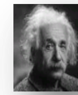
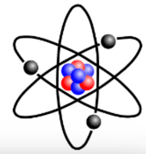


OPTICAL FIBER COMMUNICATIONS



CHAPTER 1

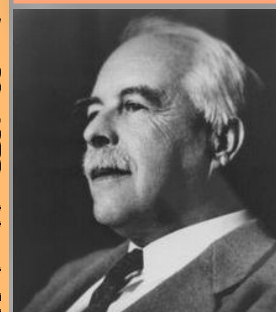
Photon

The name ***photon*** derives from the Greek word for light, *φῶς* (transliterated *phôs*)

The term photon was coined by **Gilbert Lewis** in 1926, though the concept of light in the form of discrete particles had been around for centuries and had been formalized in Newton's construction of the science of optics

(October 23, 1875 – March 23, 1946)

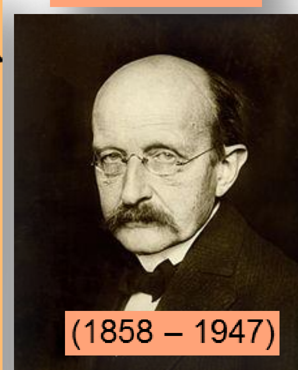
Gilbert Newton Lewis



American physical chemist

Max Planck

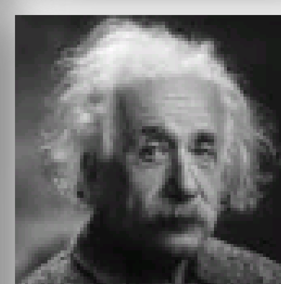
German theoretical Physics



(1858 – 1947)

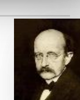
In 1900, **Max Planck** was working on black-body radiation and suggested that the energy in electromagnetic waves could only be released in "packets" of energy.
He called these packets "energy elements".

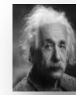
German theoretical physicist



It wasn't until **Albert Einstein** explained the photoelectric effect and realized that light energy had to be quantized that the particle theory returned.

Student: Dr. Einstein, Aren't these the same questions as last year's [physics] final exam?





Albert Einstein: Yes; But this year the answers are different.

1879 –1955

Photonics

Photonics is defined as the generation, manipulation, transport, detection, and use of light information and energy whose quantum unit is the photon.

Photonics is based on the science of optics and electronics.

S **e same questions as last year's [physics] final exam?**

A y

Photonics Opportunities

- Medicine-biomedical
- Environmental
- Energy
- Transportation
- Defense
- Public safety
- Aerospace
- Computers
- Manufacturing with photonics and test and analysis
- Communication and information technology

Concept of a photon

The particle-like nature of light is modeled with photons. A photon has no mass and no charge. It is a carrier of electromagnetic energy and interacts with other discrete particles (e.g., electrons, atoms, and molecules).

A beam of light is modeled as a stream of photons, each carrying a well-defined energy that is dependent upon the wavelength of the light. The energy of a given photon can be calculated by:

Photon energy $(E) = hc/\lambda$

where E is in joules

h = Planck's constant = $6.625\ 10^{-34}$ J·s

c = Speed of light = 2.998×10^{8} m/s

λ = Wavelength of the light in meters

Historical Development

- Fiber optics deals with study of propagation of light through transparent dielectric wageguides. The fiber optics are used for transmission of data from point to point location. Fiber optic systems currently used most extensively as the transmission line between terrestrial hardwired systems.

- The carrier frequencies used in conventional systems had the limitations in handlinmg the volume and rate of the data transmission. The greater the carrier frequency larger the available bandwith and information carrying capacity.

First generation

- The first generation of lightwave systems uses GaAs semiconductor laser and operating region was near 0.8 μm. Other specifications of this generation are as under:

  i) Bit rate : 45 Mb/s

  ii) Repeater spacing : 10 km

Second generation

i) Bit rate : 100 Mb/s to 1.7 Gb/s

ii) Repeater spacing : 50 km

iii) Operation wavelength : 1.3 μm

iv) Semiconductor : In GaAsP

Third generation

i) Bit rate : 10 Gb/s

ii) Repeater spacing : 100 km

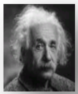
Fourth generation

Fourth generation uses WDM technique.

Bit rate : 10 Tb/s

Repeater spacing : > 10,000 km

Operating wavelength : 1.45 to 1.62 μm



Characteristics of Light

Light, electromagnetic radiation that can be detected by the human eye.

Intensity

Wavelength **Colour**

Spectral width

Polarization

Intensity

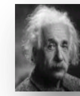
Intensity is like brightness, and **is measured as the *rate* at which light energy is delivered to a unit of surface**, or **energy per unit time per unit area.**

$$\textbf{Intensity (I)} = \frac{Power\ (P)}{Solid\ Angle\ (\Omega)}$$

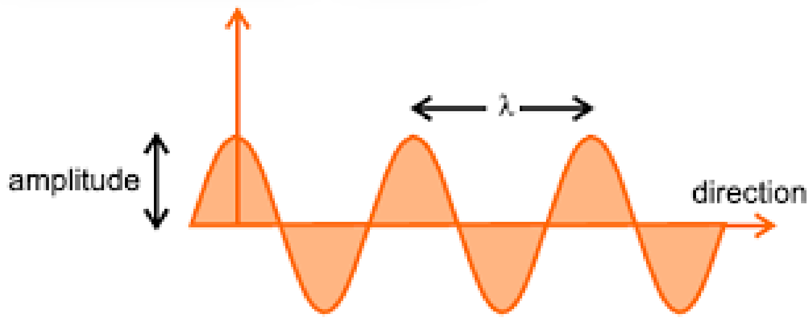
For a given value of Power, when Ω decreases, I increases.

Light which has **small Ω**, would appear **more bright** such as **Laser**.

Thus, even when the power is very small, decreasing Ω may increase the intensity.



Wavelength Colour



Wavelength is the distance between identical points in the adjacent cycles of a waveform signal propagated in space or along a wire

Color derives from the spectrum of light (distribution of light power versus wavelength) interacting in the eye with the spectral sensitivities of the light receptors.

To be completed by lecturer (on board)

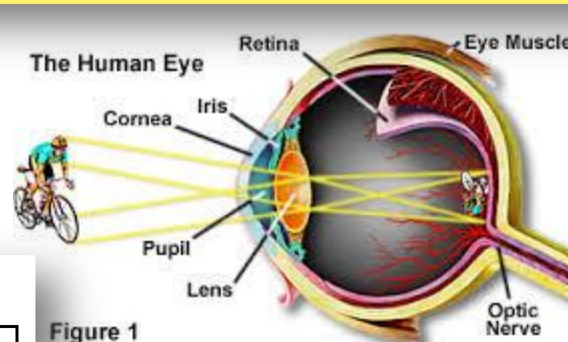
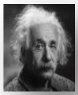


Figure 1

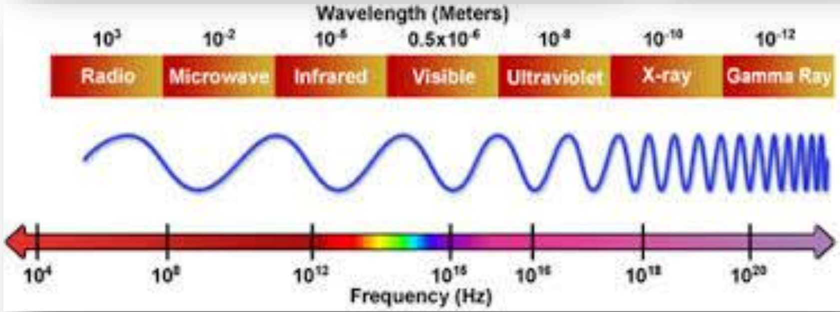
Visible Spectrum Wavelengths

Color	Wavelength Band (μm)	Representative wavelength (μm)
Extreme violet	0.39–0.41	0.40
Violet	0.39–0.45	0.43
Dark blue	0.45–0.48	0.47
Light blue	0.48–0.50	0.49
Green	0.50–0.55	0.53
Yellow-green	0.55–0.57	0.56
Yellow	0.57–0.58	0.58
Orange	0.58–0.62	0.60
Red	0.62–0.70	0.64
Deep red	0.70–0.76	0.72



The Electromagnetic Spectrum

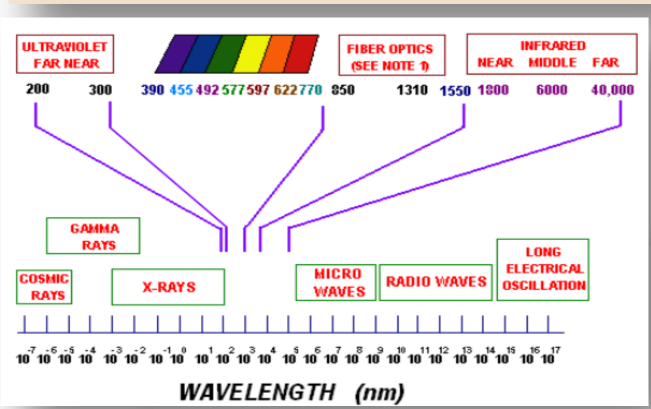
الطيف الكهرومغناطيسي



Since color is related to energy, there is also a direct relation between color, frequency, and wavelength.

