Fiber Optics

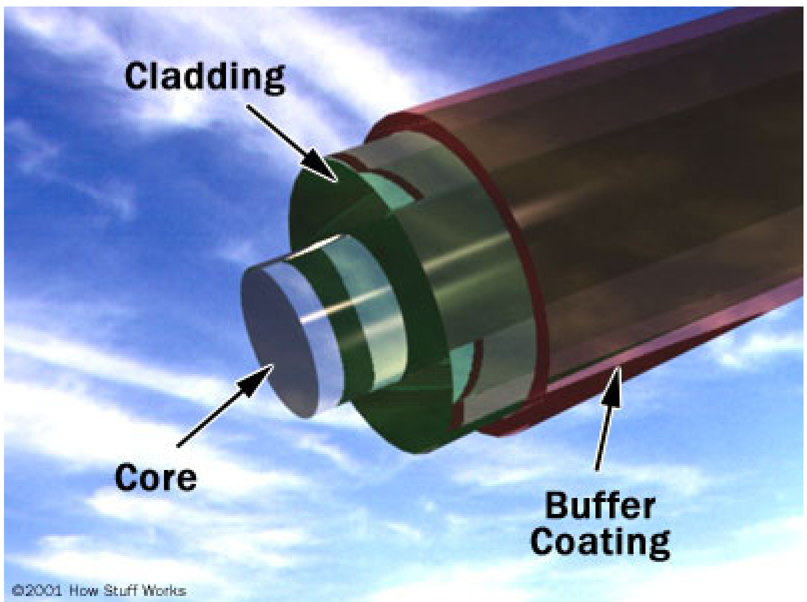
Reading Hecht 5.6

1 Introduction

You hear about fiber-optic cables whenever people talk about the telephone system, the cable TV system or the Internet. Fiber-optic lines are strands of optically pure **glass** as thin as a human hair that carry digital information over long distances. They have been used for sensing, medical imaging, mechanical engineering inspection, and in particular, for ***communication*** ***(***Cable Television, Cable Modems, DSL, Ethernet, Telephone).

What are optical fibers?

Fiber optics (optical fibers) are long, thin strands of very pure glass about the diameter of a human hair. They are arranged in bundles called **optical cables** and used to transmit light signals over long distances. (Source: **http://electronics.howstuffworks.com/fiber-optic.htm/)**



Parts of a single optical fiber

If you look closely at a single optical fiber, you will see that it has the following parts:

- **Core** - Thin glass center of the fiber where the light travels
- **Cladding** - Outer optical material surrounding the core that reflects the light back into the core
- **Buffer coating** (sheath) - **Plastic coating** that protects the fiber from damage and moisture

Hundreds or thousands of these optical fibers are arranged in bundles in optical cables. The bundles are protected by the cable's outer covering, called a jacket.

More Properties of Fibers:

The diameters of the core and cladding determine many of the optical and physical characteristics of the fiber. For example, the diameter of a fiber should be large enough to allow splicing and the attachment of connectors (see below "Fiber optical components"). However, if the diameter is too large, the fiber will be too stiff to bend and will take up too much material and space. In practice, the diameter of fiber cores ranges from 5 to 500 μm, and outer diameters of fiber claddings vary from 100 to 700 µm. To keep the light wave within the fiber core, the cladding must have a minimum thickness of one or two wavelengths of the light transmitted. The protective jackets may add as much as 100 µm to the fiber's total diameter. Typical fiber dimensions are about 500 µm.

Although ordinary glass is brittle and is easily broken or cracked, optical glass fibers usually have high tensile strength and are able to withstand hard pulling or stretching. The toughest fiber are as strong as stainless steel wires of the same diameter, and have the same tensile strength as copper wires with twice the diameter. For example, 1 km lengths of these fibers have withstood pulling forces of more than 500,00 lb/inch^2 before breaking. A 10 m long fiber can be stretched by 50 cm and still spring back to its original shape, and a fiber with 400 µm diameter can be bent into a circle with a radius as small as 2 cm.

3 How does an optical fiber transmit light?

(http://electronics.howstuffworks.com/fiber-optic.htm/)

Suppose you want to shine a flashlight beam down a long, straight hallway. Just point the beam straight down the hallway -- light travels in straight lines, so it is no problem. What if the hallway has a bend in it? You could place a mirror at the bend to reflect the light beam around the corner. What if the hallway is very winding with multiple bends? You might line the walls with mirrors and angle the beam so that it bounces from side-to-side all along the hallway. This is exactly what happens in an optical fiber.

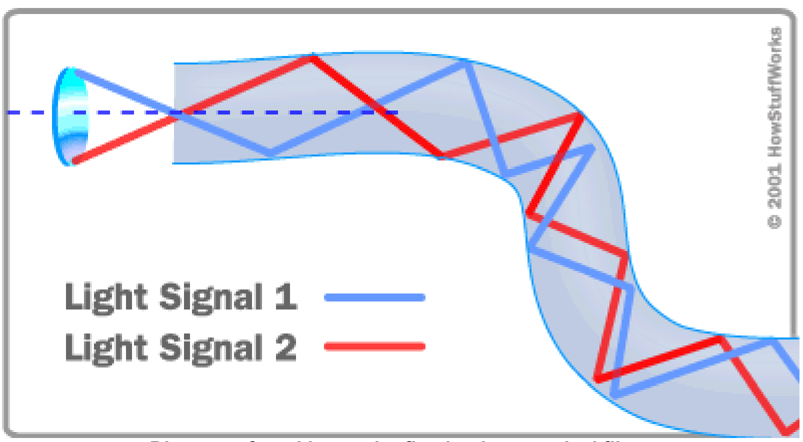


Diagram of total internal reflection in an optical fiber

The light in a fiber-optic cable travels through the core (hallway) by constantly bouncing from the cladding (mirror-lined walls), a principle called **total internal reflection**. Because the cladding does not absorb any light from the core, the light wave can travel great distances. However, some of the light signal **degrades** within the fiber, mostly due to impurities in the glass. The extent that the signal degrades depends on the purity of the glass and the wavelength of the transmitted light (for example, 850 nm = 60 to 75 percent/km; 1,300 nm = 50 to 60 percent/km; 1,550 nm (1.55 µm) is greater than 50 percent/km). Some premium optical fibers show much less signal degradation -- less than 10 percent/km at 1,550 nm.

4 Types of fibers

4.1 Based on Configuration [see Hecht p.198]

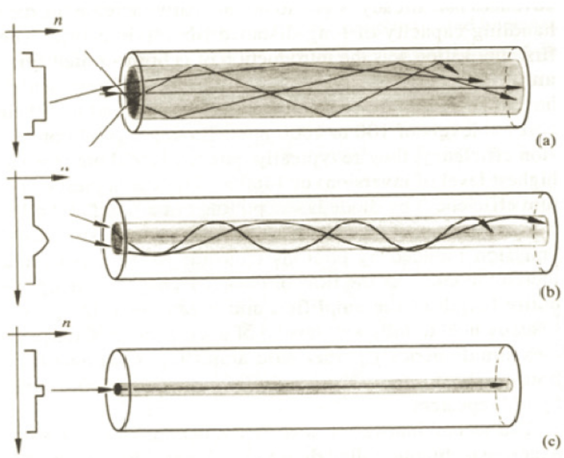


Figure 5.72 The three major fiberoptic configurations and their index profiles. (*a*) Multimode step-index fiber. (*b*) Multimode graded-index fiber. (*c*) Single-mode step-index fiber.

