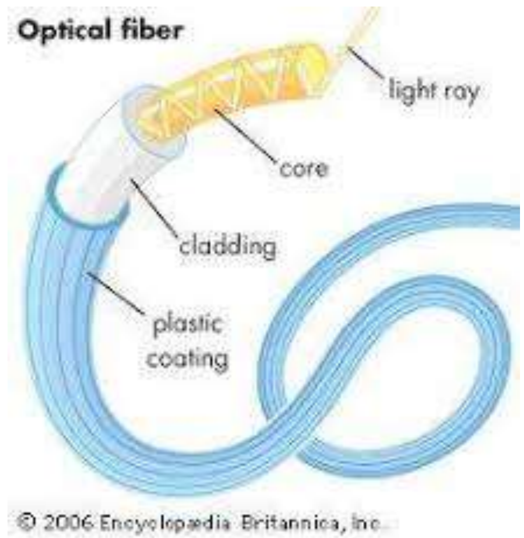
FIBER OPTICS MODULE 6

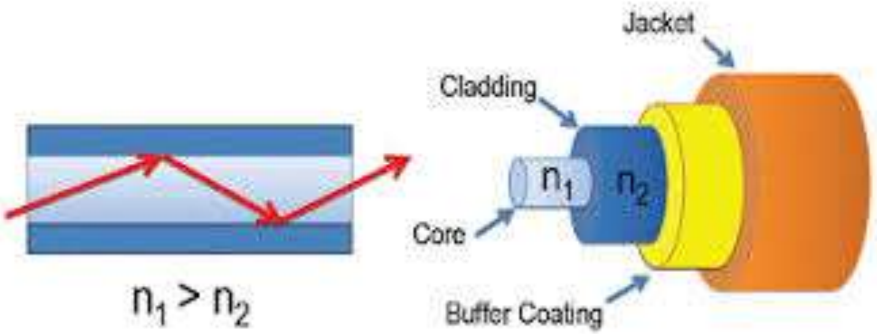
Tarun Garg
Assistant Professor
Dept. of Physics
VIT Vellore

OPTICAL FIBRE

- An optical fibre is a cylindrical dielectric waveguide made of low-loss materials such as silica glass.

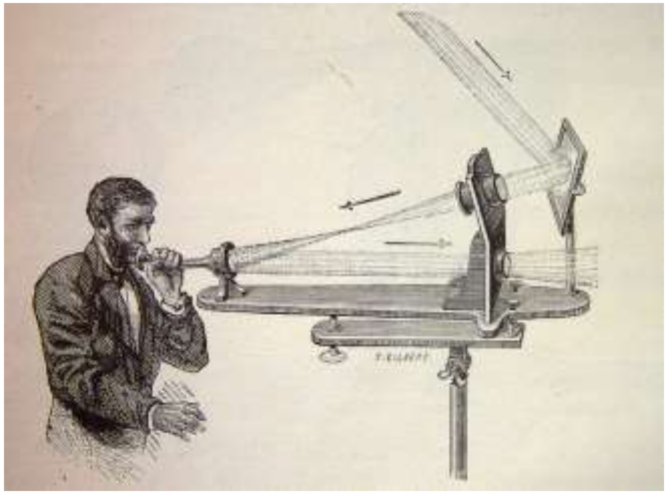


- It has a central core in which the light is guided, embedded in an outer cladding of slightly lower refractive index .



Optical Communications

- ✓ Photophones were invented in 1880 by Bell Labs for speech transmission over a distance of 200 m.
- ✓ In the early part of 20^{th} century the use of optical communications was limited to low capacity communication links.
- ✓ Lack of suitable light sources. Light transmission in atmosphere is restricted to line of sight and is severely affected by disturbances such as rain, fog, dust etc. Low frequency (longer wavelength) EM waves (radio and micro waves) are least affected by these disturbances.



Photophone transmitter

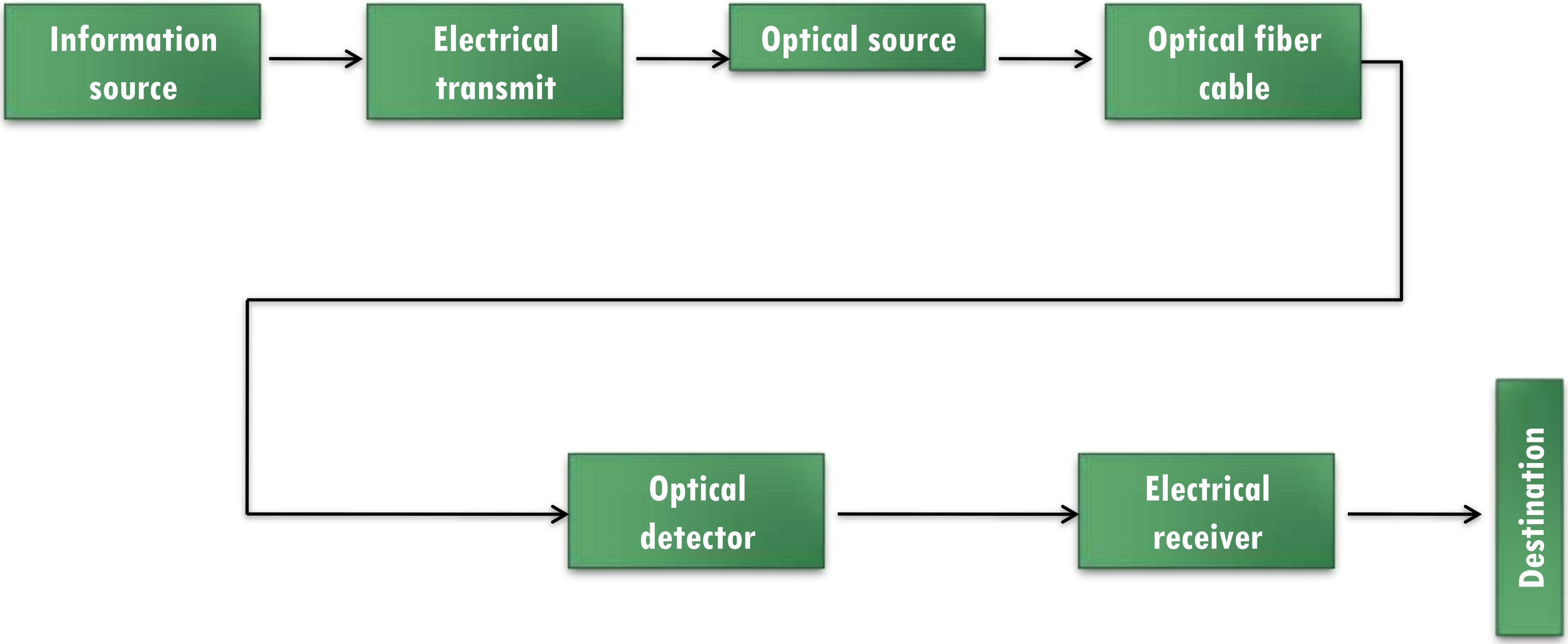
Photophone receiver

✓But these are limited in the information amount. Theoretically, greater the carrier frequency, larger is the available transmission bandwidth and thus the information carrying capacity.

✓Renewed interest in optical communication was stimulated in early 1960s after the invention of lasers. (Powerful Coherent light source)

The proposals for optical communication via dielectric waveguides or optical fibers fabricated from glass to avoid degradation of optical signal by atmosphere was simultaneously given by Kao and Hockham and Werts in 1966.