Spectrum, in optics, the arrangement according to wavelength of visible, ultraviolet, and infrared light.

We refer to the range of wavelengths of electromagnetic radiation as a spectrum.



Microwave radio frequencies -> 10^{8} nm - 3 x 10^{9} Hz

UHF frequencies -> 10^{9} nm - 3 x 10^{8} Hz

VHF frequencies -> 10^{10} nm - 3 x 10^{7} Hz

Visible Spectrum Wavelengths

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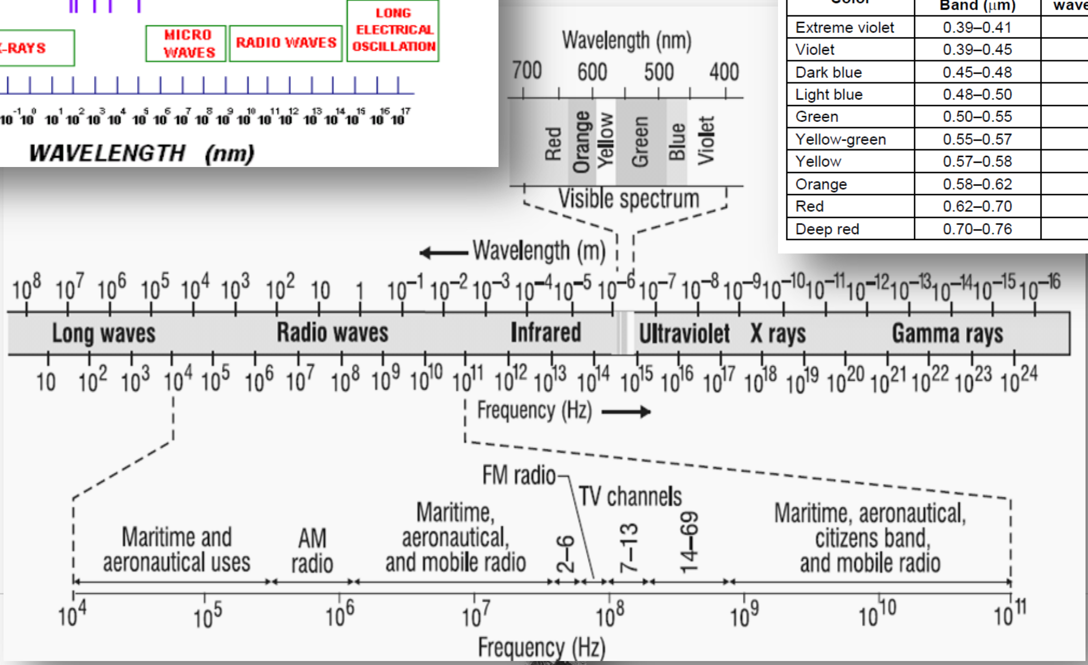


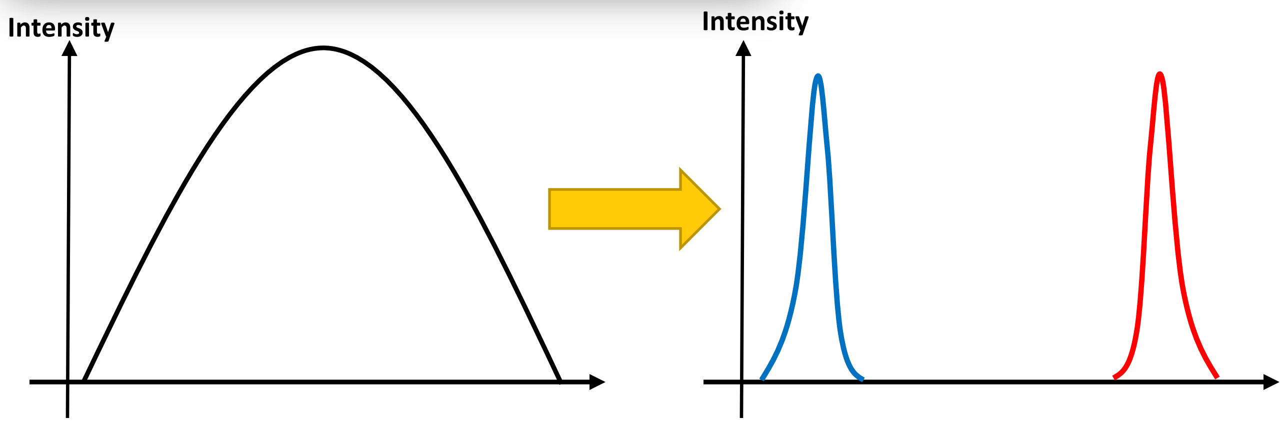
Spectral width

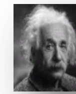
This range is usually called the "spectral width" of the light source.

All light sources produce a range or band of wavelengths

In optical communication applications, the usual method of specifying spectral width is the full width at half maximum.

This is the same convention used in bandwidth, defined as the frequency range where power drops by less than half (at most −3 dB).





Polarization

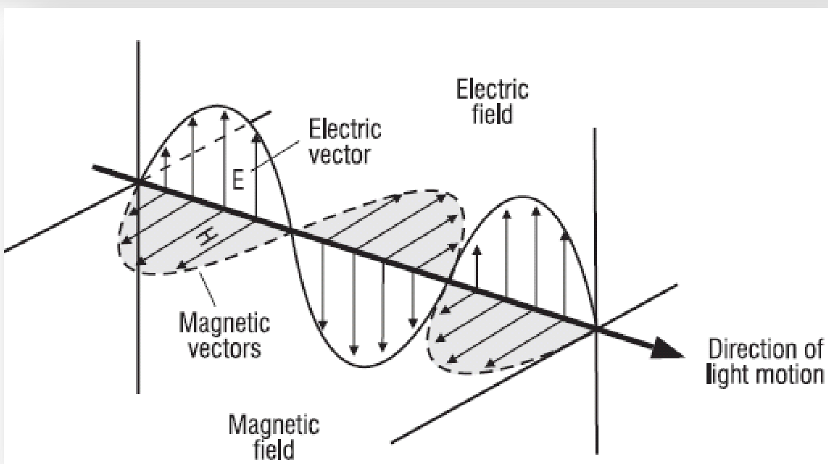
Polarization is a property of waves that can oscillate with more than one orientation.

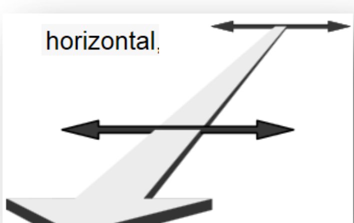
Light is a transverse electromagnetic wave that can be seen by a typical human.

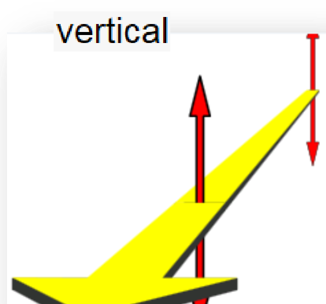
Wherever light goes, the electric and magnetic fields are oscillated perpendicular to the direction of propagation.

The electric field is vibrating in many directions; all perpendicular to the direction of propagation.

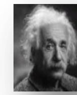
According to the direction of vibration of electric field the polarity of light can be specified.











Optical Fiber

Introduction

Guiding of light by refraction, the principle that makes fiber optics possible, was first demonstrated by Daniel Colladon and Jacques Babinet in Paris in the early 1840s.

Jean-Daniel Colladon

15 December 1802 - 30 June 1893

Swiss physicist.

Jacques Babinet

5 March 1794 – 21 October 1872

French physicist

In the mid 1970s, it was recognized that the existing copper technology would be unsuitable for future communication networks. In view of this, the telecommunication industry invested heavily in research into optical fibers.

Optical fiber provides an attractive alternative to wire transmission lines such are twisted pair and coaxial cable (or coax).