1. Stepped-index fiber
   a. Diameter: typically 50 to 200 µm for core in diameter, 20 µm thick for cladding.
   b. The oldest technology used in the first generation.
   c. Least expensive and least effective due to intermodal dispersion produced by multimode propagation. Limit application to low-speed or short-distance commnications.
   d. Suitable for imaging and handling high power due to large-core.

2. Graded-index fiber:
   a. Index profile varies from highest at the center to lower at the edge, thus the light speed is lowest at the center and highest at the edge, reducing the differences of the propagation times of different modes.
   b. Typical core diameter 20 to 90 µm
   c. Intermodal dispersion around 2 ns/km.
   d. Cost intermediate.
   e. Used in medium distance intercity applications.

Excitation of multimode fibers with core diameters of 50 µm or more are often fed by LEDs for low date rates or short distances due to spectral dispersion. Can be avoided by using lasers or operate at 1.3 µm, where silica fiber has little dispersion.

3. Single-mode fibers
   a. Core diameter 2 to 9 µm.
   b. No intermodal dispersion.
   c. Expensive. Excited by lasers.
   d. Currently, operated at 1.55 µm with attenuation 0.2 dB/km.

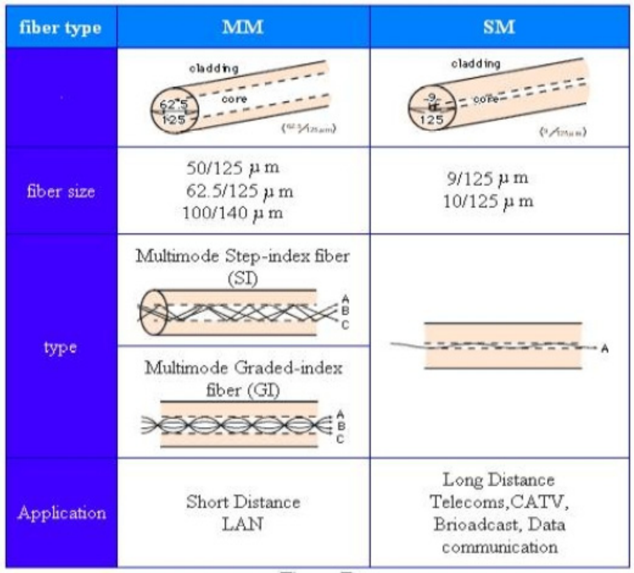
4.2 Based on Modes

In general, optical fibers can be divided into two broad categories, namely *single-mode* and *multi-mode* fibers.

Single-mode fibers have small cores (about 3.5×10^{-4} inches or 9 microns in diameter) and transmit infrared laser light (wavelength = 1,300 to 1,550 nanometers). *Note:* The small size may cause handling and connection problems. In fact, for any given fiber, tight tolerance are necessary, because even a slight variation in the dimension can cause significant changes in opical characteristics. The tolerance for the core diameter is typically about ±2 µm.

Multi-mode fibers have larger cores (about 2.5×10^{-3} inches or 62.5 microns in diameter) and transmit infrared light (wavelength = 850 to 1,300 nm) from semiconductor lasers or light-emitting diodes (LEDs).

Below is a simple comparison chart of single- and multi-mode fibers:*Note: The fiber size convention is (diameter of core)/(diameter of cladding).*



fiber type	MM	SM
fiber size	50/125 µm 62.5/125 µm 100/140 µm	9/125 µm 10/125 µm
type	Multimode Step-index fiber (SI) Multimode Graded-index fiber (GI)	
Application	Short Distance LAN	Long Distance Telecoms,CATV, Brioadcast, Data communication

4.3 Based on Materials

The core and the cladding are mad of either silicate materials (e.g., glass) or plastic. Three major combinations of these two types of material are used to make optical fibers:

1) *plastic core with plastic cladding,*
2) *glass core with plastic cladding, and*
3) *glass core and glass cladding.*

A plastic core is generally made of polystyrene or polymethyl methacrylate, while a plastic cladding is typically made of silicone or Teflon. For glass core and claddings, the silica must be extremely pure; however, very small amount of dopants such as boron, germanium, or phosphorous may be added to change the refractive indices. In some claddings, boron oxide is often added to silica to form borosilicate glass.

In comparison with glass fibers, plastic fibers are flexible, inexpensive, and easy to install and connect. Furthermore, they can withstand greater stress and with 50% less than glass fibers. However, they do not transmit light as efficiently. Due to their considerably high losses, they are used only for short runs (such as networks within buildings) and some fiber sensors. Typical plastic fibers have a large core (0.04 inches or 1 mm diameter) and transmit visible red light (wavelength = 650 nm) from LEDs.

4.4 Basic Fiberoptics

4.4.1 Ray optics analysis (Total Internal Reflection) and Numerical Aperture (NA)

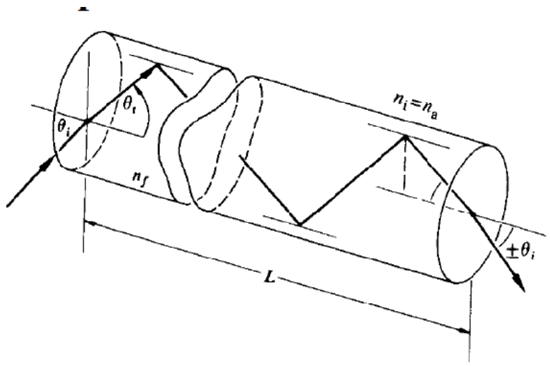


Figure 5.70 Rays reflected within a dielectric cylinder.

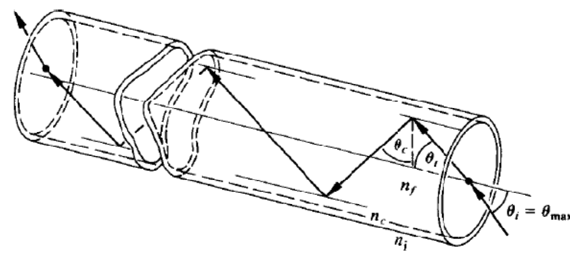


Figure 5.71 Rays in a clad optical fiber.

1. Total reflection.
2. Corning Glass Works, 1970: fiber with similar attenuation of copper cable. 1% per km, or 20 dB/km. Currently, 96% per km or better, i.e., 0.16 dB/km.
3. Benefit comparing to copper cables: low-loss, high data rate, small size and weight, immune to electromagnetic interference, low cost.
4.

