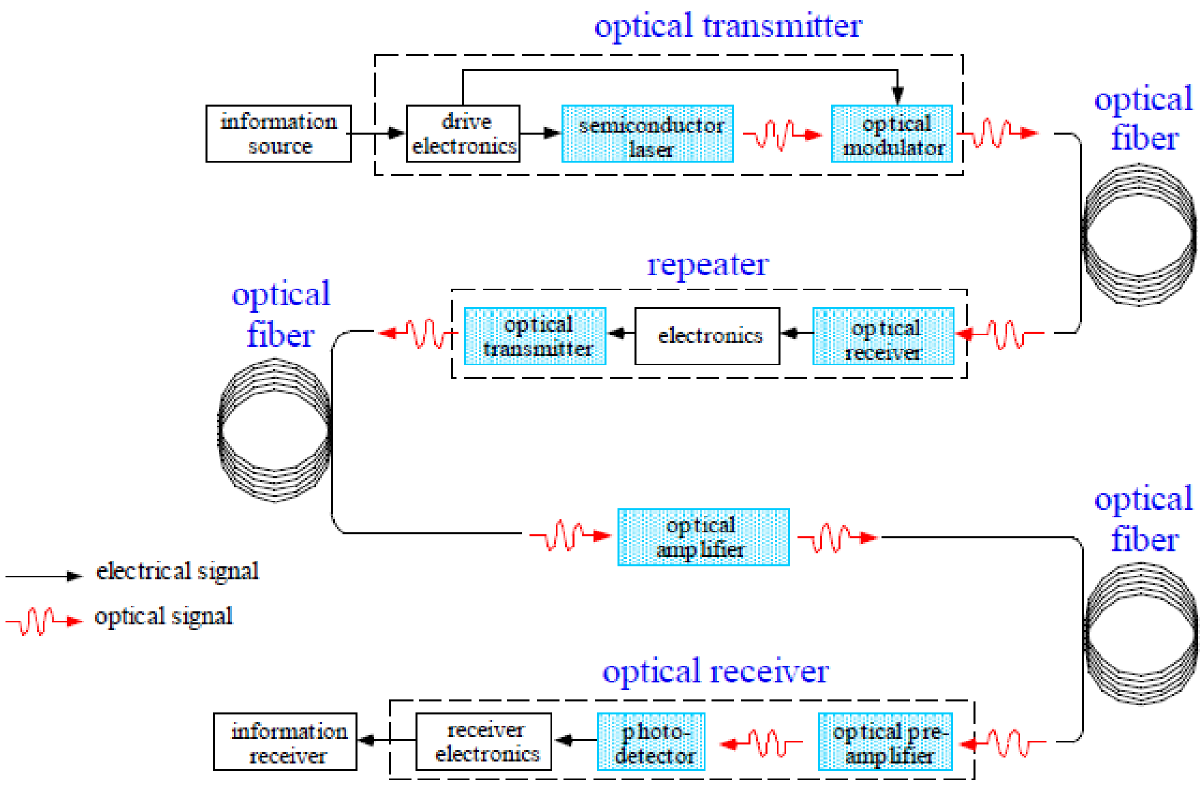
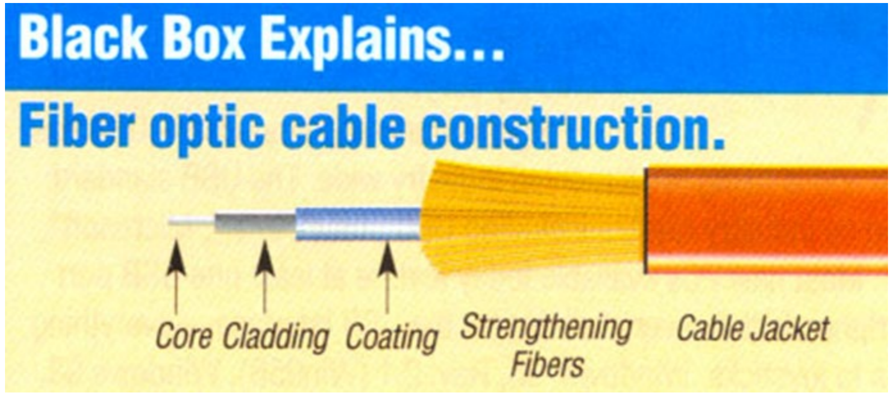
15EC431E-PHOTONICS & OPTICAL NETWORKS