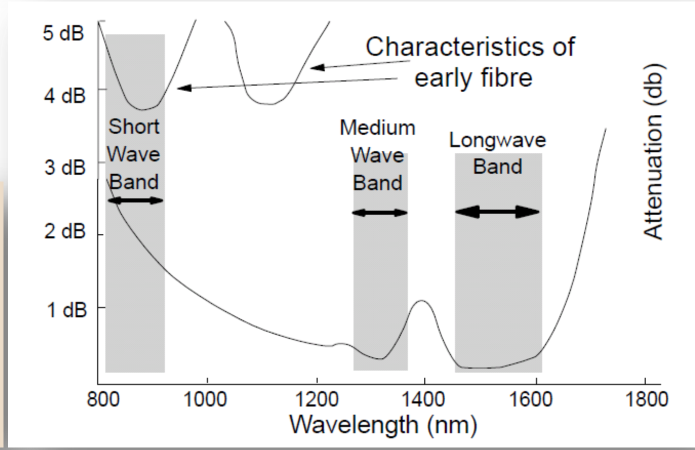
Optical fiber has the following advantages over copper:

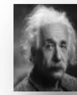
Bandwidth It provides a very high capacity for carrying information.

Attenuation It provides low attenuation and is therefore capable of transmitting over a long distance without the need of repeaters.

Comparison of Frequency Windows and Operating Wavelength Used

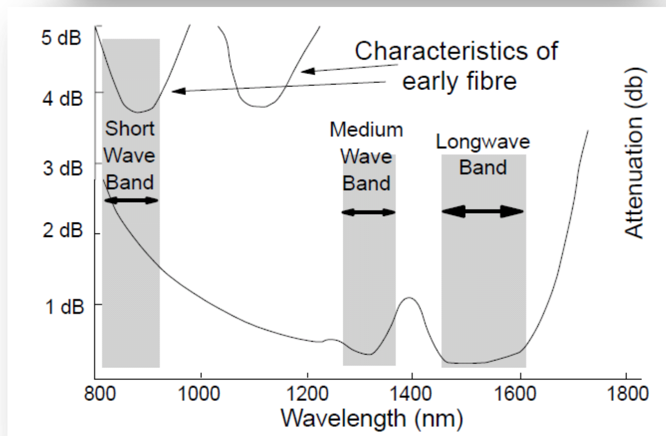
Window of Frequencies	Normal Wavelength Used
800-900 nanometers (nm)	850 nm
1250-1350 nm	1310 nm
1500-1600 nm	1550 nm



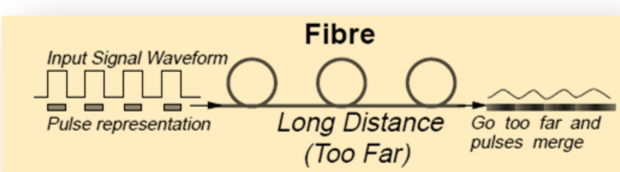


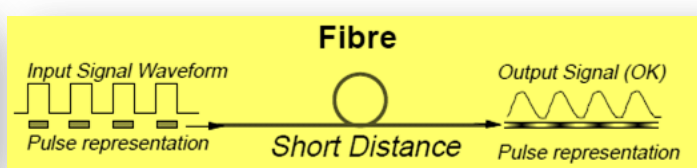
Bandwidth

Fibre Transmission Windows (Bands)

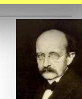


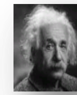
Attenuation.



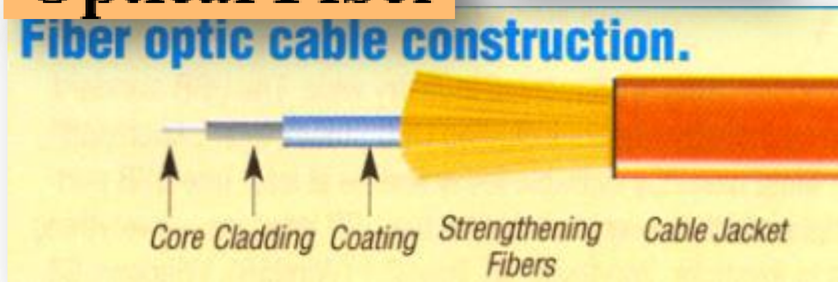


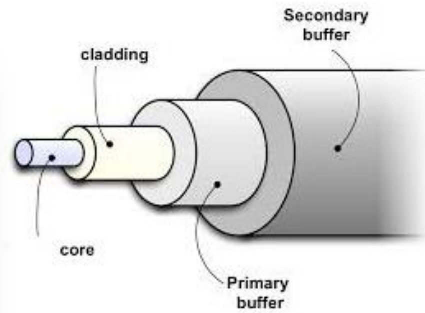






Optical Fiber structure





Fiber optic cable consists of a core, cladding, coating, strengthening fibers, and cable jacket

Core -This is the physical medium that transports optical data signals from an attached light source to a receiving device.

Cladding -This is a thin layer that surrounds the fiber core and serves as a boundary that contains the light waves and causes the refraction, enabling data to travel throughout the length of the fiber segment.

Coating -This is a layer of plastic that surrounds the core and cladding to reinforce the fiber core, help absorb shocks, and provide extra protection against excessive cable bends.

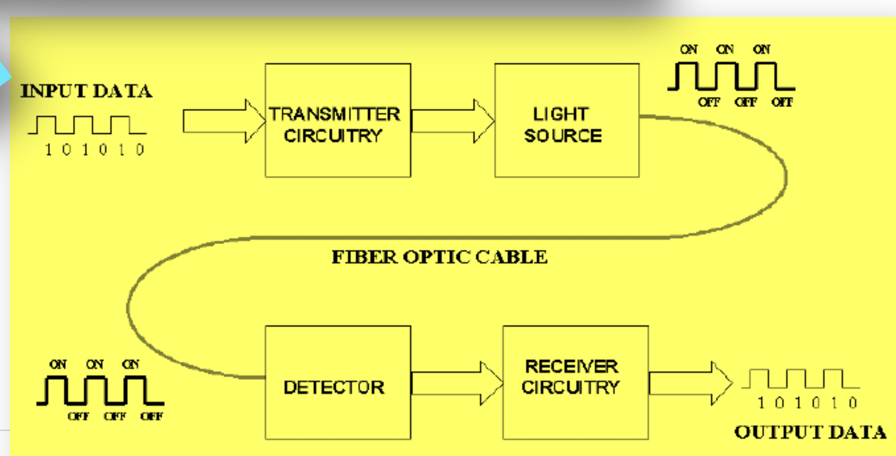
Strengthening fibers -These components help protect the core against crushing forces and excessive tension during installation.

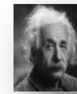
Basic Fiber Optic Communication System

Fiber optics is a medium for carrying information from one point to another in the form of light.

Unlike the copper form of transmission, fiber optics is not electrical in nature. A basic fiber optic system consists of a transmitting device that converts an electrical signal into a light signal, an optical fiber cable that carries the light, and a receiver that accepts the light signal and converts it back into an electrical signal.

Carrier is light





Tutorial

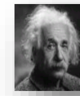
Q1- What are the characteristics of Light.

Q2- What are the properties of GOOD light source?

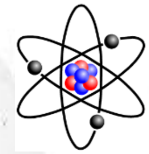
Q3- What are the meaning of Transmission windows?

Q4-Specify the ranges of OPTICAL transmission windows?

Q5- What are the advantages of Optical communication systems?



OPTICAL FIBER COMMUNICATIONS



CHAPTER 2

Principles of Light Propagation

Refractive Index

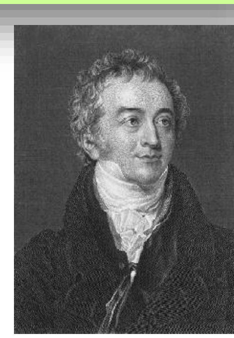
In optics the **refractive index** or **index of refraction** n of an optical medium is a dimensionless number that describes how light, or any other radiation, propagates through that medium

It is defined as

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

C is the speed of light in vacuum

v is the speed of light in the substance.