Calculation of acceptance angle θ_{max} which is the maximum incident angle for a ray to experience total reflection in the fiber.

$$\theta_c = \frac{n_c}{n_f} = \sin(90^\circ - \theta_t)$$

Thus,

$$\frac{n_c}{n_f} = \cos\theta_t = \sqrt{1 - \sin^2\theta_t}$$

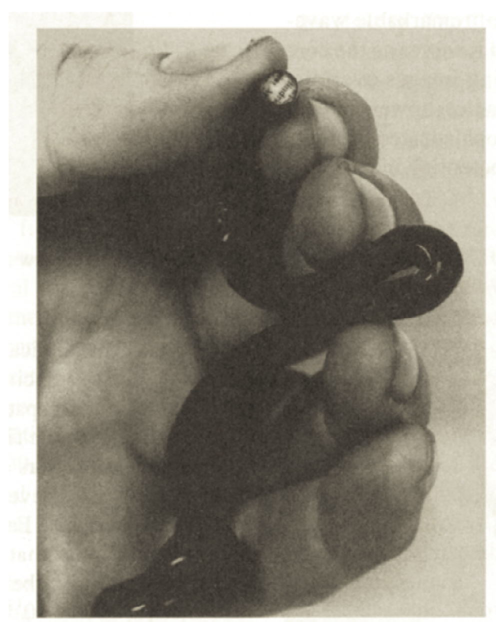
Applying Snell;s Law,

$$\sin\theta_{max} = \frac{1}{n_i}\sqrt{n_f^2 - n_c^2}$$

Numerical aperture (NA): $n_i \sin\theta_{max}$, the light-gathering power.

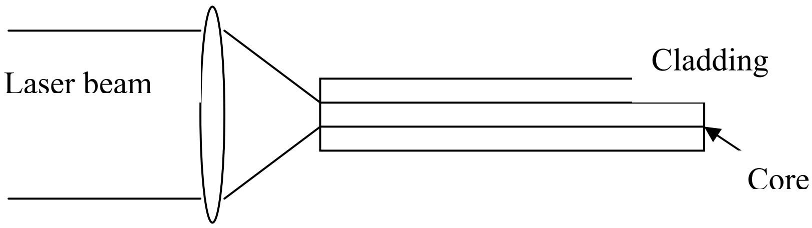
Applications in Imaging

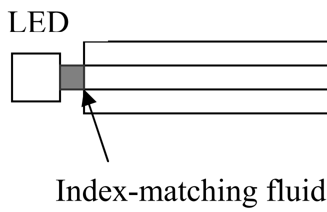
Flexible image carrier: bundle of coherent fibers.
Flexible light carrier: bundle of incoherent fibers.
Endoscope: about 200 cm in length, 5000 to 50000 fibers.



A coherent bundle of 10 μm glass fibers transmitting an image even though knotted and sharply bent.
(Photo courtesy of American ACMI Div., American Hospital Supply Corp.)

4.4.2 Coupling of light

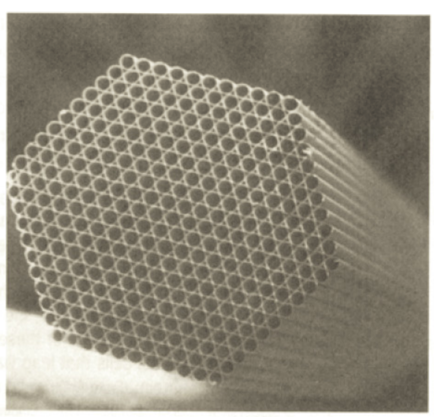




4.4.3 Capillary Optics

Use fibers to guide high-frequency EM-radiation, for example X-rays. The critical angle measured up from the surface is only 0.2° for X-rays (≈ 0.12 nm).

A single glass threaded with a diameter of 200 to 600 μm can be fabricated so that it contains thousands of fine capillary channels each from 3 to 50 μm in diameter. They can be used to collimate X-rays which is difficult using other means like conventional mirros or lenses.



A scanning electron micrograph of a single multichannel thread contair ing hundreds of hollow capillaries. (Photo courtesy X-Ray Optical Systems, Inc. Albany, NY, USA)

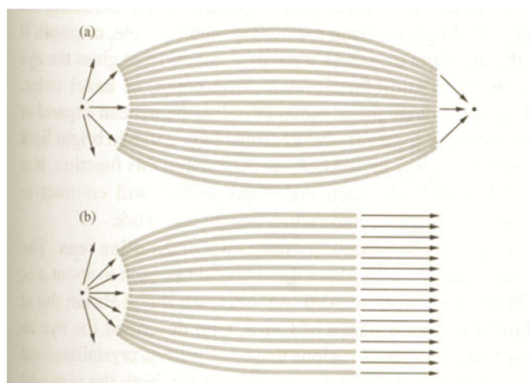


Figure 5.78 A bundle of multicapillary threads used to (a) focus or (b) collimate the X-rays from a point source.

4.5 Modal description/Internal Dispersion

See Hecht p.198-199

Depending on the launch angle into the fiber, there can be hundreds, even thousands, of different ray paths or modes by which energy can propagate down the core. This then is a **multimode fiber**, wherein each mode corresponds to a slightly different transit time. Higher-angle rays travel longer paths; reflecting from side to side, they take longer to get to the end of the fiber than do rays moving along the axis. This is loosely spoken of as **intermodal dispersion** (or often just **modal dispersion**), even though it has nothing to do with a frequency-dependent index of refraction. Information to be transmitted is usually digitized in some coded fashion and then sent along the fibers as a flood of millions of pulses or bits per second. The different transit time have the undesirable effect of changing the shape of the pulses of light that represent the signal. What started as a sharp rectangular pulse can smear out, after traveling a few kilometers within the fiber, into an unrecognized blur.

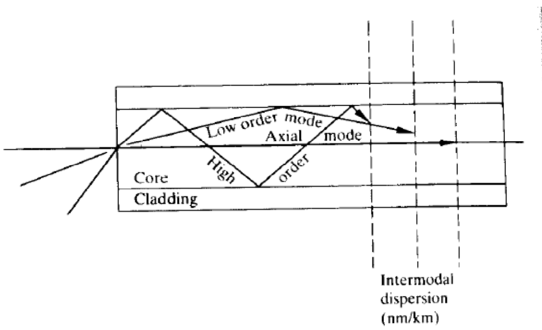


Figure 5.73 Intermodal dispersion in a stepped-index multimode fiber.

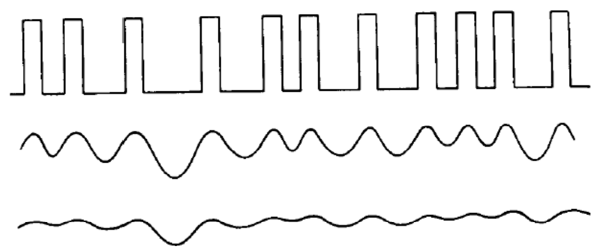


Figure 5.74 Rectangular pulses of light smeared out by increasing amounts of dispersion. Note how the closely spaced pulses degrade more quickly.

