Optical Fibers

Basics, applications,

Introduction

- An optical fiber is essentially a waveguide for light
- It consists of a **core** and **cladding** that surrounds the core
- The **index of refraction** of the cladding is less than that of the core, causing rays of light leaving the core to be refracted back into the core
- A light-emitting diode (LED) or **laser diode** (LD) can be used for the source
- Advantages of optical fiber include:
  - Greater bandwidth than copper
  - Lower loss
  - Immunity to **crosstalk**
  - No electrical hazard

Fiber v. Copper

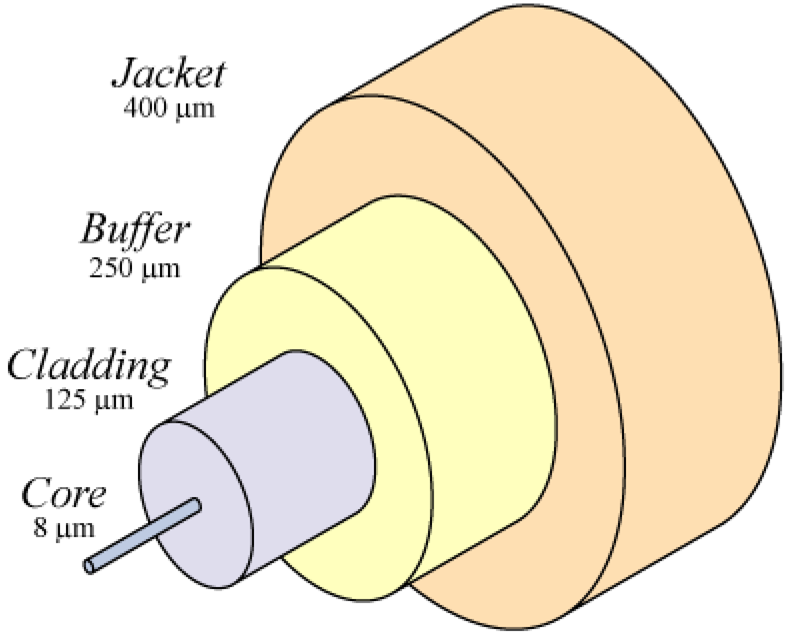
- Optical fiber transmits light pulses
  - Can be used for analog or digital transmission
  - Voice, computer data, video, etc.
- Copper wires (or other metals) can carry the same types of signals with electrical pulses

Advantages of Fiber

- Fiber has these advantages compared with metal wires
  - Bandwidth – more data per second
  - Longer distance
  - Faster
  - Special applications like medical imaging and quantum key distribution are only possible with fiber because they use light directly

Optical Fiber

- Core
  - Glass or plastic with a higher index of refraction than the cladding
  - Carries the signal
- Cladding
  - Glass or plastic with a lower index of refraction than the core
- Buffer
  - Protects the fiber from damage and moisture
- Jacket
  - Holds one or more fibers in a cable



Optical Fiber

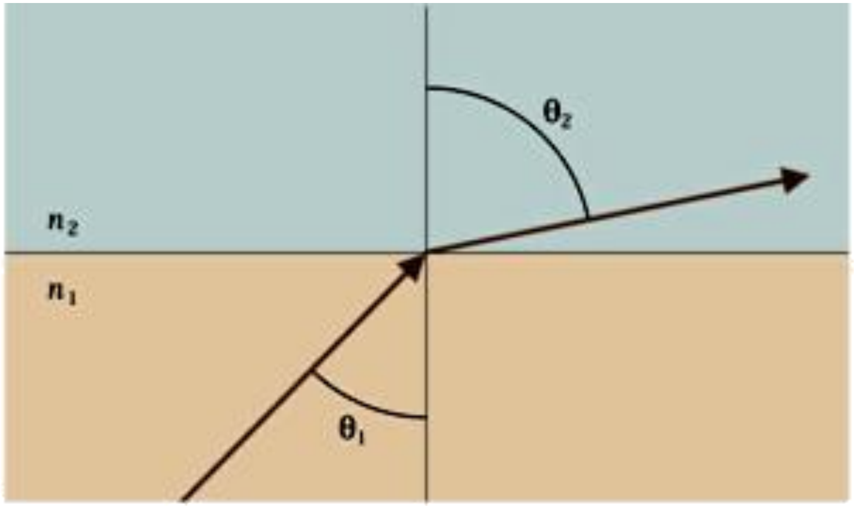
- Optical fiber is made from thin strands of either glass or plastic
- It has little mechanical strength, so it must be enclosed in a protective jacket
- Often, two or more fibers are enclosed in the same cable for increased bandwidth and redundancy in case one of the fibers breaks
- It is also easier to build a full-duplex system using two fibers, one for transmission in each direction

Total Internal Reflection

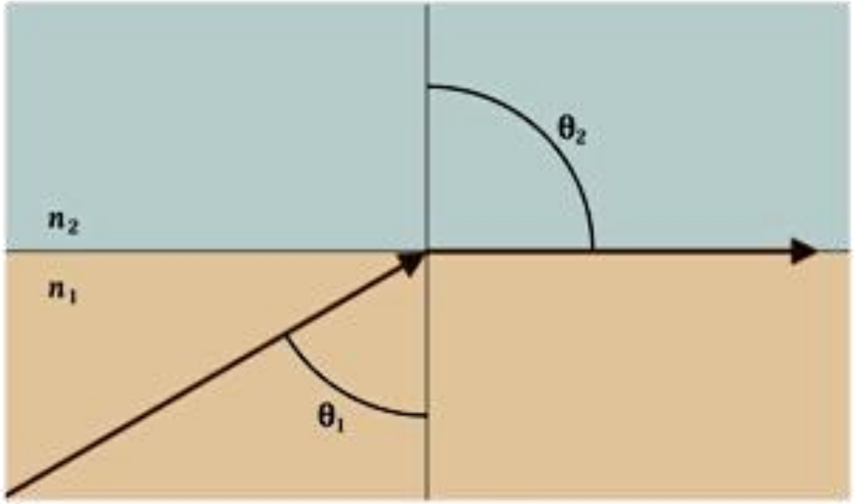
- Optical fibers work on the principle of **total internal reflection**
- With light, the refractive index is listed
- The **angle of refraction** at the interface between two media is governed by Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

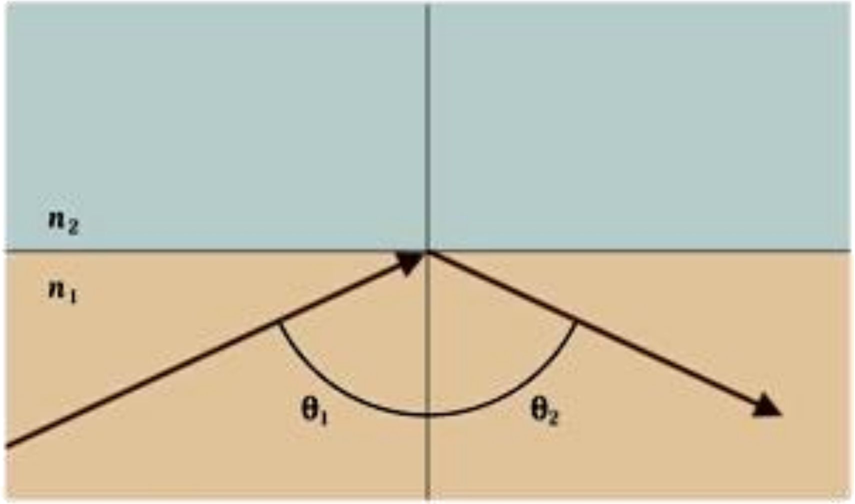
Refraction & Total Internal Reflection



(a) Angle of incidence less than critical angle



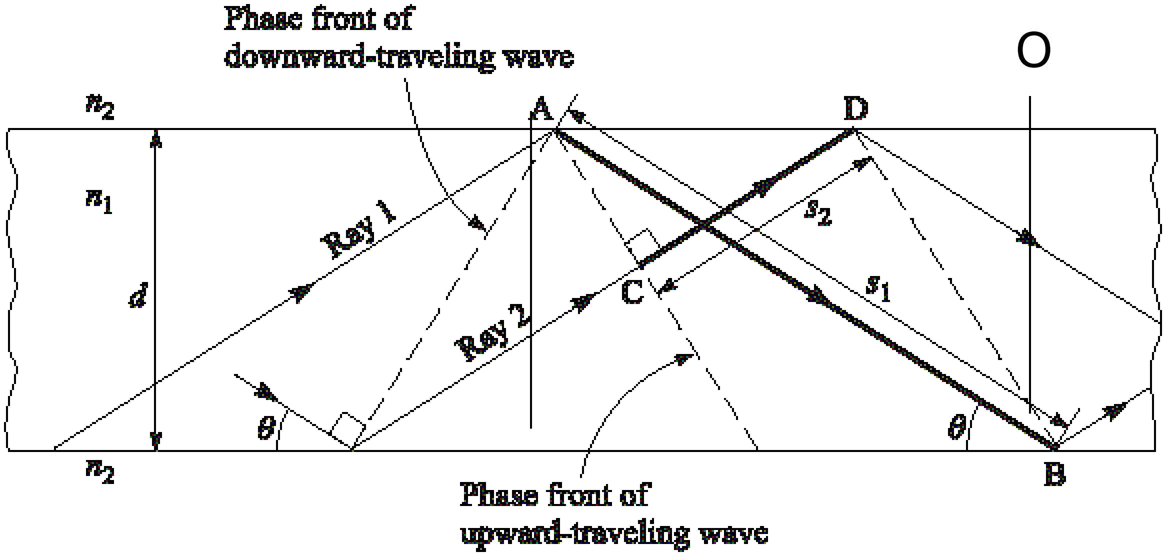
(b) Angle of incidence equal to critical angle



(c) Angle of incidence greater than critical angle

Optical rays transmission through dielectric slab waveguide

$$n_1 > n_2 ; \theta < \theta_c = \frac{\pi}{2} - \phi_c$$



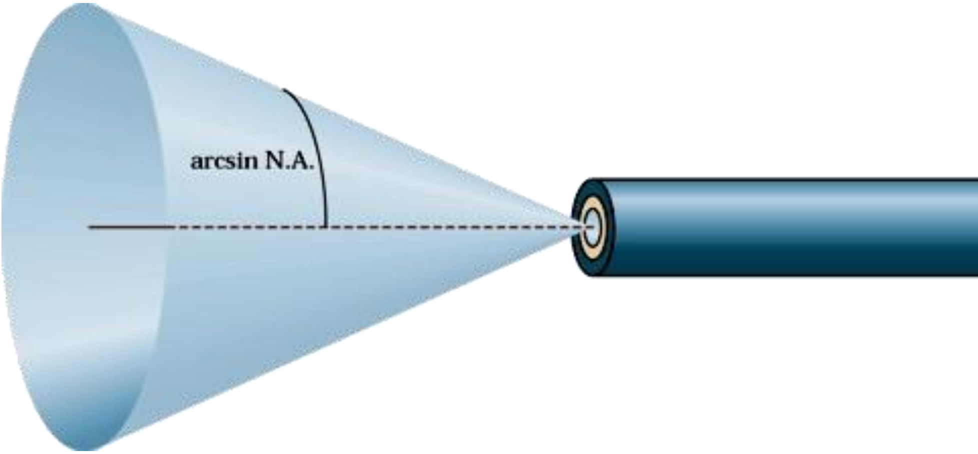
For TE-case, when electric waves are normal to the plane of incidence θ must be satisfied with following relationship:

$$\tan\left(\frac{\pi n_1 d \sin\theta}{\lambda} - \frac{m\pi}{2}\right) = \left[\frac{\sqrt{n_1{}^2 \cos^2\theta - n_2{}^2}}{n_1 \sin\theta}\right]$$

Numerical Aperture

- The **numerical aperture** of the fiber is closely related to the critical angle and is often used in the specification for optical fiber and the components that work with it
- The numerical aperture is given by the formula:
- The **angle of acceptance** is twice that given by the numerical aperture

$$N.A. = \sqrt{n_1^2 - n_2^2}$$

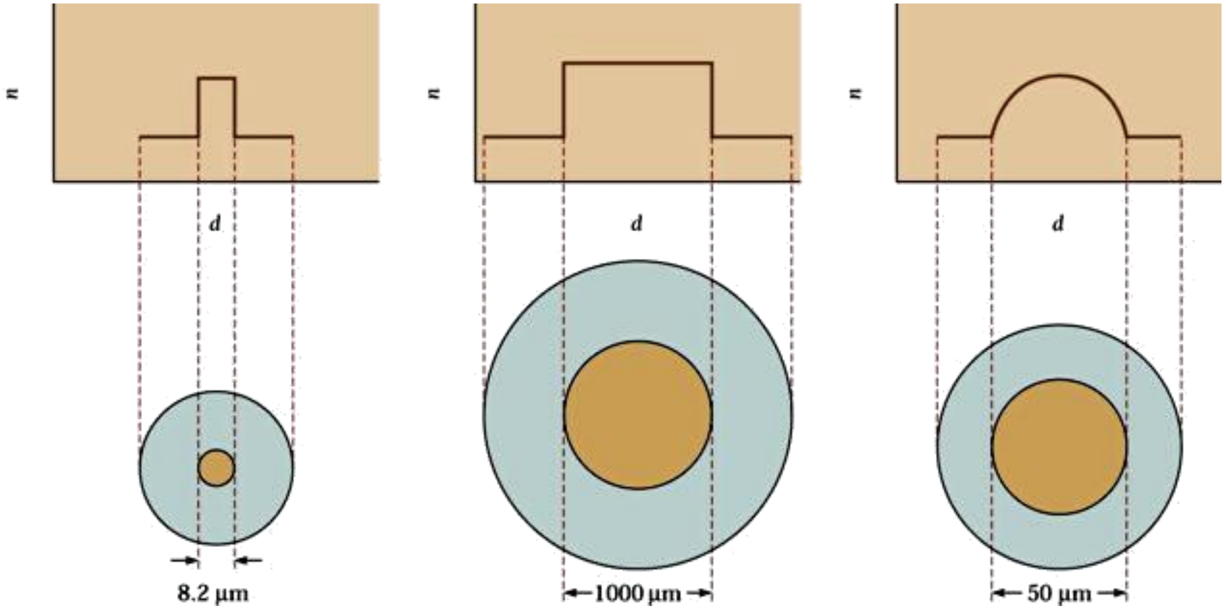


Modes and Materials

- Since optical fiber is a waveguide, light can propagate in a number of modes
- If a fiber is of large diameter, light entering at different angles will excite different modes while narrow fiber may only excite one mode
- Multimode propagation will cause **dispersion**, which results in the spreading of pulses and limits the usable bandwidth
- **Single-mode** fiber has much less dispersion but is more expensive to produce. Its small size, together with the fact that its numerical aperture is smaller than that of **multimode** fiber, makes it more difficult to couple to light sources