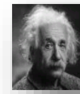
Thomas Young

who first used, and invented, the name "index of refraction", in 1807

Modelling light propagation inside optical fiber

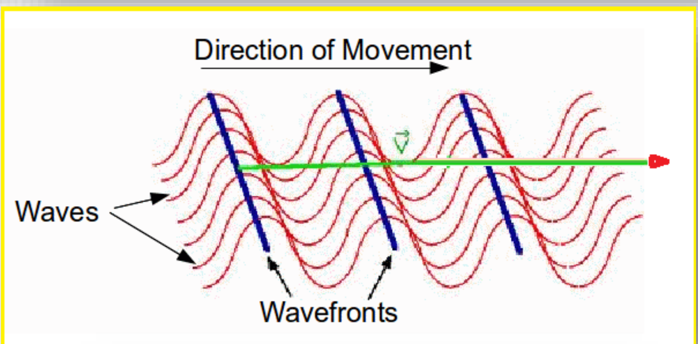
Ray Model **treats the light as rays**

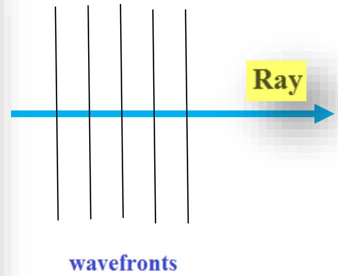
Wave Model **treats the light as electromagnetic wave**



Ray Model

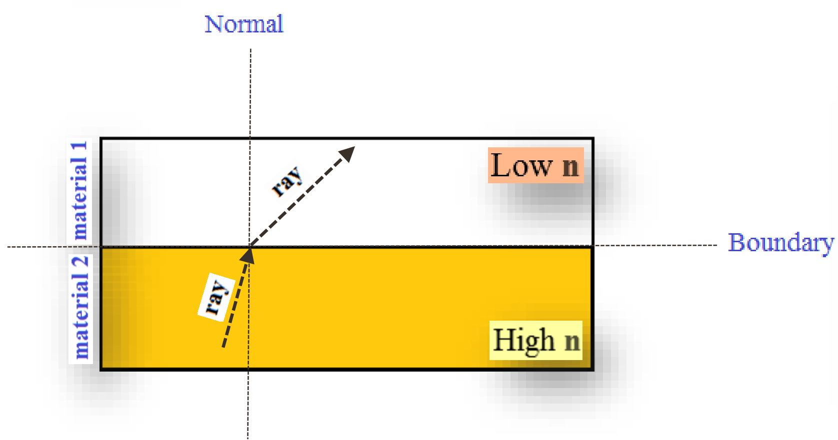
Ray :- **Line that is perpendicuar to the wavefronts of actual light**



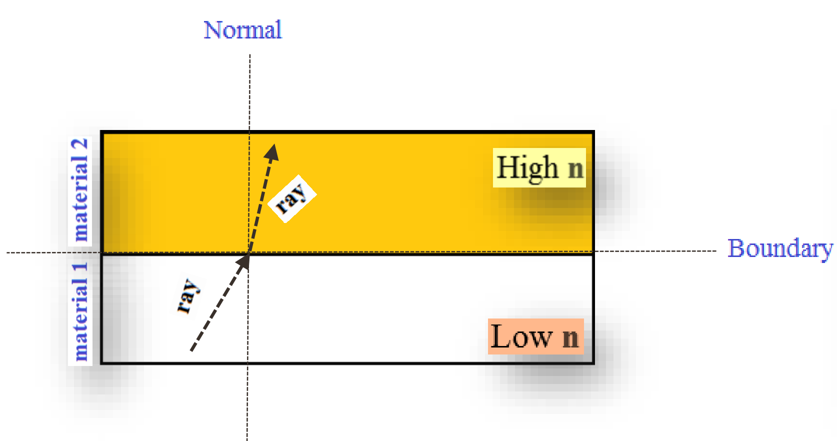


Wavefronts: Locus of points having same phase

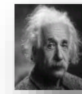
$$n = \frac{c}{v}$$



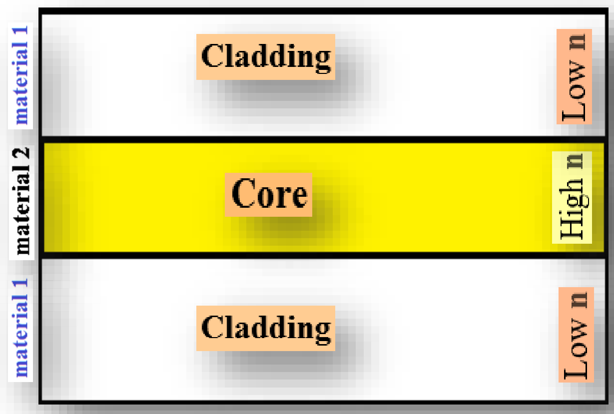
Light ray travels from High n material to Lower n material. Ray will refract away from the Normal

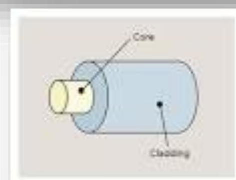


Light ray travels from Lower n material to High n material. Ray will refract towards from the Normal



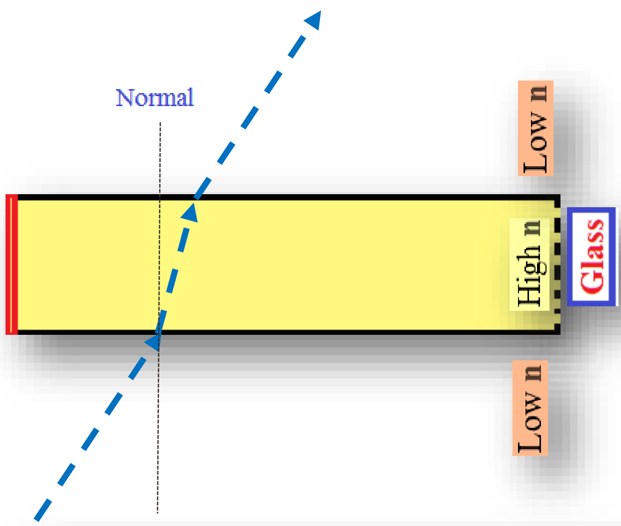
According to the fiber structure





At which conditions, light will propagate inside the core over long distance without much loss?

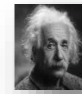
If we said that we have a structure such as a simple Glass rod,

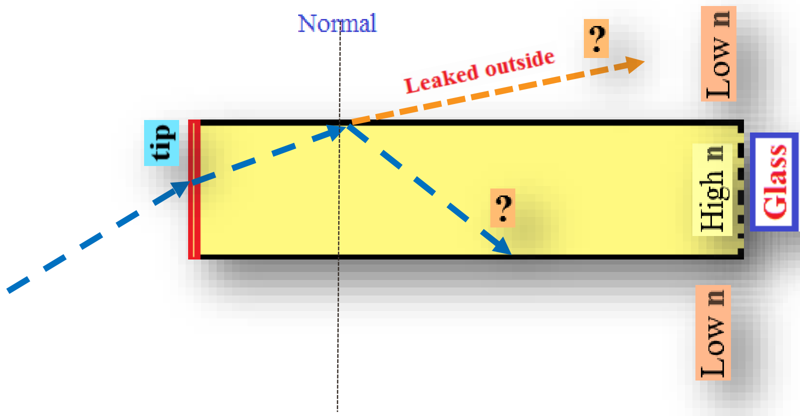


If the ray was sent to optical fiber from the sidewall, the ray will simply cross the structure and will never get guided inside the core

So, no matter howmuch light is there surrounding the optical core, if the light is injected from the sides, there is no possibility for this light getting inside the core

Thus, if we want to send the light inside the core, the light has to go from the tip (terminal) of optical fiber





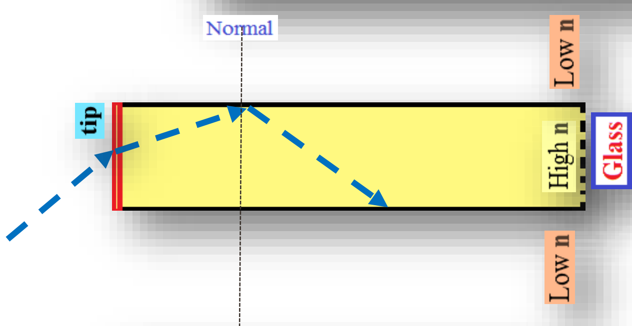
Light should be injected from the Tip of optical fiber to be get guided inside the core....with suitable angle!!

So, if the tip is not exposed to the light, no light can get guided inside optical fiber core

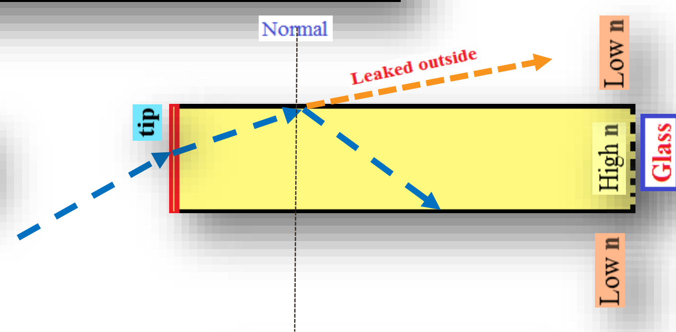
Also, if the light propagates inside the fiber, no light can come out of the core.

This would enhance security of fiber assuming the tip is protecetd

If we want the light inside the core (from the tip), at which angle the light should be launched???? so that TOTAL INTERNAL REFLECTION (TIR) can be achieved at the core-cladding region.