Greek word "phos" meaning light





Photonics

- the branch of technology concerned with the properties and transmission of photons, for example in fibre optics.
- **Photonics** is the physical science of light (photon) generation, detection, and manipulation through emission, transmission, modulation, signal processing, switching, amplification, and detection/sensing.
- Most photonic applications are in the range of visible and near-infrared light.
- The term photonics developed as an outgrowth of the first practical semiconductor light emitters invented in the early 1960s and optical fibers developed in the 1970s.

Motivation

- Photonics has found increasing applications in such areas as optical communications, optical sensing, displays and printing.
- The course covers the fundamentals and applications of optical communication networks.

After completion of this course, the student must be able to

- Understand the interaction of photons and matter, the propagation of light in waveguides and optical fibers, the operation principles of light emitting diodes, semiconductor lasers, detectors amplifiers and network Components.
- Explore the operating principles of optical communication systems including wavelength division multiplexing concepts.
- Design simple optical communication link.
- Understand the main types of architectures, protocols and standards governing modern optical networks.

Overview of Syllabus Topics:

UNIT I-INTRODUCTION TO PHOTONICS & OPTICAL FIBER

-Review of optics - The basics of optics will be covered including: Interference, diffraction, Optical coherence, polarization and material and waveguide dispersion, Dispersion shifted fiber, Signal Attenuation.

UNIT –II- OPTICAL FIBER WAVEGUIDES,SOURCES AND DETECTORS

- The module will discuss the propagation of light in optical waveguides. **Optical fibers** -The module covers the propagation of light in multimode and single mode fibers, coupling into and out of a fiber, and optical non-linearities. **Optical sources and detectors** In this module the physics of light emission and amplification in a semiconductor, light emitting diodes, semiconductor laser fundamentals and photodiodes.

Overview of Syllabus Topics:

UNIT III-OPTICAL COMPONENTS AND SYSTEM DESIGN

Principle and Operation of couplers/splitters, WDM MUX/DEMUX ,

[Optical MUX and DEMUX In order to transmit data from point to point the the different channels have the be merged on the transmitter side and separated on the receiver side]

Isolators, Circulators, Fabry Perot Filters, Mach-Zehnder Interferometer, optical switches, EDFA, Semiconductor Optical Amplifier, Optical Link Design, Power penalty - Point- to- point links, System considerations, Link Power budget, Rise time budget.

UNIT-IV – OPTICAL NETWORKS ARCHITECTURE

Optical network concepts, Topology, Metropolitan ,Area Networks, SONET/SDH, Optical specifications, SONET frame structure, Optical transport network, Broadcast and Select networks.

UNIT –V- WDM NETWORK DESIGN

WDM network elements, WDM network design, Cost tradeoffs, Virtual Topology design, and Routing and wavelength assignment, Statistical dimensioning models.

Unit-I: Introduction to Photonics and Optical Fiber

- Review of wave nature and particle nature of light.
- Interaction of light with matter-emission and absorption of radiation.
- Review of optics, Reflection and refraction of plane waves.
- Fresnel's formulas, Interference and interferometers.
- Diffraction, Optical coherence, Polarization of light.
- Material and Waveguide Dispersion.
- Dispersion shifted fiber.
- Signal Attenuation.

