Unit 4
Fiber Optics

Unit Objectives

After completion of this unit you will be able to identify and describe the following concepts:

1. General concepts—Core/cladding, Acceptance angle, Refractive index
2. Types of Optical Fiber —Single-mode, Multi-mode, Step index, Graded index
3. Sources and detectors—LASERs, diodes, source wavelength
4. Connectors and splices—Types of connectors and splices
5. Basic link budgets
6. Interpreting OTDR measurements

Introduction

A beam of light can be guided by a transparent material from one point to another. The earliest recorded demonstration of this concept was in the mid-1800s, when British physicist John Tyndall guided light down pipes filled with water in order to illuminate the stream of water as it exited the pipe.

The idea of using **glass** fibers to guide light for communications purposes had to wait until fiber loss (attenuation) could be reduced. In 1970 a research team working at Corning announced that they had developed a single-mode fiber with attenuation characteristics below 20 dB/Km. By the 1980s, when optical fiber was being laid over national routes, fiber attenuation was reduced to as little a 0.5 dB/Km @ 1300 nm (nanometers). Modern fibers can even perform at lower attenuation levels.

4-1 General Fiber Optic Concepts

In order to understand how optical fiber works, we must first review the fundamentals of optics. Optical fiber can be made of glass or plastic. We will consider glass fiber because it is the most common optical fiber in use today.

4-1.2 Speed of Light

As light travels through a medium, its velocity is a function of the **refractive index** of the medium. The refractive index of a vacuum is the base reference equal to **1**. In a vacuum light travels at a rate of 300,000,000 meters per second. It is important to note that the refractive index of air is 1.00029. We typically consider the refractive index of the air to be equal to **1** (a vacuum) for practical purposes.

As light moves through a medium with a higher refractive index than 1, its velocity is reduced. The refractive index (***n***) of a given medium can be determined by dividing the speed of light in a vacuum (***c***) by the speed of light in the particular medium (***v***) as shown in the formula below. The refractive index of **glass** is approximately **1.5**. This means that light travels through glass fiber at approximately 2/3 the speed of light in a vacuum (200,000,000 meters per second).

$$n = \frac{c}{v} \qquad or \qquad v = \frac{c}{n}$$

4-1.3 Reflection and Refraction

Refer to Figure 4.1. When a ray of light strikes the boundary between materials (or media) with different refractive indices (n_1 and n_2) the incident ray is **reflected** and **refracted**. The reflected ray will have an angle (θ_2) equal to the angle of the incident ray (θ_1). Any light that crosses the boundary will be refracted (bent). The amount of refraction is a function of the difference in refractive indices of the two materials.

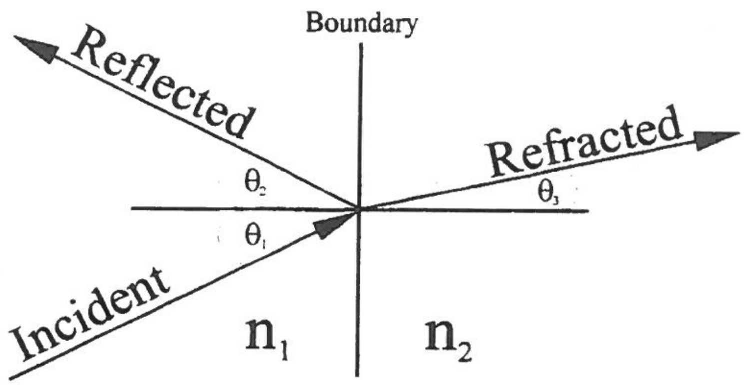


Figure 4.1 Reflection and Refraction

Reflection and refraction divide the ray into two parts:

- ✓ Light **reflected away** from the boundary
- ✓ Light **passing into** the medium

Reflection is more significant when there is a **large difference between n_1 and n_2** and at **high boundary angles**. There is an angle at which **all of the light will be reflected** at the boundary. This is referred to as the **critical angle**. It is a function of the difference in refractive indices and angle of incidence. Before going further lets take a look at an optical fiber. Refer to Figure 4.2.

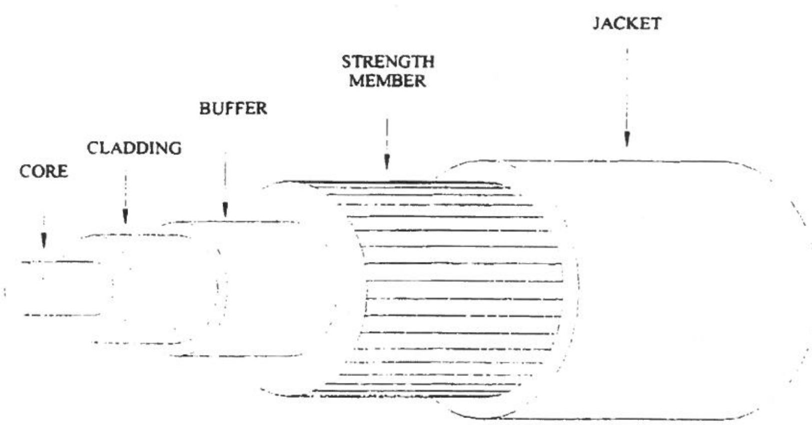
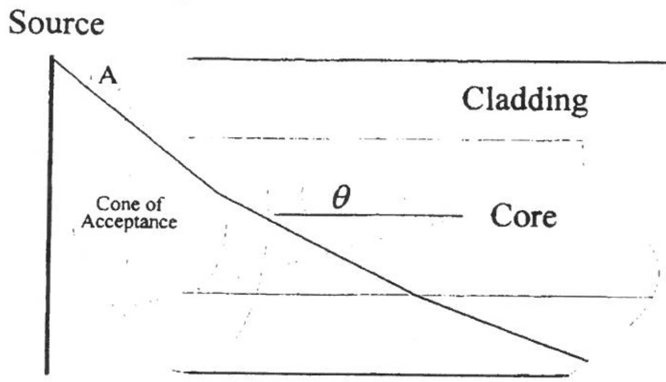


Figure 4.2 Optical Fiber Construction

Optical fiber is made up of a light-carrying **core** surrounded by a **cladding** that traps light in the core. Surrounding the cladding is the buffer. This protects the glass fiber from physical damage. The strength member isolates the fiber from tensile forces.

The **core material is made with a higher refractive index than the cladding,** causing the light to be **totally reflected** at the core-cladding boundary for all light that strikes the boundary above a certain angle. This is the previously mentioned **critical angle**. We will take a closer look at the optical fiber input to see how this works. Refer to Figure 4.3.



$$NA = \sqrt{n_{core}^2 - n_{cladding}^2}$$

$$NA = \sin\theta$$

$$Cone\ of\ Acceptance = 2 \cdot (\sin^{-1}\theta)$$

Figure 4.3 ***Cone of Acceptance and Numerical Aperture in Optical Fiber***

Rays of light that are launched into the core at too steep an angle (**A**) will **not be reflected** at the core-cladding boundary. This light energy will pass into the cladding and be lost. Any rays of light that enter the core within the **"Cone of Acceptance"** will strike the core-cladding boundary above the critical angle and **be reflected** back into the core. This light gathering ability of a fiber is referred to as the **Numerical Aperture** (NA) and is a function of the difference in the refractive indices between the core and cladding (refer to formulas in Figure 4.3). The greater the difference between the refractive indices, the larger the NA and the "Cone of Acceptance". Formulas are shown for explanatory purposes only.

4-2 Types of optical fiber

Optical fiber can be made of silica (glass) or plastic. Since glass is the most common type in use we will focus on it. The two major categories of optical fiber are based on the **mode** of travel through the core. The fiber categories are **multi-mode** and **single mode**. A mode is a stable **propagation path**. As the name implies **multi-mode** fiber allows for **many propagation paths** through the fiber and **single-mode** fiber allows for **only one path**.

Multi-mode fiber comes in two general types: **Step-index** and **Graded-index.** The difference between them is the way in which light is guided through the core. **Step-index fiber** allows light to travel through the core by means of **reflection. Graded index fiber refracts** the light through the core. We will take a look at each of these fiber types in turn.