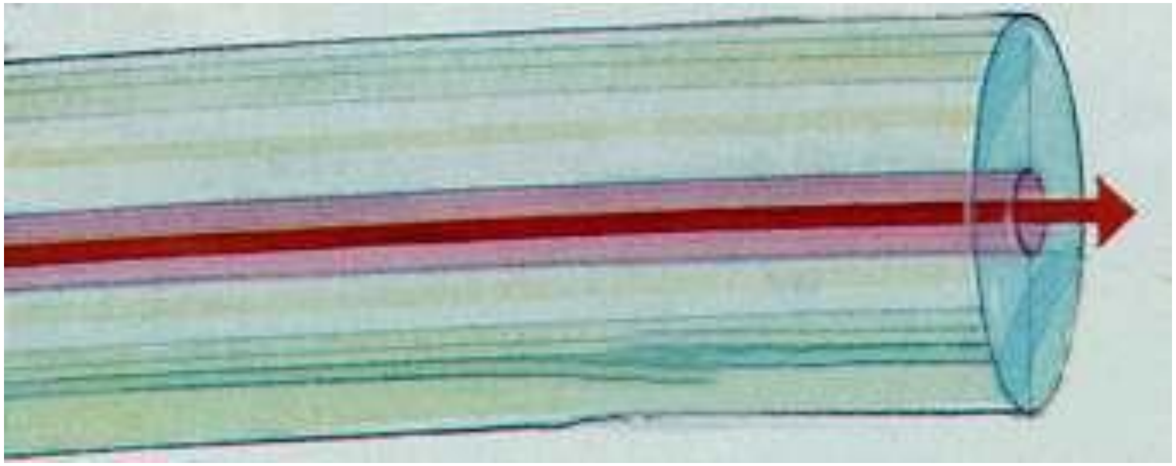
Types of Fiber

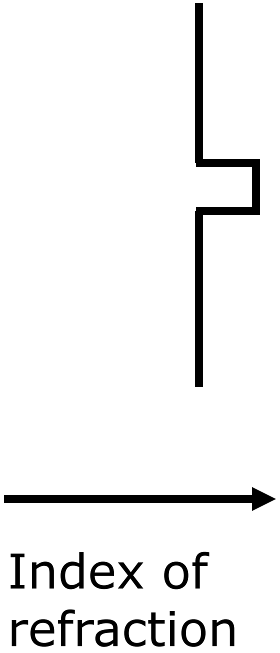
- Both types of fiber described earlier are known as **step-index** fibers because the index of refraction changes radically between the core and the cladding
- **Graded-index** fiber is a compromise multimode fiber, but the index of refraction gradually decreases away from the center of the core
- Graded-index fiber has less dispersion than a multimode step-index fiber



Singlemode Fiber

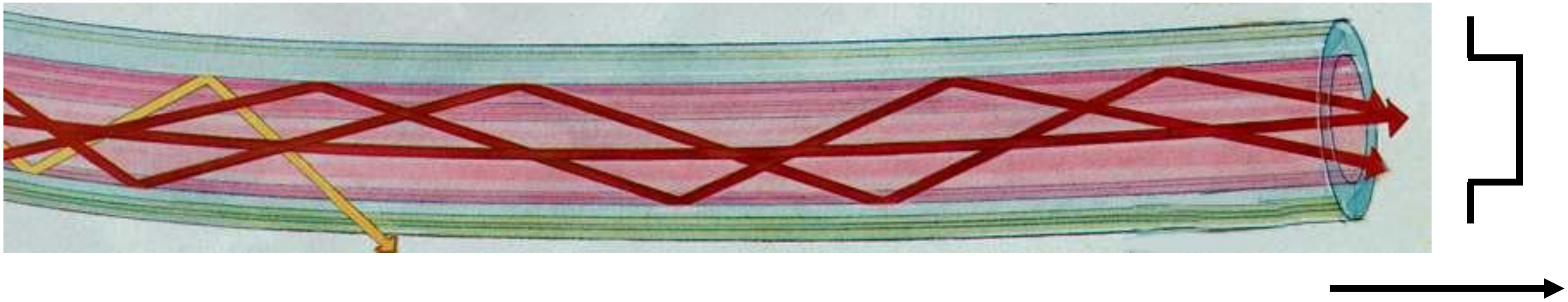
- Singlemode fiber has a core diameter of 8 to 9 microns, which only allows one light path or *mode*





Multimode Step-Index Fiber

- Multimode fiber has a core diameter of 50 or 62.5 microns (sometimes even larger)
  - Allows several light paths or *modes*
  - This causes *modal dispersion* – some modes take longer to pass through the fiber than others because they travel a longer distance

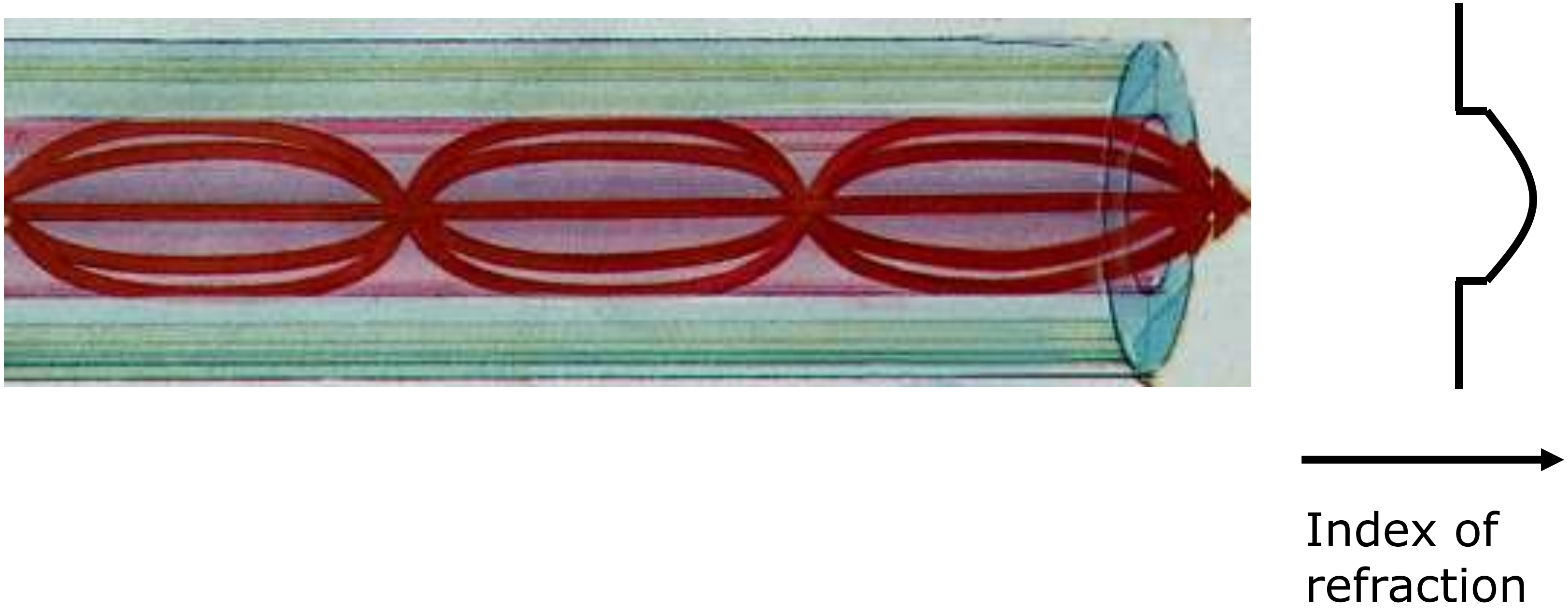


-
  - See animation at link Ch 2f

Index of refraction

Multimode Graded-Index Fiber

- The index of refraction gradually changes across the core
  - Modes that travel further also move faster
  - This reduces *modal dispersion* so the bandwidth is greatly increased



Step-index and Graded-index

- Step index multimode was developed first, but rare today because it has a low bandwidth (50 MHz-km)
- It has been replaced by graded-index multimode with a bandwidth up to 2 GHz-km

Mathematical approach

Modal Theory of Step Index fiber

- General expression of EM-wave in the circular fiber can be written as:

$$\vec{E}(r,\phi,z,t) = \sum_m A_m \vec{E}_m(r,\phi,z,t) = \sum_m A_m \vec{U}_m(r,\phi) e^{j(\omega t - \beta_m z)}$$

$$\vec{H}(r,\phi,z,t) = \sum_m A_m \vec{H}_m(r,\phi,z,t) = \sum_m A_m \vec{V}_m(r,\phi) e^{j(\omega t - \beta_m z)}$$

- Each of the characteristic solutions $\vec{E}_m(r,\phi,z,t)\ \&\ \vec{H}_m(r,\phi,z,t)$ is called ***m*th mode** of the optical fiber.
- It is often sufficient to give the E-field of the mode.

$$\vec{U}_m(r,\phi) e^{j(\omega t - \beta_m z)} \qquad \mathrm{m} = 1,2,3\ldots$$

- The modal field distribution, $\vec{U}_m(r,\phi)$, and the mode propagation constant, β_m are obtained from solving the Maxwell's equations subject to the boundary conditions given by the cross sectional dimensions and the dielectric constants of the fiber.

- Most important characteristics of the EM transmission along the fiber are determined by the mode propagation constant, $\beta_m(\omega)$, which depends on the mode & in general varies with frequency or wavelength. <u>This quantity is always between the plane propagation constant (wave number) of the core & the cladding media</u> .

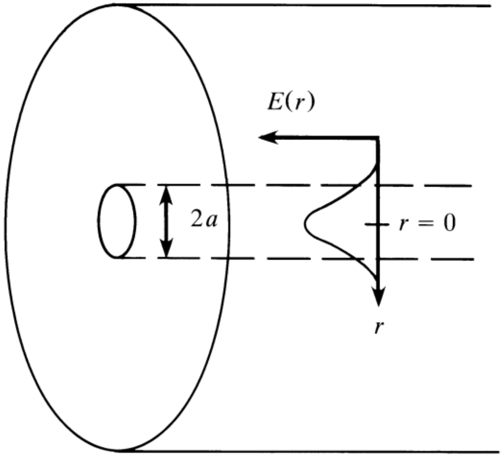
$$n_2 k < \beta_m(\omega) < n_1 k$$

- At each frequency or wavelength, there exists only a finite number of guided or propagating modes that can carry light energy over a long distance along the fiber. Each of these modes can propagate in the fiber only if the frequency is above the **cut-off frequency**, ω_c , (or the source wavelength is smaller than the cut-off wavelength) obtained from cut-off condition that is:

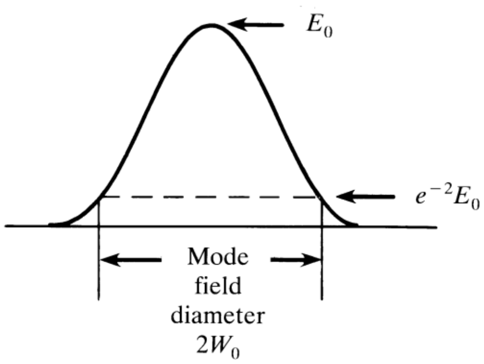
$$\beta_m(\omega_c) = n_2 k$$

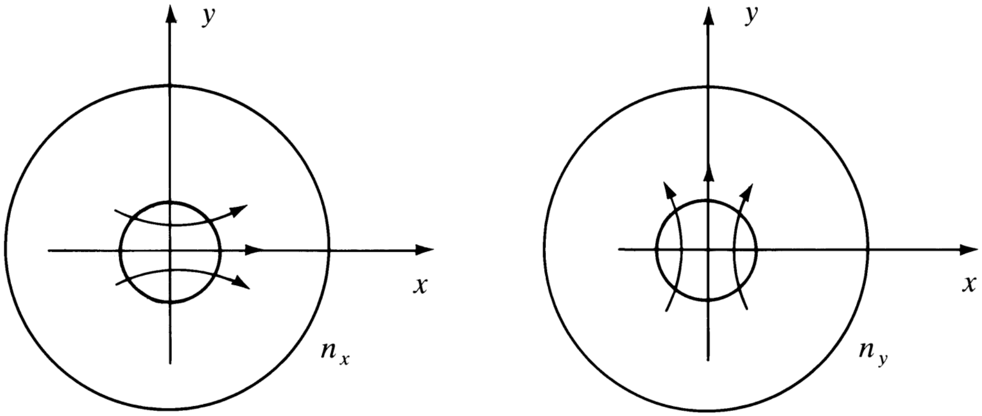
- To minimize the signal distortion, the fiber is often operated in a **single mode** regime. In this regime only the lowest order mode (fundamental mode) can propagate in the fiber and all higher order modes are under cut-off condition (non-propagating).
- **Multi-mode** fibers are also extensively used for many applications. In these fibers many modes carry the optical signal collectively & simultaneously.

Fundamental Mode Field Distribution



Mode field diameter





Horizontal mode

Vertical mode

Polarizations of fundamental mode

Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000

Mode designation in circular cylindrical waveguide (Optical Fiber)

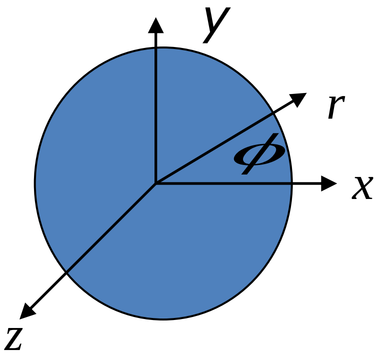
TE_{lm} modes : The electric field vector lies in transverse plane.

TM_{lm} modes : The magnetic field vector lies in transverse plane.

Hybrid HE_{lm} modes : TE component is larger than TM component.

Hybrid EH_{lm} modes : TM component is larger than TE component.

l= # of variation cycles or zeros in ϕ direction.
m= # of variation cycles or zeros in *r* direction.