Introduction to Photonics and Optical Technologies

- Light influences our lives today in several ways
- Light will play an even more significant role in the future, enabling a revolution in world fiber-optic communications, new modalities in the practice of medicine, biotechnology, optical sensing, lighting and exploration of the frontiers of science, and much more.
- Key technologies for the next century:
  - Photonics and Optical technologies
  - Nanotechnology, Biotechnology

Introduction to Photonics and Optical Technologies (Cont'd)

- The development of the laser in the 1960s produced light with a property never seen before on Earth.
- Coherent light can be directed, focused, and propagated in new ways that are impossible for incoherent light.
- This property of laser light has made possible
  - Fiber-optic communications, compact disks, laser surgery, and a host of other applications.
  - Applications of incoherent light, including optical lithography systems for patterning computer chips, high-resolution microscopes, adaptive optics for Earth-based astronomy, infrared sensors for everything from remote controls to night-vision equipment, and new high-efficiency lighting sources.

Definition: Photonics

- Photonics is the field of science and engineering encompassing the physical phenomena and technologies associated with the generation, transmission, manipulation, detection, and utilization of light.
- Three major developments which enabled the developments during the last 40 years.
  - Invention of the laser
  - Fabrication of low loss optical fibers
  - Introduction of semiconductor devices

Introduction to Photonics

- During the last decade the term photonics has come in use. This term, which was coined in analogy with electronics.
- It reflects the growing tie between optics and electronics stimulated by the increasing role of semiconductor materials and devices in optical systems.
  - Electronic involves the control of charges and
  - Photonics involves the control of photons. The terms optics and photonics are not clear separated.

Some Photonic Applications

- **Telecommunication** – Lasers, modulators, fibers, detectors for communication systems – Free-space optical links
- **Information and Communication Technology** – CCD and CMOS sensors for imaging – Data storage and retrieval (CD, DVD, BluRay) – Optical interconnects (mainly in high performance computing context today)
- Security – Intrusion detection – Laser radar (LIDAR)
- Lighting – LEDs for indoor lighting – LEDs and Lasers for artistic lighting
- Energy – Solar cells
- Biophotonics – Optical tweezers, optical scalpels – Optical tomography
- Military
  - – Surveillance – Weapon guidance – Countermeasures and laser guns
- **Sensors and spectroscopy** – ”Smart cameras” for image processing/machine vision –
- Many, many applications, including sensors for measuring:
  - Position, distance, thickness etc.
  - Angular rate (ring laser/fiber gyroscopes)
  - Gas concentration (using absorption).


Blu-Ray disc


LED-TV


Environmental monitoring

Fiber-optic gyroscope


LED light bulb

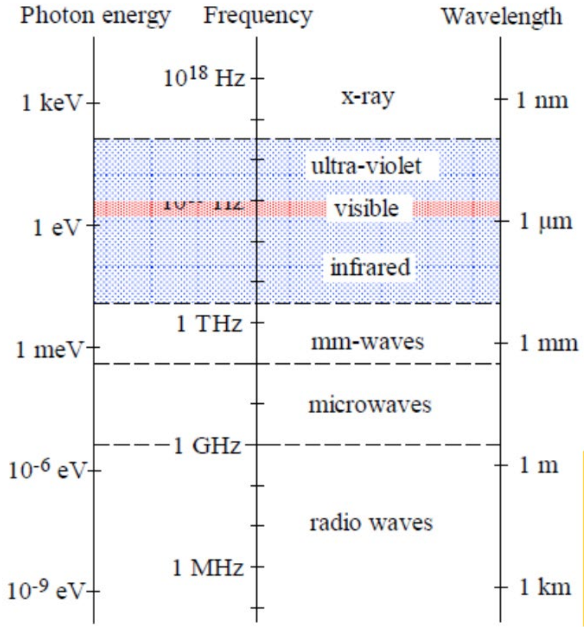

Optical communication


Solar cell

Definition: Optics

- **Optics** is the branch of physics which involves the behaviour and properties of light, including its interactions with matter and the construction of instruments that use or detect it.
- Optics usually describes the behaviour of visible, ultraviolet, and infrared light.
- Because light is an electromagnetic wave, other forms of electromagnetic radiation such as X-rays, microwaves, and radio waves exhibit similar properties.