4-2.2 Step Index Multi-mode Fiber

Refer to Figure 4.4. The first type of fiber we will consider is **step-index multi-mode** fiber. Multi-mode fiber has a relatively large core —typically 50 to 200 μm (micrometers). This allows for large light sources and **maximum light coupling**. The term step-index means that the difference between the core and cladding refractive indices is **abrupt** (refer to graph in Figure 4.4). The abrupt change in ***n*** causes any light that is within the cone of acceptance to be **reflected** within the core as it travels.

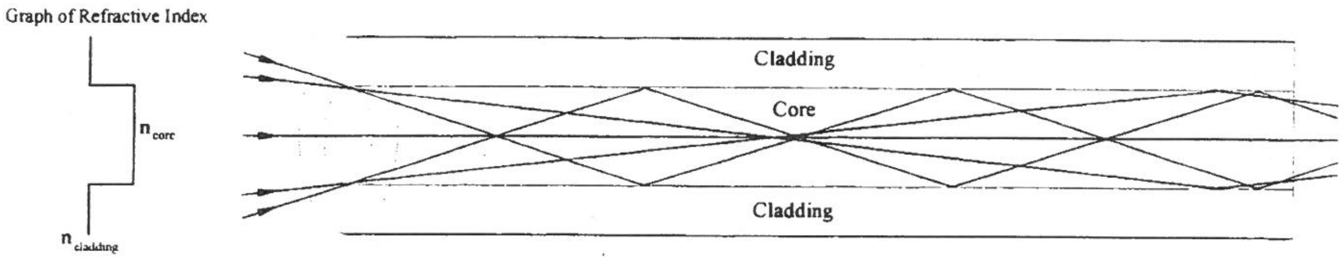


Figure 4.4 Step-Index Multi-mode Optical Fiber

Light travels many modes in multi-mode fiber. Figure 4.4 shows three of those modes. The light path of two of the modes shown is off-axis so the light rays **reflect** at the core-cladding boundary as they move through the fiber. The third mode shown is the **axial mode**. This path is **through the center** of the fiber. Remember: "The shortest distance between two points is a straight line." So, the axial path is the shortest path through the fiber. Light waves that enter at higher angles will take longer paths. Since the light is travelling at the same speed through the core, light travelling over longer paths arrives later.

The difference in path length causes problems over distance at high data rates. Since the light is travelling at the same speed through the core, light travelling over longer paths arrives later. Spreading (dispersing) of the signal arrival times tends to "smear" the signal at the receiver. This problem is referred to as **modal dispersion**. The effect of modal dispersion is illustrated in Figure 4.5. Notice that as the original pulse travels over many paths through the fiber, **different modes will arrive at different times**. The different arrival times spread the pulse at the detector. As the data rate increases, the dispersed pulse can **overlap separate bit times**. When this occurs, **information cannot be recovered.**

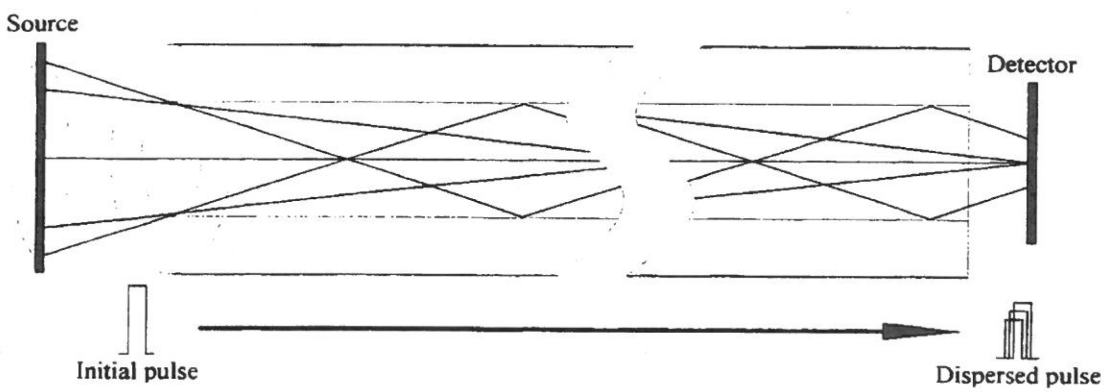


Figure 4.5 Modal Dispersion in Step-index Multi-mode Fiber

4-2.3 Graded Index Multi-mode Fiber

When transporting high-speed data over distance, there are two ways to reduce the effects of modal dispersion. The first way we will consider is the use of multi-mode graded-index optical fiber. The second way (considered in the next section) is to **only allow one mode** through the fiber. We will first take a look at multi-mode graded index to see how it reduces modal dispersion.

Graded index fiber still has many modes, but reduces the effects of signal dispersion by using a different technique for propagating the many modes through the core. Instead of the light being reflected at the core-cladding boundary, as in step-index multi-mode fiber, the light is refracted (bent) as it moves away from the core.

Refer to Figure 4.6. Notice that there are still many modes of propagation, but what is different with graded-index fiber is the way in which light is refracted as it moves away from the core. This bending of light is due to the **gradual change in refractive index** (refer to graph in Figure 4.6) within the core. Notice that the highest refractive index is at the center of the core. As light moves **away from the center, the refractive index gradually decreases**. You will remember that light velocity is a function of refractive index—the higher the refractive index, the slower light travels. So, **light at the center of the core (axial mode) moves slower** than light away from the center. The difference in refractive index also causes the bending of light, curving it back towards the core.

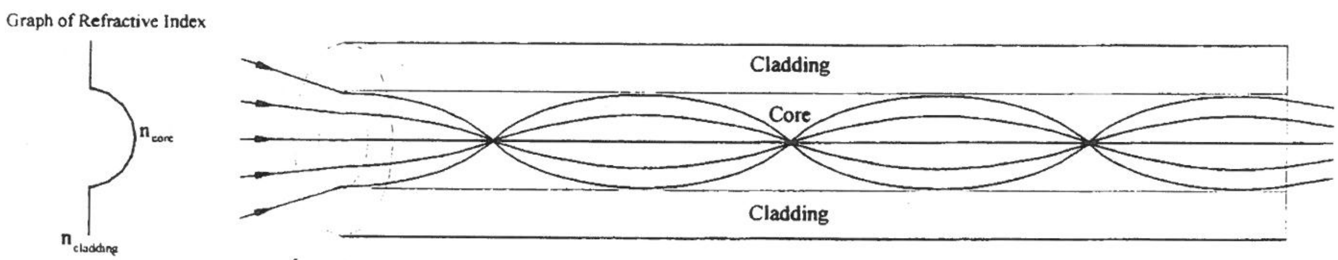


Figure 4.6 Graded-Index Multi-mode Fiber

The effect of light propagating through the core at different velocities is that as light travels away from the center of the core it **travels farther (longer path), but faster**. The end result (Figure 4.7) is that even though there are many modes of propagation through the core, the difference in arrival times at the receive end (detector) among the many modes is reduced.

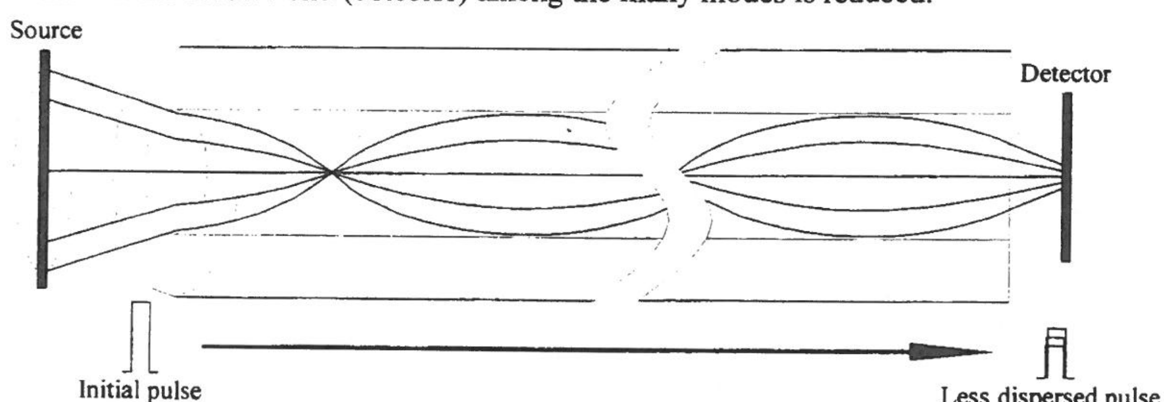


Figure 4.7 Reduced Modal Dispersion in Graded-index Multi-mode Fiber

So far we have considered two types of fiber. Both of which have relatively large cores and a difference between the core and cladding refractive indices of up to 3%. Remember: the greater the difference between n_{core} and $n_{cladding}$ the greater the critical angle. A larger critical angle means a larger cone of acceptance. Thus, more light can be coupled into the fiber (good news), but there are more modes of propagation (bad news) reducing the bandwidth over distance.