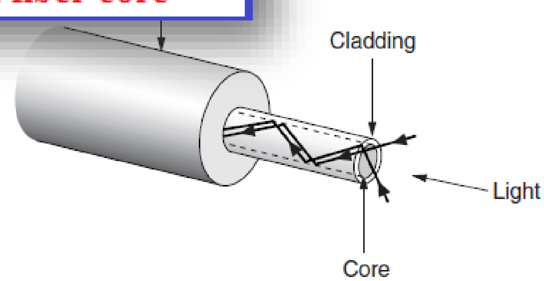
Total Internal Reflection

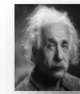


Partial Reflection

Important

Total Internal Reflection (TIR) is extremely essential if we want the light to be guided along the optical fiber core

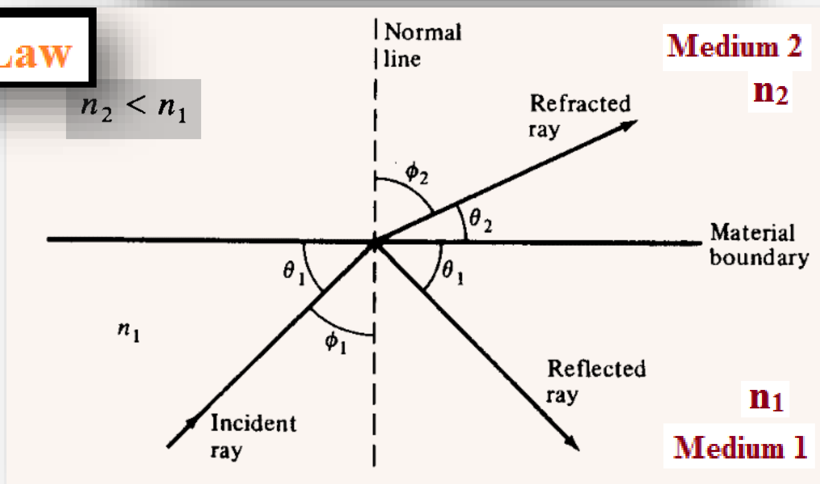




Total Internal Reflection

Snell's Law

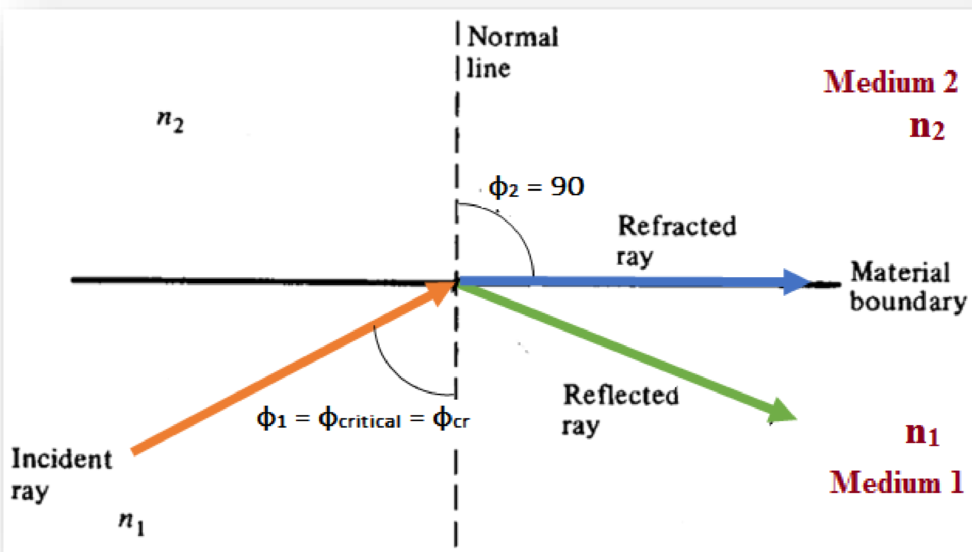
$n_2 < n_1$



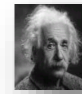
Willebrord Snel
(1580-1626)
Dutch Math.

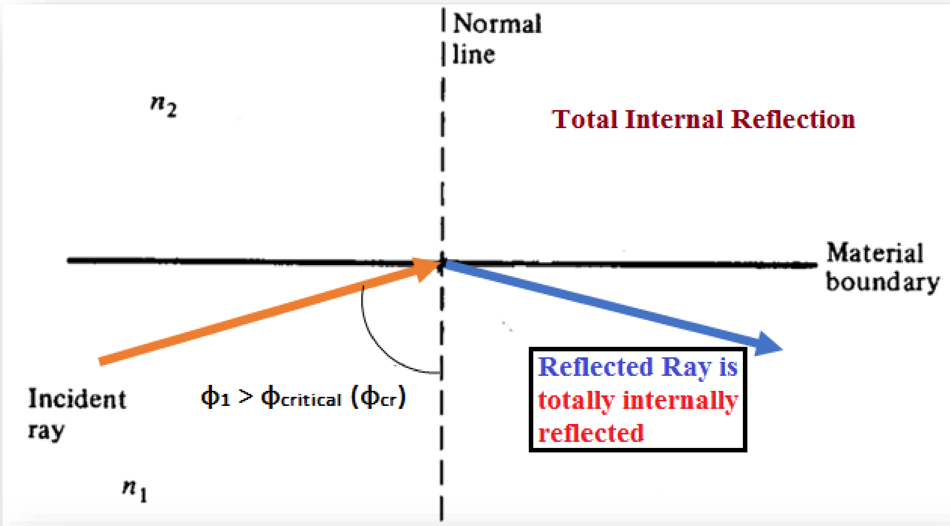
$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

Snell's Law



If we increase Φ_1 , then Φ_2 becomes close to 90°





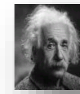
If ϕ_1 increases more and becomes larger than critical angle ϕ_{cr} then, the whole Ray will be internally reflected

Conditions of TIR

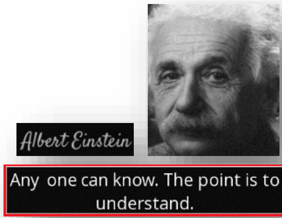
(1) Refractive index of medium 1 (core) should be larger than refractive index of medium 2 (cladding)

(2) ϕ_1 should be larger than $\phi_{critical}$ (ϕ_{cr})

Area for Lecturer



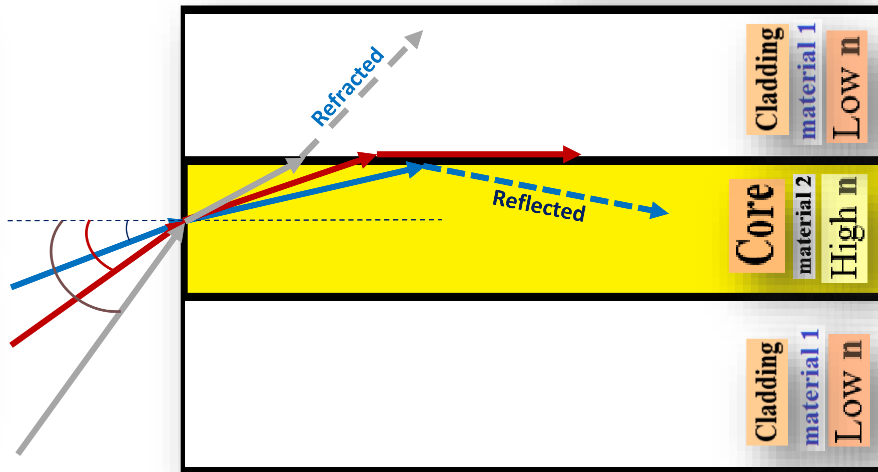
QUESTION **How the light rays can be launched inside optical fiber ?**



For a given light source which is capable of sending light from all directions, the fiber is selecting ONLY light coming from a CERTAIN ANGLE

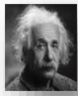
The fiber accepts ONLY those rays which have a launching angle LESS than $\Theta_{o,\,max}$

ONLY Ray which has $\Theta_o < \Theta_{o,max}$ will be launched inside fiber core