The electromagnetic spectrum



The carrier frequency is much higher in lightwave systems than in microwave systems

Lightwave systems typically use infrared light

Frequency: $\nu \approx 200$ THz
Wavelength: λ, typ. 1.55 µm
Light velocity in vacuum:
$c \approx 2.998 \times 10^8$ m/s

Optics - Applications

- Areas of major importance for the future Optics in Information Technology and Telecommunications
- Information Transport
- Information Processing
- Optical Storage
- Displays Optics in Health Care and Life Sciences
- Surgery and Medicine
- Tools for Biology
- Biotechnology Optical Sensing, Lighting, and Energy
- Optical Sensors and Imaging Systems
- Lighting (Solid State Lighting)
- Optical Sensors and Lighting in Transportation
- Energy (Solar Cells)

Photonics & Optics

Photonics

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Optics

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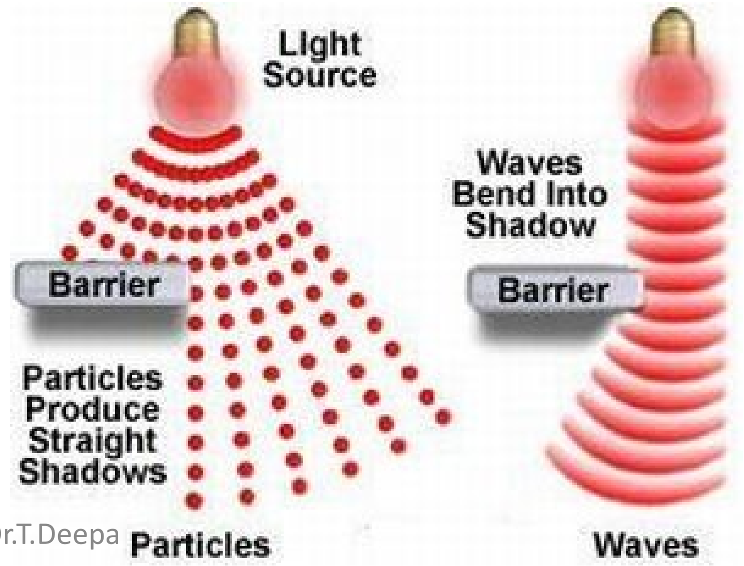
The Dual Nature of Light

- Light is a form of energy.
- Sometimes it behaves like **a particle (called a photon), which explains how light travels in straight lines**
- Sometimes it behaves like **a wave, which explains how light bends (or diffracts) around an object**.
- For this reason, **light is said to have a dual nature**



A Quick Review of "Light" & Photons
History: Newton & Huygens on Light

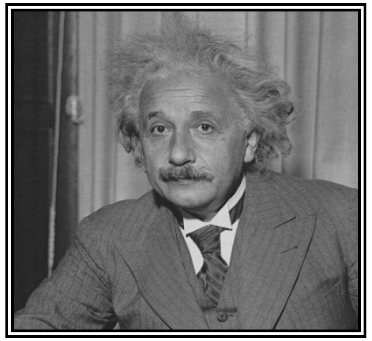
- **Light as waves**
- **Light as particles**

Christiaan Huygens

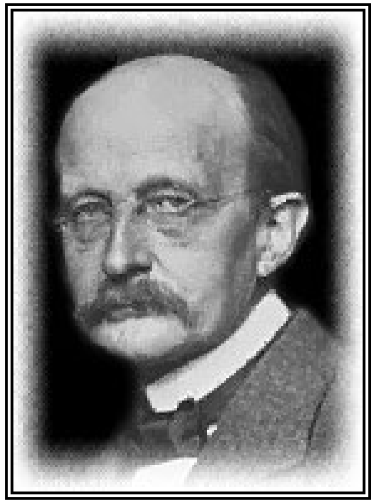
Isaac Newton

They <u>strongly</u> <u>disagreed</u> with each other!

Light – Einstein & Planck



- **1905 Einstein** – Related the wave & particle properties of light when he looked at the **Photoelectric Effect**.



- **Planck** – Solved the "black body" radiation problem by making the (first ever!) quantum hypothesis: Light is quantized into quanta (photons) of energy

E = hν. ***Wave-Particle duality.***

(particles) **(waves)**

- Light is emitted in multiples of a certain minimum energy unit. The size of the unit – **the photon.**
- Explains how an electron can be emitted if light is shined on a metal
- The energy of the light is not spread but propagates like particles .