4-2.4 Single-mode Fiber

Refer to Figure 4.8. When transporting high-speed signals over long distances, another type of fiber is used. This is **single-mode fiber**. As the name implies, there is only one mode of propagation through the core. This is accomplished in two ways:

1. Keep the core diameter small—3-10 μmeters
2. Keep cone of acceptance small by reducing the difference in refractive indices between core and cladding--< 0.5 %

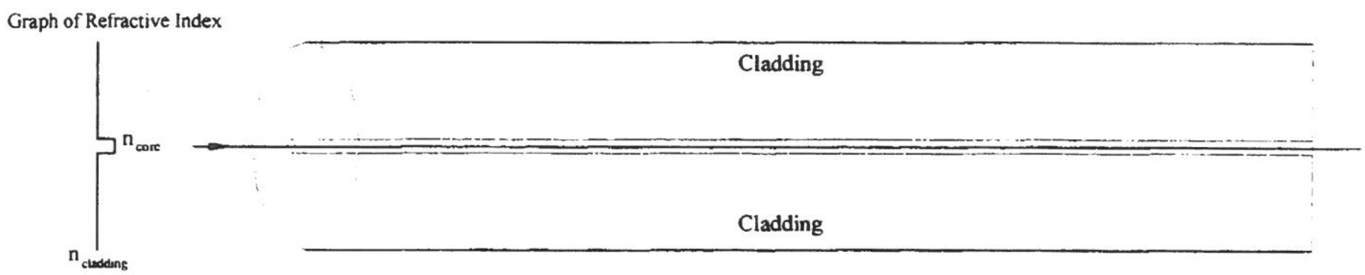


Figure 4.8 Single mode Fiber

Single mode fiber offers the highest attainable performance allowing for data rates in the Gigabit/sec region and distances of hundreds of kilometers. It is also the most difficult fiber to use, requiring precision splices and connectors.

Because a high-speed signal can travel so far over single mode fiber, we run into another type of dispersion—**Chromatic dispersion**. This type of signal spreading is caused by a combination of the light source and the characteristics of optical fiber. Chromatic dispersion is also referred to as **Material Dispersion** because it is due to the material properties of optical fiber. We will consider the light source in more detail in section 3.

It has been stated that the velocity of light through optical fiber is based on the refractive index—this is a valid statement. What also needs to be stated in order to understand chromatic dispersion is that the **refractive index is slightly different for different wavelengths** (colors) of light. The effect of the slight difference in refractive index is that some wavelengths will travel slightly faster than others. Figure 4.9 illustrates that different colors of light (shown in shades of gray) travelling over a long distance at slightly different velocities will arrive at different times.

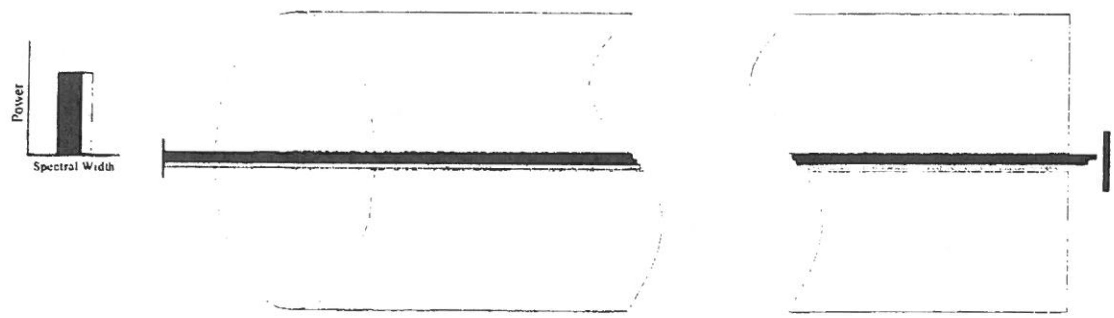


Figure 4.9 Chromatic Dispersion in Single-mode Fiber

There are two things that can be done to reduce chromatic dispersion:

1. Use a source that has a narrow spectrum—reducing the number of colors launched in to the fiber.
2. Choose a portion of the light spectrum that has the lowest difference in velocity through the fiber for a given spectrum width.

Both of these have to do with the source of light, so they will be addressed in the next section.

Refer to the following table containing various optical fiber types and characteristics. We will complete the table in section 5 (Link Budgets). For now, we are listing types and characteristics that have been presented in this section.

Fiber Type	**Core/Cladding diameter (μm)**	**Numerical Aperture**	**Source Type**	**Attenuation (dB/Km)**			MHz-Km
				850nm	**1310nm**	**1550nm**	
Multimode							
Step Index	50/125	0.240					
Step Index	200/380	0.270					
Graded Index	50/125	0.200					
Graded Index	62.5/125	0.275					
Graded Index	100/140	0.290					
Single Mode	5/125	0.100					
Single Mode	10/125	0.100					

Exercise 4-1 Fiber Optics

Fill in the blanks.

1. The n_{core} is ___________ than the $n_{cladding}$ in an optical fiber.
2. A ray of light will be __________ as it moves from one medium to another.
3. A fiber with a _________ difference between n_{core} and $n_{cladding}$ will have **more** modal dispersion than a fiber of the same diameter with a __________ difference between n_{core} and $n_{cladding}$
4. _________ __________ multi-mode fiber propagates light by refraction.
5. Smearing of the received light is caused by ______________ of the light as it propagates through the fiber.
6. The Numerical Aperture of a fiber is **0.25**. What is the angle of the "Cone of Acceptance"? ____________ degrees

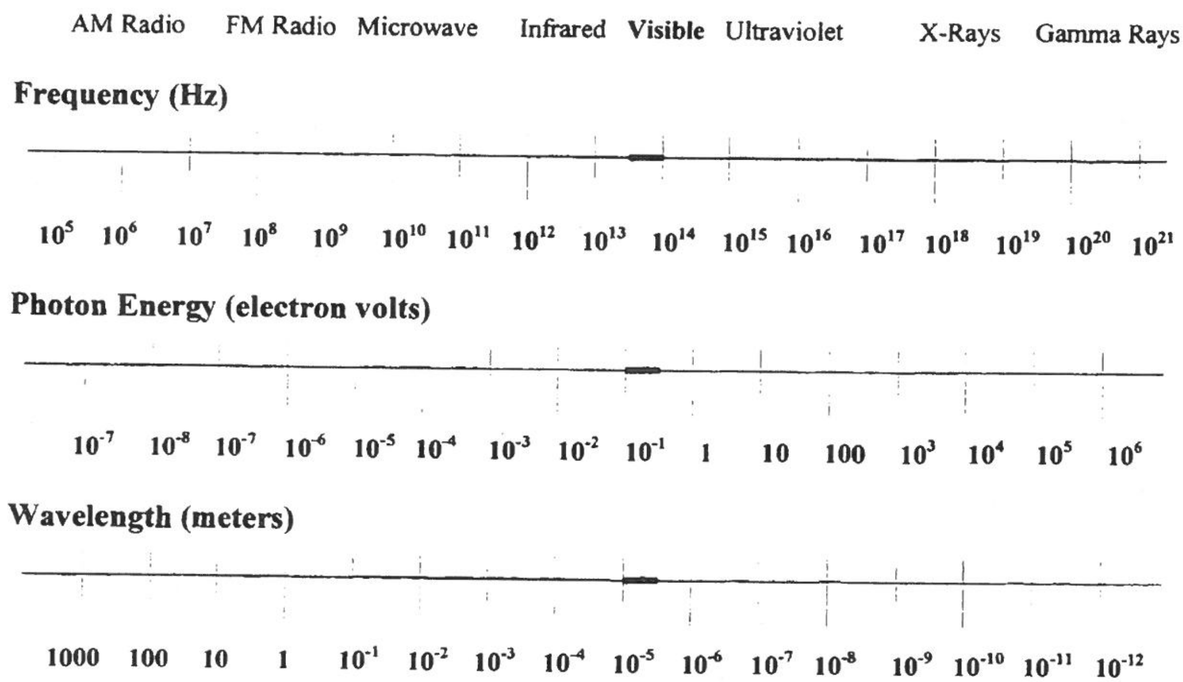
4-3 Sources and Detectors—Spectrum Issues

