach places. Fiber optic lighting systems are used for emergency lighting, automotive lighting, traffic signals, signage, lighting sensors, and decorative lighting. Sometimes, their only detector is the human eye. There are many popular entertainment applications as well, including fiber optic decorations, artificial flowers, and hand-held bundles of fiber which show different colored lights using a white light source and a rotating color filter wheel.

As we can see, the field of fiber optics is very broad and touches many different disciplines. A comprehensive review is beyond the scope of this book; instead, we intend to describe the most common components used in fiber optic systems, including enough working knowledge to actually put these systems into practice (such as relevant equations and figures of merit).

1.1 Optical Fiber Principles

As noted earlier, we can direct light from one point to another simply by shining it through the air. We often visualize light in this way, as a bundle of **light rays** traveling in a straight line; this is one of the most basic approaches to light, called **geometric optics**. It is certainly possible to send useful information in this way (imagine signal fires, smoke signals, or ship-to-shore lights), but this requires an unobstructed straight line of light, which is often not practical. Also, light beams tend to spread out as they travel (imagine a flashlight spot, which grows larger as we move the light further away from a wall). We could make light turn corners using an arrangement of mirrors, but this is hardly comparable to the ease of running an electrical wire from one place to another. Also, mirrors are not perfect; whenever light reflects from a mirror, a small amount of light is lost. Too many reflections will make the optical signal too weak for us to detect. To fully take advantage of optical signaling, we need it to be at least as easy to use as a regular electrical wire, and have the ability to travel long distances without significant loss. These are the principal advantages of an optical fiber.

Instead of using mirrors, optical fibers guide light with limited loss by the process of **total internal reflection**. To understand this, we need to know that light travels more slowly through transparent solids and liquids than through a vacuum, and travels at different speeds through different materials (of course, in a vacuum the speed of light is about 300,000,000 m/s). The relative speed of light in a material compared with its speed in vacuum is called the **refractive index**, **n**, of the material.

For example, if a certain kind of glass has a refractive index of 1.4, this means that light will travel through this glass 1.4 times more slowly than through vacuum. The bending of light rays when they pass from one material into another is called **refraction**, and is caused by the change in refractive index between the two materials. Refractive index is a useful way to classify different types of optical materials; to give a few examples, water has a refractive index of about 1.33, most glass is around 1.5–1.7, and diamond is as high as 2.4. For now, we will ignore other factors that might affect the refractive index, such as changes in temperature. We can note, however, that refractive index will be different for different wavelengths of light (to take an extreme example, visible light cannot penetrate your skin, but X-rays certainly can). At optical wavelengths, the variation of refractive index with wavelength is given by the **Sellmeier equations**.

Total internal reflection is described by **Snell's Law**, given by Equation 1.1, which relates the refractive index and the angle of incident light rays. This equation is illustrated by Figure 1.1, which shows two slabs of glass with a ray of light entering from the lower slab to the upper slab. Here, n_1 is the index of refraction of the first medium, θ_1 is the angle of incidence at the interface, n_2 is the index of refraction of the second medium, and θ_2 is the angle in the second medium (also called the angle of refraction). Snell's Law states that

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \qquad (1.1)$$

Thus, we can see that a ray of light will be bent when it travels across the interface. Note that as we increase the angle θ_1, the ray bends until

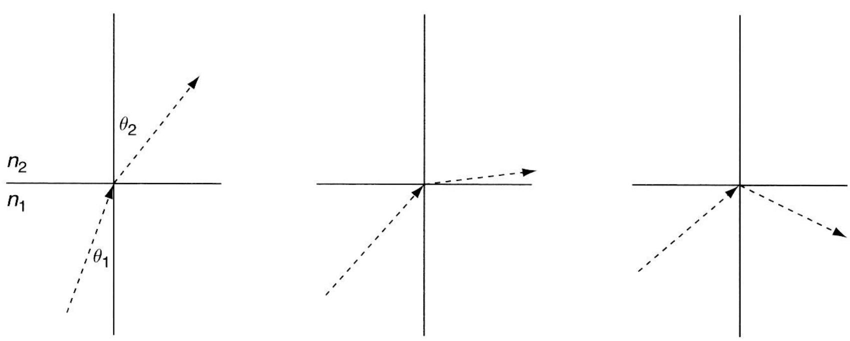

Figure 1.1 Illustration of Snell's Law showing how an incident light ray is bent as it travels from a slab of glass with a high refractive index into one with a lower refractive index, eventually leading to total internal reflection.

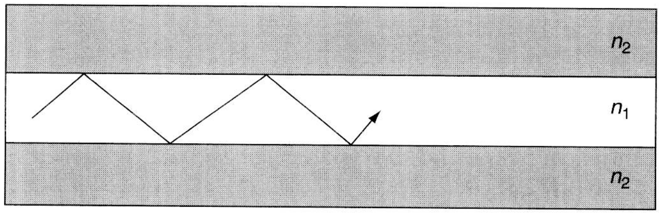

Figure 1.2 A sandwich of glass slabs with different indices of refraction used to guide light rays.

it is parallel with the interface; if we continue increasing θ_1, the light is directed back into the first medium! This effect is called **total internal reflection**, and it occurs whenever the refractive index of the first media is higher than the second media ($n_1 > n_2$). Now, imagine if we sandwich the high index glass between two slabs of lower index glass, as shown in Figure 1.2. Because total internal reflection occurs at both surfaces, the light bounces back and forth between them and is guided through the middle piece of glass. This is a basic optical waveguide. We can extend this approach by constructing a glass fiber, with a higher refractive index material surrounded by a lower refractive index material. Since the fiber **core** has a higher index of refraction than the surrounding **cladding**, there is a critical angle, θ_c, where incident light will be reflected back into the fiber and guided along the core. The critical angle is given by Equation 1.2,

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \tag{1.2}$$

Thus, if we make a fiber with a higher refractive index in the core and surround it with a lower index material as the cladding (as in Figure 1.3), then launch light waves at less than the critical angle, the

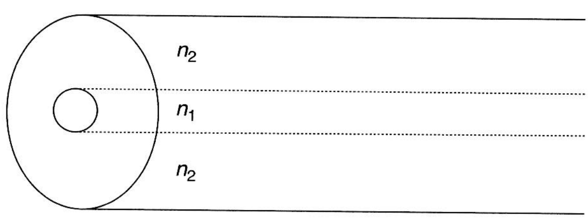

Figure 1.3 A cylindrical strand of glass with a higher index core forms an optical fiber.