Example:

Let axial length be L, the shortest length of ray path. Then, the longest path $L_{\max}$ is when the incident angle is θ_c. The time difference Δt becomes

$$\Delta t = \frac{L_{\max} - L}{v_f} = \frac{L n_f^2}{c n_c} - \frac{L n_f}{c} = \frac{L n_f}{c}\left(\frac{n_f}{n_c} - 1\right)$$

If $n_f = 1.5$ and $n_c = 1.489$, then $\Delta t / L = 37$ ns/km, or a separation of distance 7.4 m/km. In order to make the signal readable, the spatial separation might need to be twice of the spread-out width. If the line is 1 km long, the output pulse is 7.4 m long, the separation should be 14.8 m or 74 ns apart, which is 13.5 Million/s.

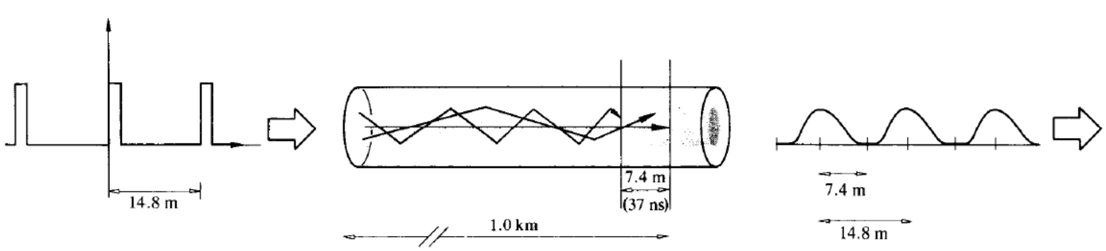
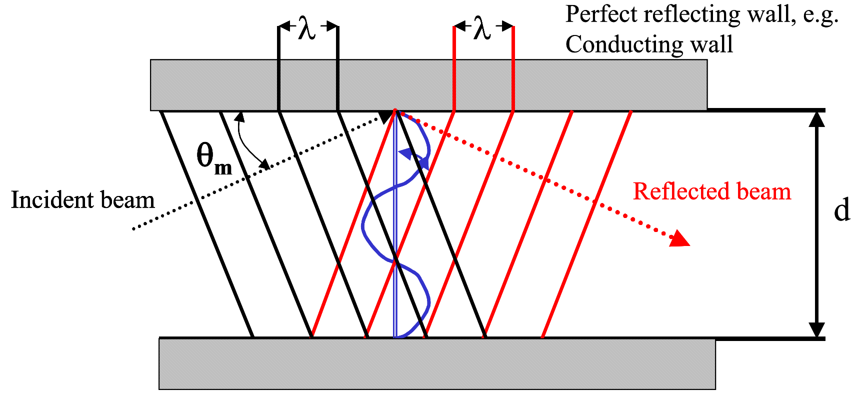


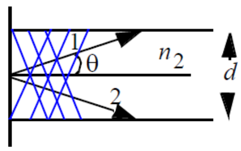
Figure 5.75 The spreading of an input signal due to intermodal dispersion.

A waveguide with perfect reflecting walls



Wave picture

We can capture much of the wave physics of fibers and waveguides by considering a wave guide with perfectly reflecting walls. The boundary condition on the wall is that the electric field must be zero. The wave equation solutions are then cosines in the transverse direction with an integer number of half-wavelengths between the walls. Different "modes" correspond to varying numbers of these half-wavelengths.



The interference pattern between rays 1 and 2 gives a sinusoidal fringe pattern. This fringe pattern must contain an integer number of half-waves to satisfy the BC.

From the above diagram, we can see the correspondence between the various transverse modes and the propagation angle for the corresponding rays. This can be expressed as

$$2d\sin\theta_m = \frac{(m+1)\lambda}{n_2} \qquad m = 0, 1, \ldots$$

Low order modes propagate at shallower angles than higher order modes. The cutoff angle imposed by θ_c then imposes a mode cutoff. Mode numbers below the cutoff will propagate with low loss, while higher order modes are lost. For reasons we will discuss in a moment, it is often desirable to design the guide such that only the very lowest order mode will propagate, and all higher order modes will be lost. The condition for the second mode (m = 1) to be lost is that $\theta_1 > \theta_c$

$$\sin\theta_1 \simeq \theta_1 = \frac{\lambda}{dn_2}$$

The condition for single mode operation is then

$$\frac{\lambda}{dn_2} > \theta_c, \quad \text{or} \quad d < \frac{\lambda}{n_2\theta_c}$$

Take $\lambda = 1.3\mu\text{m}, \quad n_2 = 1.45, \quad n_1 = 1.4$

$\theta_c = 0.26 \text{ rad}, \quad d < 3.4\mu\text{m}$

5 Attenuation in Fibers

The attenuation or loss of fiber is usually specified in decibels per kilometer (dB/km) of fiber length.

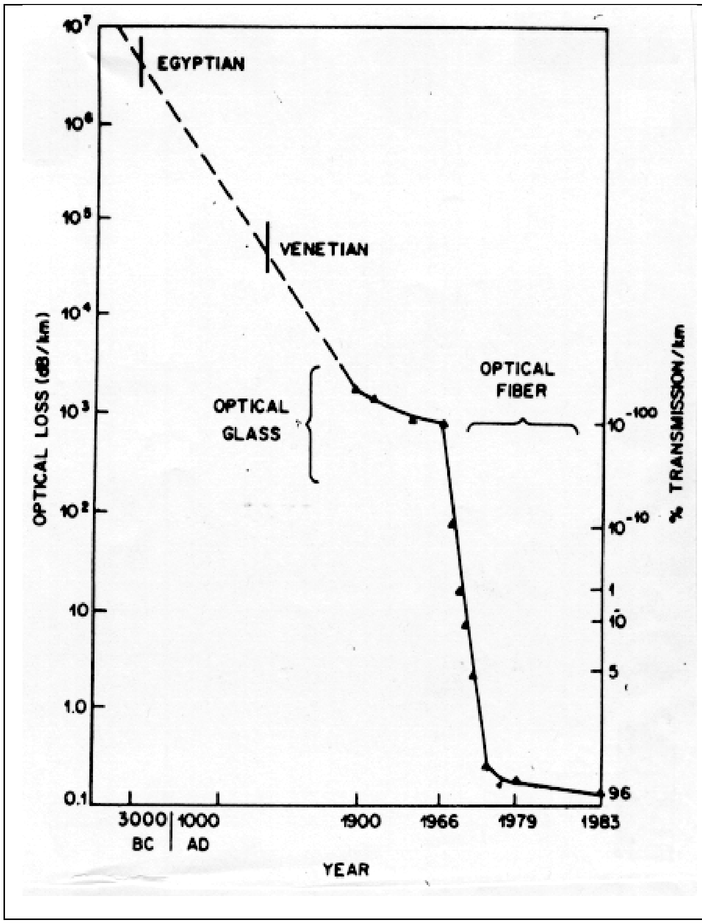
Recall ➔ $dB = -\log_{10}(P_o/P_i) = -\alpha L/10$ or $P_o/P_i = 10^{-\alpha L/10}$