Now that we have considered how light is guided through fiber, we will take a look at how it is launched (sources) and how it is received (detectors). The first issue to consider is the nature of light.

Light is Electromagnetic Energy, just as radio—AM and FM, for example—and X-rays. So, let's see where light is in the electromagnetic (E-M) spectrum. Refer to the chart below. Notice that we can consider E-M energy in several ways: Frequency, Photon Energy and Wavelength. When considering Radio Frequencies (RF) we typically use the **frequency** of the E-M energy. When we consider light, we typically use **wavelength** (λ). **Wavelength is a statement of how far a wave travels in one cycle**. This is shown in the formula below. The reference velocity is the speed of light in a vacuum.

$$\lambda = \frac{velocity}{frequency}$$

Electromagnetic Spectrum



The range of **colors that we can see** is actually in a narrow range from approximately 700 nm (deep red) to 400 nm (violet). The spectrum typically used in optical fiber systems is in the infrared region below the visible region of light. Actually some optical fiber systems use wavelengths within the visible region, in the far-red region of visible light.

We will only consider the most common region from 800 nm to 1600 nm. Within this region of light there are **three common *windows***. The term **window** refers to a range of wavelengths that are matched to the properties of the optical fiber. The three windows we will consider are **850 nm, 1310 nm and1550 nm**. Each of these windows has characteristics that make it the best choice for a specific application.

850 nm window: Short distance applications using **inexpensive** components—multi-mode fiber and LED sources (discussed in next section). This wavelength has the **highest attenuation** (loss) of the three windows considered.

1310 nm window: This is the wavelength region that has the **least chromatic dispersion.** It is used in high speed, long distance applications over single mode fiber.

1550 nm window: This is the wavelength region that has the **lowest attenuation** (dB/Km).

4-3.2 Sources of Light

There are basically **two types of sources** used in fiber optics: Light Emitting Diodes (**LEDs**) and **Lasers.** Each source type has characteristics that determine its suitability for a given application. Refer to the table below comparing LED and Laser characteristics.

Characteristic	LED	Laser
Power Output	Lower	Higher
Bandwidth	Lower	Higher
Output Pattern (NA)	Wider	Narrower
Spectral Width	Wider	Narrower
Single mode capable	No	Yes
Lifetime	Better	Good
Cost	Lower	Higher

Let's consider each in turn.

Power Output

A Laser is capable of emitting far more power than an LED. LED output power is in the microWatt (μW) range. Lasers are capable of powers in the milliWatt (mW) range and higher.

Bandwidth

The bandwidth of a source is a function of its on/off transition speed. The faster the transition speed, the higher the bandwidth. Lasers can transition between states (on/off) in less than a nanosecond. (10^{-9} seconds). LED transition times are measured in nanoseconds.

Output Pattern and Coupling Loss

Refer to Figure 4.10. The output pattern is a statement of how much the light spreads out as it leaves the source. A smaller output pattern allows for more light to be coupled into the optical fiber. The output pattern is based on the **emission diameter** and the **Numerical Aperture** (NA) of the source. If the **emission diameter is larger than the core diameter** or the **NA of the source is larger than the NA of the fiber core**, some **optical power will be lost**.

The amount of light transferred from the source to the core is a function of the **square of the difference** between the **diameters** and NAs of the core and source. We will quantify this relationship in an example.

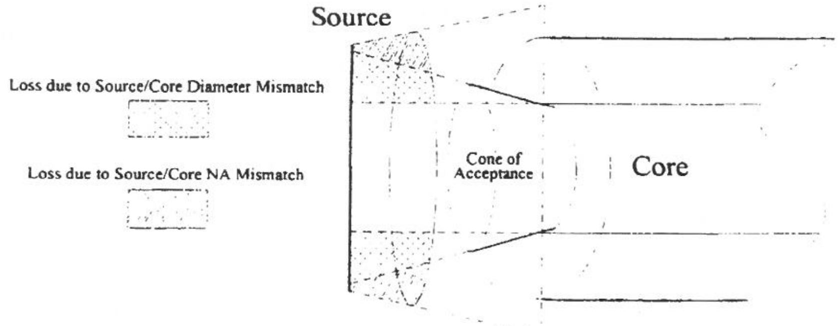


Figure 4.10 Source Coupling Loss

The **percent (%) of light coupled** from the source to the core due to diameter or NA mismatch can be determined with the following formulas.

$$\%Coupled_{diameter} = \left(\frac{diameter_{fiber}}{diameter_{source}}\right)^2 \cdot 100 \qquad \%Coupled_{NA} = \left(\frac{NA_{fiber}}{NA_{source}}\right)^2 \cdot 100$$

Example:

Source diameter = 100 μm
Fiber core diameter = 62.5 μm

Source NA = 0.30
Fiber NA = 0.26

$$\%Coupled_{diameter} = \left(\frac{62.5}{100}\right)^2 \cdot 100 = 39\% \qquad \%Coupled_{NA} = \left(\frac{0.26}{0.30}\right)^2 \cdot 100 = 75\%$$

The **total percent of light coupled** from the source to the core due to diameter and NA mismatch is found by multiplying 39% times 75% = **29.2%.** We will convert these values into *decibels* in the link budget section (section 5).

No diameter loss occurs when the fiber diameter is larger than the source diameter. No NA loss occurs when the NA of the fiber is greater than the NA of the Source.

Spectral Width

Lasers and LEDs do not emit a single wavelength of light. They both emit a range of wavelengths. This range of emitted wavelengths is referred to as Spectral Width. Refer to Figure 4.11.

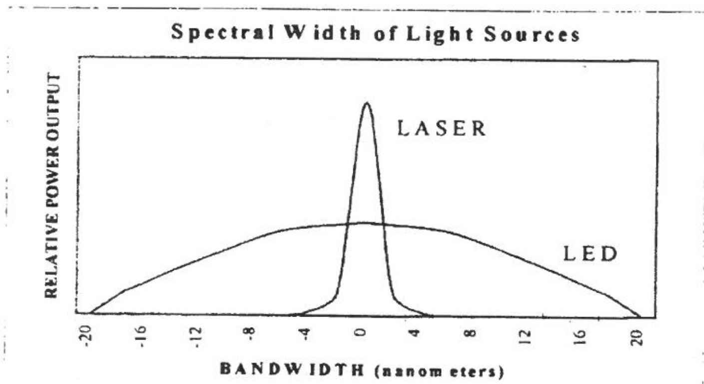


Figure 4.11 Spectral Width of Light Sources

You can see that the spectral width of the Laser is narrower than the LED. Spectral width only becomes important when transporting high data rates over long distances, as with single mode fiber. You will recall the issue of **chromatic dispersion** (section 4-2.4). The narrower the width of the light source, the less chromatic dispersion. Since **Lasers** can provide a small, intense beam of light with a narrower spectral width than LEDs, they **are required when using single mode fibers**.