Schematic of Optical Fibre Communications



Advantages of Optical Fiber Communications

- ✓ **Enormous potential bandwidth:** Optical carrier frequency in the range of 10^{13} to 10^{16} Hz yields a far greater potential transmission bandwidth than metallic cable systems (500 MHz)
- ✓ **Small size and weight:** Diameters no greater than a human hair
- ✓ **Electrical isolation:** Made up of glass and plastic polymers and hence no earthing problem.
- ✓ **Immunity to interference and crosstalk**
- ✓ **Signal security**
- ✓ **Low transmission loss:** 0.2 dB/km
- ✓ **Ruggedness, flexibility and potential low cost**

FIBER TYPES

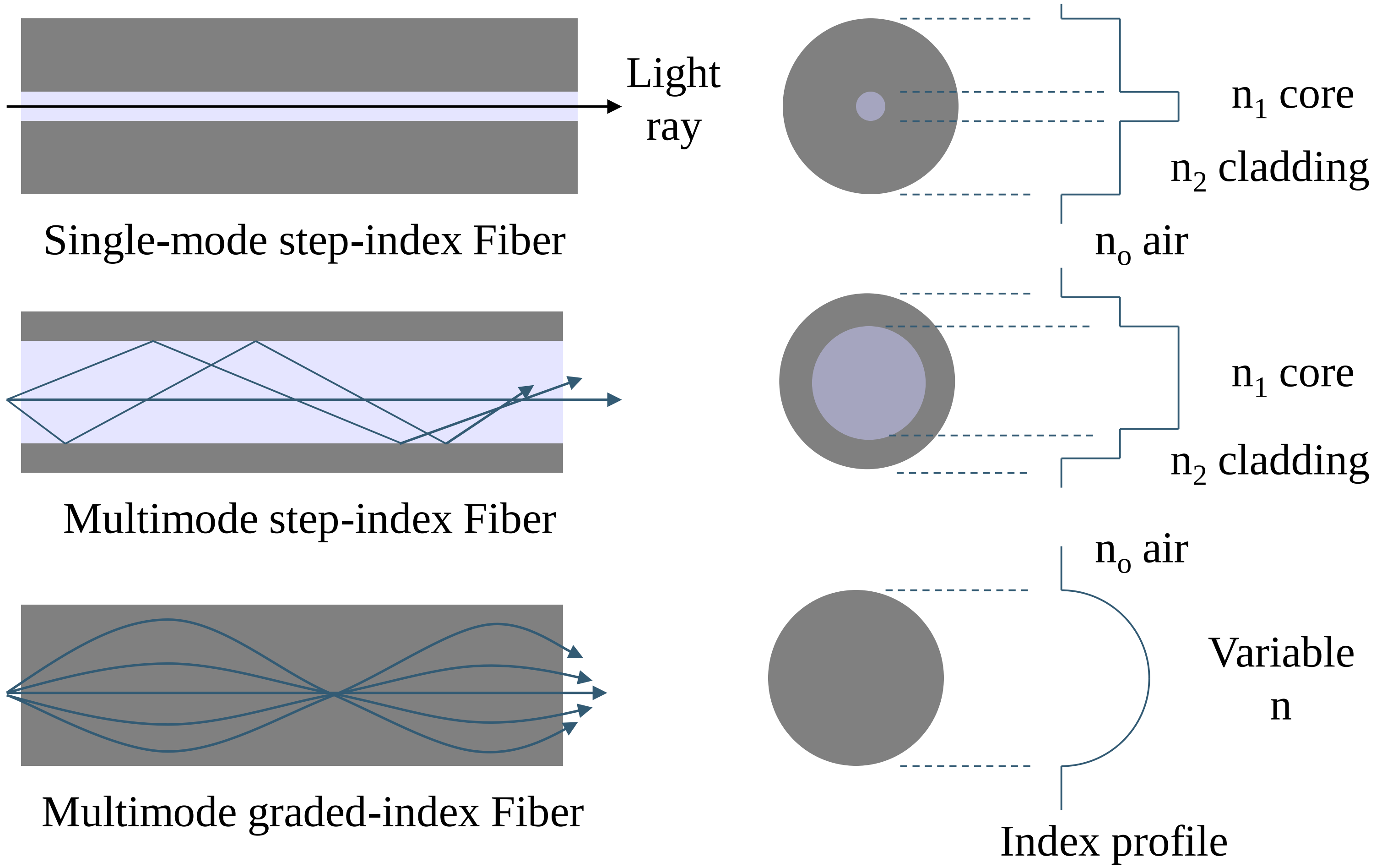
Based on No. of modes of operation (the path which the light is traveling on)

- Single Mode
- Multi Mode

Index profile

- Step
- Graded

TYPES OF OPTICAL FIBER



SINGLE-MODE STEP-INDEX FIBER

Advantages:

- Minimum dispersion: all rays take same path, same time to travel down the cable. A pulse can be reproduced at the receiver very accurately.
- Less attenuation, can run over longer distance without repeaters.
- Larger bandwidth and higher information rate

Disadvantages:

- Difficult to couple light in and out of the tiny core
- Highly directive light source (laser) is required
- Interfacing modules are more expensive

MULTI MODE

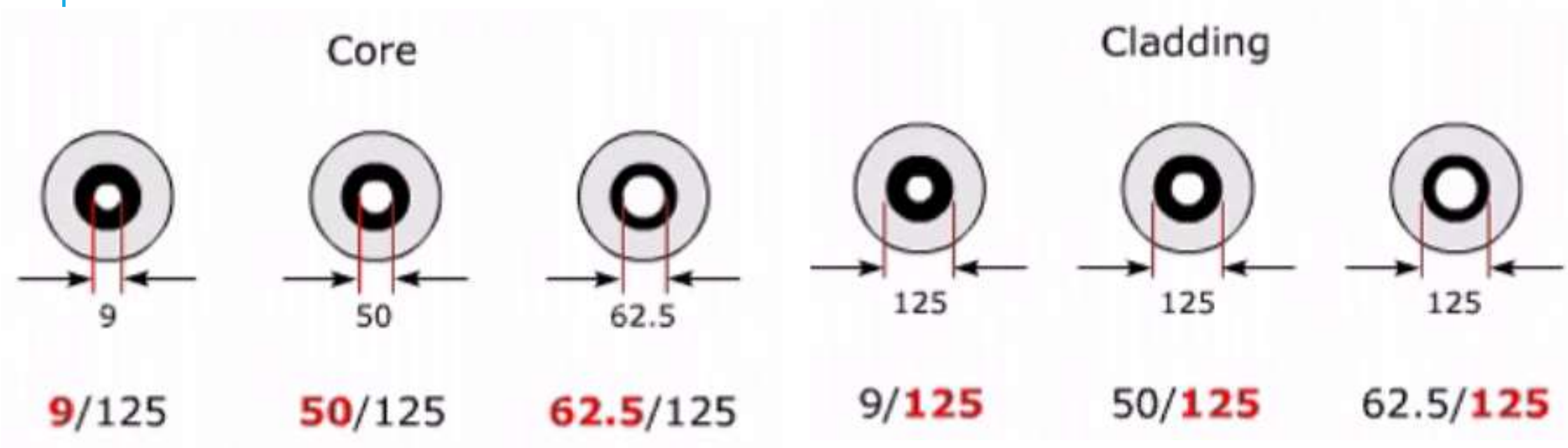
Multimode step-index Fibers:

- inexpensive
- easy to couple light into Fiber
- result in higher signal distortion

Multimode graded-index Fiber:

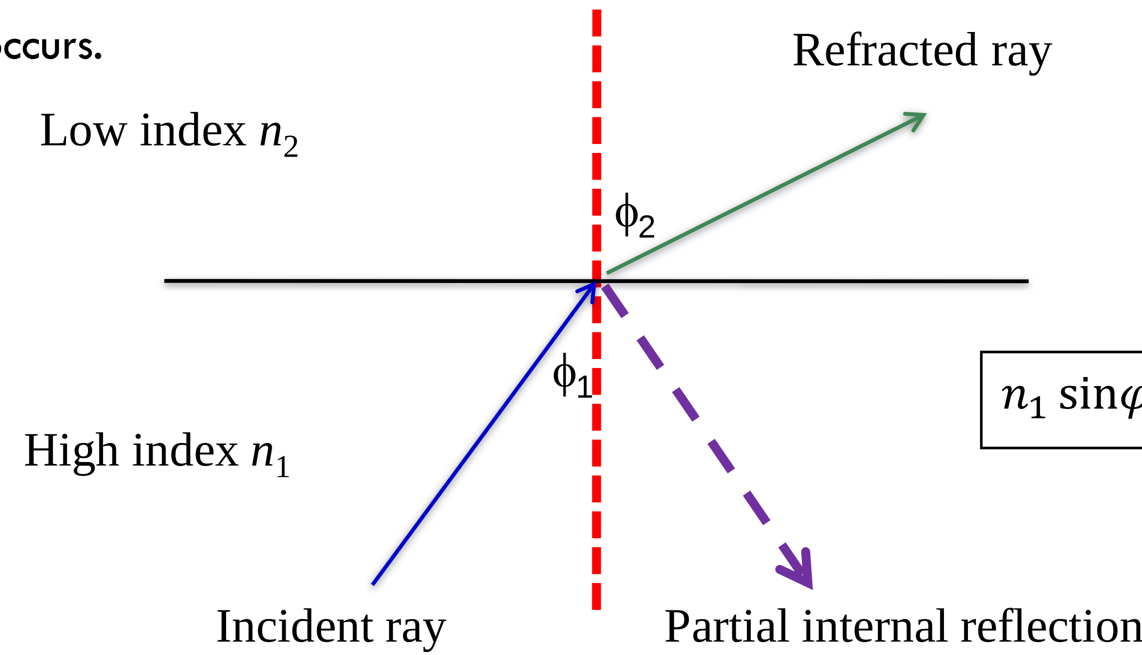
- intermediate between the other two types of Fibers

WHAT DO THE FIBER TERMS 9/125, 50/125 AND 62.5/125 (MICRON)?