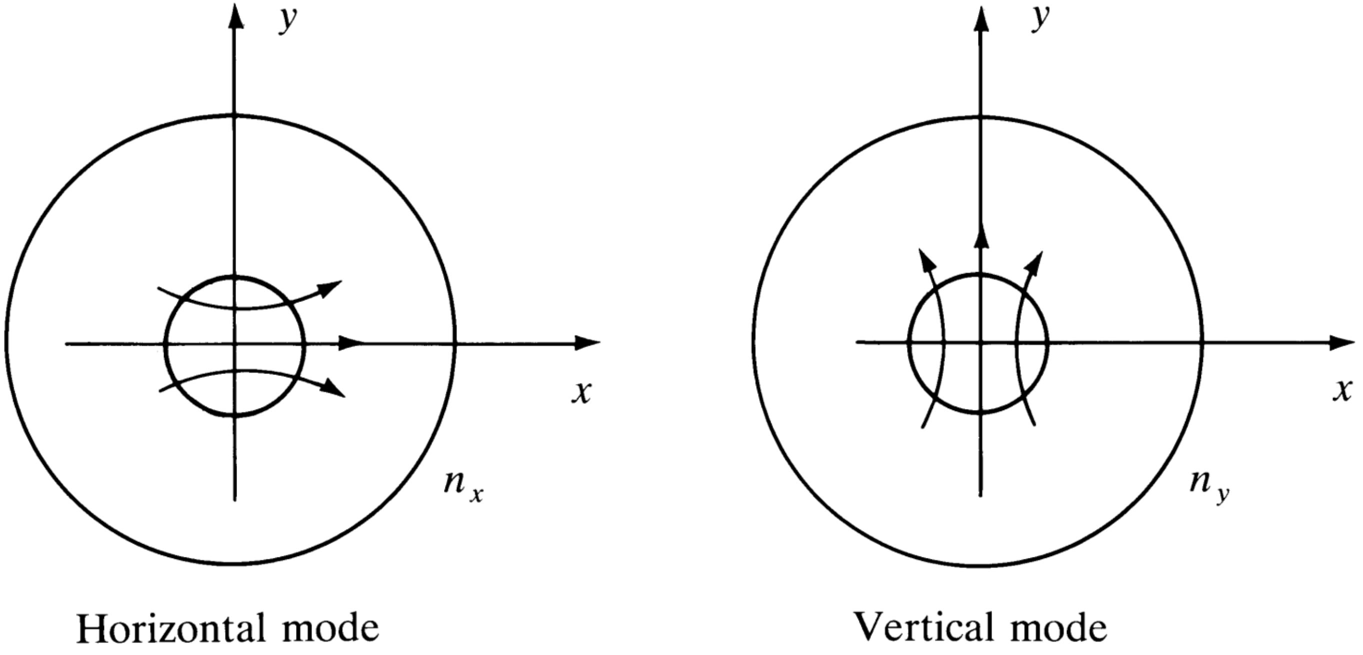


Linearly Polarized (LP) modes in weakly-guided fibers ($n_1 - n_2 << 1$)

$$\mathrm{LP}_{0m}(\mathrm{HE}_{1m}), \mathrm{LP}_{1m}(\mathrm{TE}_{0m} + \mathrm{TM}_{0m} + \mathrm{HE}_{0m})$$

Fundamental Mode: $\mathrm{LP}_{01}(\mathrm{HE}_{11})$

Two degenerate fundamental modes in Fibers (Horizontal & Vertical HE_{11} Modes)



Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000

Mode propagation constant as a function of frequency

- Mode propagation constant, $\beta_{lm}(\omega)$, is the most important transmission characteristic of an optical fiber, because the field distribution can be easily written in the form of eq. [2-27].
- In order to find a mode propagation constant and cut-off frequencies of various modes of the optical fiber, first we have to calculate the **normalized frequency**, *V*, defined by:

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1{}^2 - n_2{}^2} = \frac{2\pi a}{\lambda}\mathrm{NA} \qquad [2\text{-}30]$$

a: radius of the core, λ is the optical free space wavelength,
n_1 & n_2 are the refractive indices of the core & cladding.

V-Number and Fiber Modes

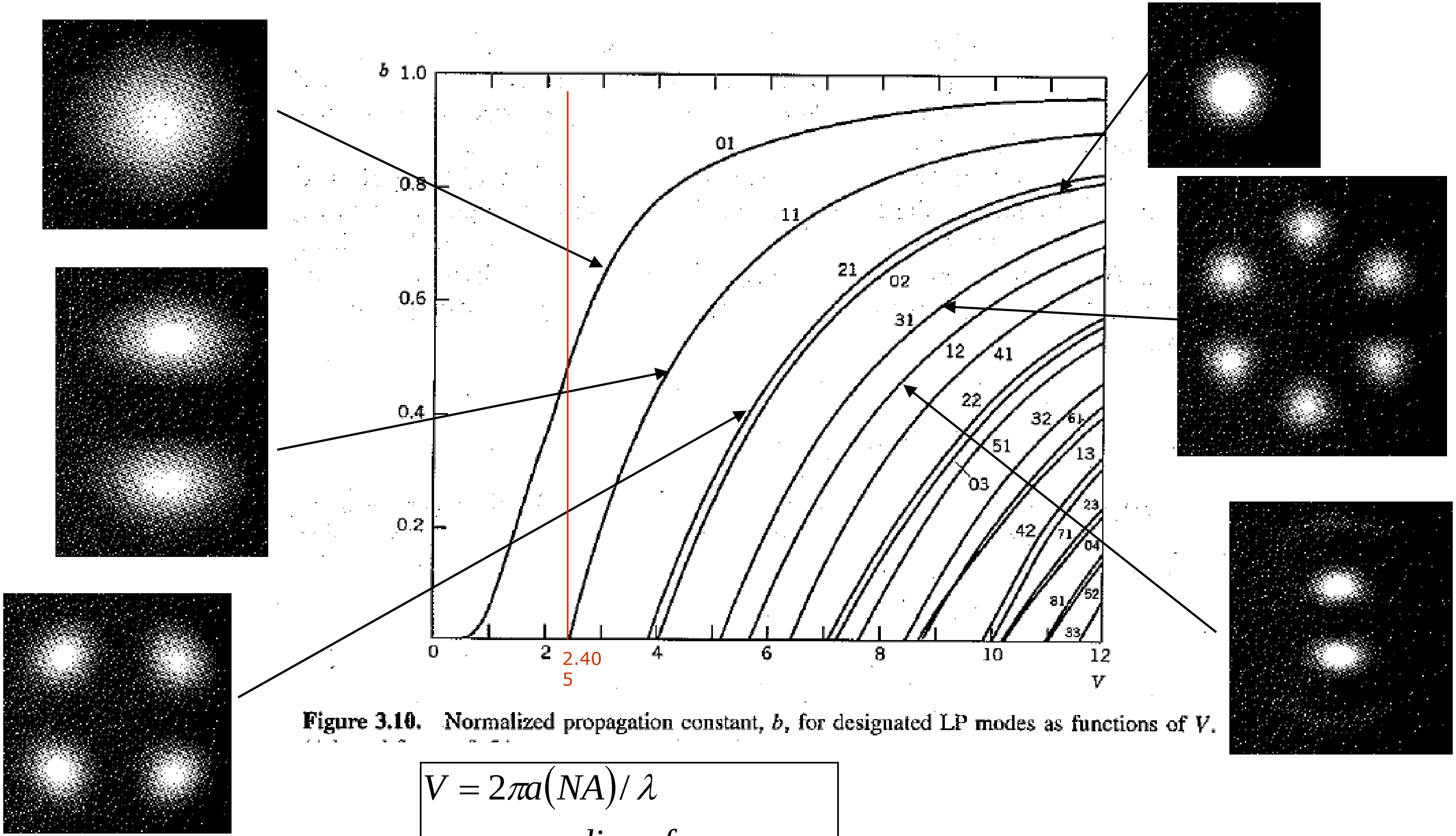


Figure 3.10. Normalized propagation constant, b, for designated LP modes as functions of V.

$$V = 2\pi a(NA)/\lambda$$

a : *radius of core*

λ : *wavelength of ligth*

Cut-off Wavelength

Definition: the wavelength below which multiple modes of light can be propagated along a particular fiber, i.e., $\lambda >= \lambda_c$, single mode, $\lambda < \lambda_c$, multi-mode

$$\boxed{\lambda_c = \frac{2\pi a}{2.405} \times NA}$$

Single mode Operation

- The cut-off wavelength or frequency for each mode is obtained from:

$$\beta_{lm}(\omega_c) = n_2 k = \frac{2\pi n_2}{\lambda_c} = \frac{\omega_c n_2}{c}$$

- **Single mode operation** is possible (Single mode fiber) when:

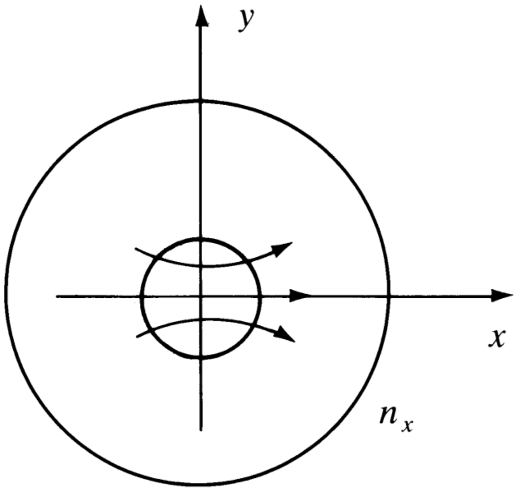
$$V \leq 2.405$$

Only HE_{11} can propagate faithfully along optical fiber

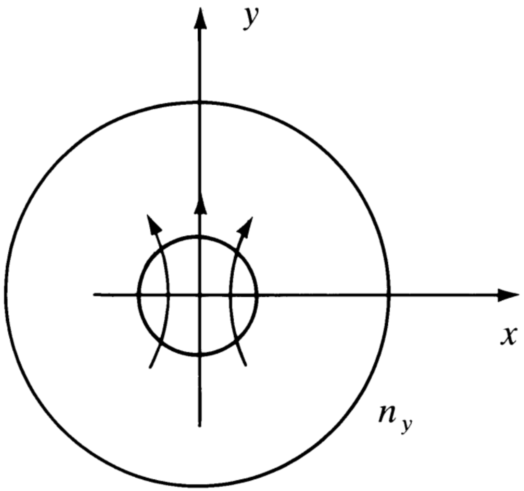
Birefringence in single-mode fibers

- Because of asymmetries the refractive indices for the two degenerate modes (vertical & horizontal polarizations) are different. This difference is referred to as **birefringence**, B_f :

$$B_f = n_y - n_x$$



Horizontal mode

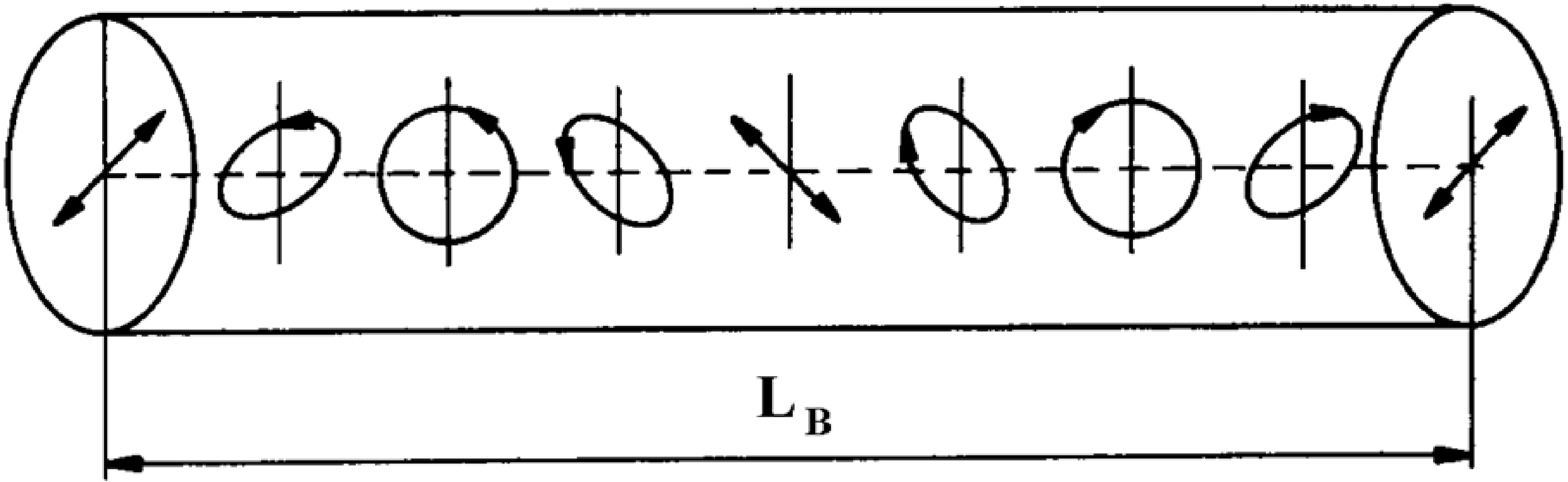


Vertical mode

Fiber Beat Length

- In general, a linearly polarized mode is a combination of both of the degenerate modes. As the modal wave travels along the fiber, the difference in the refractive indices would change the phase difference between these two components & thereby the state of the polarization of the mode. However after certain length referred to as **fiber beat length,** the modal wave will produce its original state of polarization. This length is simply given by:

$$L_{\mathbf{B}} = \frac{2\pi}{kB_f}$$



Multi-Mode Operation

- Total number of modes, *M*, supported by a multi-mode fiber is approximately (When *V* is large) given by:

$$M \approx \frac{V^2}{2}$$

- **Power distribution in the core & the cladding:** Another quantity of interest is the ratio of the mode power in the cladding, P_{clad} to the total optical power in the fiber, *P*, which at the wavelengths (or frequencies) far from the cut-off is given by:

$$\frac{P_{clad}}{P} \approx \frac{4}{3\sqrt{M}}$$

Sources and Wavelengths

- Multimode fiber is used with
  - LED sources at wavelengths of 850 and 1300 nm for slower local area networks
  - Lasers at 850 and 1310 nm for networks running at gigabits per second or more

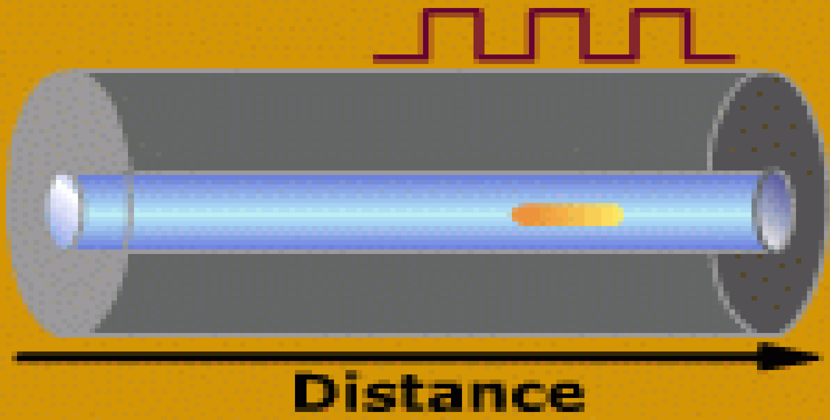
Sources and Wavelengths

- Singlemode fiber is used with
  - Laser sources at 1300 and 1550 nm
  - Bandwidth is extremely high, around 100 THz-km

Fiber Optic Specifications

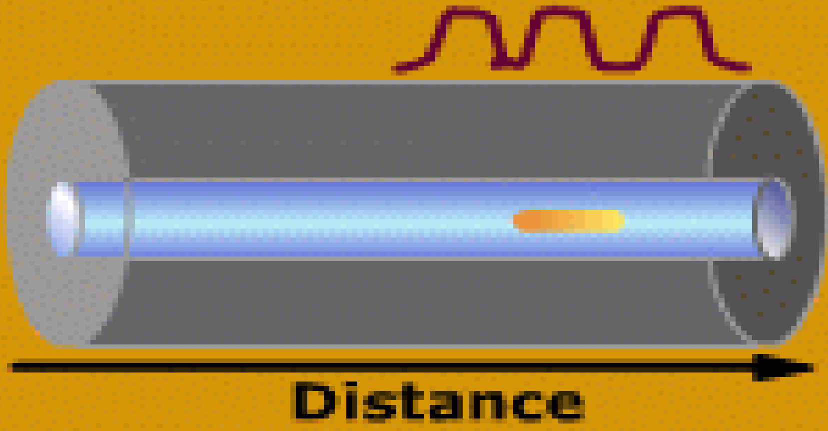
- Attenuation
  - Loss of signal, measured in dB
- Dispersion
  - Blurring of a signal, affects bandwidth
- Bandwidth
  - The number of bits per second that can be sent through a data link
- Numerical Aperture
  - Measures the largest angle of light that can be accepted into the core