SO there is some kind of Light Efficiency associated with Optical Fiber

Area to be used by lecturer in class

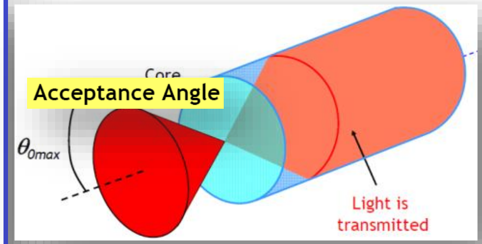


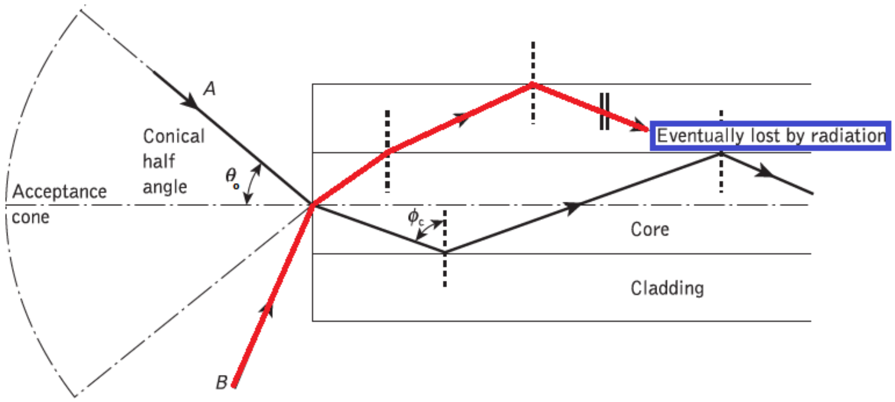
The quantity ($n \sin \Theta_{o, max}$) is telling you that light collection efficiency

$$=$$

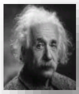
Energy or wave coming

and you have some kind of Aperture siting infront of the fiber. The energy is captured by Aperture





$$P_{fiber} = \pi\,(NA)^2\,P_{Laser}$$

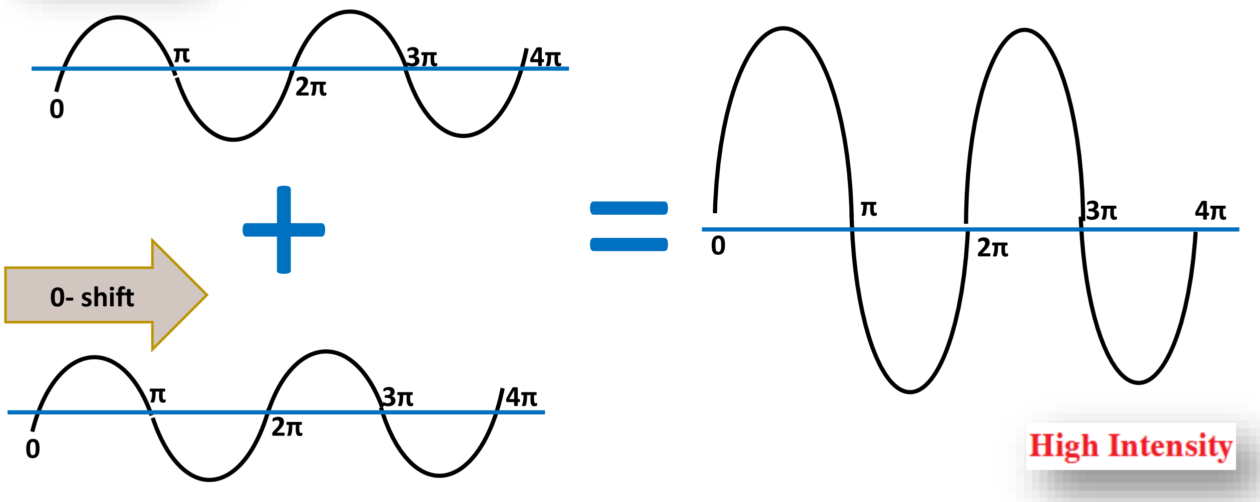


Wave Model

The waves (or wavefronts) that corresponds to Rays, overlaps and intersect or interfere with each other

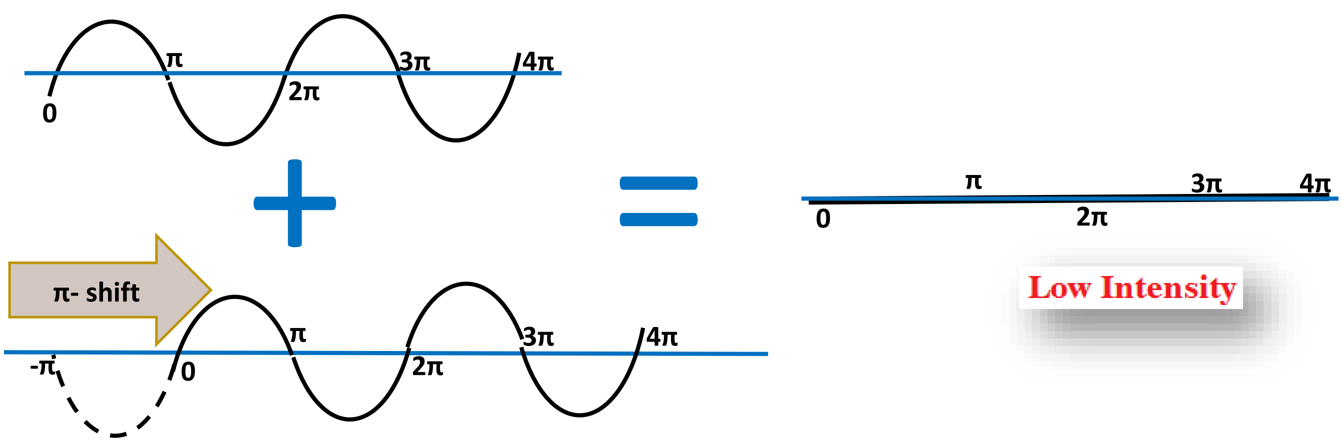
Interference

instructive

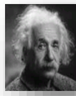


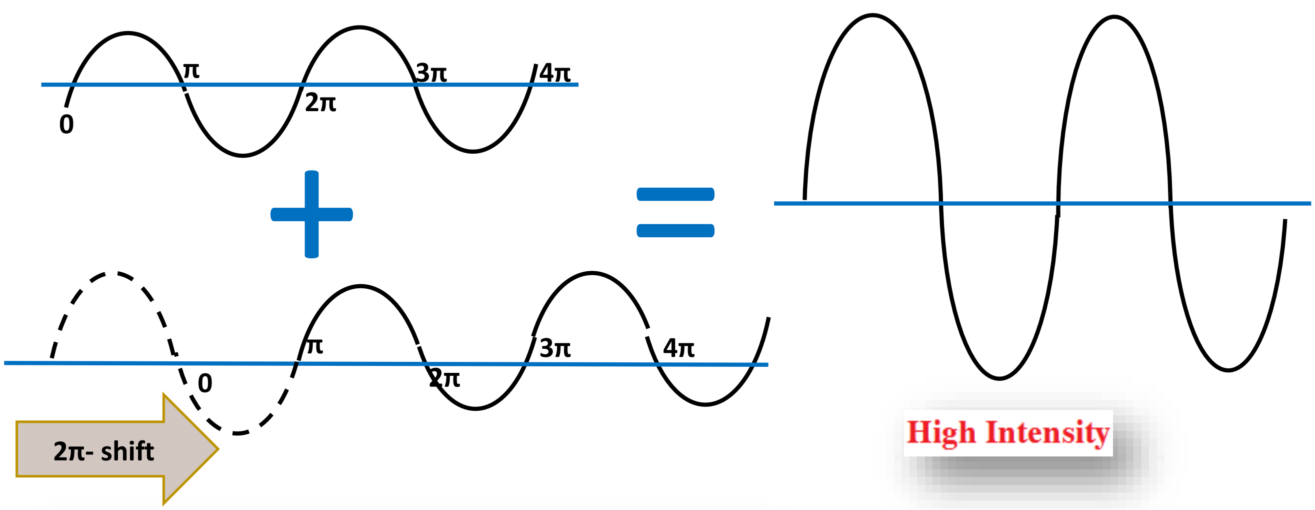
High Intensity

destructive

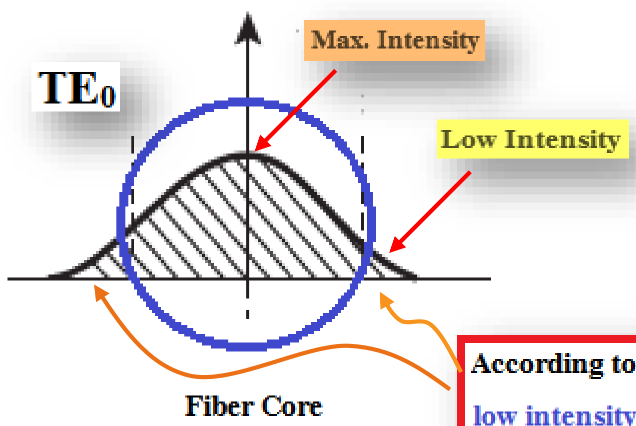


Low Intensity



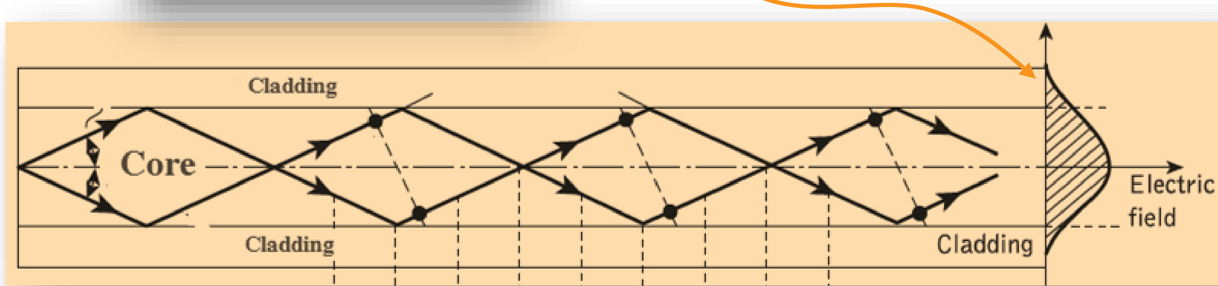


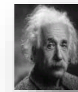
Therefore, light intensity will be looked liked