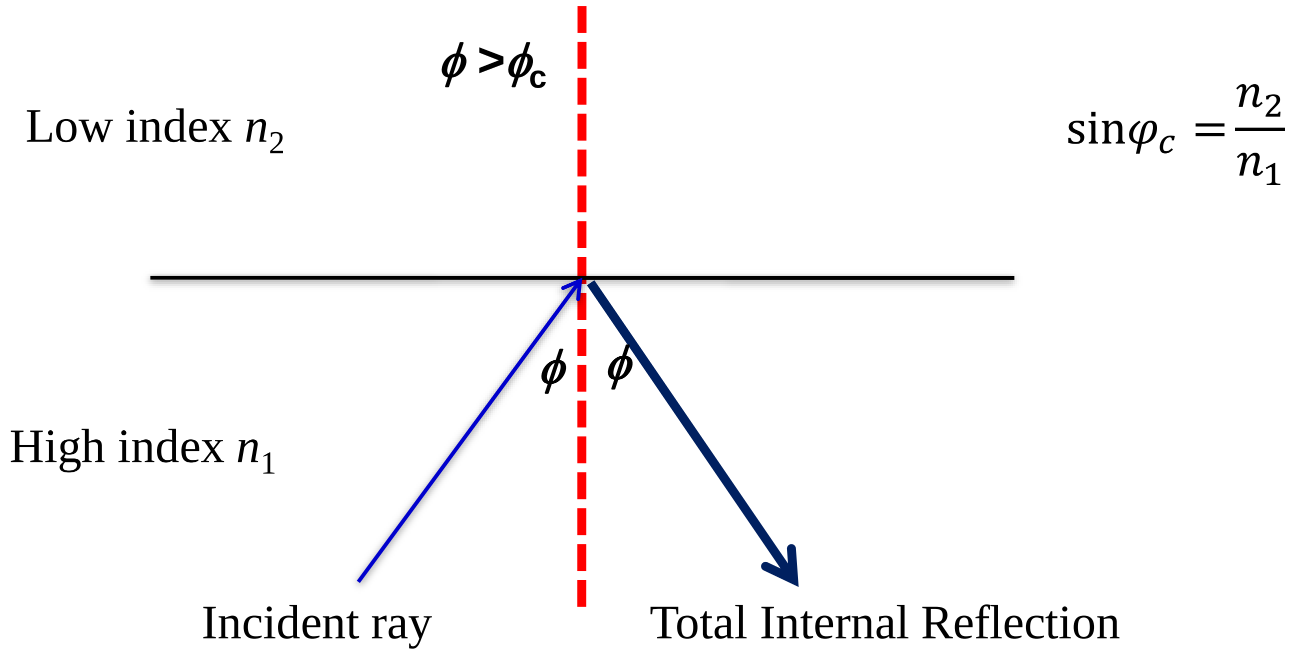
Basic Principle for Optical Fiber Communications

The basic principle for light propagation in an optical fiber is **Total Internal Reflection**. Electromagnetic waves travel slowly in an optically dense medium compared to that of a rarer medium. Light propagation in a medium depends on its **refractive index** which is the ratio of speed of light in vacuum to the speed of light in the medium. When a ray is incident on the interface between two dielectrics of differing refractive indices **refraction** occurs.

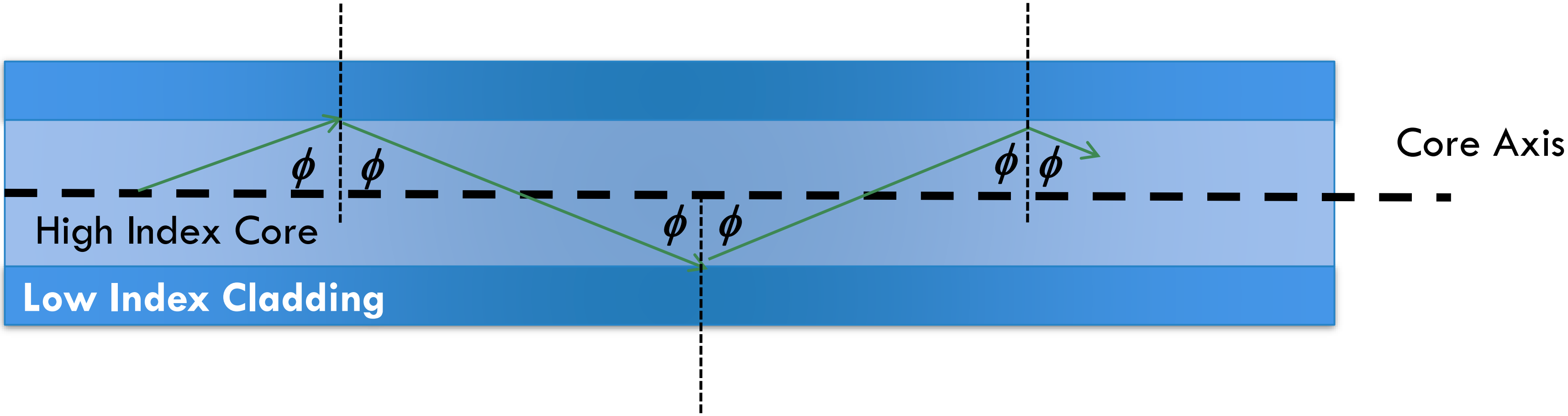


$$n_1 \sin\varphi_1 = n_2 \sin\varphi_2$$

As n_1 is greater than n_2, the angle of refraction is always greater than the angle of incidence. Thus, when the angle of refraction is 90° and the refracted ray emerges parallel to the interface between the dielectrics the angle of incidence must be less than 90°. This is the limiting case of refraction and the angle of incidence is now known as critical angle ϕ_c.

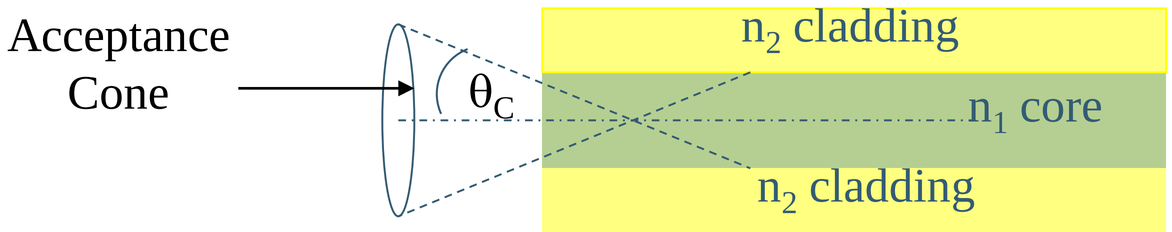


Transmission of light ray in a perfect optical fiber



Any discontinuities or imperfections at the core-cladding interface would result in refraction rather than total internal reflection.