Attenuation



Attenuation is expressed in dB/km

Dispersion



Dispersion is expressed in ps/(nm*km)

Measuring Bandwidth

- The *bandwidth-distance product* in units of MHz×km shows how fast data can be sent through a cable
- A common multimode fiber with bandwidth-distance product of 500 MHz×km could carry
  - A 500 MHz signal for 1 km, or
  - A 1000 MHz signal for 0.5 km
    - From Wikipedia

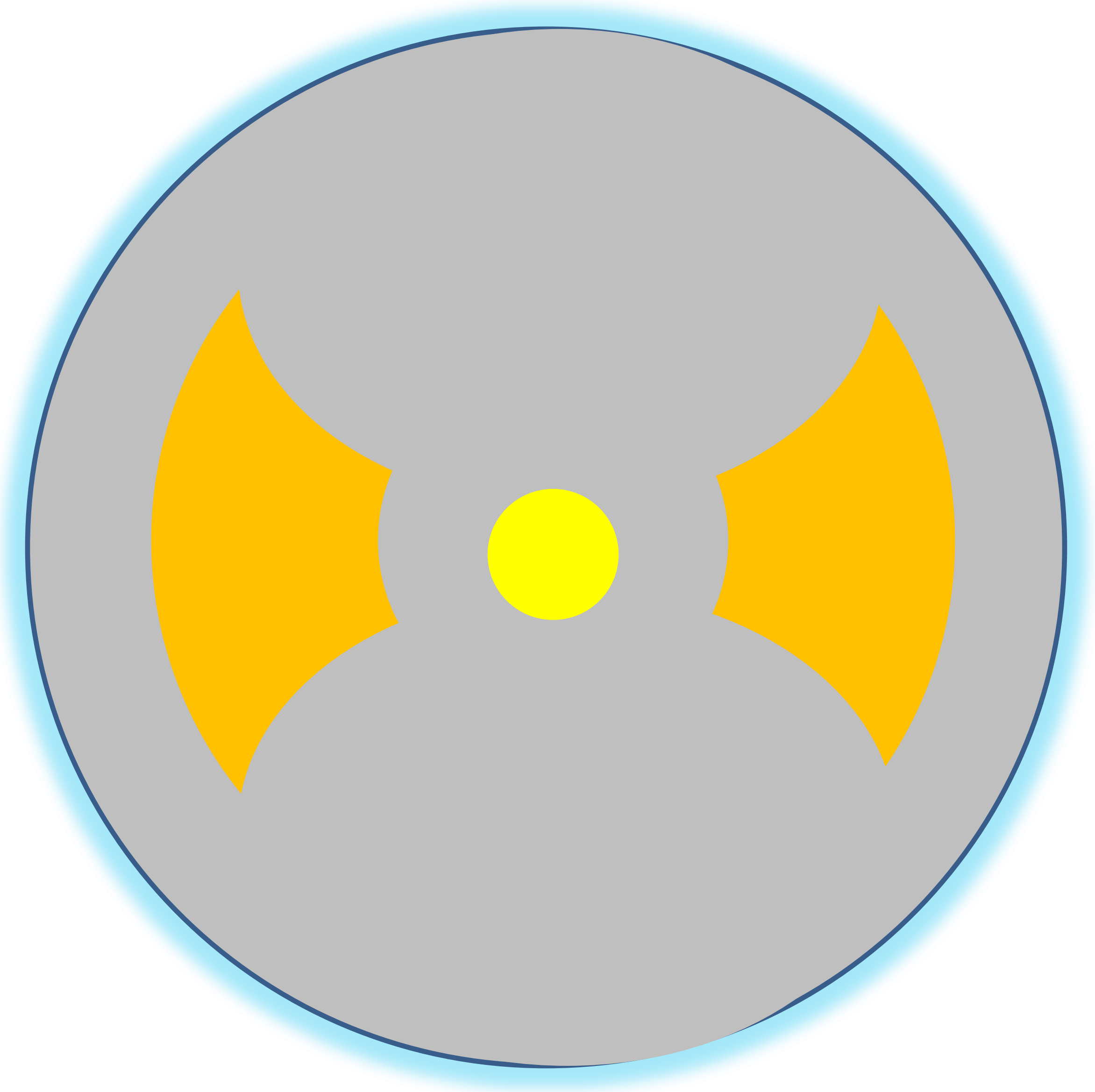
Popular Fiber Types

- At first there were only two common types of fiber
  - – 62.5 micron multimode, intended for LEDs and 100 Mbps networks
    - There is a large installed base of 62.5 micron fiber
  - – 8 micron single-mode for long distances or high bandwidths, requiring laser sources
    - Corning’s SMF-28 fiber is the largest base of installed fiber in the world.

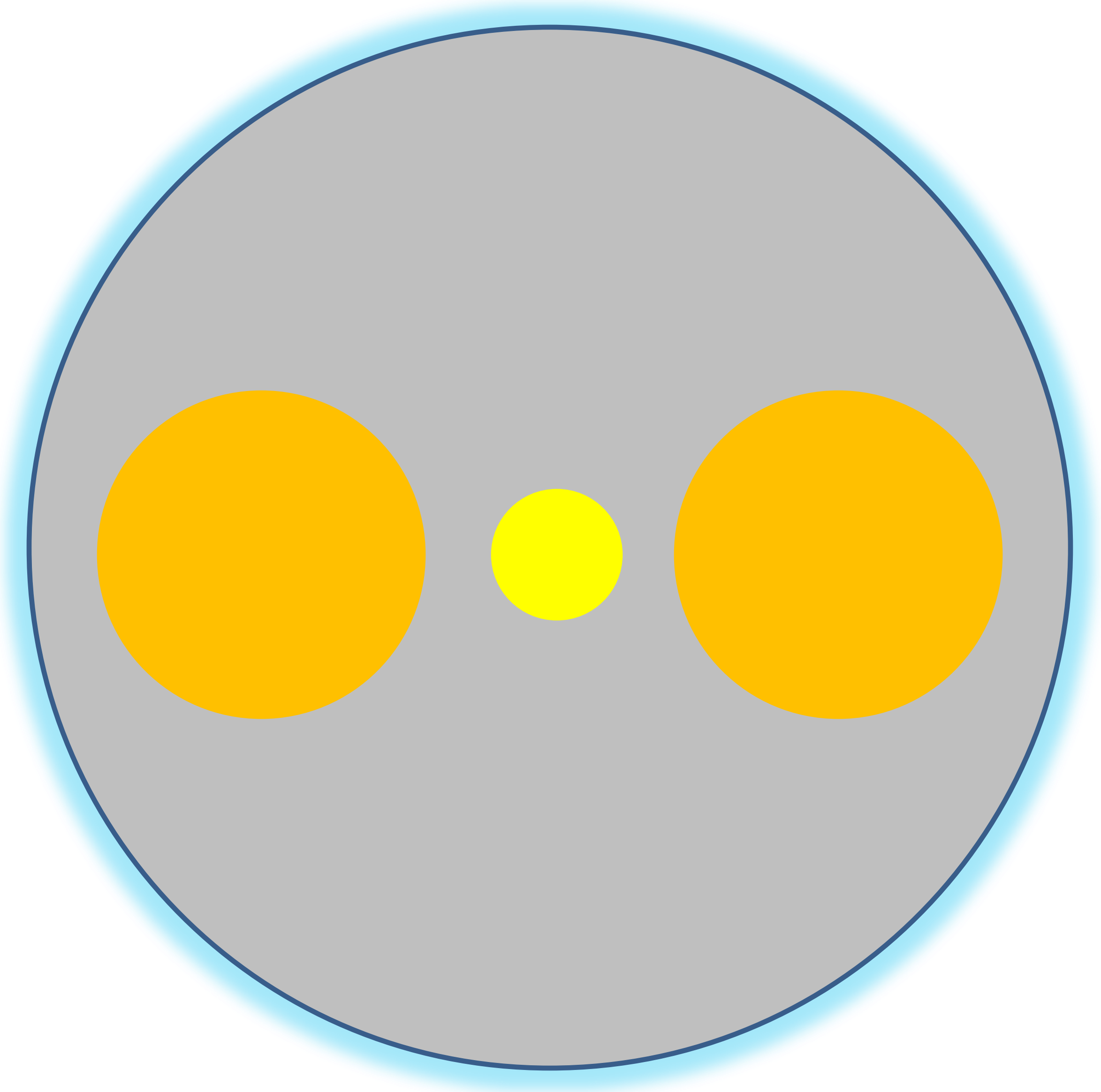
Gigabit Ethernet

- 62.5 micron multimode fiber did not have enough bandwidth for Gigabit Ethernet (1000 Mbps)
- LEDs cannot be used as sources for Gigabit Ethernet – they are too slow
- So Gigabit Ethernet used a new, inexpensive source:
  - Vertical Cavity Surface Emitting Laser (VCSEL)

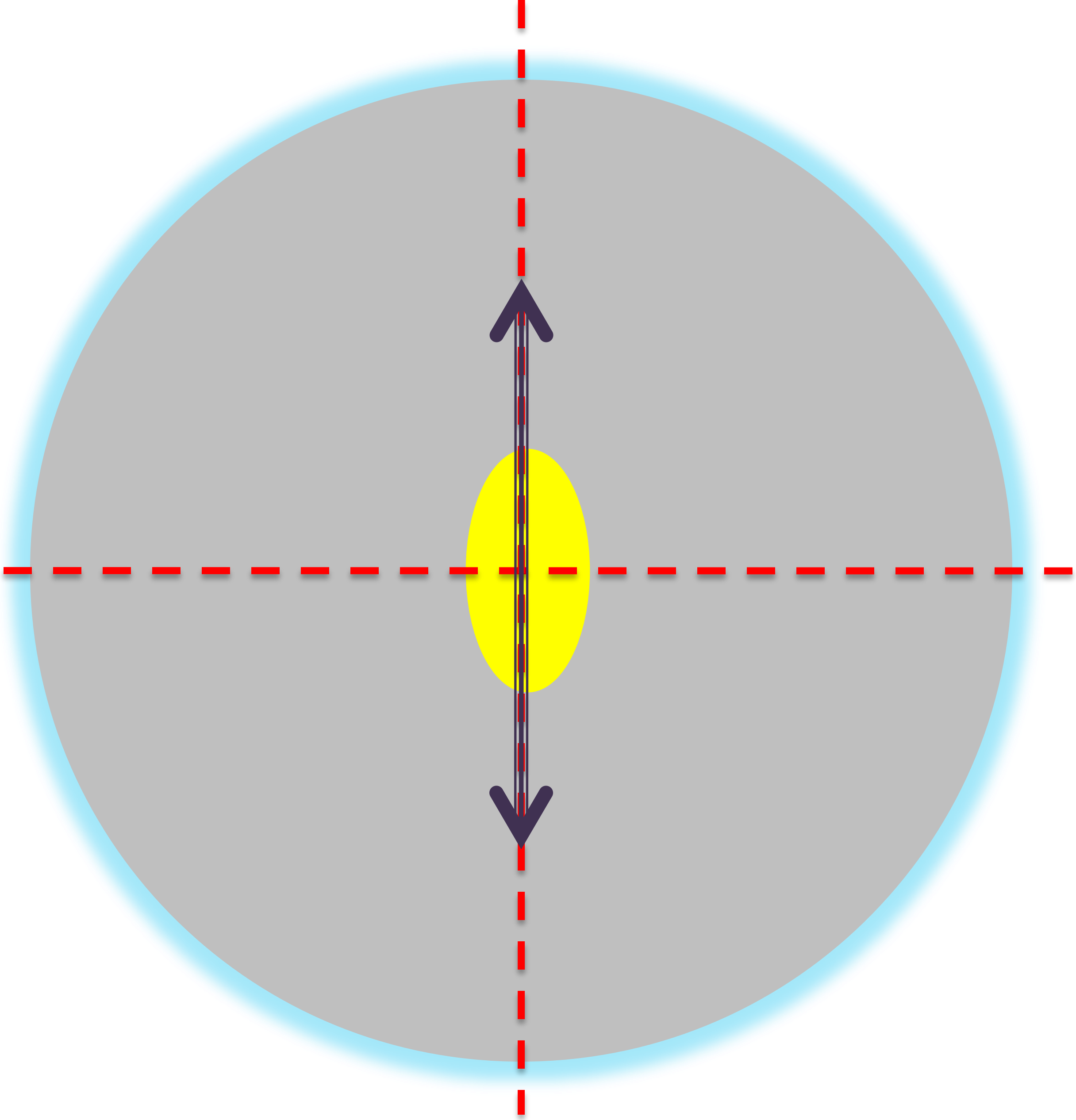
Other types of optical fibers



Birefringent Fiber (Bow-Tie)



Birefringent Fiber (Panda)



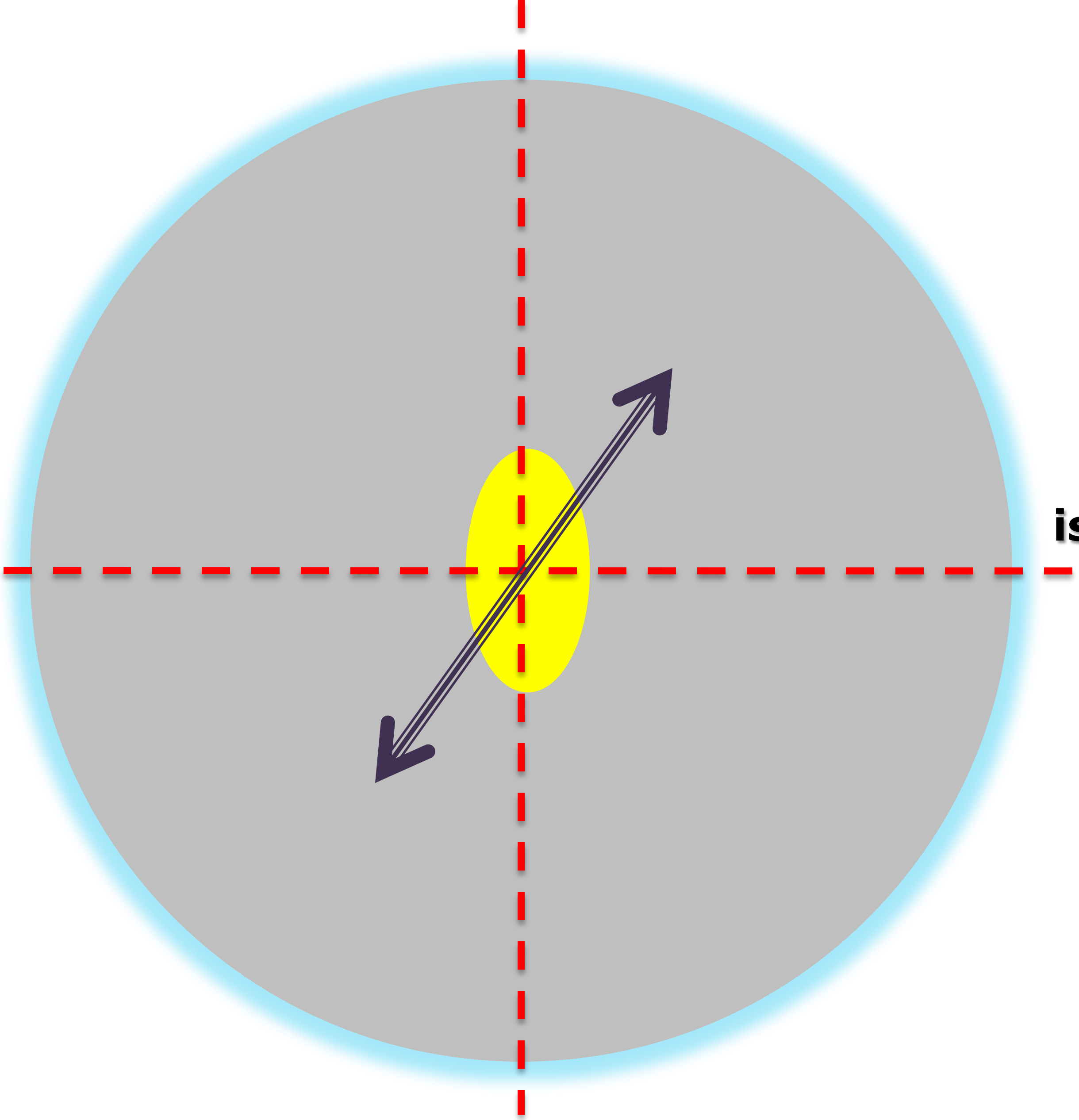
0°

Only one polarization mode is excited

↓

Linear polarization propagates unchanged

2 symmetry axes (birefringence axes)