Cost and Reliability
An advantage of LEDs is their lower cost and longer life than Lasers. This is why they are typically used in Local Area Network (LAN) equipment. Lasers are typically more expensive and less reliable than LEDs, but their high power and lower spectral width make them the choice for high bit rate, long distance applications.

4-3.3 Light Detectors

A detector performs an opposite function from the source. The source converts an electrical signal into light energy; the **detector turns the light energy back into an electrical signal.** There are basically two types of detectors used in fiber optics: PIN (P-Intrinsic-N) diodes and Avalanche Photo Diodes (APD). Each of these detectors has characteristics that determine its suitability for a given application. Refer to the comparison chart, showing typical values, below.

Detector Type	Material	Wavelength (nm)	Rise Time (ns)	Responsivity (A/W)	Dark Current (nA)
PIN	Silicon	300-1100	0.5	0.5	1
PIN	Germanium	500-1800	0.1	0.7	200
PIN	InGaAs	900-1700	0.3	0.6	10
APD	Silicon	400-1000	0.5	75	15
APD	Germanium	1000-1600	1	35	700
APD	InGaAs	1000-1700	0.25	12	100

The values provided for each type of photo diode are for comparison purposes only. Now, let's take a look at the characteristics referred to in the table.

Material Type and Wavelength
The type of material used in the fabrication of the photo diode determines the operating wavelength.

Rise Time
The time required for a photodiode to respond to light input and produce an output is its rise time. The **bandwidth of a detector is limited by its rise time**. You will notice that the rise times between PIN diodes and APDs are similar.

Responsivity
Responsivity is a statement of the sensitivity of a detector. Since optical energy is being converted to electrical current, the measure of detector sensitivity is the number of amps of current for a given amount of optical power in Watts. Thus, the **units of responsivity** are **Amps per Watt or A/W**. There is a significant difference between the responsivity of PIN diodes and

APDs. The sensitivity of APDs makes them the choice for loss-limited systems such as long distance links.

Dark Current
Dark current is a statement of the amount of inherent noise in a detector. In other words, when there is no light being received, there is a small amount of current generated due to random motion of electrons. Since an actual light signal must produce more current, dark current established the minimum detectable signal level.

Coupling Loss
The last issue regarding detectors has to do with a mismatch in the diameter and NA of the detector and the fiber. This type of loss is similar to source coupling loss. The percent of light transferred from the core to the detector due to diameter or NA mismatch can be determined with the following formulas.

$$\%Coupled_{diameter} = \left(\frac{diameter_{detector}}{diameter_{fiber}}\right)^2 \cdot 100 \qquad \%Coupled_{NA} = \left(\frac{NA_{detector}}{NA_{fiber}}\right)^2 \cdot 100$$

Example:

Fiber core diameter = 62.5 μm
Detector diameter = 50 μm

Fiber NA = 0.26
Detector NA = 0.22

$$\%Coupled_{diameter} = \left(\frac{50}{62.5}\right)^2 \cdot 100 = 64\% \qquad \%Coupled = \left(\frac{0.22}{0.26}\right)^2 \cdot 100 = 71.6\%$$

The **total percent of light coupled** from the core to the detector due to diameter and NA mismatch is found by multiplying 64% times 71.6% = **45.8%.** We will convert these values into *decibels* in the link budget section (section 5).

No diameter loss occurs when the detector diameter is <u>larger than the fiber diameter</u>. No NA loss occurs when the NA of the detector is <u>greater than the NA of the fiber</u>.

Exercise 4-2 Sources and Detectors

1. An optical source with a power output of 0.2 mW and a diameter of 70μm is coupled into a core with a diameter of 50μm. Assuming no loss due to a NA mismatch, determine how much power is coupled into the fiber. ____________ mW

2. A signal exits an optical fiber to a detector. The detector diameter is 100 μm and the NA is 0.25. What percentage of the signal leaving the core will be seen by the detector when using the following optical fibers.

	Fiber A	**Fiber B**	**Fiber C**
Diameter =	50μm	80μm	200μm
NA =	0.24	0.22	0.28
	______%	______%	_____%

4-4 Connectors and Splices

Connectors for optical fibers come in many shapes and sizes. There are single fiber, dual fiber and multi fiber connectors. We will first look at a simple definition of a connector.

A connector is a device designed to be mated, and unmated, **repeatedly** to a matching device (socket) for the purpose of transferring energy from one point to another.

Notice the word **repeatedly** in the definition. This is the difference between a connector and a splice. A splice is a more permanent type of junction than a connector. Some modern splicing techniques, as we will see later in this section, tend to blur this distinction.

No matter how a connector is made, they all have some common functions. Refer to Figure 4.12 showing a generic fiber connector construction. All optical connectors provide strain relief, fiber protection and accurate core alignment.

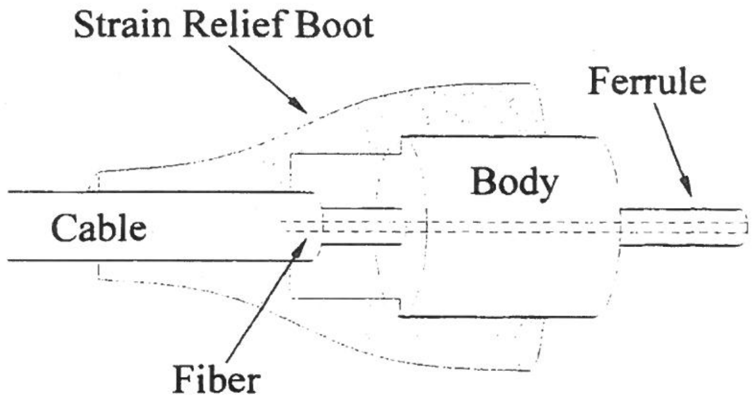


Figure 4.12 Generic Connector

The strength member of the fiber cable is typically attached to the **body** of the connector and protected by a **strain relief boot**. The fiber is mounted inside a long, thin cylinder called a **ferrule**. The ferrule provides accurate alignment of the fiber and protects it from mechanical damage. The end of the fiber is at the end of the ferrule. Ferrules can be made of ceramic, metal and even plastic.

Connectors are typically used where configurations are likely to change and at terminal points—transmitters and receivers. The following is a list of some of the areas where connectors are used.

- ✓ Patch panels
- ✓ Signal entry points in buildings
- ✓ Connections between terminal equipment and networks
- ✓ Temporary and portable equipment connections

Figure 4.13 shows some common **single fiber connector** types. Notice the similarity to the generic connector in Figure 4.12. The most common of the connectors illustrated are the **ST** and **SC** connectors.

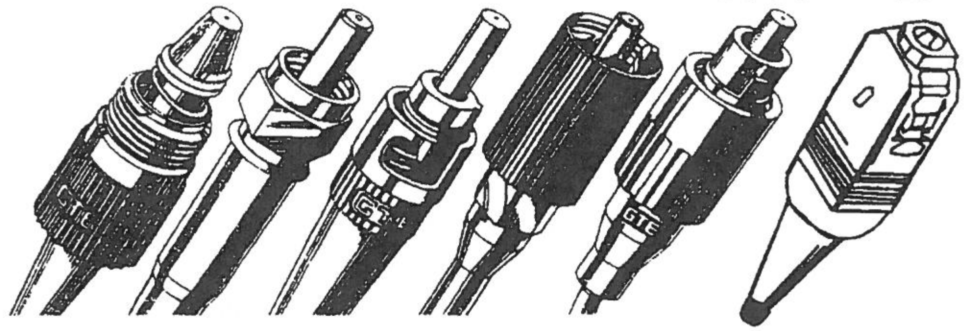


Figure 4.13 ***Some Common Single Fiber Connectors***

4-4.2 Connector Losses

Since fiber optic connectors are designed to allow for maximum light transfer at the connector junction, we need to consider some of the problems associated with that transfer of light. The following are some of the factors associated with connector junction losses.

Fiber Core Alignment

The ferrule is responsible for aligning the core at the connector junction. Consider the alignment accuracy required for core diameters of 5 to 100 μm. As the core size decreases, the possibility of slight misalignment increases. Refer to Figure 4.14.