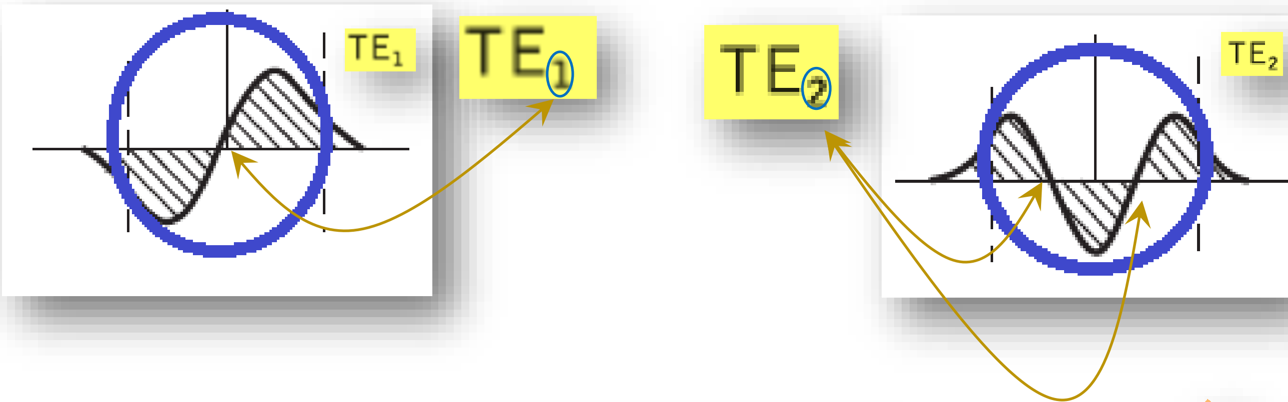


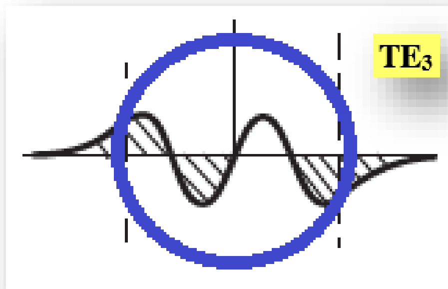
According to WAVE MODEL, there is some low intensity around the core (in cladding)

This intensity distribution is called MODE









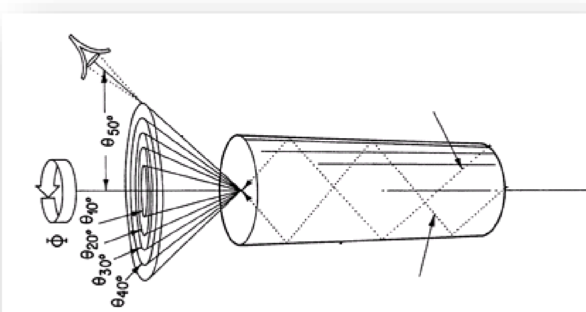
some Optical Modes

According to wave theory, only even number of π factors of phase shift of interferenced waves will be propagated, i.e. 0, 2π, 4π, 6π.

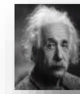
Thus, within accepting angle range, ONLY discrete (specified) values of launching angles of RAYS will be propagated inside core.

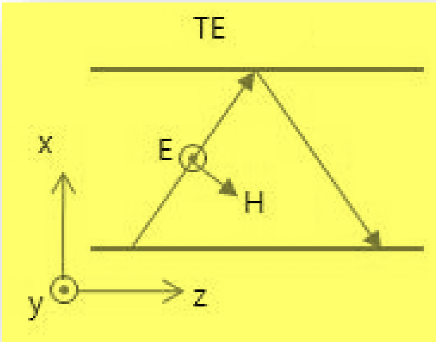
Those rays will have instructive interferenced waves

Very important

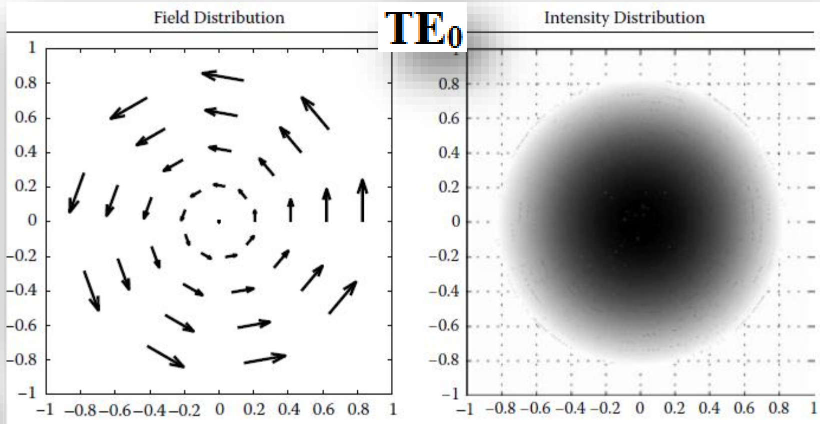


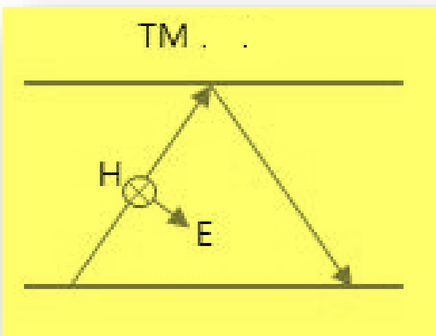
Each angle θ = Specified Ray =
= Waves interference
= Intensity distribution (pattern)
= MODE



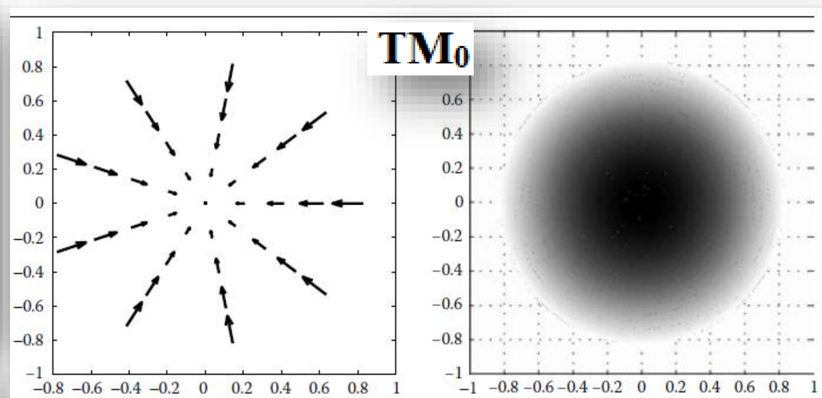


TE = Transverse Electric Field

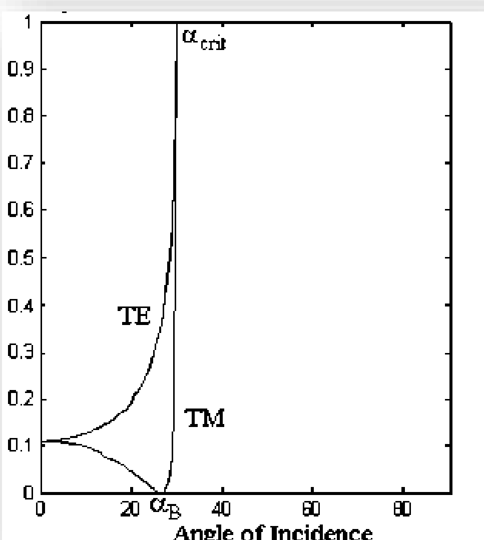




TM = Transverse Magnetic Field

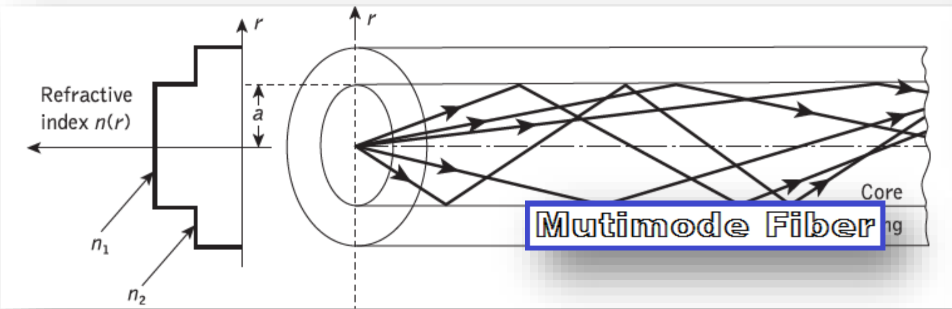


TE and TM waves are typically transmitted and reflected with different amplitudes