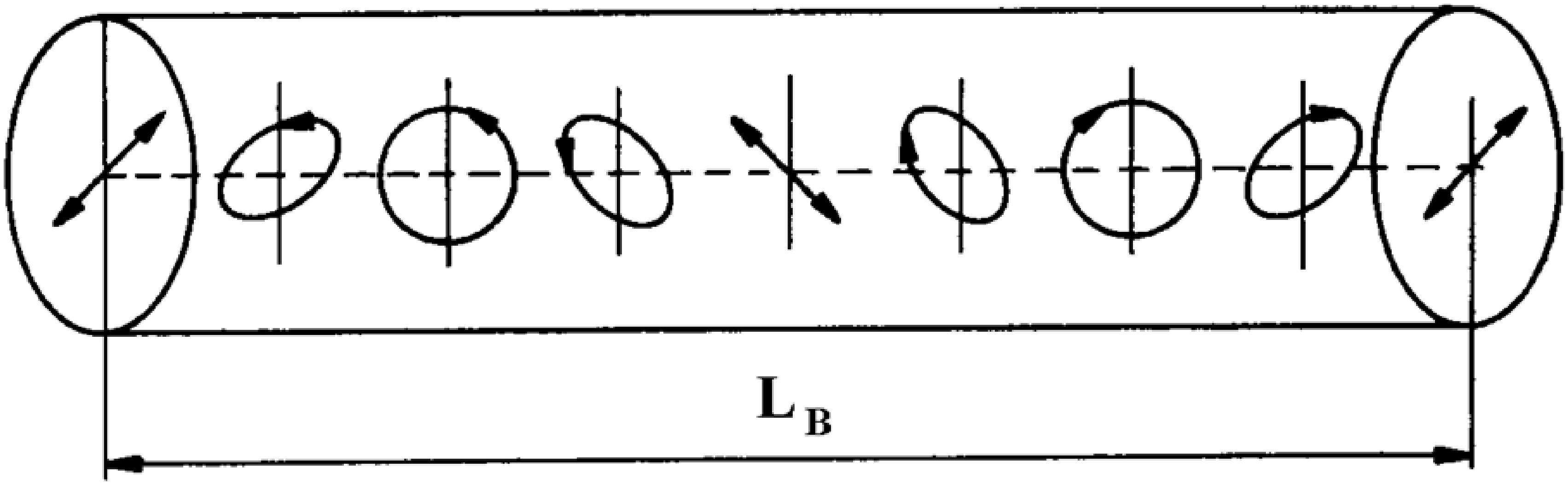


45°

Two polarization modes are excited

Linear polarization is changing periodically

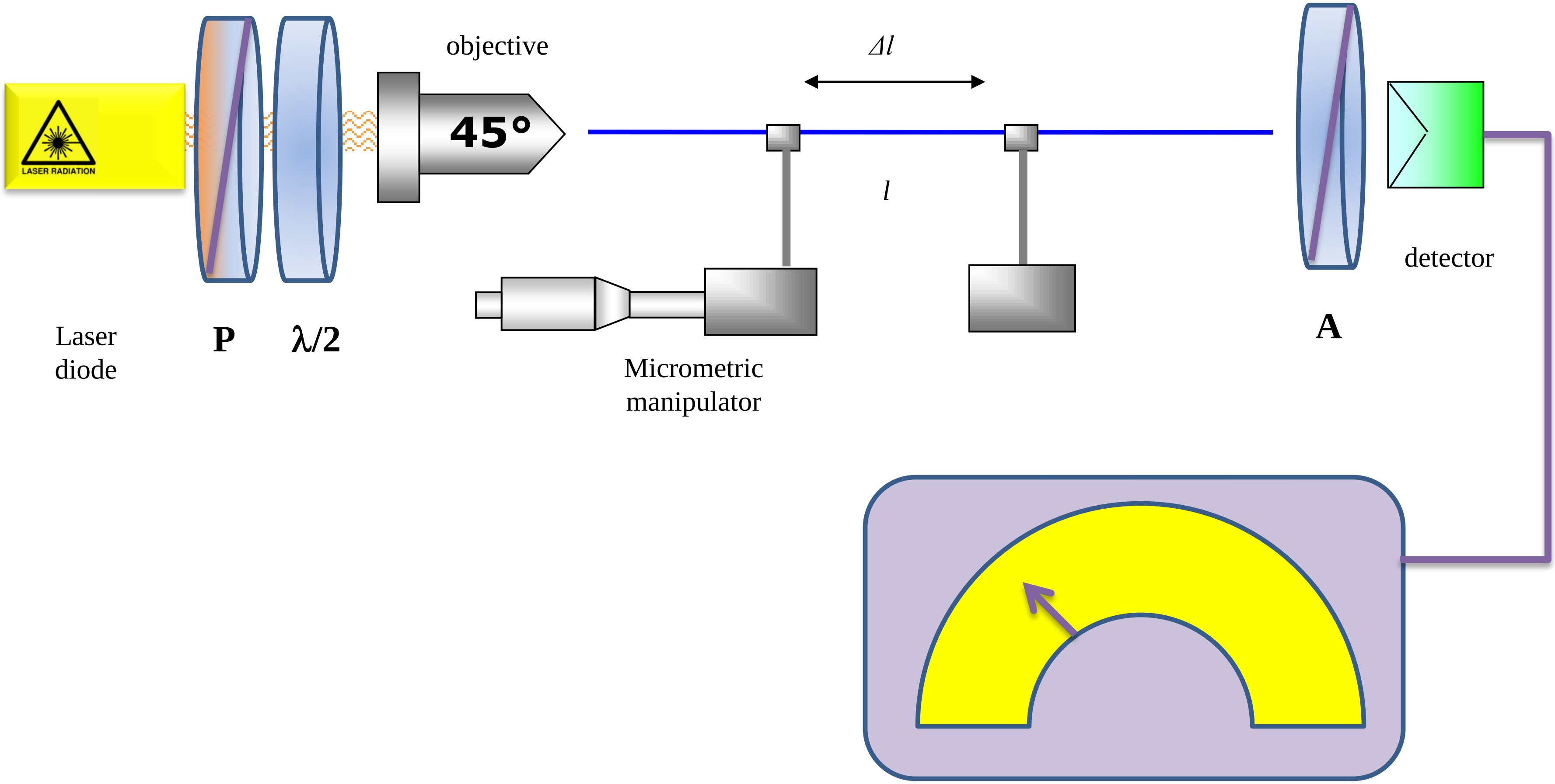
2 symmetry axes (birefringence axes)



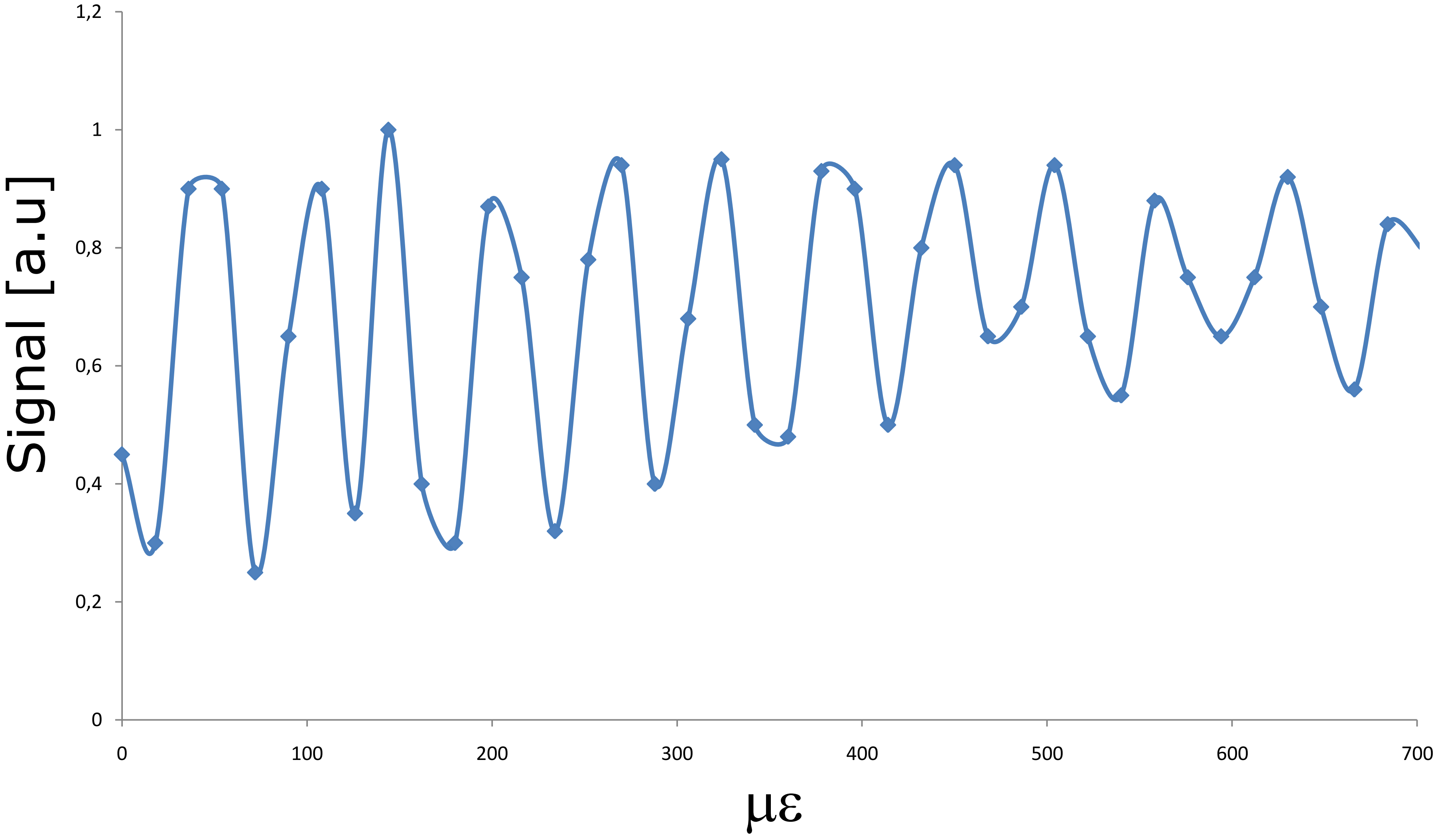
The Beat Length

the length corresponding to full evolution of state of polarization

Masuring the **Beat Length**



Results

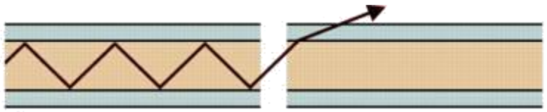


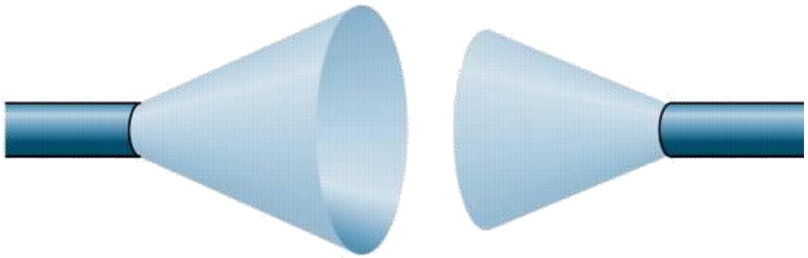
Connectors & Splices

- Frequently there is the need to temporarily or permanently joint two pieces of fiber. To achieve this, many different types and styles of mechanical assemblies have been designed.
- Many types of connectors were designed based on cost and performance as the key objectives.
- Merits of each connector are in the ability to hold the close tolerances necessary for good connection and in the repeatability of multiple connections.

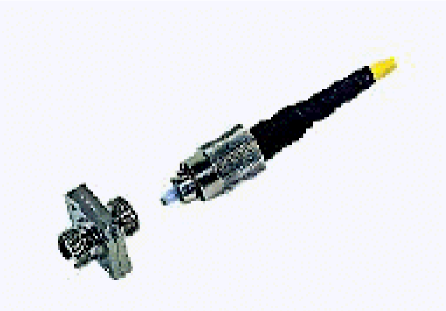
Fiber-Optic Connectors

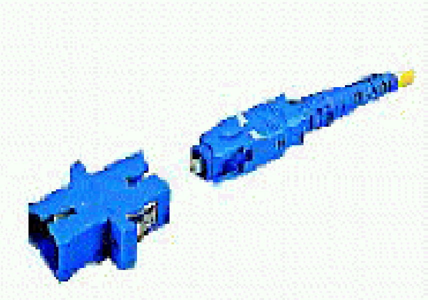
- Coupling the fiber to sources and detectors creates losses as well, especially when it involves mismatches in numerical aperture or in the size of optical fibers
- Good connections are more critical with single-mode fiber, due to its smaller diameter and numerical aperture
- A *splice* is a permanent connection and a *connector* is removable

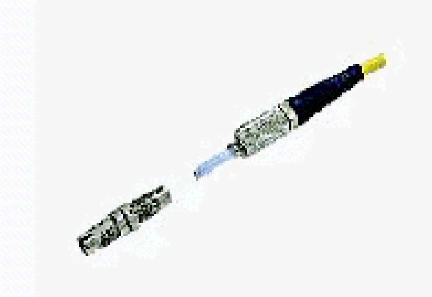

(a) Path of escaping ray

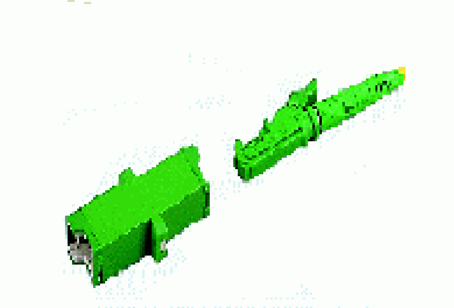

(b) Different cones of acceptance

Common Connector Types


FC Adapters & Connectors


SC Adapters & Connectors


DIN Adapters & Connectors

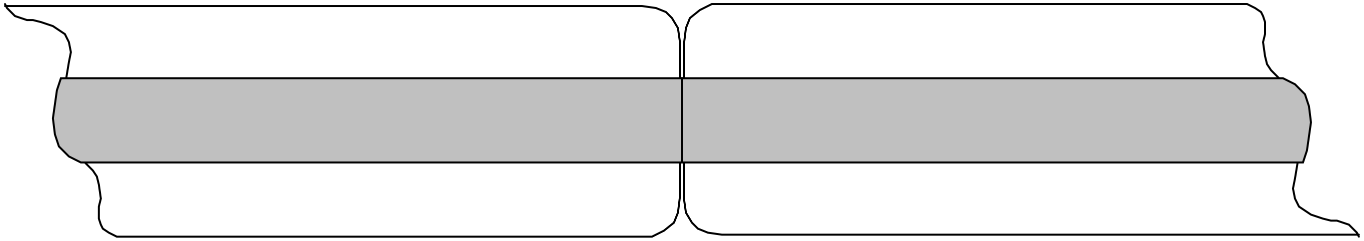

E-2000 Adapters & Connectors


ST Adapters & Connectors

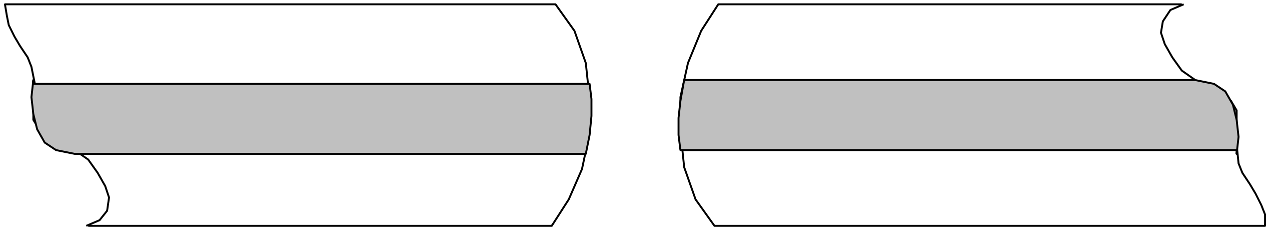
- FC and SC connectors are the most common in domestic market, ST connectors are mostly used in telephony applications and E-2000 is popular overseas.