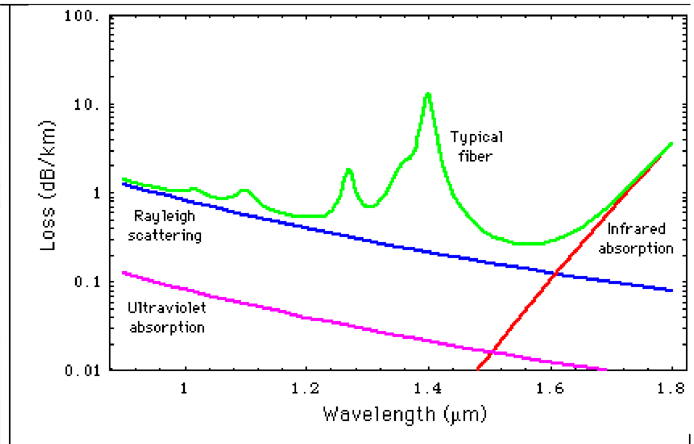
P_i : the power-in,

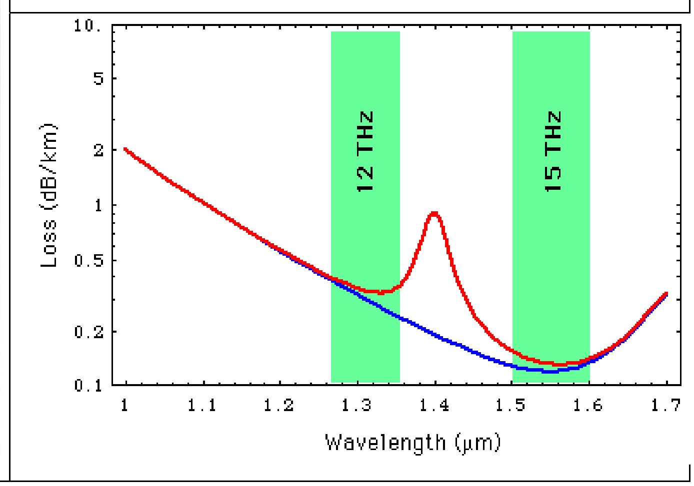
P_o : the power-out

α: the attenuation,

L: fiber length







As a rule, reamplification of the signal is necessary when the power has dropped by a factor of about 10^{-5} (50 dB). Commercial optical glass, the kind of material available for fibers in the mid-1960s, has an attenuation of about 1000 dB/km. Light, after being transmitted 1 km through the glass, would drop in power by a factor of 10^{-100}, and regenerators would be needed every 50 m (which is little better than communicating with a string and two tin cans). By 1970 the attenuation was down to about 20 dB/km for fused silica (quartz, SiO_2), and it was reduced to as little as 0.16 dB/km in 1982. The above left figure shows the progress on reducing optical loss of optical glass or fiber over the years. This tremendous decrease in attenuation was achieved mostly by removing impurities (especially the ions of iron, nickel, and copper) and reducing contamination by OH groups. The above right figures display schematics representation of typical attenuation/loss versus wavelength for typical low-loss, single-mode silica optical fibers (diameter ~10 μm). For wavelengths less than 1.5 μm, the attenuation is dominated by Rayleigh scattering, plus the absorption by impurities such as the hydroxyl ions (OH) from very small amounts of water dissolved in the glass. At wavelengths longer than 1.6 μm, infrared absorption sets in strongly. The loss due to waveguide imperfection is below is low ~0.03 db/km (not shown). The minimum attenuation of about 0.2 dB/km occurs at λ = 1.55 μm. The absorption mean free path (where the power drops by 1/e) at the minimum is 22 km. Today the purest fibers can carry signals up to 80 km (power dropped ~20dB) before needing reamplification.

Four special wavelengths can be used for fiber optic transmission with low loss levels:

Window	Wavelength	Loss/Attenuation
1st wavelength	850 nm	3 dB/km
2nd wavelength	1310 nm	0.4 dB/km
3rd wavelength	1550 nm (C band)	0.2 dB/km
4th wavelength	1625 nm (L band)	0.2 dB/km

Therefore, one or more **optical regenerators** is spliced along the cable to boost the degraded light signals.

An optical regenerator consists of optical fibers with a special coating (**doping**). The doped portion is "pumped" with a laser. When the degraded signal comes into the doped coating, the energy from the laser allows the doped molecules to become lasers themselves. The doped molecules then emit a new, stronger light signal with the same characteristics as the incoming weak light signal. Basically, the regenerator is a laser amplifier for the incoming signal.

Optical Receiver

The **optical receiver** is like the sailor on the deck of the receiving ship. It takes the incoming digital light signals, decodes them and sends the electrical signal to the other user's computer, TV or telephone (receiving ship's captain). The receiver uses a **photocell** or **photodiode** to detect the light.

6 Advantages of optical fibers

Why are fiber-optic systems revolutionizing telecommunications? Compared to conventional metal wire (copper wire), optical fibers are:

- **Low loss** - The loss of signal in optical fiber is less than in copper wire.
- **No crosstalk between fibers** – Higher security
- **Light signals→No electromagnetic interference** - Unlike electrical signals in copper wires, light signals from one fiber do not interfere with those of other fibers in the same cable. This means clearer phone conversations or TV reception.
- **Less expensive** - Several miles of optical cable can be made cheaper than equivalent lengths of copper wire. This saves your provider (cable TV, Internet) and you money.
- **Thinner** - Optical fibers can be drawn to smaller diameters than copper wire.
- **Lightweight** - An optical cable weighs less than a comparable copper wire cable. Fiber-optic cables take up less space in the ground.
    - For example, a 40 km long glass fiber core weighs only 1 kg, whereas a 40 km long copper wire with a 0.32 mm outer diameter weighs about 30 kg.

- **Flexible** - Because fiber optics are so flexible and can transmit and receive light, they are used in many flexible digital cameras for the following purposes:
  - **Medical imaging** - in bronchoscopes, endoscopes, laparoscopes
  - **Mechanical imaging** - inspecting mechanical welds in pipes and engines (in airplanes, rockets, space shuttles, cars)
  - **Plumbing** - to inspect sewer lines
- **Huge bandwidth**
- **Higher carrying capacity** - Because optical fibers are thinner than copper wires, more fibers can be bundled into a given-diameter cable than copper wires. This allows more phone lines to go over the same cable or more channels to come through the cable into your cable TV box.
- **Low power** - Because signals in optical fibers degrade less, lower-power transmitters can be used instead of the high-voltage electrical transmitters needed for copper wires. Again, this saves your provider and you money.
- **Digital signals** - Optical fibers are ideally suited for carrying digital information, which is especially useful in computer networks.
- **Non-flammable** - Because no electricity is passed through optical fibers, there is no fire hazard.

Because of these advantages, you see fiber optics in many industries, most notably telecommunications and computer networks. For example, if you telephone Europe from the United States (or vice versa) and the signal is bounced off a communications satellite, you often hear an echo on the line. But with transatlantic fiber-optic cables, you have a direct connection with no echoes.