ACCEPTANCE CONE & NUMERICAL APERTURE

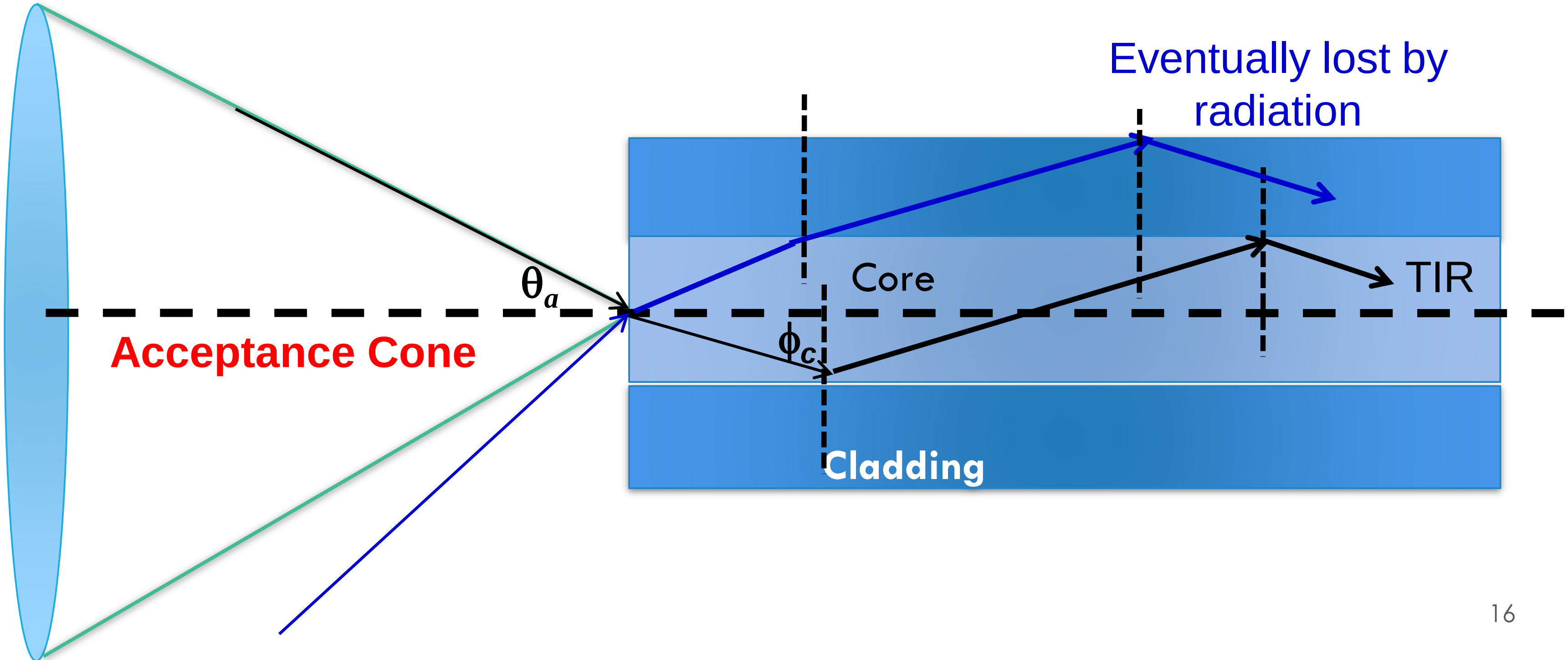


-If the angle too large → light will be lost in cladding

-If the angle is small enough → the light reflects into core and propagates

Acceptance angle

Only rays with a sufficiently shallow grazing angle (i.e. with an angle to the normal greater than ϕ_c) at the core cladding interface are transmitted by total internal reflection. Hence, not all rays entering the fiber core will continue to be propagated down its length.



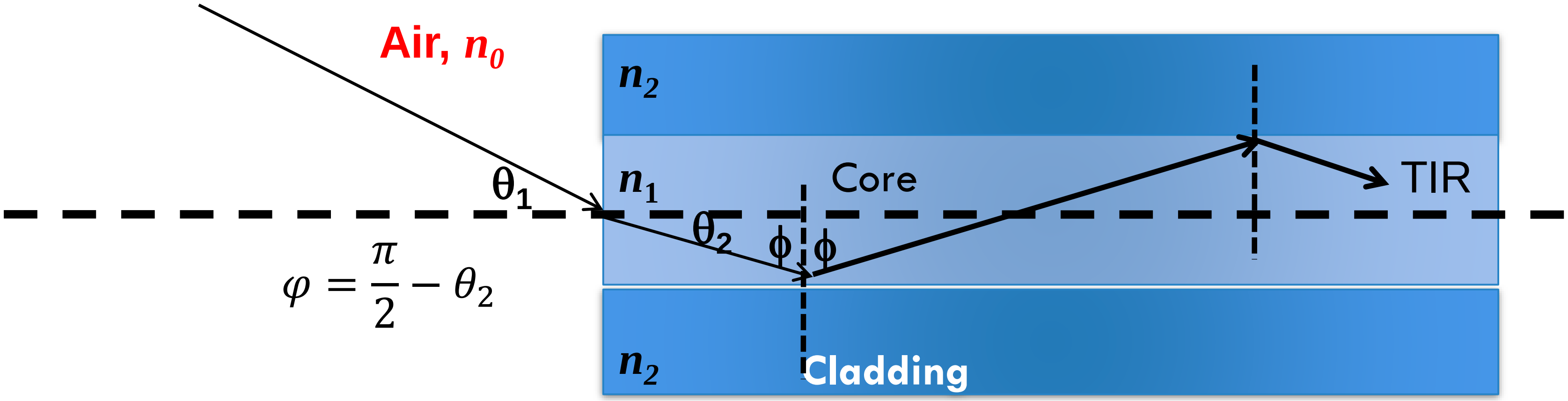
Acceptance angle

- Any rays which are incident on into the fiber core at an angle greater than θ_a will be transmitted to the core-cladding interface at an angle less than ϕ_c and will not be totally internally reflected.

- Thus, for rays to be transmitted by total internal reflection within the fiber core they must be incident on the fiber core within an acceptance cone defined by the conical half angle θ_a.

- Hence, θ_a is the maximum angle to the axis at which light may enter the fiber in order to be propagated and is often referred to as the acceptance angle for the fiber.

Relation between acceptance angle and refractive index is achieved through **Numerical Aperture**



Using Snell's law to the refraction at the air-core interface,

$$n_0 \sin\theta_1 = n_1 \sin\theta_2$$

Here, ϕ is greater than the critical angle at the core-cladding interface.

$$n_0 \sin\theta_1 = n_1 \cos\varphi = n_1\sqrt{1 - \sin^2\varphi}$$

Consider the limiting case for total internal reflection.

- ✓ ϕ becomes equal to the critical angle for the core-cladding interface.
- ✓ θ_1 becomes equal to the acceptance angle for the fiber.

$$n_0 \sin\theta_a = \sqrt{n_1^2 - n_2^2}$$

$$NA = n_0 \sin\theta_a = \sqrt{n_1^2 - n_2^2}$$

Numerical aperture (NA) may also be given in terms of the relative refractive index difference Δ between the core and the cladding which is defined as:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \approx \frac{n_1 - n_2}{n_1}$$

For Δ <<1

$$(n_1^2 - n_2^2) = 2n_1^2\Delta$$

Therefore

$$NA = \sqrt{2n_1^2\Delta}$$

$$NA = n_1\sqrt{2\Delta}$$

V-NUMBER OR NORMALIZED FREQUENCY

V – number determines how many modes a fiber can support, It is given by,

$$V = \frac{\pi d}{\lambda} NA$$

where d is the diameter of the core, λ is the wavelength of light used and NA is the numerical aperture of the fibre.

$$V = \frac{\pi d}{\lambda} \sqrt{n_1^2 - n_2^2}$$

or

$$V = \frac{\pi d}{\lambda} n_1 \sqrt{2\Delta}$$

If V < 2.405, then the fibre is single mode fibre (SMF)

If V > 2.405, then the fibre is multimode fibre (MMF)

V = 2.405 corresponds to cut off wavelength, λ_c

CONT'D...

The total number of modes traveling in a fibre depends on the V– Number and is related as:

For Step Index Fibre:

$$N = \frac{V^2}{2}$$

For Graded Index Fibre:

$$N = \frac{V^2}{4}$$

PROBLEMS BASED ON NA, ACCEPTANCE ANGLE AND V-NUMBER

1. The core diameter of a multimode step index fibre is 60 μm. The relative refractive index difference is 0.013. The core refractive index is 1.46. Determine the number of guided modes when the operating wavelength is 0.75 μm.

2. Determine V-number for a step index fibre having a 0.25 micrometer core radius and n_1=1.48, n_2=1.46. How many modes propagates in this fibre if operated at 0.82 μm wavelength.

3. A single mode fibre is made with a core diameter of 10 μm and is coupled to a laser light of wavelength 1.3 μm. Its core glass has refractive index of 1.55. Calculate

   a) the refractive index of cladding

   b) acceptance angle

Transmission Characteristics

- ❖ The transmission through an optical fiber is limited by attenuation (or loss) and dispersion.
- ❖ In 1970s, it was realized that the attenuation was largely due to absorption in the glass caused by impurities such as iron, copper, manganese etc. Hence, research was stimulated towards a new generation of “pure” glasses for use in optical fiber communication. It lead to silica based glass fibers with losses less than 0.2 dB/km.
- ❖ The other characteristic is bandwidth which is mostly limited by signal dispersion within the fiber. It determines the number of bits of transmission transmitted in a given time period.