Physical Contact Connectors

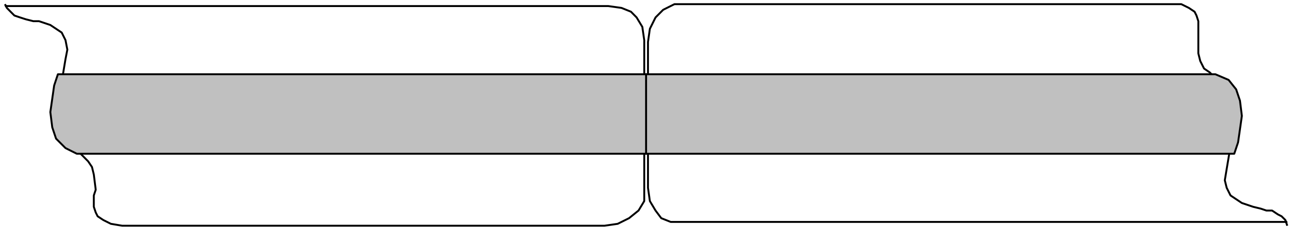
- The differences in connectors types are mainly in the mechanical assembly that holds the ferrule in position against another, identical ferrule.
- The FC, SC and ST are all examples of physically contacting (PC) connectors. Physically contacted is where the fiber ends are mated in physical contact with each other.



Physical Contact Connectors



PC Connectors Prior to Mating

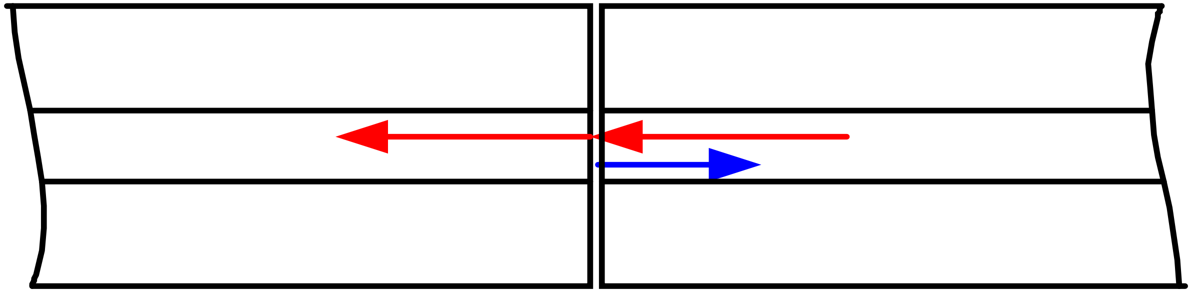


PC Connectors After Mating

- Physical Contact connectors are polished with a convex shape that is meant to slightly deform when two connectors are brought together.

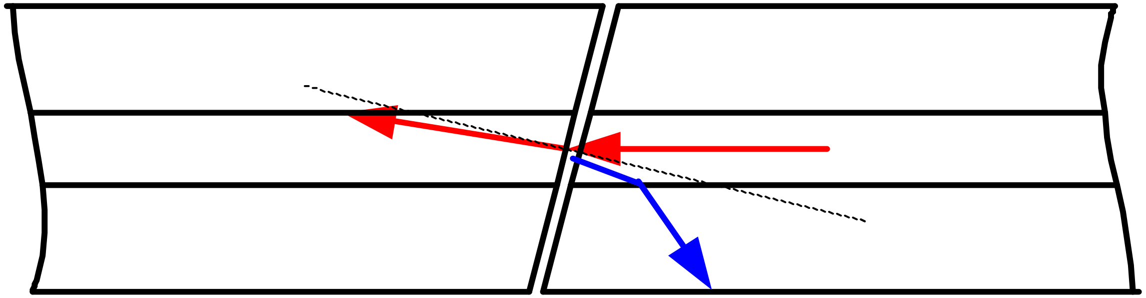
UPC Ferrule Configuration

- Ultra Polished connectors (UPC) have a flat end surface where both the ceramic and fiber are polished to the same plain.
- The UPC connector provides very low insertion losses, however, whatever light is reflected will propagate back toward the source.
- UPC connectors are typically used near receivers, since and back reflections will be attenuated as they propagate back through the fiber.



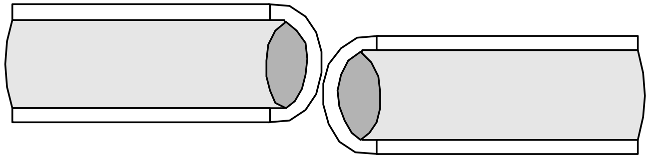
APC Ferrule Configuration

- Angled Polished connectors (APC) are polished with an 8° end surface angle.
- The APC has slightly higher insertion losses than the UPC style, however the angled end directs back reflections into the cladding.
- APC connectors are typically used near sources (i.e. transmitters or EDFAs) where back reflections will quickly reduce system performance.

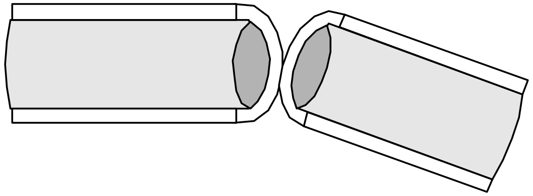


Common Connector Faults

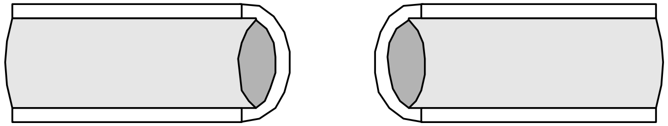
Lateral Offset



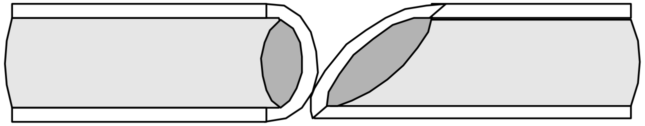
Angular Misalignment



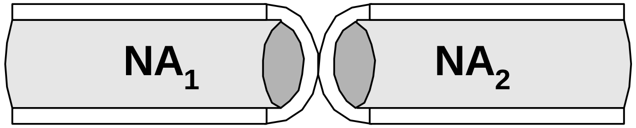
End Separation



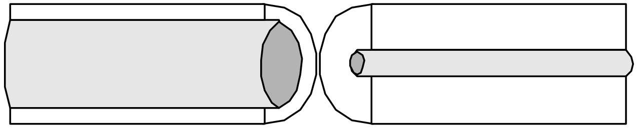
Angular Misalignment



Numerical Aperture Mismatch



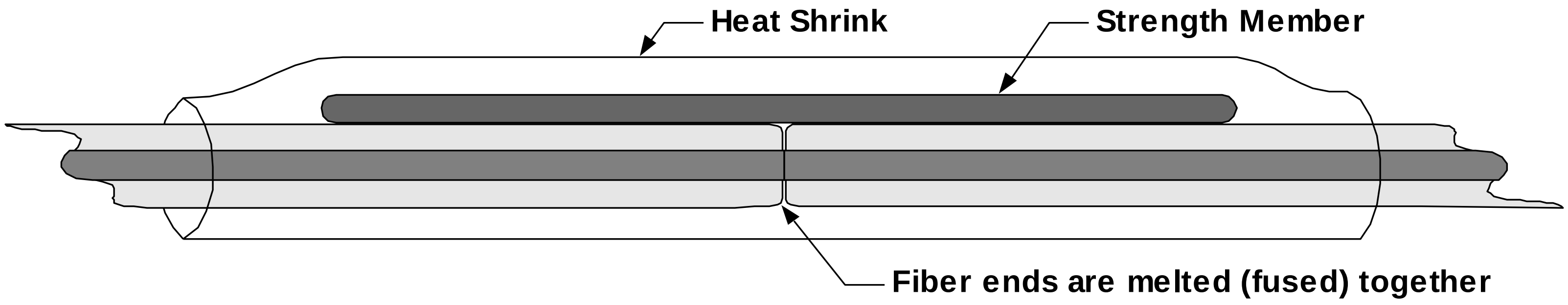
Core Diameter Mismatch



- Angular misalignment caused by mating an APC connector to a UPC connector is extremely common and will cause approximately 3-5 dB of attenuation.

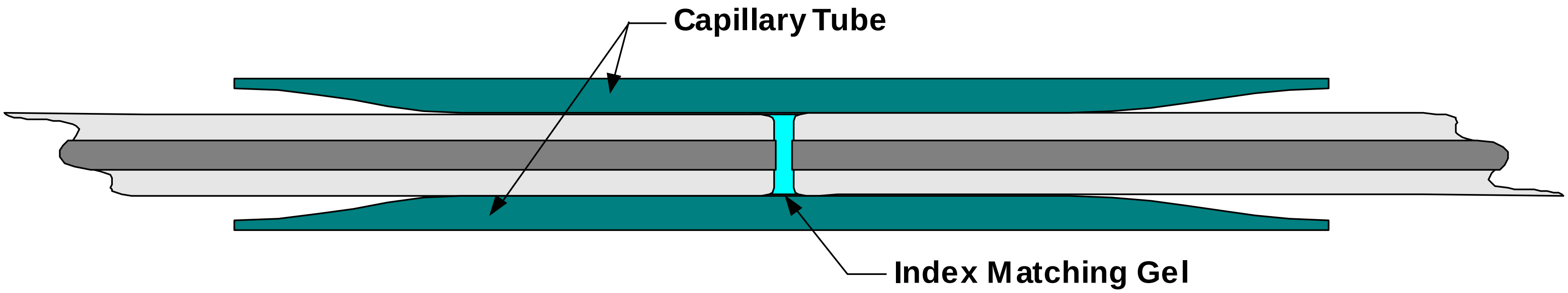
Fusion Splices

- Fusion splices are created by heating both fiber ends with a high current electric arc and then bringing them into contact with one another.
- Fusion splices are permanent and have extremely low loss
- Splice loss is typically 0.02db
- Fusion Splice equipment is expensive and can be difficult to use in the field



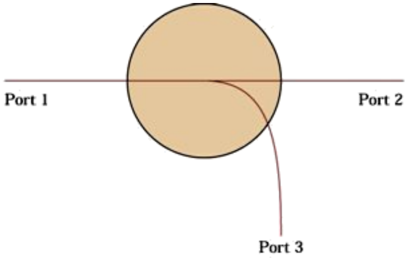
Mechanical Splices

- Fiber ends are butted together and mechanically locked into place in a funneled capillary.
- Inside the tube is a small amount of Index Matching Gel that reduces the amount of reflection at the fiber ends interface.
- Mechanical Splices can be permanent or reusable, but splice loss is typically 0.1db to 0.2db and degrades with each use.
- Splice tubes are less than $10.00

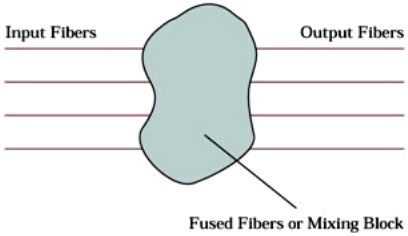


Optical Couplers and Switches

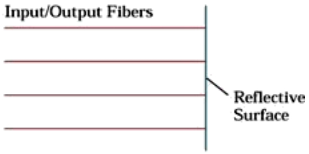
- As with coaxial cable and microwave waveguides, it is possible to build power splitters and directional couplers for fiber-optic systems
- It is more complex and expensive to do this with fiber than with copper wire
- Optical couplers are categorized as either star couples with multiple inputs and outputs or as tees, which have one input and two outputs



(a) Schematic representation of directional coupler



(b) Transmissive



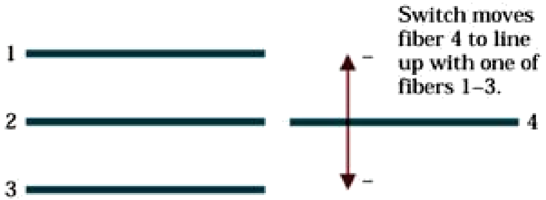
(c) Reflective

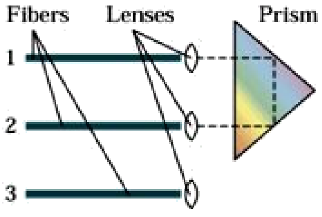
Coupler Construction

- Optical couplers can be made in many different ways:
  - A number of fibers can be fused together to make a transmissive coupler
  - A reflective coupler allows a signal entering on any fiber to exit on all other fibers, so the coupler is bidirectional

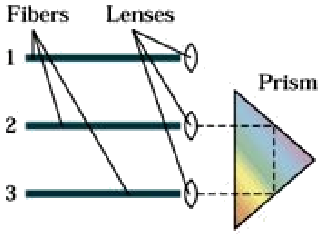
Optical Switches and Relays

- Occasionally, it is necessary to switch optical signals from one fiber to another
- The simplest type of optical switch moves fibers so that an input fiber can be positioned next to the appropriate output fiber
- Another approach is direct the incoming light into a prism, which reflects it into the outgoing fiber. By moving the prism, the light can be switched between different output fibers
- Lenses are necessary with this approach to avoid excessive loss of light