Photons

- When dealing with events on the atomic scale, it is often best to regard light as composed of quasi- particles: photons

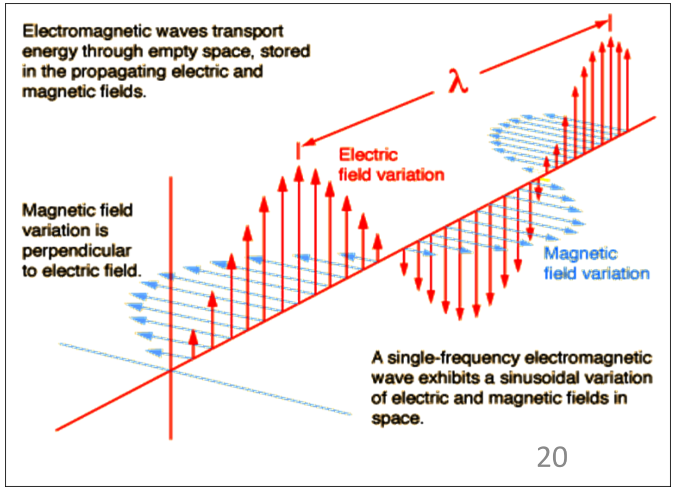
- ***Photons*** are Quanta of light

Electromagnetic radiation is quantized & occurs in finite "bundles" of energy ≡ ***Photons***

- The energy of a single photon in terms of its frequency ν, or wavelength λ is,

- $E_{ph} = h\nu = (hc)/\lambda$

Maxwell – Electromagnetic Waves



Light as an Electromagnetic Wave

- ***Light as an electromagnetic wave*** **is characterized by a combination** of a **time-varying *electric field* (E)** & **a time-varying magnetic field (H)** propagating through space.
- **Maxwell's Equations** give the result that **E** & **H** satisfy the same wave equation:

$$\nabla^2 (\mathbf{E}, \mathbf{H}) = \frac{1}{c^2}\left(\frac{\partial^2}{\partial t^2}\right)(\mathbf{E}, \mathbf{H})$$

Changes in the fields propagate through free space with speed c.

Speed of Light, c

- The frequency of oscillation, ν of the fields & their wavelength, λ_o in vacuum are related by: $c = \nu\lambda_o$
- In any other medium the speed, **v** is given by: $v = c/n = \nu\lambda$

  $n \equiv$ ***refractive index*** of the medium

  $\lambda \equiv$ ***wavelength*** in the medium

  $\mu_r \equiv$ ***relative magnetic permeability*** of the medium

  $\varepsilon_r \equiv$ ***relative electric permittivity*** of the medium

$$n = \sqrt{\mu_r \varepsilon_r}$$

The speed of light in a medium is related to the electric & magnetic properties of the medium. The speed of light c, in vacuum, can be expressed as

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

ε_0 = electric permittivity

μ_0 = magnetic permeability

Fiber Systems vs Wireless Systems

- Fiber systems:
- High data rates
- Long distances
- One “ether” per system
- Static links
- Expensive installation

- Wireless systems:
- “Low” data rates
- Short distances
- Shared “ether” – Limiting regulations – Cross-talk problems
- Enables mobility
- Easy and flexible installation.

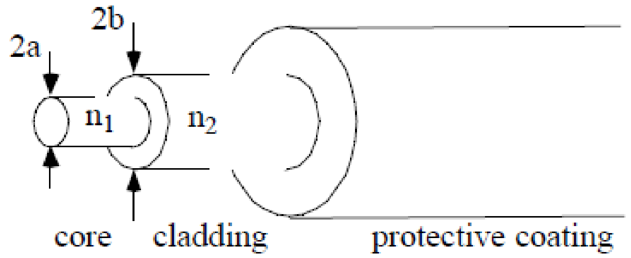
Wireless and optical fiber communication are complementary rather than competing technologies