Figure 4.14 ***Core Misalignment***

Either of the problems shown in Figure 4.14 can cause a loss of signal. Some connectors compensate for this problem by providing a slight cam action that offsets the center for a better match.

Numerical Aperture and Core Diameter Mismatch

These issues have already been discussed in sections 4-3.2 and 4-3.3.

Internal Reflection

You will recall that when light rays hit a boundary between two different refractive indices, some of the light will be reflected. This is easily illustrated with a flashlight. If you shine a flashlight directly through a window, you will see the light hit an object on the other side of the window, but you will also see a small reflection of the light on the window. The reflected light that you see is light that is not making it through the window—lost light. This reflection loss is referred to as **Fresnel loss.**

The reflection loss is noticeable (approximately 0.3 dB) when there is an **air gap between the fiber ends**. Proper termination of the fiber in the connector and polishing keeps Fresnel loss to a minimum.

4-4.3 Splices

A splice is a permanent junction between two fibers. The two main categories of splices are fusion splices and mechanical splices.

Whether a splice or a connector is used, the reasons for loss of light at a junction are the same. The actual total loss of a splice will typically be lower than the loss of a connector.

Fusion Splicing

As the name implies, **fusion splicing** melts the glass fiber and fuses the ends together. This is a relatively **expensive process** yielding losses in a range of 0.05 to 0.2 dB.

Mechanical Splicing

Less expensive techniques have been developed for splicing fibers together. Mechanical splicing is performed by **clamping** two fibers together. The clamping structure is designed to provide for alignment and matching of the core index of refraction. Matching of the core refractive index can be done using a special epoxy or gel. These are referred to as **index matching epoxy** and **index matching gel**. The use of index matching gel allows for a more **semi-permanent type of splice** that in some case can be disassembled and reassembled. Mechanical splices are simpler to perform and require less sophisticated equipment than fusion splices, but are typically higher in loss (0.2 to 0.3 dB) than fusion splicing.

4-5 Link Budgets

So far, we have considered how optical fiber systems work. Now we will put this knowledge into practice. Link budgets are not about budgeting money, although cost factors are considered. A link budget is about determining the performance of a communications link based on parameters of the various components that make up the link.

Before we go further let's complete the table that was started in section 4-2.4. The attenuation shown is approximate.

Fiber Type	**Core/Cladding diameter (μm)**	**Numerical Aperture**	**Source Type***	**Attenuation (dB/Km)**			MHz-Km
				850nm	**1310nm**	**1550nm**	
Multimode							
Step Index	50/125	0.240	LED	5.0			33 @ 850 nm
Step Index	200/380	0.270	LED	6.0			6 @ 850 nm
Graded Index	50/125	0.200	LED,LD	2.4	0.6	0.5	600 @ 850nm 1500 @ 1310 nm
Graded Index	62.5/125	0.275	LED,LD	3.0	0.7	0.3	200 @ 850 nm 1000 @ 1310 nm
Graded Index	100/140	0.290	LED	3.5	1.5	0.9	300 @ 850 nm 500 @ 1310 nm
Single Mode	5/125	0.100	LD	2.3			5000 @ 850 nm
Single Mode	10/125	0.100	LD		0.3	0.2	83000 @ 1300

* LED—Light Emitting Diode, LD—Laser Diode

4-5.2 A Simple Link

In order to determine performance of a link we must first take a look at the parameters to be considered. Figure 4.15 illustrates the parameters of a basic fiber optic system consisting of a transmitter, receiver and a link connecting them.

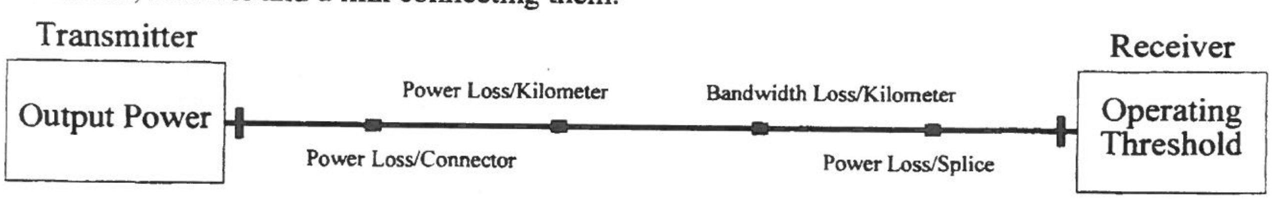


Figure 4.15 A Fiber Optic System

> The function of a communications link is to transfer information from a source with a **specific bandwidth** requirement (based on the signaling rate—refer to unit 2) **over a given distance** and successfully recover it at the receiver.

A link budget is done to determine the performance of a link. As the above statement suggests, there are **two performance issues** to be considered:

1. The **power margin** of the link
2. The **maximum bandwidth** of the link

When considering the power in a link budget, losses and gains are stated in decibels. Decibel gains are added and decibel losses are subtracted. Using decibels makes determining power margins relatively simple. So before we can go any further we will have a short review of decibels.

4-5.3 Decibel Review

A ***decibel*** is defined as 10 times the *base 10* logarithm of the ratio between two powers. So what's a logarithm? A logarithm of a number is the power to which a *base* must be raised to equal the number. Since decibels use base 10, let's show some examples.

Number	Power of Ten	Base 10 logarithm	Decibels
1,000	10^{3}	3	30 dB
40,000	$10^{4.6}$	4.6	46 dB
1,000,000	10^{6}	6	60 dB
.001	10^{-3}	-3	-30 dB
.000002	$10^{-5.7}$	-5.7	-57 dB

The following formula is used to convert a power ratio to a decibel value.

$$Decibels = 10 \cdot log_{10}\left(\frac{Power_2}{Power_1}\right)$$

Example 1:

Consider a source with a power output of 10mW going over a link and measuring 100µW at the other end. What is the loss (negative gain) of the link in decibels?

Source input = 10 mW
Link output = 100 µW

$$Gain_{dB} = 10 \cdot log_{10}\left(\frac{100 \cdot 10^{-6} W}{10 \cdot 10^{-3} W}\right) = -20\,dB$$

Decibels can also be used to state absolute power values. The following formula converts Watts into dBm (decibels relative to one milliwatt).

$$Power_{dBm} = 10 \cdot log_{10}\left(\frac{Power}{1mW}\right)$$

Example 2:

Let's try determining the loss in the previous example by first converting the power values into dBm and determining the loss over the link.

$$Source_{dBm} = 10 \cdot log_{10}\left(\frac{10mW}{1mW}\right) = 10\,dBm \qquad Link_{dBm} = 10 \cdot log_{10}\left(\frac{100\mu W}{1mW}\right) = -10\,dBm$$

Now that we have both the source input and the link output in dBm, all we need to do in order to determine link loss is to subtract the link output from the source input.

10 dBm –(-10 dBm) = 20 dB loss

Losses can be stated as **negative gains** as in example 1 (-20 dB of gain), or simply as **positive losses** as in example 2 (20 dB of loss). The answer is the same. Either way is acceptable as long as you are consistent. Having all values in decibels makes the process simple addition or subtraction.

4-5.4 Performing a Link Budget

Now that we have had a brief review of decibels, let's see how useful they can be in performing a basic link budget. Refer to Figure 4.16 showing a source, link, connectors, splices and a receiver. Determine the amount of margin (level above threshold) for the following link. Use the fiber optic table (in section 4-5) to find fiber loss. In order to perform the link budget we must first state the requirements for this link.

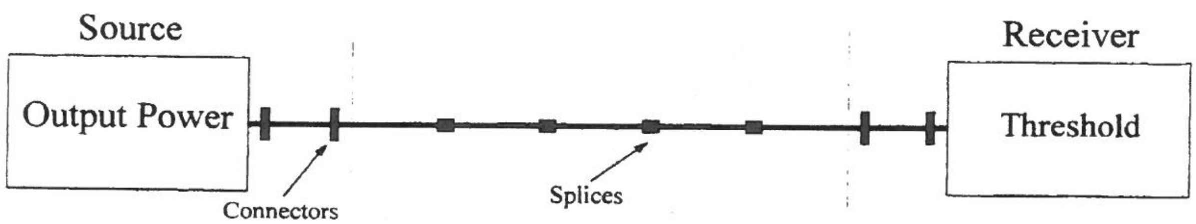


Figure 4.16 Basic Link

Link Requirement
Two locations **5 Km** apart require a data link capable of providing **50 MHz** of bandwidth.