Ports 1 and 2 connected together



Ports 2 and 3 connected together

Don’t Mix Fiber Types

- You can’t mix singlemode and multimode fiber – you lose 20 dB at the junction (99% of the light!)
- Mixing 50 micron and 62.5 micron multimode is not as bad, but you lose 3 dB (half the power) which is usually unacceptable

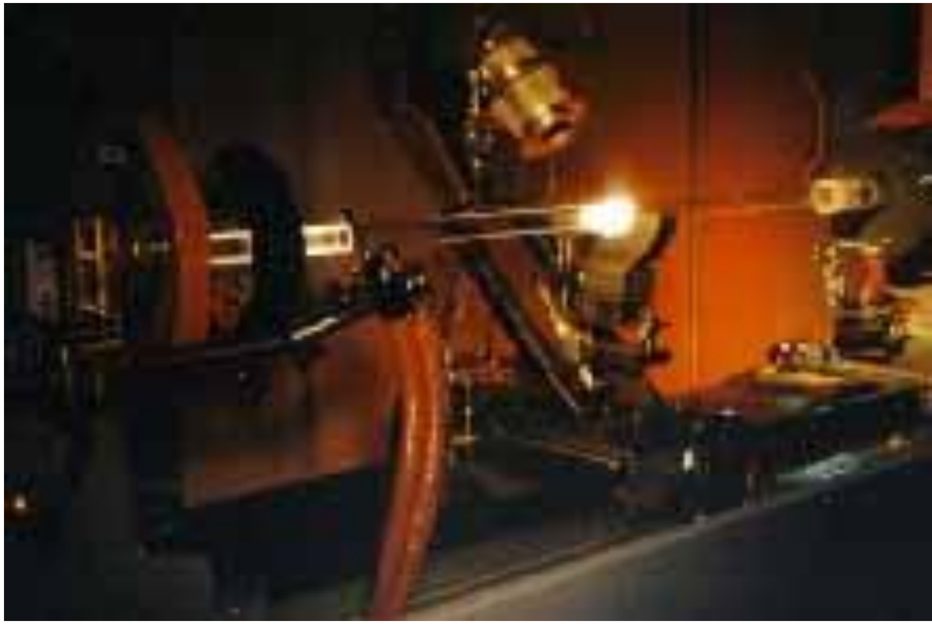
Fiber Manufacture

Three Methods

- Modified Chemical Vapor Deposition (MCVD)
- Outside Vapor Deposition (OVD)
- Vapor Axial Deposition (VAD)

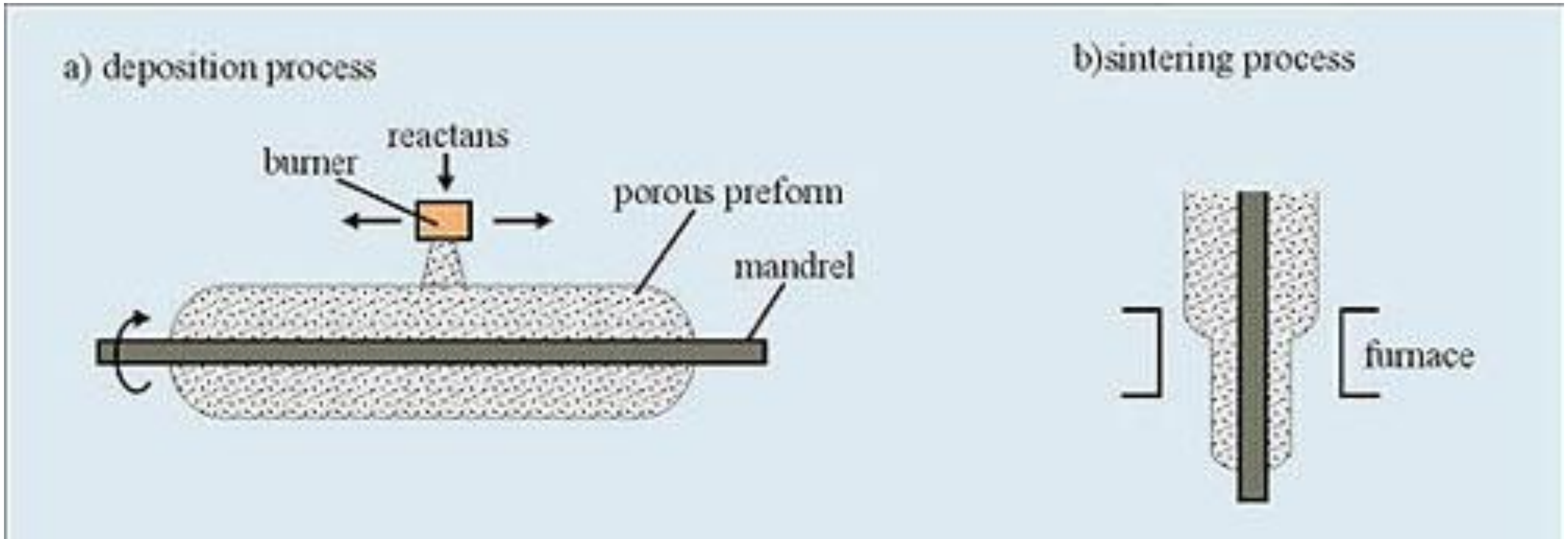
Modified Chemical Vapor Deposition (MCVD)

- A hollow, rotating glass tube is heated with a torch
- Chemicals inside the tube precipitate to form *soot*
- Rod is collapsed to crate a *preform*
- Preform is stretched in a *drawing tower* to form a single fiber up to 10 km long



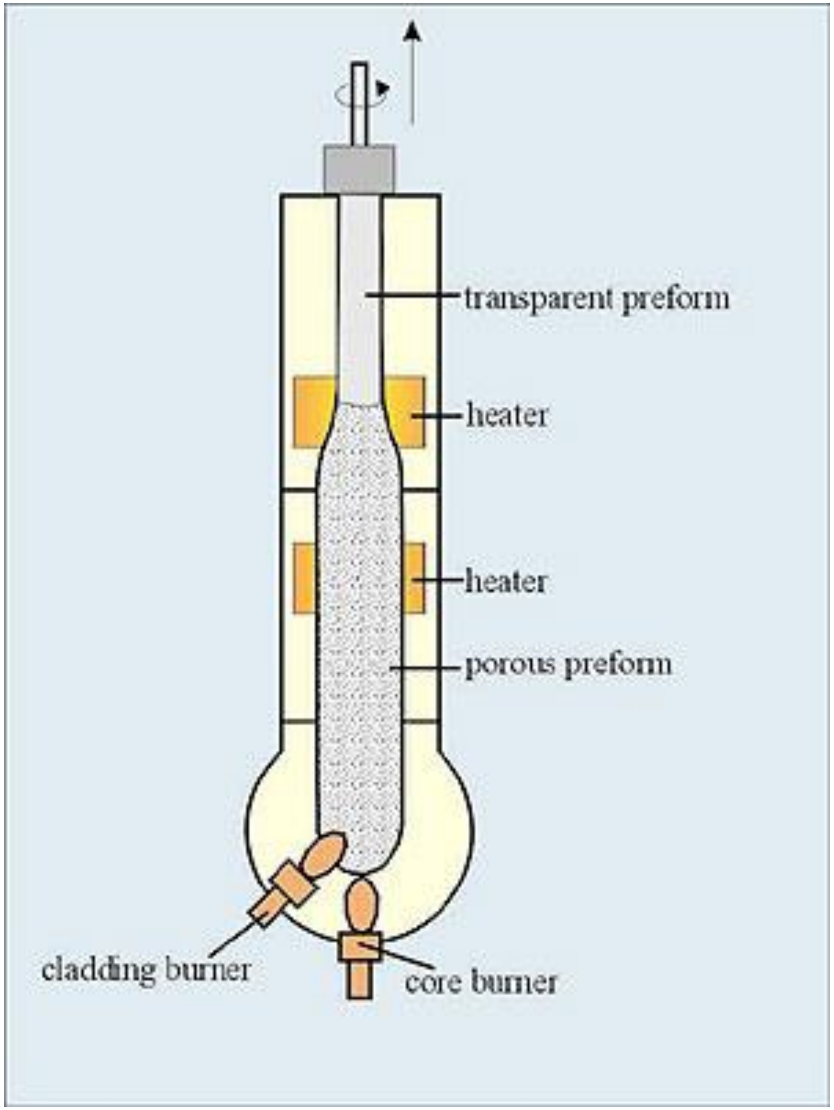
Outside Vapor Deposition (OVD)

- A mandrel is coated with a porous preform in a furnace
- Then the mandrel is removed and the preform is collapsed in a process called *sintering*
  - Image from csrg.ch.pw.edu.pl



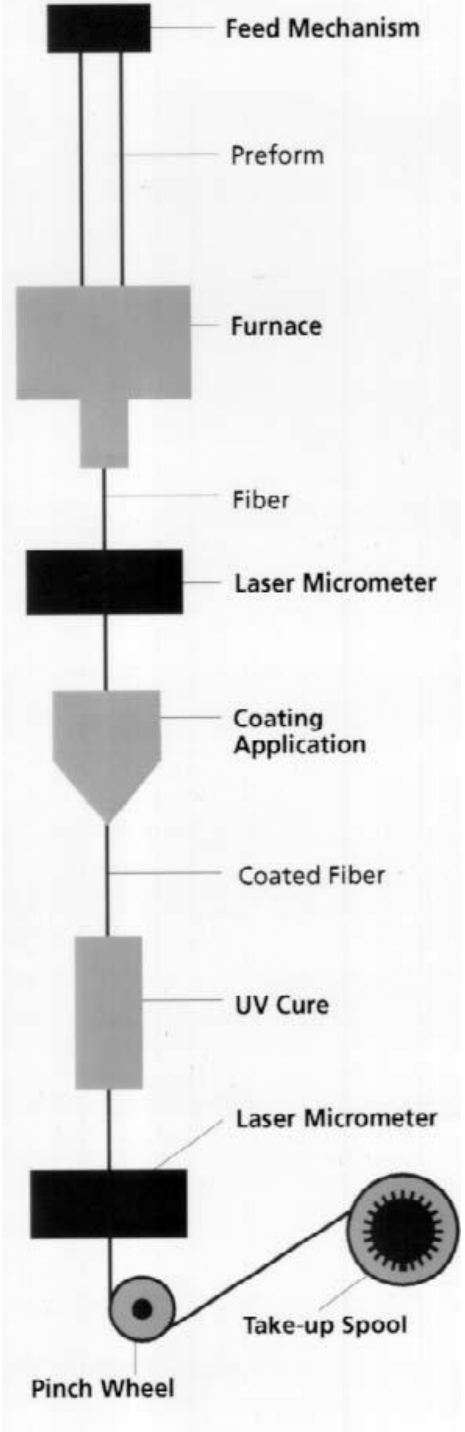
Vapor Axial Deposition (VAD)

- Preform is fabricated continuously
- When the preform is long enough, it goes directly to the drawing tower
  - Image from csrg.ch.pw.edu.pl



Drawing

- The fiber is drawn from the preform and then coated with a protective coating



Index of Refraction

- When light enters a dense medium like glass or water, it slows down
- The index of refraction (n) is the ratio of the speed of light in vacuum to the speed of light in the medium
- Water has n = 1.3
  - Light takes 30% longer to travel through it
- Fiber optic glass has n = 1.5
  - Light takes 50% longer to travel through it

Fiber Applications

Step-index Multimode

- Large core size, so source power can be efficiently coupled to the fiber
- High attenuation (4-6 dB / km)
- Low bandwidth (50 MHz-km)
- Used in short, low-speed datalinks
- Also useful in high-radiation environments, because it can be made with pure silica core

Graded-index Multimode

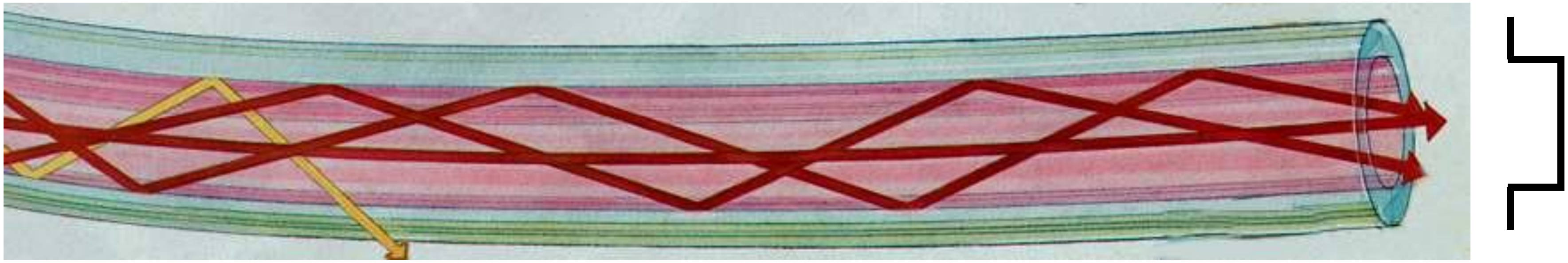
- Useful for “premises networks” like LANs, security systems, etc.
- 62.5/125 micron has been most widely used
  - Works well with LEDs, but cannot be used for Gigabit Ethernet
- 50/125 micron fiber and VSELS are used for faster networks

Three Types of Dispersion

- Dispersion is the spreading out of a light pulse as it travels through the fiber
- Three types:
  - Modal Dispersion
  - Chromatic Dispersion
  - Polarization Mode Dispersion (PMD)

Modal Dispersion

- Modal Dispersion
  - Spreading of a pulse because different modes (paths) through the fiber take different times
  - Only happens in multimode fiber
  - Reduced, but not eliminated, with graded-index fiber



Chromatic Dispersion

- Different wavelengths travel at different speeds through the fiber
- This spreads a pulse in an effect named *chromatic dispersion*
- Chromatic dispersion occurs in both singlemode and multimode fiber
  - Larger effect with LEDs than with lasers
  - A far smaller effect than modal dispersion

Polarization Mode Dispersion

- Light with different polarization can travel at different speeds, if the fiber is not perfectly symmetric at the atomic level
- This could come from imperfect circular geometry or stress on the cable, and there is no easy way to correct it
- It can affect both singlemode and multimode fiber.