7 Fiber Communication Technology

1. One copper telephone line can carry 24 conversation (64 Kbit each). Mid 80s, single fiber can carry 6000 conversation (400 Mb/s). 1990, solitons attain 4Gb/s.
2. Typically, copper coaxial cables require repeater every 2-6 km, while fibers require only every 50 km or more.
3. Erbium-doped fiber amplifiers (EDFA):
   a. Direct amplification of light without conversion. Used as repeaters to replace conventional electronic hybrid repeats.
   b. Single-mode fiber doped with erbium at levels of 100 to 1000 ppm. Typically pumped by diode lasers at 980 nm (for highest level of population inversion) or 1480 nm (for the highest quantum efficiency) putting out power around 200 mW.

4. WDM (wavelength-division-multiplexing) Technology

(http://en.wikipedia.org/wiki/Wavelength-division_multiplexing)

A WDM system uses a multiplexer at the transmitter to join the signals together, and a demultiplexer at the receiver to split them apart. With the right type of fiber it is possible to have a device that does both simultaneously, and can function as an optical add-drop multiplexer. The optical filtering devices used have traditionally been etalons, stable solid-state single-frequency Fabry-Perot interferometers in the form of thin-film-coated optical glass.

The concept was first published in 1970, and by 1978 WDM systems were being realized in the laboratory. The first WDM systems only combined two signals. Modern systems can handle up to

160 signals and can thus expand a basic 10 Gbit/s fiber system to a theoretical total capacity of over 1.6 Tbit/s over a single fiber pair.

8 How are optical fibers made?

(http://electronics.howstuffworks.com/fiber-optic.htm/)

Now that we know how fiber-optic systems work and why they are useful -- how do they make them? Optical fibers are made of extremely pure **optical glass**. We think of a glass window as transparent, but the thicker the glass gets, the less transparent it becomes due to impurities in the glass. However, the glass in an optical fiber has far fewer impurities than window-pane glass. One company's description of the quality of glass is as follows: If you were on top of an ocean that is miles of solid core optical fiber glass, you could see the bottom clearly.

Making optical fibers requires the following steps:

4) *Making a preform glass cylinder*
5) *Drawing the fibers from the preform*
6) *Testing the fibers*

Making the Preform Blank

The glass for the preform is made by a process called **modified chemical vapor deposition** (MCVD).

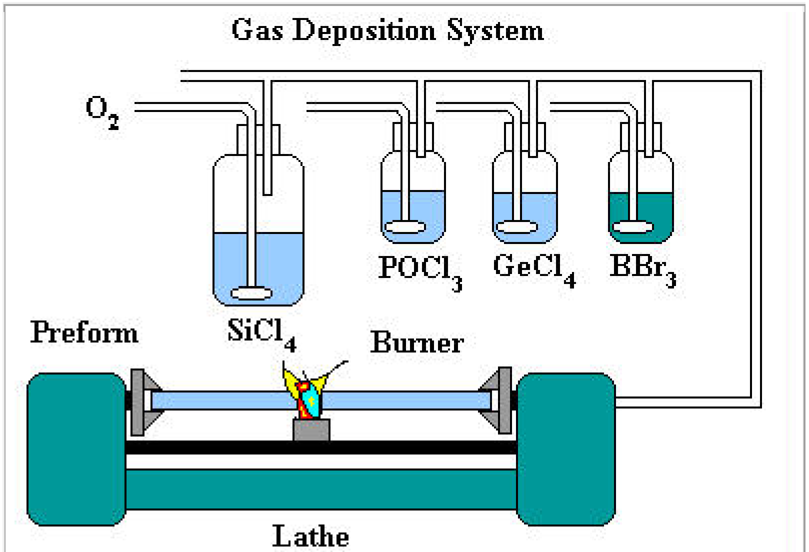


Image courtesy Fibercore Ltd.
MCVD process for making the preform blank

In MCVD, oxygen is bubbled through solutions of silicon chloride ($SiCl_4$), germanium chloride ($GeCl_4$) and/or other chemicals. The precise mixture governs the various physical and optical properties (index of refraction, coefficient of expansion, melting point, etc.). The gas vapors are then conducted to the inside of a **synthetic silica** or **quartz tube** (cladding) in a special **lathe**. As the lathe turns, a torch is moved up and down the outside of the tube. The extreme heat from the torch causes two things to happen:

- The silicon and germanium react with oxygen, forming silicon dioxide (SiO_2) and germanium dioxide (GeO_2).
- The silicon dioxide and germanium dioxide deposit on the inside of the tube and fuse together to form glass.

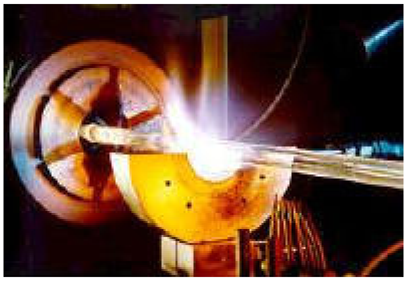


Photo courtesy Fibercore Ltd.
Lathe used in preparing the preform blank

The lathe turns continuously to make an even coating and consistent blank. The purity of the glass is maintained by using corrosion-resistant plastic in the gas delivery system (valve blocks, pipes, seals) and by precisely controlling the flow and composition of the mixture. The process of making the preform blank is highly automated and takes several hours. After the preform blank cools, it is tested for quality control (index of refraction).

Drawing Fibers from the Preform Blank

Once the preform blank has been tested, it gets loaded into a **fiber drawing tower**.

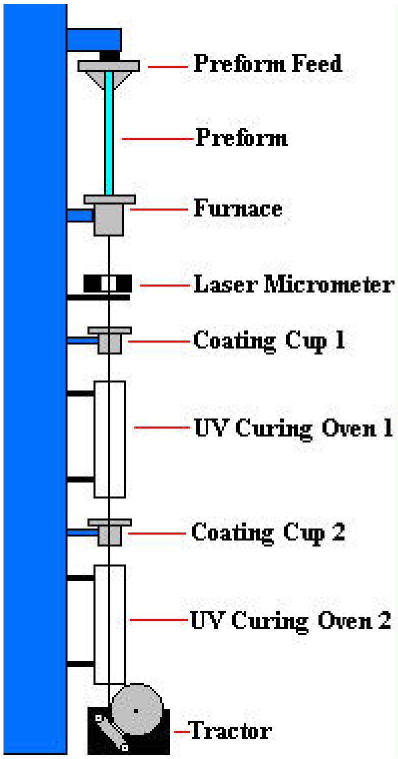


Diagram of a fiber drawing tower used to draw optical glass fibers from a preform blank

The blank gets lowered into a graphite furnace (3,452 to 3,992 degrees Fahrenheit or 1,900 to 2,200 degrees Celsius) and the tip gets melted until a molten glob falls down by gravity. As it drops, it cools and forms a thread.

The operator threads the strand through a series of coating cups (buffer coatings) and ultraviolet light curing ovens onto a tractor-controlled spool. The tractor mechanism slowly pulls the fiber from the heated preform blank and is precisely controlled by using a **laser micrometer** to measure the diameter of the fiber and feed the information back to the tractor mechanism. Fibers are pulled from the blank at a rate of 33 to 66 ft/s (10 to 20 m/s) and the finished product is wound onto the spool. It is not uncommon for spools to contain more than 1.4 miles (2.2 km) of optical fiber.