We now have our distance (assume a straight path) and bandwidth requirements. The component selection is a function of distance, bandwidth and cost. Let's start with the bandwidth.

Bandwidth

If you look at the right-most column of the fiber optics chart, you will see a parameter called **MHz-Km**. This is the statement of the bandwidth of an optical fiber. It is a function of the fiber NA, core diameter and the type of light source used. The value of MHz-Km is the product of multiplying the **bandwidth required (in MHz) times the length of the link (in Km)**. In our example the calculation would be 50 MHz · 5 Km = **250 MHz-Km**. We now know that we must select an optical fiber that can provide at least 250 MHz-Km. Let's go back to the chart and find an optical fiber that can use an LED source (to save money) and provide 250 MHz-Km.

There are several selections that fit the bandwidth requirements. In this example, the **Graded Index 100/140 will be used with a 1310 nm diode source**. Single mode would be too expensive to implement.

Power

When considering power requirements, there is an easy way to determine how mush loss can be tolerated over a link. The concept is called **System Gain**. System gain is found by subtracting the receiver threshold (in dBm) from the source power output (in dBm). In this link example (refer to Figure 4.17) we will use an LED source with an output power of 0.5 mW and a receiver with a threshold of –30 dBm. Converting the source power to dBm with the following formula:

$$Power_{dBm} = 10 \cdot log_{10}\left(\frac{0.5mW}{1mW}\right) = -3\,dBm$$

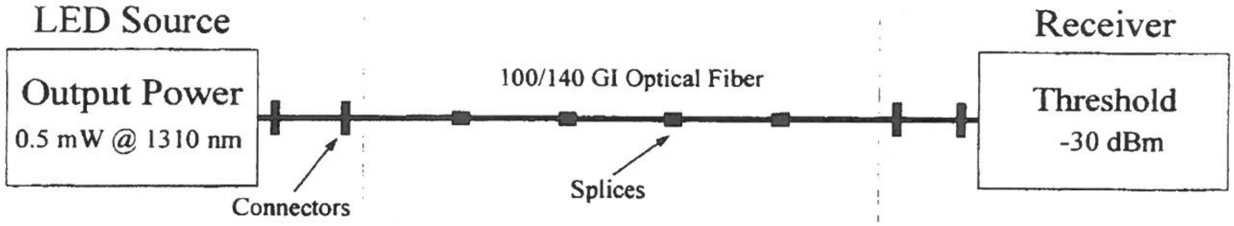


Figure 4.17 Example Link with Selected Components

System gain in this example will be –3 dBm – (-30 dBm) = ***27 dB****. This will be the* ***maximum attenuation allowed for this link****. If we assume a* ***3 dB margin*** *is required for proper operation, then the total allowed losses are reduced to* ***24 dB.***

Total Connector Losses

Total connector losses is based on the number of connectors and the loss per connector. You should recall that connector loss is based primarily on mismatch of source/core diameter and NA. We will perform the calculation in **decibel form** for the source and provide a value for all other connectors in the example. Refer to the following formulas and parameters.

Source

$$loss_{diameter} = 10 \cdot log_{10}\left(\frac{diameter_{core}}{diameter_{source}}\right)^2$$

$$loss_{NA} = 10 \cdot log_{10}\left(\frac{NA_{core}}{NA_{source}}\right)^2$$

Detector

$$loss_{diameter} = 10 \cdot log_{10}\left(\frac{diameter_{detector}}{diameter_{core}}\right)^2$$

$$loss_{NA} = 10 \cdot log_{10}\left(\frac{NA_{detector}}{NA_{core}}\right)^2$$

Values for determining Source connector loss

Source diameter = 120 μm
Core diameter = 100μm

Source NA = 0.27
Source NA = 0.28

$$loss_{diameter} = 10 \cdot log_{10}\left(\frac{100\mu m}{120\mu m}\right)^2 = -1.58\,dB$$

$$loss_{NA} = 10 \cdot log_{10}\left(\frac{0.27}{0.28}\right)^2 = -.03\,dB$$

Total loss of **source connector = 1.61 dB**

Total Losses
Now that we have calculated for the total source connector loss, we can continue the link budget, considering **all loss values**. The following table lists all component values, and their sources, for the system illustrated from Figure 4.17.

Parameter	Value/unit	Total
Output Power		-3 dBm
Source Connector (calculated)	1.61 dB	1.61 dB
Loss/connector of other connectors (given)	1.2 dB	$1.2\text{ dB} \cdot 3 = 3.6\text{ dB}$
Fiber loss/KM @ 1310 nm (table)	1.5 dB	$1.5\text{ dB} \cdot 5 = 7.5\text{ dB}$
Loss per splice (given)	0.3 dB	$0.3\text{ dB} \cdot 4 = 1.2\text{ dB}$

We now have all of the pieces necessary to perform the link budget. All that needs to be done is to **subtract all of the losses from the source power**. This will provide the signal level into the receiver. The following formula will be used to determine receive input level.

$$Re\,ceive\ Input_{dBm} = Source\ Power_{dBm} - total\ connector\ loss_{dB} - total\ splice\ loss_{dB} - total\ fiber\ loss_{dB}$$

Substituting the variables in the formula:

$$Re\,ceive\ Input_{dBm} = -3\,dBm - (1.61\,dB + 3.6\,dB) - 1.2\,dB - 7.5\,dB = -16.91\,dBm$$

Subtracting the threshold level of the receiver from actual receive input level will **determine the link margin**.

$$M\,arg\,in_{dB} = Re\,ceive\ Input_{dBm} - Re\,ceiver\ Threshold_{dBm}$$

Substituting the variables in the formula:

$$M\,arg\,in_{dB} = -16.91\,dBm - (-30\,dBm) = 13.09\,dB$$

This link provides more than the 3 dB minimum margin and satisfies the stated bandwidth requirement.

Exercise 4-3 Link budgets

1. Select a multi-mode optical fiber from the fiber table that will satisfy the following requirement.
   Bandwidth = 100 MHz
   Distance = 12 Km
   System Gain = 18 dB
   Total losses due to connectors and splices = 6 dB

   Cable ________________ Source λ ________ nm

2. A source outputs –15 dBm. TX conn. loss = 1.2 dB, RX conn. loss = 0.8 dB, fiber loss = 3.5 dB/Km and the receiver threshold is –24 dBm. The length of the link is 150 meters with no splices. What is the margin of this link? ________ dB

3. An optical fiber is rated at 400 MHz/Km. What is its bandwidth limit over a 2 Km link? ________ MHz

4-6 *Optical Time Domain Reflectometers (OTDR)*

An OTDR is a highly complex test instrument used in optical fiber systems. The OTDR is used to qualify an optical fiber link. It can determine the distance to a fiber break, abnormal conditions, splices and connectors. It can also indicate the fiber attenuation over distance.

The OTDR measures **reflected** and **scattered** energy of a transmitted pulse. The scattered light is caused by variation in density and composition of the optical fiber. The reflected energy (Fresnel loss) is due to abrupt changes in refractive index of the fiber.

The display of an OTDR (refer to Figure 4.18) is an X-Y plot. The X-axis is typically the distance, or length, of the fiber under test. The Y-axis indicates relative power, typically in decibels.