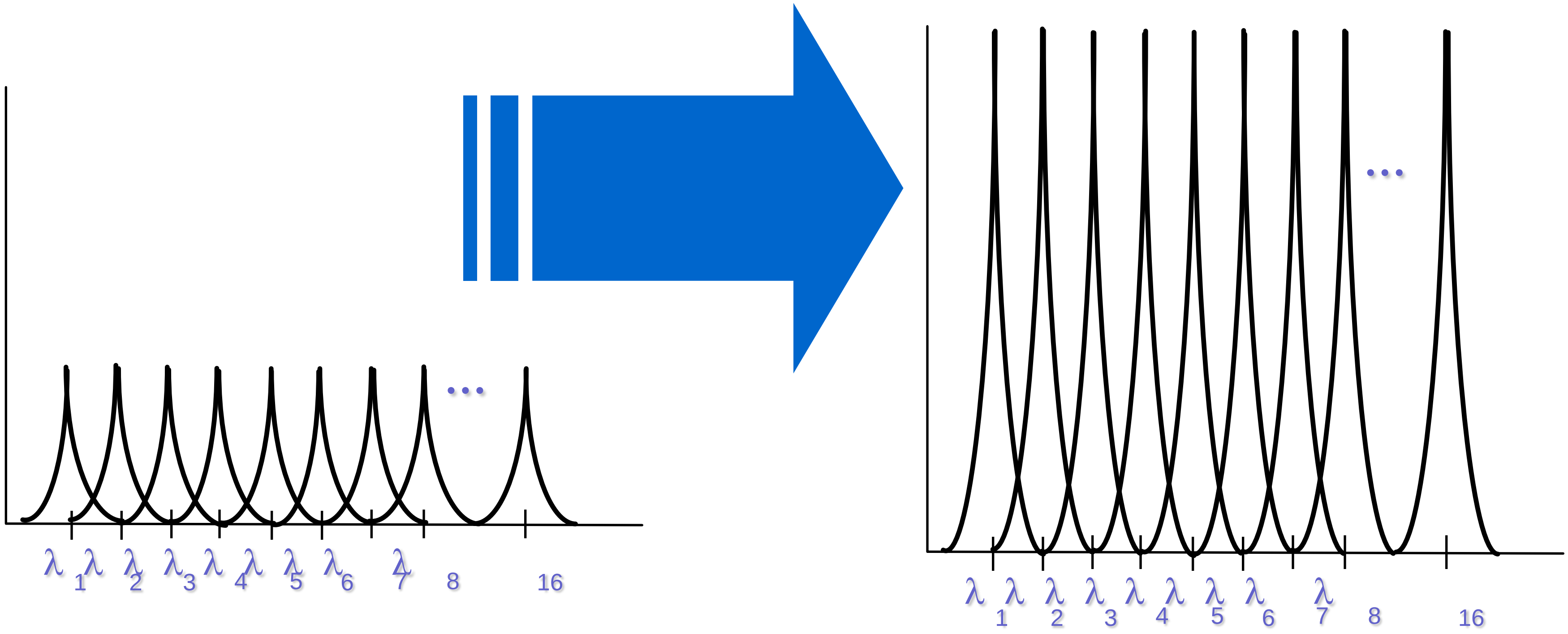
Modal Distribution

- In graded-index fiber, the off-axis modes go a longer distance than the axial mode, but they travel faster, compensating for dispersion
  - But because the off-axis modes travel further, they suffer more attenuation

Equilibrium Modal Distribution

- A long fiber that has lost the high-order modes is said to have an *equilibrium modal distribution*
- For testing fibers, devices can be used to condition the modal distribution so measurements will be accurate

Optical Line Amplification

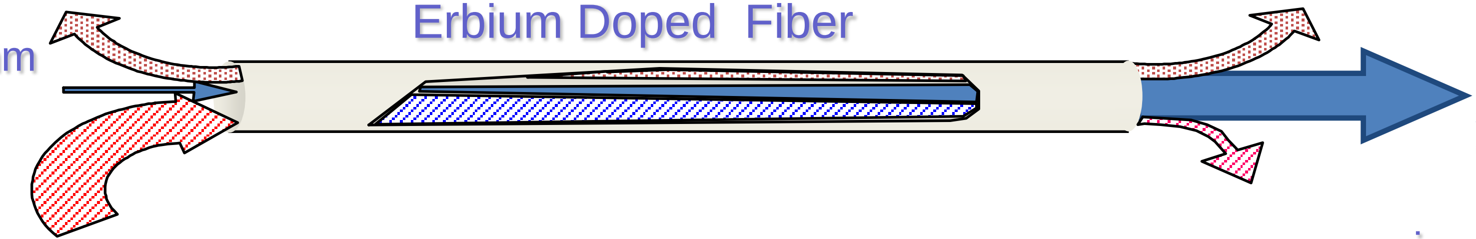


Attenuated Channels

Amplified Channels

All Wavelengths Amplified with One Amplifier

EDFA Operation



amplified
spontaneous
emissions

amplified
spontaneous
emissions

Erbium Doped Fiber

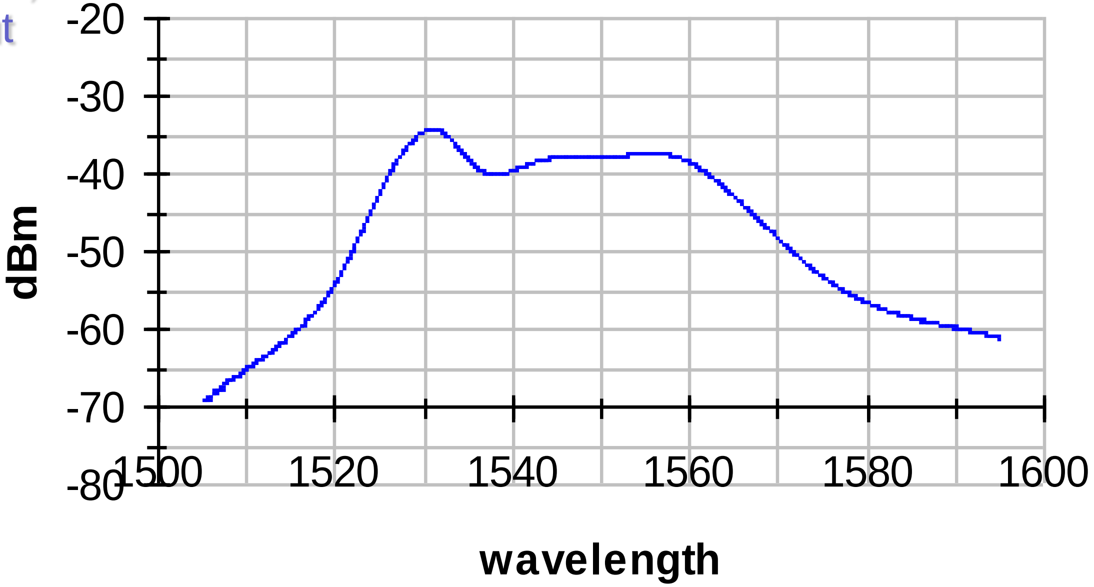
1550 nm
band
signal
input

1550 nm
band
signal
output

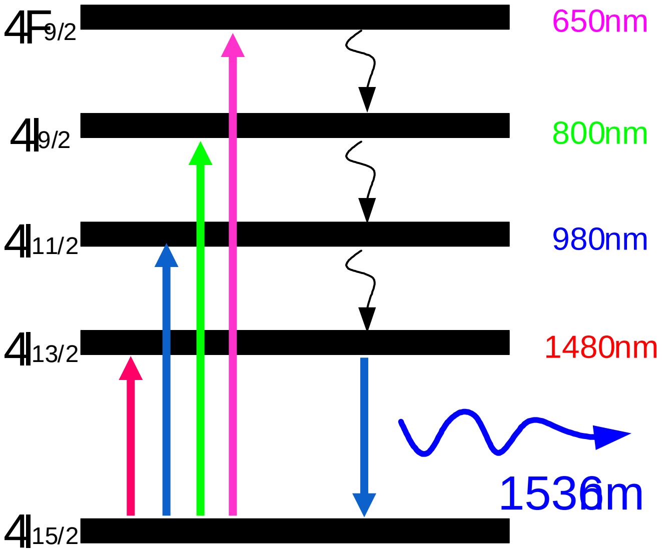
(980 and 1480 nm)
pump signal input

pump signal output
(980 and 1480 nm)

Spectrum of a typical EDFA



EDFA Operation

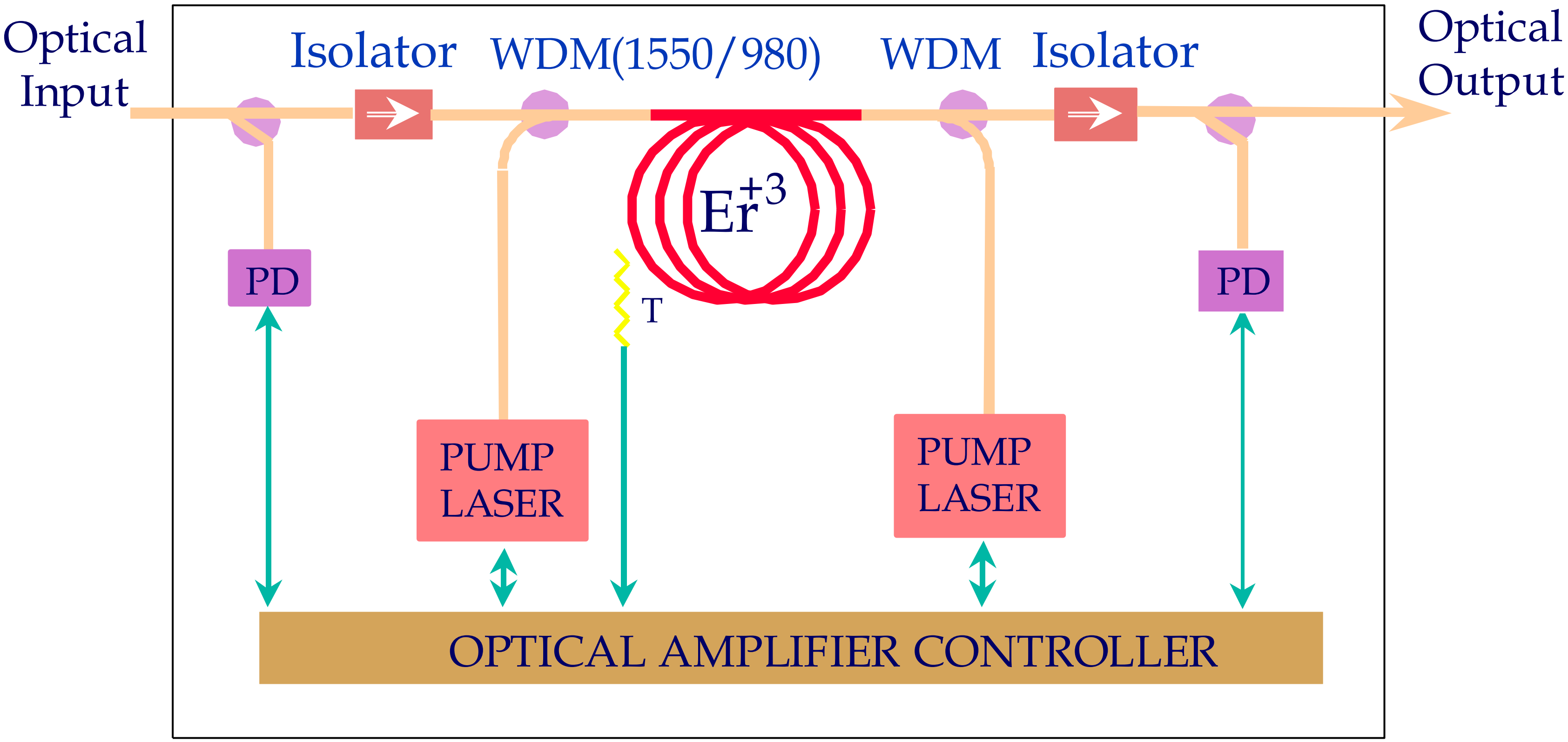


- Pump lasers (typically 980nm and 1480nm) are used to excite the Erbium doped fiber to a higher energy state.

- Pump lasers (typically 980nm and 1480nm) are used to excite the Erbium doped fiber to a higher energy state.

- The Erbium fiber resides in the 4I-13/2 state until triggered by a passing 1550nm photon, at which time a duplicate photon is released.

EDFA



- Erbium Doped Fiber Amplifiers (EDFAs) are the amplification device most commonly used in fiber systems.

Decibel Units

Optical Loss in dB (decibels)

Power In

Data Link

Power Out

- If the data link is perfect, and loses no power
  - The loss is 0 dB
- If the data link loses 50% of the power
  - The loss is 3 dB, or a change of – 3 dB
- If the data link loses 90% of the power
  - The loss is 10 dB, or a change of – 10 dB
- If the data link loses 99% of the power
  - The loss is 20 dB, or a change of – 20 dB

$$\text{dB} = 10 \log (\text{Power Out} / \text{Power In})$$

Absolute Power in dBm

- The power of a light is measured in milliwatts
- For convenience, we use the dBm units, where

  -20 dBm = 0.01 milliwatt

  -10 dBm = 0.1 milliwatt

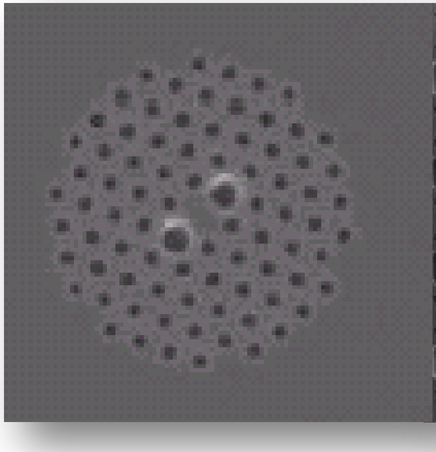
  0 dBm = 1 milliwatt

  10 dBm = 10 milliwatts

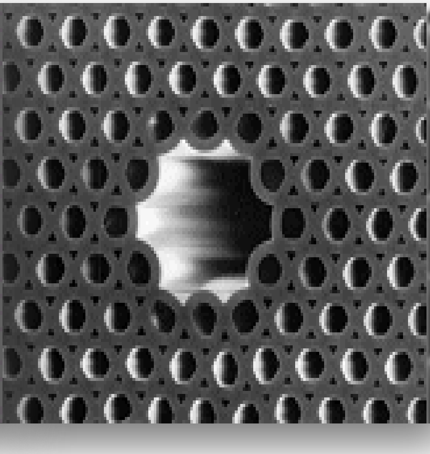
  20 dBm = 100 milliwatts

Photonic Crystal Fibers

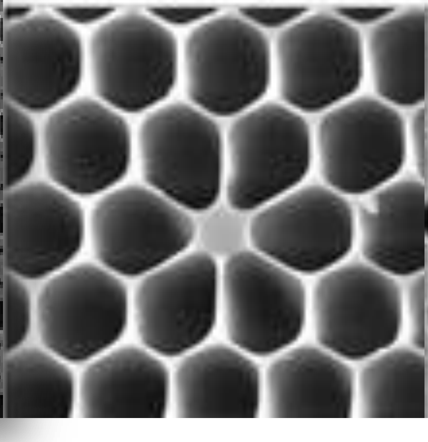
- 2-D photonic crystal with defect near the core region along the fiber axis
- Structure made of one type of glass with the matrix of periodically placed micro-chanels forming a photonic crystal structure.



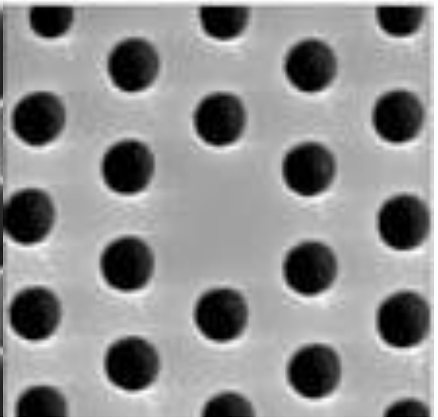
birefringent



Hollow-core



nonlinear



isotropic