Attenuation

- Attenuation determines the maximum transmission distance prior to signal restoration. OFC became especially attractive when the transmission losses of fibers were reduced below those of the competing metallic conductors. (< 5 db/km)
- Signal attenuation in optical fibers (or that of metallic cable) is usually expressed in the units of decibel. Decibel is used for comparing two power levels.

$$dB = 10\log_{10}\frac{P_i}{P_o}$$

For a particular optical wavelength,

P_i → input (transmitted) optical power

P_o → output (received) optical power

In OFC, attenuation is usually expressed in dB per unit length (dB/km)

$$\alpha_{dB}L = 10\log_{10}\frac{P_i}{P_o}$$

α_{dB} → signal attenuation/length

L → Fiber length

MATERIAL ABSORPTION LOSSES IN SILICA GLASS FIBERS

❖ This loss mechanism is related to material composition and the fabrication process for the fiber. Absorption of light may be :

Intrinsic: caused by the interaction with one or more of the major components of the glass

Extrinsic: caused by impurities within the glass

Intrinsic absorption

- Pure silica-based glass has *two* major intrinsic absorption mechanisms at optical wavelengths:

(1) a *fundamental UV absorption* edge, the peaks are centered in the *ultraviolet wavelength region*. This is due to the *electron transitions* within the glass molecules. The tail of this peak may extend into the the shorter wavelengths of the fiber transmission spectral window.

(2) A fundamental *infrared and far-infrared absorption edge*, due to *molecular vibrations* (such as Si-O). The tail of these absorption peaks may extend into the longer wavelengths of the fiber transmission spectral window.

Extrinsic absorption

- Major extrinsic loss mechanism is caused by absorption due to water (*as the hydroxyl or OH^- ions*) introduced in the glass fiber during *fiber pulling by means of oxyhydrogen flame*.

- These OH^- ions are bonded into the glass structure and have absorption peaks (due to *molecular vibrations*) at 1.39 μm. The fundamental vibration of the OH^- ions appear at 2.73 μm.

- Since these OH^- absorption peaks are sharply peaked, narrow spectral windows exist around 1.3 μm and 1.55 μm which are essentially unaffected by OH^- absorption.

- The lowest attenuation for typical silica-based fibers occur at wavelength 1.55 μm at about 0.2 dB/km, approaching the *minimum possible attenuation* at this wavelength.

Impurity absorption

- ***Impurity absorption***: most impurity ions such as OH^-, Fe^{2+} and Cu^{2+} form absorption bands in the *near infrared* region where both electronic and molecular absorption losses of the host silica glass are very low.
- Near the peaks of the impurity absorption bands, an impurity concentration as low as *one part per billion* can contribute to an absorption loss as high as 1 dB km^{-1}.
- In fact, fiber-optic communications were not considered possible until it was realized in 1966 (Kao) that most losses in earlier fibers were caused by impurity absorption and then ultra-pure fibers were produced in the early 1970s (Corning).

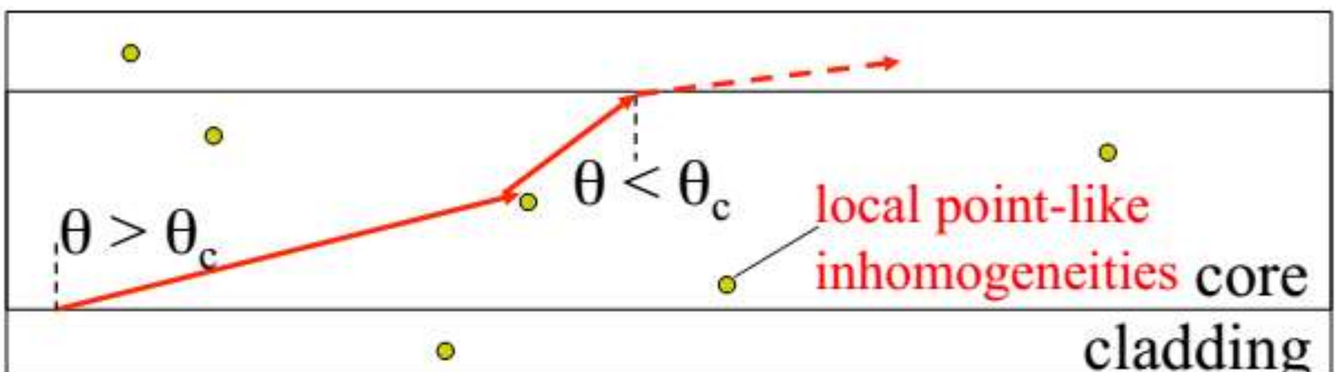
- Today, impurities in fibers have been reduced to levels where losses associated with their absorption are negligible, with the exception of the OH^- radical.

Impurity Ion	Loss due to 1ppm of impurity (dB/km)	Absorption Peak Wavelength (μm)
Fe^{2+}	0.68	1.1
Fe^{3+}	0.15	0.4
Cu^{2+}	1.1	0.85
Cr^{3+}	1.6	0.625
V^{4+}	2.7	0.725
OH^{-}	1.0	0.95
OH^{-}	2.0	1.24
OH^{-}	4.0	1.38

Scattering loss

Scattering results in attenuation (*in the form of radiation*) as the scattered light may not continue to satisfy the total internal reflection in the fiber core.

One major type of scattering is known as *Rayleigh scattering*.



The scattered ray can escape by refraction according to Snell's Law.

Rayleigh scattering

- *Rayleigh scattering* results from random *inhomogeneities* that are small in size compared with the wavelength.

$$\circ \ll \lambda$$

- These inhomogeneities exist in the form of *refractive index fluctuations* which are frozen into the *amorphous* glass fiber upon fiber pulling. Such fluctuations *always exist and cannot be avoided* !

Rayleigh scattering results in an attenuation (dB/km) $\propto 1/\lambda^4$

Waveguide scattering (Mie Scattering)

- ***Imperfections in the waveguide structure*** of a fiber, such as nonuniformity in the size and shape of the core, perturbations in the core-cladding boundary, and defects in the core or cladding, can be generated in the manufacturing process.

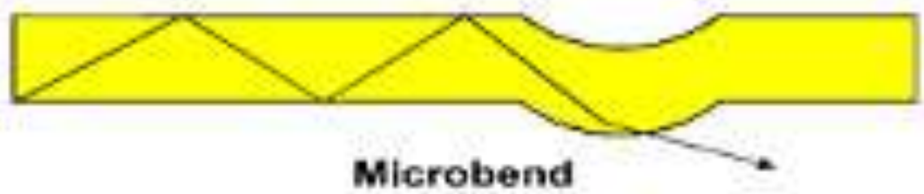
- Environmentally induced effects, such as stress and temperature variations, also cause imperfections.

- The imperfections in a fiber waveguide result in additional scattering losses. They can also induce coupling between different guided modes.

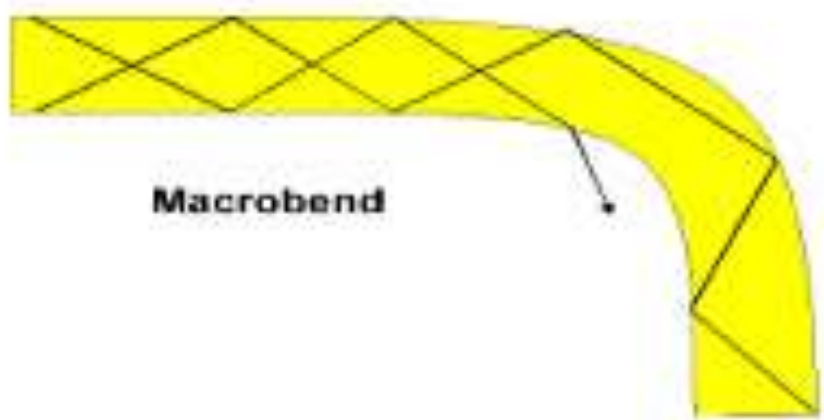
Bending loss

- At a bend the propagation conditions alter and light rays which would propagate in a straight fibre are lost in the cladding.
- Macrobending, for example due to tight bends
- Microbending, due to microscopic fibre deformation, commonly caused by poor cable design

Microbending is commonly caused by poor cable design



Macrobending is commonly caused by poor installation or handling



DISPERSION

- Dispersion is the broadening of actual time-width of the pulse due to material properties and imperfections.
- As pulse travels down the fiber, dispersion causes pulse spreading. This limits the distance travelled by the pulse and the bit rate of data on optical fiber.