Photo courtesy Corning
Finished spool of optical fiber

Testing the Finished Optical Fiber

The finished optical fiber is tested for the following:

- **Tensile strength** - Must withstand 100,000 lb/in^2 or more
- **Refractive index profile** - Determine numerical aperture as well as screen for optical defects
- **Fiber geometry** - Core diameter, cladding dimensions and coating diameter are uniform
- **Attenuation** - Determine the extent that light signals of various wavelengths degrade over distance
- **Information carrying capacity** (bandwidth) - Number of signals that can be carried at one time (multi-mode fibers)
- **Chromatic dispersion** - Spread of various wavelengths of light through the core (important for bandwidth)
- **Operating temperature/humidity range**
- **Temperature dependence of attenuation**
- **Ability to conduct light underwater** - Important for undersea cables

Once the fibers have passed the quality control, they are sold to telephone companies, cable companies and network providers. Many companies are currently replacing their old copper-wire-based systems with new fiber-optic-based systems to improve speed, capacity and clarity.

9 Optical Fiber Communications

9.1 Fiber communication systems

Fiber-optic relay systems consist of the following:

- **Transmitter** - Produces and encodes the light signals
- **Optical fiber** - Conducts the light signals over a distance
- **Optical regenerator** - May be necessary to boost the light signal (for long distances)
- **Optical receiver** - Receives and decodes the light signals

Transmitter

The **transmitter** is like the sailor on the deck of the sending ship. It receives and directs the optical device to turn the light "on" and "off" in the correct sequence, thereby generating a light signal.

The transmitter is physically close to the optical fiber and may even have a lens to focus the light into the fiber. Lasers have more power than LEDs, but vary more with changes in temperature and are more expensive. The most common wavelengths of light signals are 850 nm, 1,300 nm, and 1,550 nm (infrared, non-visible portions of the spectrum).

Optical Regenerator

As mentioned above, some **signal loss** occurs when the light is transmitted through the fiber, especially over long distances (more than a half mile, or about 1 km) such as with undersea cables.

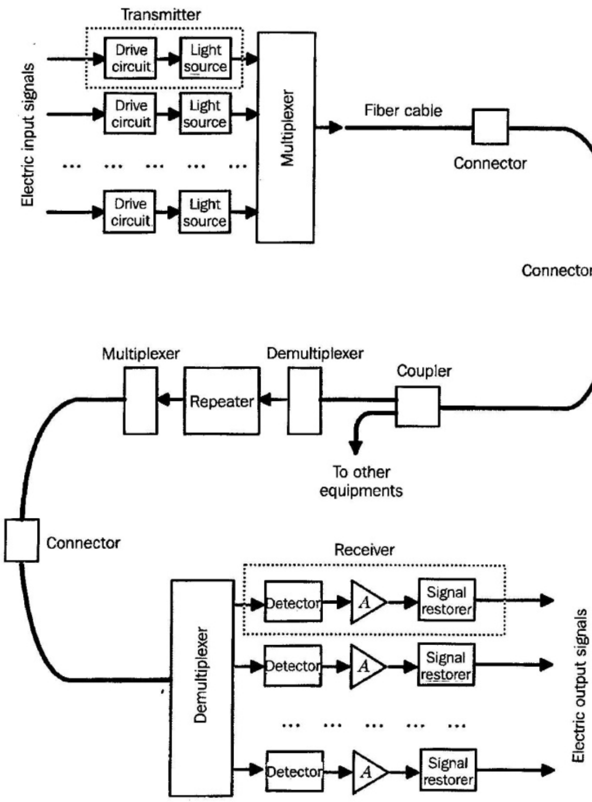


FIGURE 12.16 An optical fiber communication system.

9.2 Components

9.2.1 Splices and Connectors

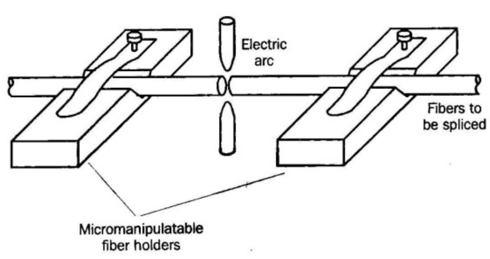


FIGURE 12.17 Fusion splicing of optical fibers.

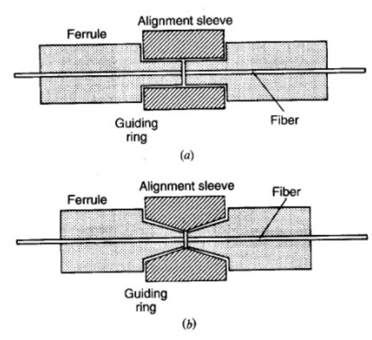


FIGURE 12.18 Two popular butt-joint fiber connectors: (a) straight sleeve connector; (b) tapered sleeve connector.

A significant factor in any fiber optic system installation is the interconnection of fibers in a low-loss manner. These interconnections occur at the optical source, the photodetector, the intermediate points within a cable where two fibers are joined, and the intermediate in a link where two cables are connected. The particular technique selected for joining the fibers depends on where a permanent bond or an easily demountable connection is desired. A permanent bond is generally referred to as a splice, where a demountable joint is known as a connector

A fiber optic ***splice*** makes a *permanent* joint between two fibers or two groups of fibers. There are two types of fiber optic splices--mechanical splices and fusion splices. Even though removal of some mechanical splices is possible, they are intended to be permanent. Another type of connection that *allows for system reconfiguration* is a fiber optic ***connector***. Fiber optic connectors permit easy coupling and uncoupling of optical fibers. Fiber optic connectors sometimes resemble familiar electrical plugs and sockets.

9.2.2 Couples and Switches

- *Couplers and waveguide devices*

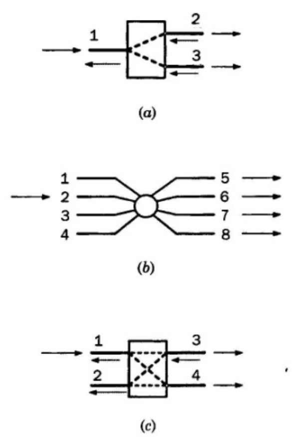


FIGURE 12.19 Examples of couplers: (a) T-coupler; (b) star coupler; (c) directional coupler.

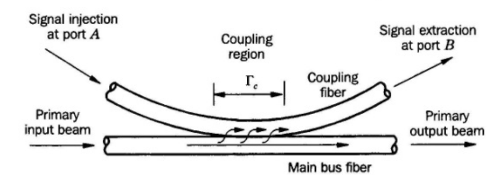


FIGURE 12.20 Schematic diagram of a directional optical fiber coupler.