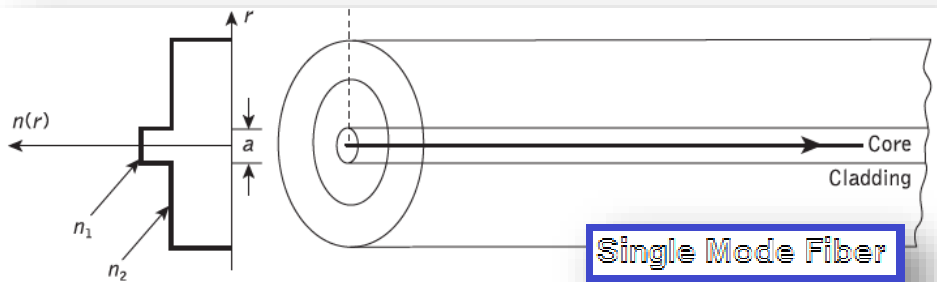
Reflected Beam

In terms of MODES, there are TWO types of Optical Fiber ⇨ **Single Mode Fiber** ⇨ **Multimode Fiber**



- **-Multi Ray**
- **-Large Core diameter**
- **-Multi intensity distribution**

- **-Low cost**
- **-Used for Short distance**
- **-High dispersion**



One Ray
Small Core diameter
One intensity distribution

- **-High cost**
- **-Used for Long distance**
- **-Low dispersion**

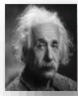
V-number or *V-parameter*

An important parameter connected with the cutoff condition is the *normalized frequency* V (also called the *V-number* or *V-parameter*) defined by

$$V^2 = \left(\frac{2\pi a}{\lambda}\right)^2 (n_1^2 - n_2^2)$$

which is a dimensionless number that determines how many modes a fiber can support. The number of modes that can exist in a waveguide as a function of V

$$V = \frac{2\pi a}{\lambda}(n_1^2 - n_2^2)^{1/2} \leq 2.405$$ single-mode fiber



The total number of modes M entering the fiber is

$$M \simeq \frac{2\pi^2 a^2}{\lambda^2}\left(n_1^2 - n_2^2\right) = \frac{V^2}{2}$$

The total average cladding power

$$\left(\frac{P_{clad}}{P}\right)_{total} = \frac{4}{3} M^{-1/2}$$

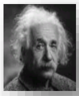
Cutoff Wavelength

An important parameter for single-mode fibers is the *cutoff wavelength*. This is designated by λ_{cutoff} and specifies the smallest wavelength for which all fiber modes except the fundamental mode are cut off; that is, the fiber transmits light in a single mode only for those wavelengths that are greater than λ_{cutoff}.

The fiber can support more than one mode if the wavelength of the light is less than the cutoff. Thus if a fiber is single-mode at 1310 nm, it is also single-mode at 1550 nm, but not necessarily at 850 nm.

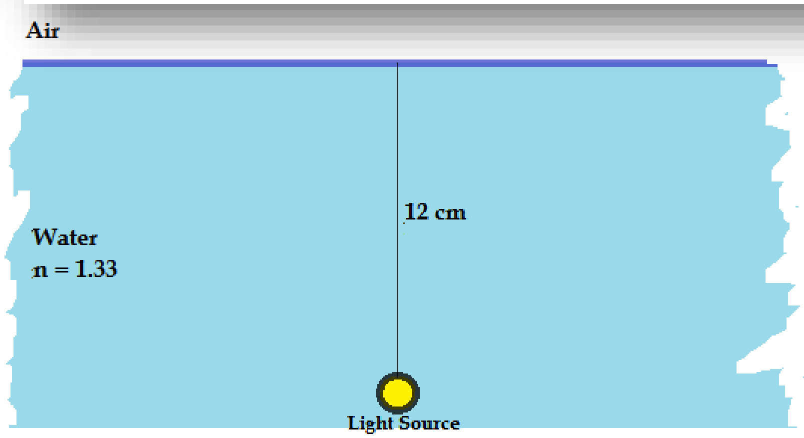
When a fiber is fabricated for single-mode use, the cutoff wavelength usually is chosen to be much less than the desired operating wavelength. For example, a fiber for single-mode use at 1310 nm may have a cutoff wavelength of 1275 nm.

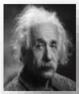
$$\lambda_{cutoff} = \frac{2\pi a}{2.405}\left(n_1^2 - n_2^2\right)^{1/2}$$



Questions

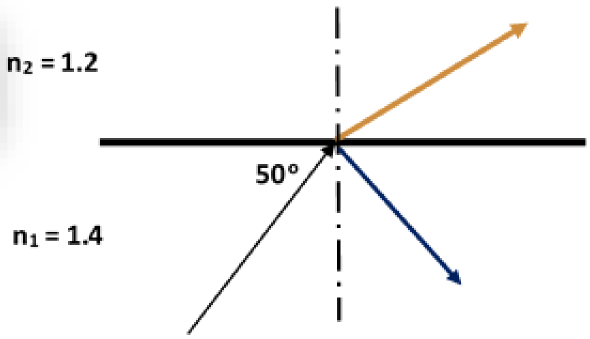
Q1 **A point source of light is 12 cm below the surface of a large body of water (n =1.33). What is the area of largest circle on the water surface through which, the light can emerge?**

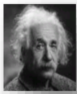




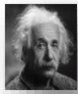
Q2 A ray of light is travelling in air and strikes a surface with refractive index 1.2 and make an angle of 35 degree. Determine, refracted, reflection and critical angles.

Q3 For the figure shown, find all the corrsponding important angles?

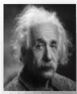




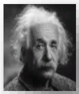
Q4 Light traveling in air strikes a glass plate at an angle $\theta_1 = 33°$, where θ_1 is measured between the incoming ray and the glass surface. Upon striking the glass, part of the beam is reflected and part is refracted. If the refracted and reflected beams make an angle of 90° with each other, what is the refractive index of the glass?



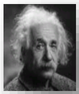
Q5 Consider three layers optical waveguide which consists of cladding, core and substrate with refractive indices n_{cl} =1.2, n_c =1.5 and n_s = 1.4, respectively. A ray of light is incident on the core-cladding interface and defines an angle of 60° to the normal to the interface. Determine, with discussion, whether this ray of light will remain confined within the guiding (i.e. core) layer.



Q6 Calculate the numerical aperture of a step-index fiber having $n_1 = 1.48$ and $n_2 = 1.46$. What is the maximum entrance angle $\theta_{0,\max}$ for this fiber if the outer medium is air with $n = 1$?

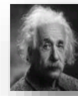


Q7 Determine the normalized frequency at 0.82 μm for a step-index fiber having a 25-μm core radius, $n_1 = 1.48$, and $n_2 = 1.46$. How many modes propagate in this fiber at 0.82 μm? How many modes propagate at a wavelength of 1.3 μm? What percentage of the optical power flows in the cladding in each case?



Q8 Find the core radius necessary for single-mode operation at 820 nm of a step-index fiber with $n_1 = 1.480$ and $n_2 = 1.478$. What is the numerical aperture and maximum acceptance angle of this fiber?

Q9 A manufacturer wishes to make a silica-core, step-index fiber with $V = 75$ and a numerical aperture NA = 0.30 to be used at $1.3\ \mu m$. If $n_1 = 1.458$, what should the core size and cladding index be?



Q11 How the light can be injected (launched) to optical fiber, from the tip or sidewall? justify your answer.

Q12 What are the differences between Ray and Wave theories in explaining the propagation of light inside waveguide or optical fiber ?

Q13 What is the difference between Single mode and multimode optical fibers in terms of (1) Mode (ray theory) (2) Mode (wave theory) (3)cost (4) distance of communication (5) diameter of core and (6) dispersion.

Q14