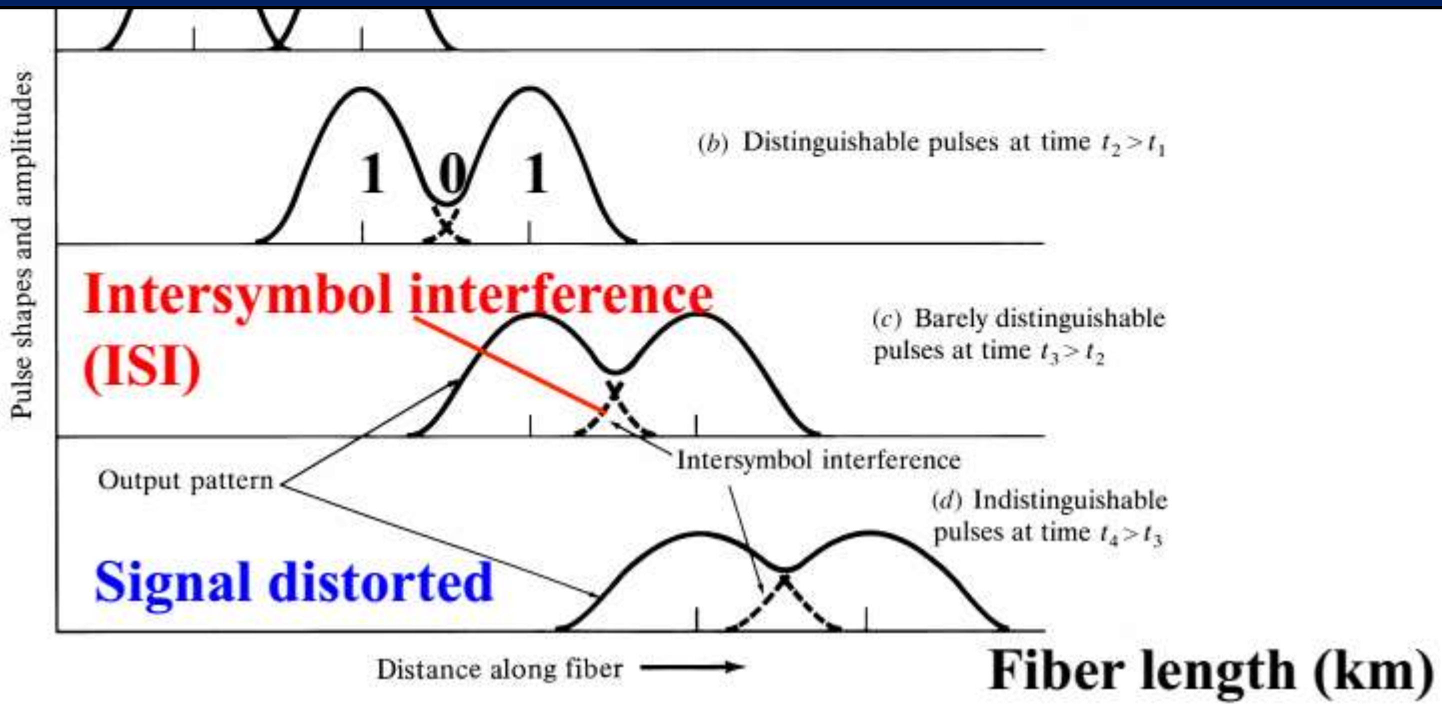
- **Two types of Dispersion:**

Intramodal

Intermodal

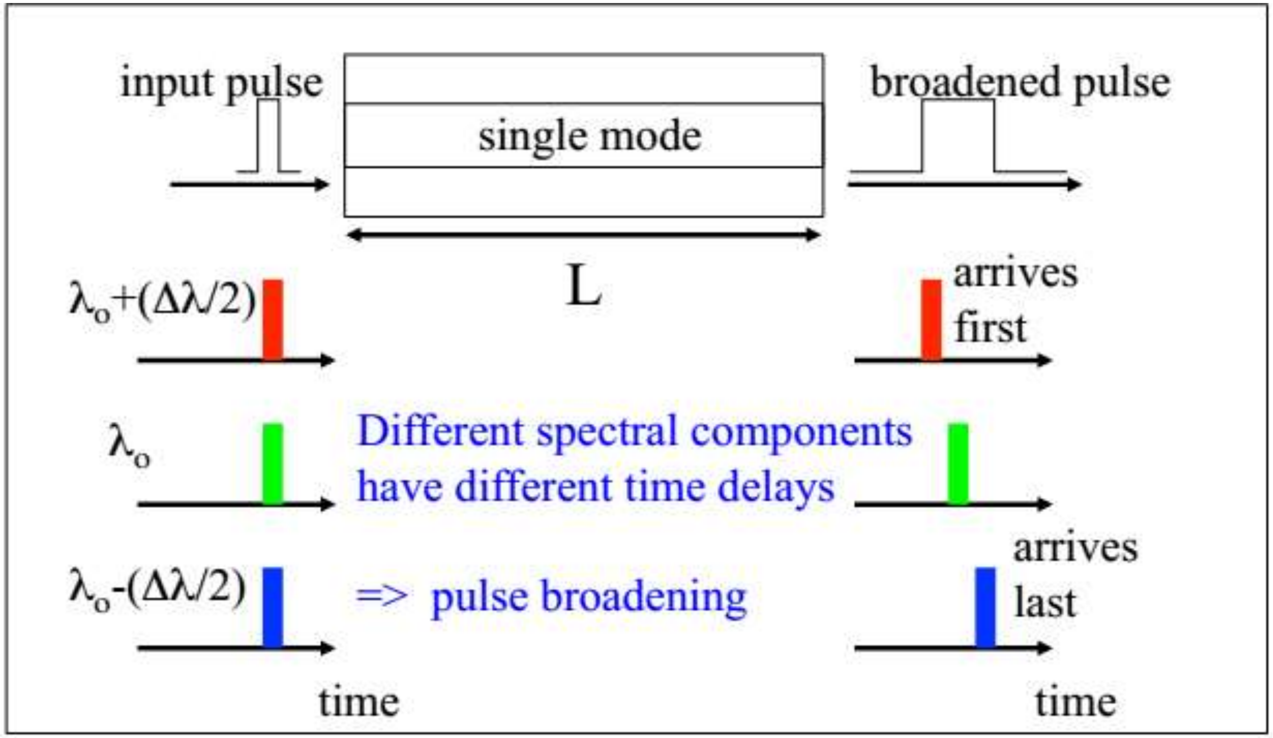
DISPERSION

The number of optical signal pulses which may be transmitted in a given period and therefore the information carrying capacity of the fiber, is restricted by the amount of pulse dispersion per unit length. The pulse broadening increases linearly with fiber length and thus the bandwidth is inversely proportional to distance.