Communication systems may also divide or combine optical signals between fibers. Fiber optic couplers distribute or combine optical signals between fibers. Couplers can distribute an optical signal from a single fiber into several fibers. Couplers may also combine optical signals from several fibers into one fiber

- *Switches - $LiNbO_3$ external modulators*

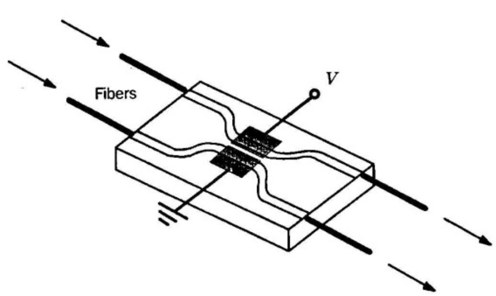


FIGURE 12.22 A 2 × 2 switch using an integrated optic directional coupler.

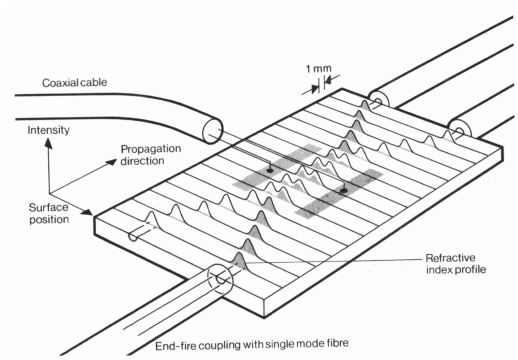


Figure 1 Electrooptic directional coupler in $LiNbO_3$. The index profiles of two waveguides in the crystal surface are shown together with the light power (shaded areas) in the guides with the coupler in the cross state. The incident light from a fiber (lower right) is switched between the output ports by applying a voltage to the electrodes (depicted as shaded stripes).

9.2.3 Amplifiers and Repeaters

Optical Amplifiers - Erbium-doped fiber amplifier (EDFA)

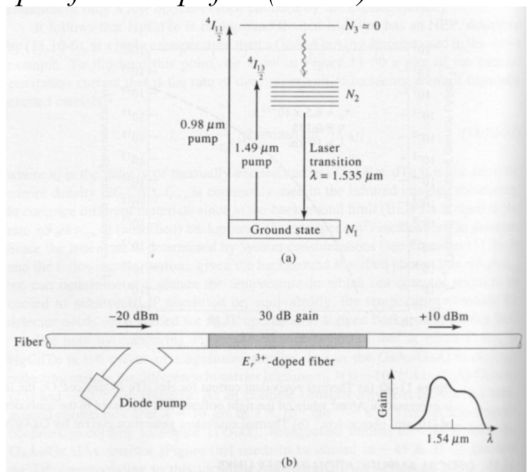
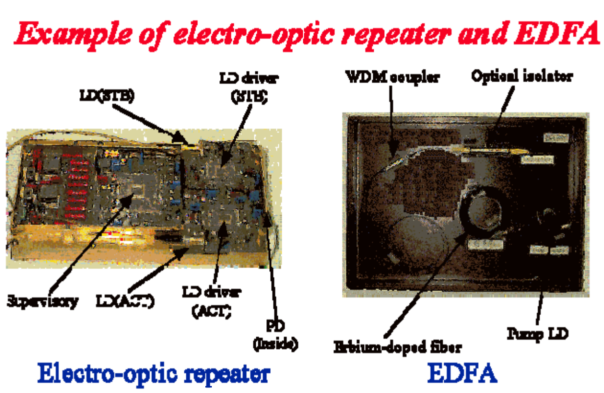


Figure 11-31 (a) The pertinent energy level diagram of E_r^{3+} in silica for pumping at $\lambda = .98$ μm (preferred). (b) A schematic diagram showing the amplifying fiber spliced into the transmission fiber and the method for coupling the pump radiation into the fiber.

Erbium-doped fiber amplifier (EDFA) is a fiber-based device used to amplify optical signals in fiber-optic communications systems. EDFAs consist of optical fibers having a core doped with ions of the rare-earth element erbium at levels of 100 to 1000 ppm. Light from one or more external diode lasers (around 200-300 mW) in either of two pump bands, 980 nm (for the highest level of inversion) or 1480 nm (for the highest quantum efficiency), is coupled into the fiber, exciting the erbium atoms. Faded Optical signals at wavelengths between about 1530 and 1620 nm entering the fiber stimulate the excited erbium atoms to emit photons at the same wavelength as the incoming signal. This amplifies a weak optical signal to higher power. EDFAs can simultaneously amplify signals over a range of wavelengths, making them compatible with wavelength-division-multiplexed (WDM) systems. Usually EDFAs work in one of two bands: the C (conventional) band from approximately 1530 to 1570 nm, or the L (long) band from approximately 1570 to 1610 nm. The number of optical channels that fits into each band depends on the channel spacing. Fiber amplifiers overcome attenuation losses in optical fiber, stretching transmission to hundreds or thousands of kilometers without the need for a more-complex electronic hybrid repeater. Simultaneous amplification of many optical channels made WDM practical over long distances. Amplification also can compensate for losses which occur when optical power is split among multiple routes, which is done to reduce costs and/or allow new network topologies.

Repeaters:

Long-haul links (eg., undersea trans-oceanic): 90's systems - EDFA repeaters.



10 Time- and Wavelength-Division Multiplexing

"Multiplexing" means the use of a single pathway to simultaneously transmit several signals which nonetheless retain their individuality.

10.1 Wavelength Division Multiplexing (WDM)

10.2 Dense Wavelength Division Multiplexing (DWDM)

At present it's not hard to send upwards of 160 optical channels carrying different signals, all transmitted at the same time over the same fiber at different frequencies. Ant it won't be long before 1000 channels perfiber is commonplace.

10.3 Current status and future

For recent technological advances, see for example

Jeff Hecht, "Fiber to the Home – Why 'the Last Mile' is Truly the Hardest", Optics & Photonics News, p.32, March 2003 Vol. 14 (3).

Paul Bonenfant, "The Evolution of SONET/SDH over WDM", Optics & Photonics News, p.32, March 2003 Vol. 14 (3).

Jagdeep Shah, "Optical CDMA", p. 42, Optics & Photonics News, April 2003 Vol. 14 (4).

11 All optical switch

All-optical switch utilizing **MOEMS** (Micro-Opto-Electro-Mechanical Systems) is commercially available nowadays. Electronic switches are bulky and relatively slow by optical standard. All-optical switches can alleviate the so-called electronic bottleneck. **MOEMS** switches have already been deployed into the network. See Hecht's book for short introduction on MOEMS or search web (e.g. http://www.google.com or http://www.scirus.com)for more information.

12 Reference:

1. *Craiq C. Freudenrich, "How Fiber Optics Work", http://electronics.howstuffworks.com/fiber-optic.htm/*
2. Ch. 5.6 in "Optics," *E. Hecht, (Addison-Wesley, Reading, Mass., 2002).*
3. "Understanding fiber optics," *J. Hecht, (Prentice Hall, Upper Saddle River, NJ, 2002).*
4. "Optical electronics in modern communications," *A. Yariv, (Oxford University Press, New York, 1997).*
5. Ch. 12 "Fiber Optics" in "Introduction to optical engineering," *F. T. S. Yu & X. Yang, (Cambridge University Press, Cambridge, Eng. ; New York, 1997).*