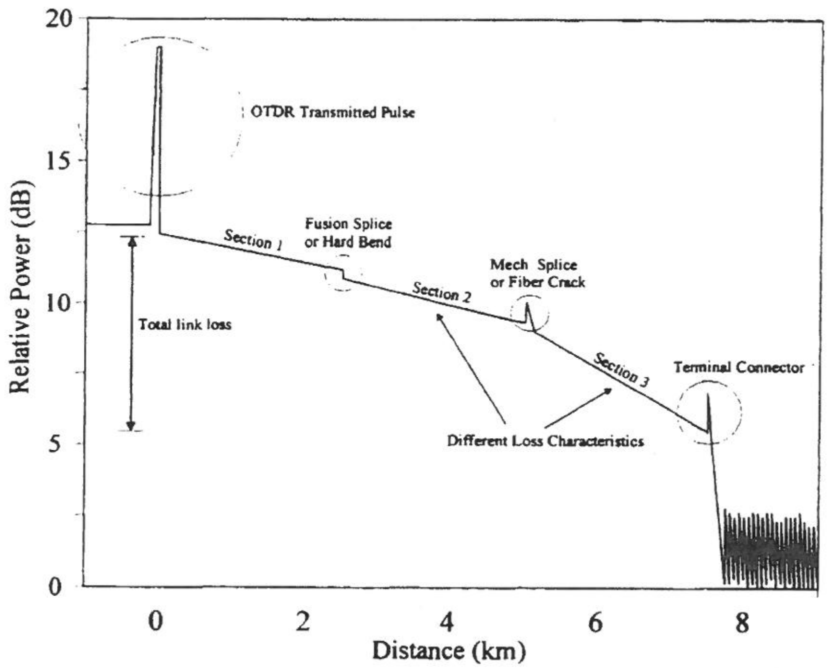


Figure 4.18 Display of an Optical Time Domain Reflectometer

4-6.2 *Uses of an OTDR*

An OTDR is a valuable tool for qualifying fiber links, testing for changes in link parameters and locating abnormal conditions such as fiber cuts. Refer to Figure 4.18 as we consider what is shown by an OTDR presentation.

Measuring loss per unit length

The loss per unit length is shown in the form of a slope as the OTDR pulse travels along the fiber. Notice the slope of the three sections illustrated. You can see that section 3 has a greater slope than the other two sections. This means that a fiber with a higher loss per unit length was placed into the system.

Finding and Evaluating Splices and Connectors

The fusion splice, due to the lack of an air gap or other change in refractive index, typically is seen as a small loss point. As stated in Figure 4.18, a bend can also show up as a small loss point. This is because a hard bend can cause light to exceed the critical angle (section 4.1) and pass into the cladding. Notice the mechanical splice, or crack, shows up as a spike. This is because there is a high reflection back to the source at this point. The terminating connector has a high spike because it is not connected to a receiver. This means that the light is going from glass to the air. The high difference in refractive indices causes a large reflection.

Fault Location
Another source of high reflection would be a fiber break. This is not illustrated in Figure 4.18, but it would look similar to the terminal connector spike.

Exercise 4-4 OTDR Measurements

Refer to Figure 4.18 and fill in the blanks.

1. The total loss of all three links is approximately ______ dB.
2. Each section of the illustrated link is _______ Km in length.
3. The approximate loss of section 3 is _______ dB.
4. If the terminal connector were placed in index matching gel, the terminal spike would ____________.

Unit 4 Summary

- ✓ The refractive index of a medium is a statement of how fast light travels through the medium, relative to light.
- ✓ Optical fiber is constructed of a core, which carries light, surrounded by a cladding.
- ✓ The refractive index of the core is greater than the refractive index of the cladding.
- ✓ The light gathering ability of an optical fiber is referred to as its Numerical Aperture (NA) and is a function of the difference between the refractive indices of the core and cladding.
- ✓ There are two general types of optical fiber: Multi-mode and single mode.
- ✓ There are two types of multi-mode fiber: Step index and graded index.
- ✓ Step index multi-mode fiber propagates light by reflecting it at the core/cladding boundary.
- ✓ The large core diameter of step index multi-mode fiber allows for several modes of propagation, causing the signal to be "smeared" over distance.
- ✓ Graded index multi-mode fiber propagates the signal by refraction.
- ✓ The center of the core of graded index fiber has the highest refractive index, slowly reducing towards the cladding.
- ✓ Light travels faster as it moves away from the center of the core in graded index fiber, so the amount of signal "smearing" due to different modes of propagation is reduced.
- ✓ The less "smearing" (also called dispersion) of a signal, the higher bandwidth over distance.
- ✓ Single mode optical fiber propagates only one mode, so there is no dispersion of the signal due to multiple modes of propagation and a high bandwidth signal can travel much further.
- ✓ Single mode fiber is limited in bandwidth due to the slightly different rates at which light travels through fiber, causing "smearing" of the signal. This is referred to as chromatic dispersion.
- ✓ There are 3 common operating windows in fiber optics: 850 nm, 1310 nm and 1550 nm.
- ✓ LED sources are inexpensive, but have a wide spectral width and low output power.
- ✓ Lasers are higher in power and have a narrower spectral width, but are relatively expensive.
- ✓ PIN detectors are relatively inexpensive, but do not have the responsivity of APDs.
- ✓ Connectors are used where repeated mating and un-mating is required.
- ✓ Connectors protect and guide the core for accurate, low loss mating.
- ✓ Two very common connectors are ST and SC connectors.
- ✓ Splices are more permanent than connectors and typically have lower losses.
- ✓ There are two types of splices: Fusion and mechanical.
- ✓ Fusion splices are more time consuming, but have a lower loss than mechanical splices.
- ✓ Connectors and splices have similar loss problems: misalignment, core and NA mismatch.
- ✓ All optical fiber is rated for attenuation (in dBs) and bandwidth over distance (MHz-Km).
- ✓ A link budget is done to determine the performance of a link over a given distance at a given bandwidth requirement.
- ✓ An OTDR is a valuable tool for determining link parameters, locating abnormalities (such as breaks).

The purpose of this unit is to provide a general understanding of the subject areas addressed. For more information on the topics covered in this unit, refer to the Web sites and reference books listed in the **Study Guide for the Digital Communications and Computer Literacy Test**.

Answers to Exercises

Exercise 4-1 Fiber Optics

1. The n_{core} is _greater_ than the $n_{cladding}$ in an optical fiber.
2. A ray of light will be _refracted_ as it moves from one medium to another.
3. A fiber with a _large_ difference between n_{core} and $n_{cladding}$ will have **more** modal dispersion than a fiber of the same diameter with a _small_ difference between n_{core} and $n_{cladding}$
4. _Graded_ _index_ multi-mode fiber propagates light by refraction.
5. Smearing of the received light is caused by _dispersion_ of the light as it propagates through the fiber.
6. The Numerical Aperture of a fiber is **0.25**. What is the angle of the "Cone of Acceptance"? _28.9_ degrees

Exercise 4-2 Sources and Detectors

1. An optical source with a power output of 0.2 mW and a diameter of 70µm is coupled into a core with a diameter of 50µm. Assuming no loss due to a NA mismatch, determine how much power is coupled into the fiber. _0.102_ mW

2. A signal exits an optical fiber to a detector. The detector diameter is 100 µm and the NA is 0.25. What percentage of the signal leaving the core will be seen by the detector when using the following optical fibers.

	Fiber A	**Fiber B**	**Fiber C**
Diameter =	50µm	80µm	200µm
NA =	0.24	0.22	0.28
	_0_%	_0_%	_22.3_%

Answers to Exercises (cont.)

Exercise 4-3 Link budgets

1. Select a multi-mode optical fiber from the fiber table that will satisfy the following requirement.
   Bandwidth = 100 MHz
   Distance = 12 Km
   System Gain = 18 dB
   Total losses due to connectors and splices = 6 dB

   Cable Graded index, 50/125 Source λ 1310 nm

2. A source outputs –15 dBm. TX conn. loss = 1.2 dB, RX conn. loss = 0.8 dB, fiber loss = 3.5 dB/Km and the receiver threshold is –24 dBm. The length of the link is 150 meters with no splices. What is the margin of this link? 6.475 dB

3. An optical fiber is rated at 400 MHz/Km. What is its bandwidth limit over a 2 Km link? 200 MHz

Exercise 4-4 OTDR Measurements

1. The total loss of all three links is approximately 6.5 dB.
2. Each section of the illustrated link is 7.5 Km in length.
3. The approximate loss of section 3 is 3.5 dB.
4. If the terminal connector were placed in index matching gel, the terminal spike would decrease .