Intramodal (Chromatic) dispersion

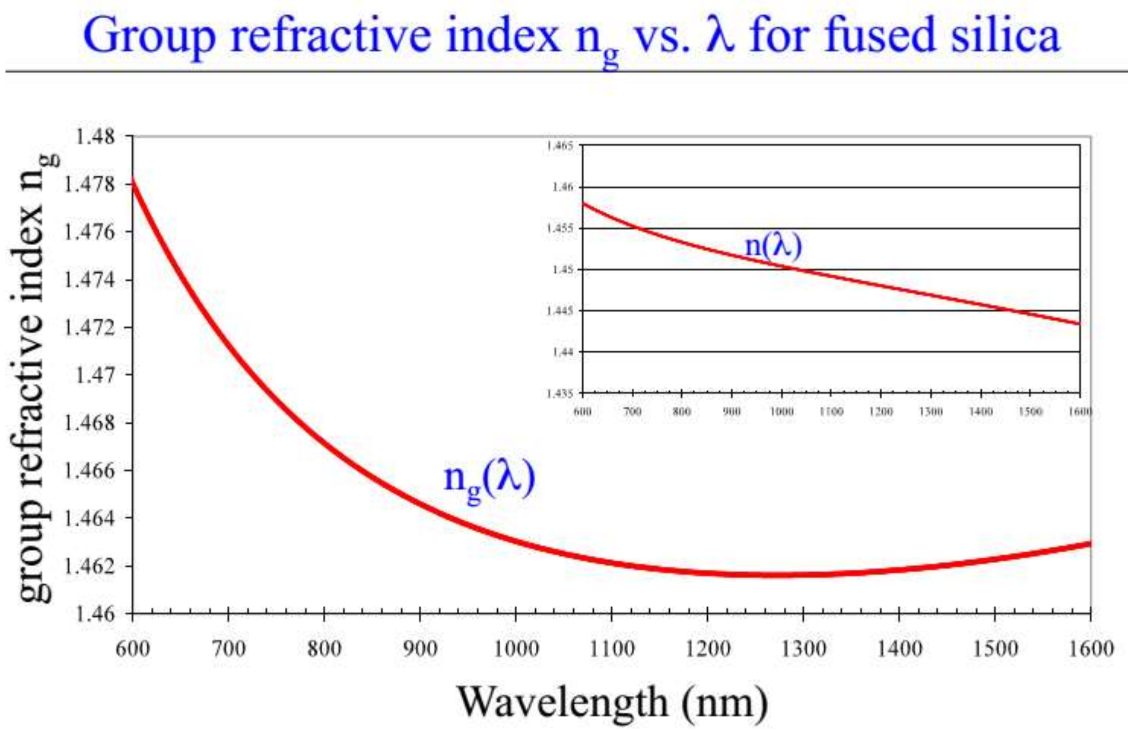
- Pulse broadening within a single mode is called as intramodal dispersion or chromatic dispersion
- Results from the finite spectral line width of the optical source.
- Optical light sources do not emit just a single frequency but a band of frequencies. Hence, there may be propagation delay differences between the different spectral components of the transmitted signal. This causes broadening of each transmitted mode and hence intramodal dispersion.



- The delay differences may be caused by:
  - Dispersive properties of the waveguide material **(material dispersion)**
  - Guidance factors within the fiber structure **(waveguide dispersion)**

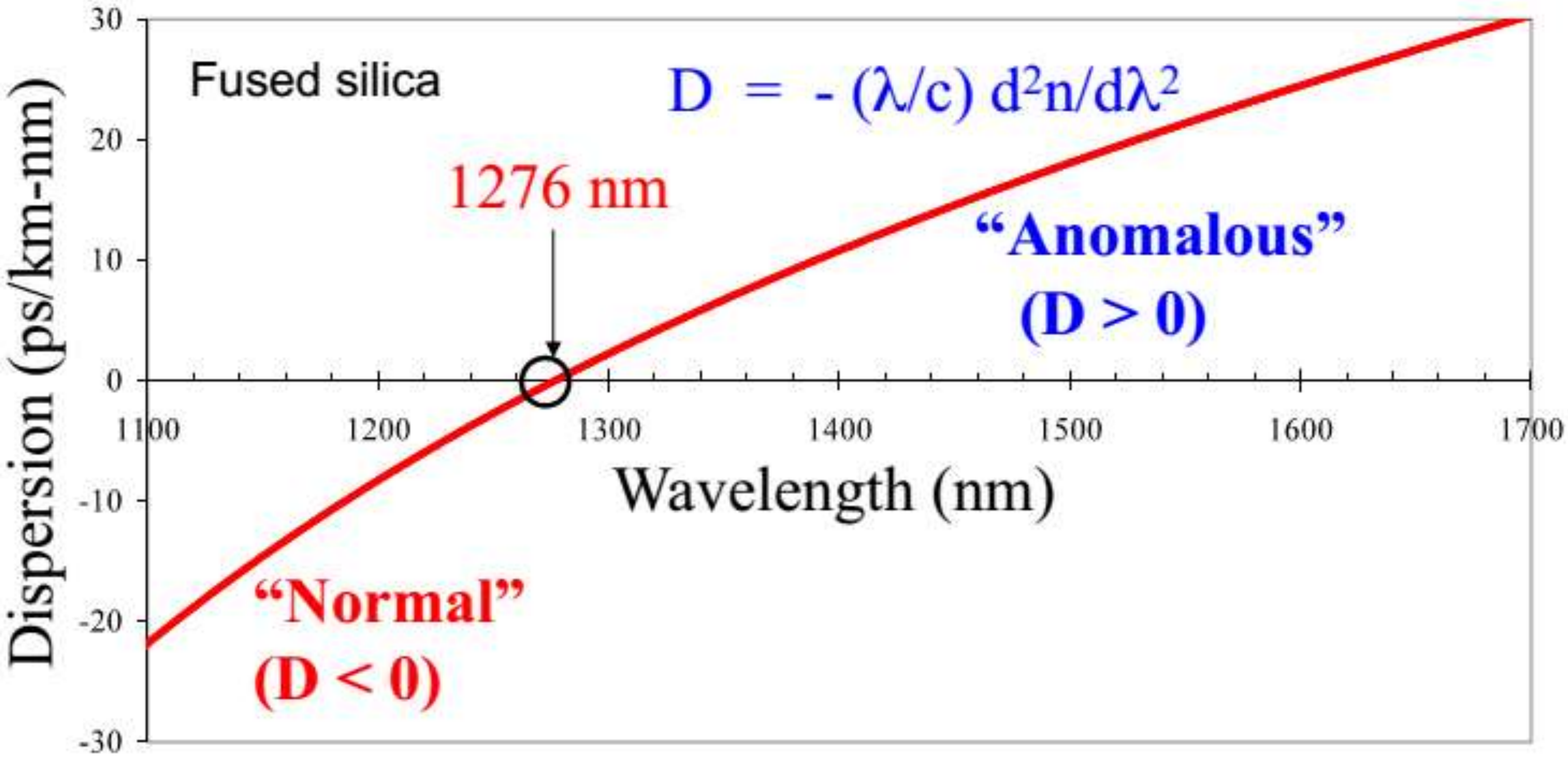
Material Dispersion

- It is the pulse spreading due to the dispersive properties of material
- It arises from variation of refractive index of the core material as a function of wavelength
- Material dispersion is a property of glass and will always exist irrespective of the structure of the fiber
- Results when different spectral components of a pulse travel at different group velocities.



❖ A material is said to exhibit material dispersion when the 2nd order derivative of refractive index of core with respect to wavelength is not equal to zero.

❖ Material dispersion $D(\lambda)$ is given by: $D(\lambda) = -\frac{\lambda}{c}\frac{d^2n}{d\lambda^2}$ $\frac{d^2n}{d\lambda^2} \neq 0$



Material dispersion $D_{mat} = 0$ at $\lambda \sim 1276$ nm for fused silica.

This λ is referred to as the ***zero-dispersion wavelength*** λ_{ZD}.

Chromatic (or *material*) dispersion $D(\lambda)$ can be zero;
or
negative => longer wavelengths travel *faster* than shorter wavelengths;
or
positive => shorter wavelengths travel *faster* than longer wavelengths.

Waveguide Dispersion

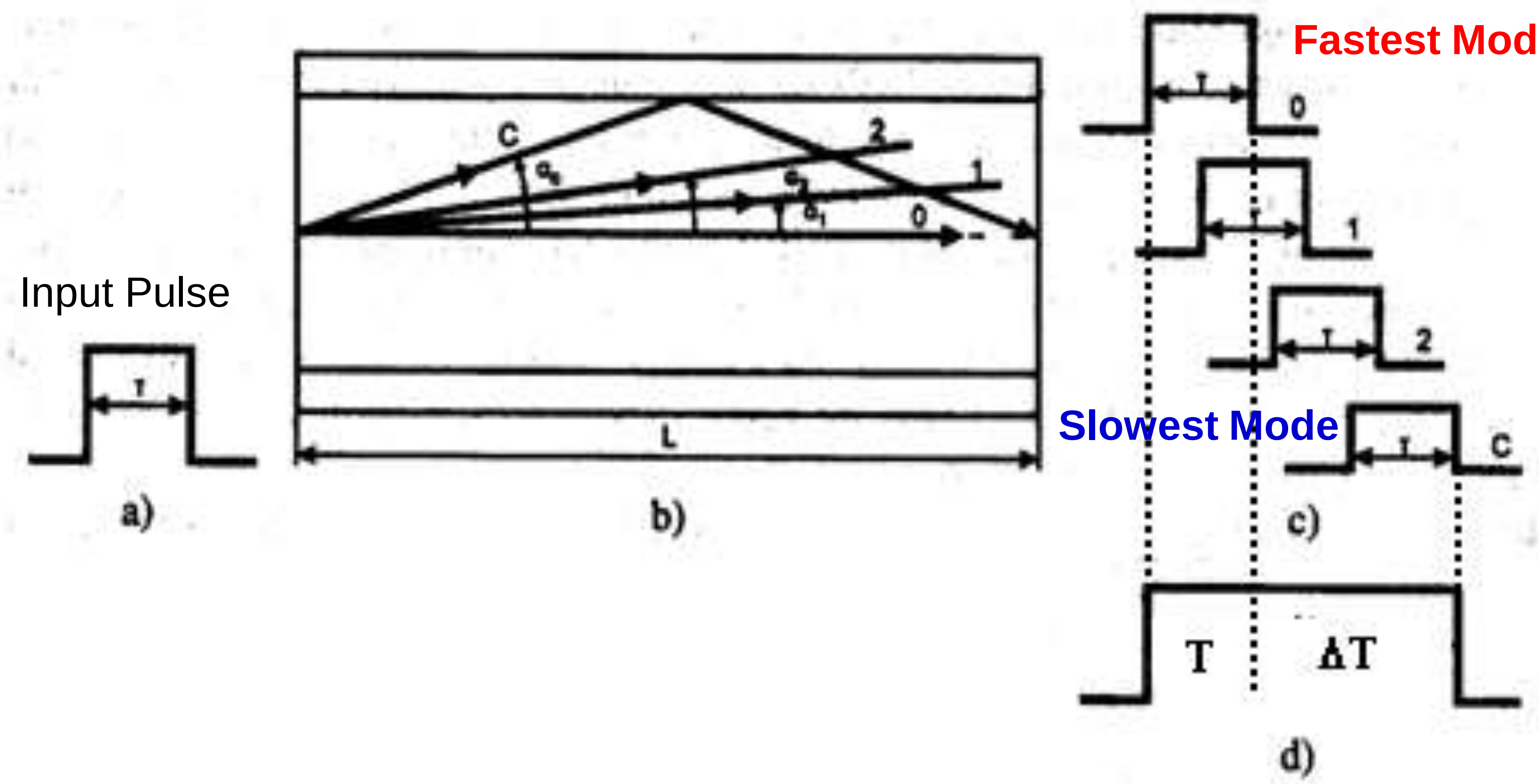
- It occurs because a single mode fiber confines only about 80% of the optical power to the core.
- Dispersion thus arises since the 20% light propagating in the cladding travels faster than light confined to the core.
- The amount of waveguide dispersion depends on the structure of the fiber and can be varied by altering the parameters such as NA, core radius etc.

$$\Rightarrow D(\lambda) = D_{mat}(\lambda) + D_{wg}(\lambda)$$

Intermodal dispersion

- Sometimes referred as **Modal (or mode) dispersion.**
- Dispersion caused by multipath propagation of light energy is referred to as intermodal dispersion.When numerous waveguide modes are propagating, they all travel with different group velocities. Signal degradation occurs due to different values of group delay for each individual mode at a single frequency.
- In digital transmission, we use light pulse to transmit bit 1 and no pulse for bit 0. When the light pulse enters fiber it is breakdown into small pulses carried by individual modes. At the output individual pulses are recombined and since they are overlapped receiver sees a long broadened pulse.
- Parts of the wave arrive at the output before other parts, spreading out the waveform. Hence, it is also known as multimode dispersion.
- It is independent of the source line width.
- It does not occur in a single mode fiber.

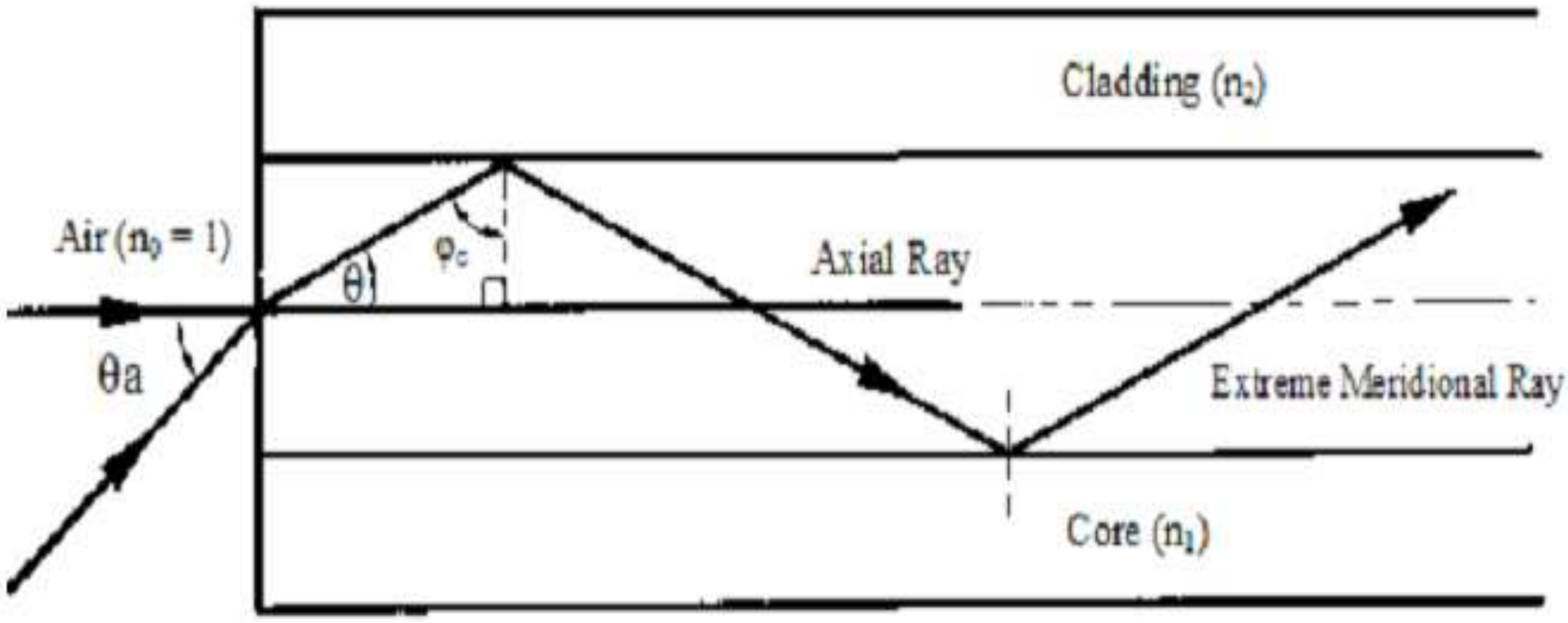
Intermodal dispersion



Output Pulse

Intermodal Dispersion in Multimode step index fiber

Paths taken by the axial and an extreme meridional ray(a ray incident on core-cladding interface at critical angle and hence refracted ray travels along core-cladding interface) in a perfect multimode step index fiber is shown here.



T_{Min} → Minimum delay time (time taken for the axial ray to travel along a fiber of length L)

T_{Max} → Maximum delay time (time taken for the meridional ray to travel along a fiber of length L)

$$T_{Min} = \frac{distance}{velocity} = \frac{L}{(C/n_1)} = \frac{Ln_1}{C}$$

$$T_{Max} = \frac{L/\cos\theta}{(C/n_1)} = \frac{Ln_1}{C\cos\theta}$$

$$\sin\phi_c = \frac{n_2}{n_1} = \cos\theta$$

$$T_{Max} = \frac{Ln_1^2}{Cn_2}$$

$$\delta T_s = T_{Max} - T_{Min} = \frac{Ln_1^2\,\Delta}{Cn_2} \cong \frac{Ln_1\Delta}{C} \cong \frac{L(NA)^2}{2n_1 C}$$

$$NA = n_1\sqrt{2\Delta}$$

$$\Delta = \frac{(NA)^2}{2(n_1)^2}$$

Delay difference for $\Delta << 1$

- # Optical Sources
  - Optical source is often considered to be the active component in an optical fiber communication system
  - Fundamental function is to convert electrical energy into optical energy (light)

- Three main types of optical sources
  - Wide band **continuous spectra source** (incandescent lamp)
  - Monochromatic **incoherent** sources (**Light Emitting Diodes LED**)
  - Monochromatic **coherent** sources (**Laser**)

Characteristics of optical sources for OFC

- ❖ Light output should be highly directional.
- ❖ Most accurately track the electrical input signal to minimize distortion and noise. Ideally, the source should be linear.
- ❖ Should emit light at wavelengths where the fiber has low losses and low dispersion and where the detectors are efficient.
- ❖ Should have a very narrow spectral line width in order to minimize dispersion in the fiber.