Properties of Optical Fiber

- **Advantages:**
- Low attenuation (~0.2 dB/km)
- Large bandwidth (1.55 μm–1.3 μm = 250 nm > 30 THz)
- Low weight, compact, flexible
- Isolated from the environment – No crosstalk from other fibers or microwave sources
- Low sensitivity to environmental conditions — Immune to electromagnetic interference
- Provides electrical isolation between terminals – No ground loops, damage cannot cause sparking
- **Disadvantages:**
- Not wireless, installation is costly and slow
- Hardware is expensive compared to mass-produced electronics

Basics of Fiber Optic Waveguide

- Composed of two layers, called the core and the cladding.
- The core and cladding have different refractive indices, with the core having a refractive index of n1, and the cladding having a refractive index of n2.
- Wave-guiding: n1 > n2 .
- The Refraction Index is a way of measuring the speed of light in a material.
- The index of refraction is calculated by dividing the speed of light in a vacuum by the speed of light in another medium.
- Light travels fastest in a vacuum. The actual speed of light in a vacuum is 300,000 kilometers per second, or 186,000 miles per second.
- Most commonly used fiber material is silica (SiO_2)
- • To change index of refraction dopants are added
- – Dopants can increase or decrease the index of refraction
- – Can dope either the core or the cladding



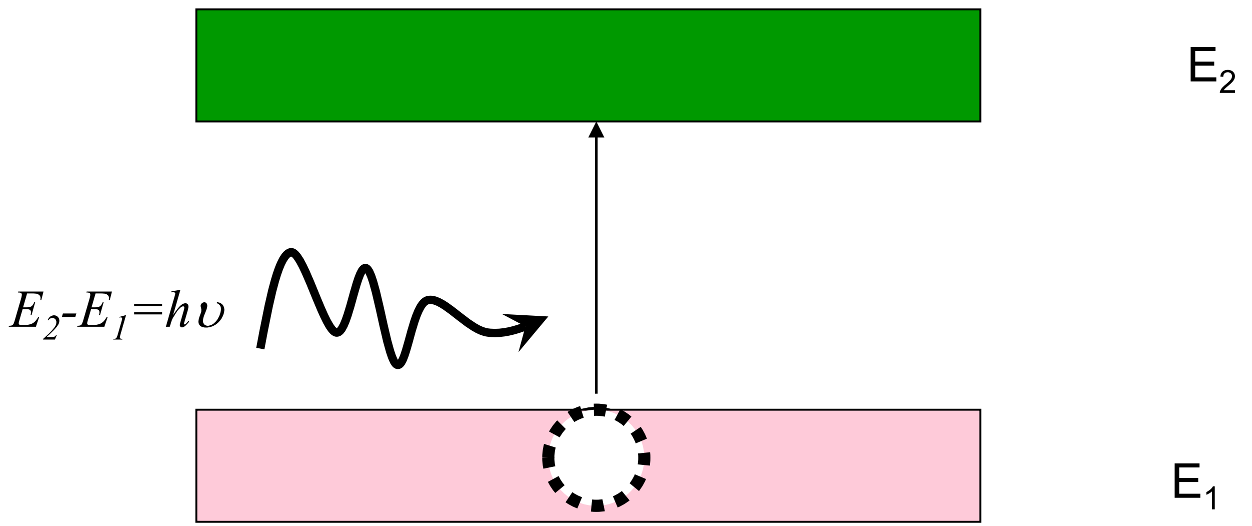
Definition of LASER

- **A LASER is a quantum mechanical optical device that amplifies light by a process called STIMULATED EMISSION.**
- **LASER - Light Amplification by Stimulated Emission of Radiation**
- A **laser** is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term "laser" originated as an acronym for "**light amplification by stimulated emission of radiation**".
- The first laser was built in 1960 by Theodore H. Maiman at Hughes Research Laboratories, based on theoretical work by Charles Hard Townes and Arthur Leonard Schawlow.

- **Inspiration for LASERS: Albert Einstein - 1917**

Interaction of Light with Matter

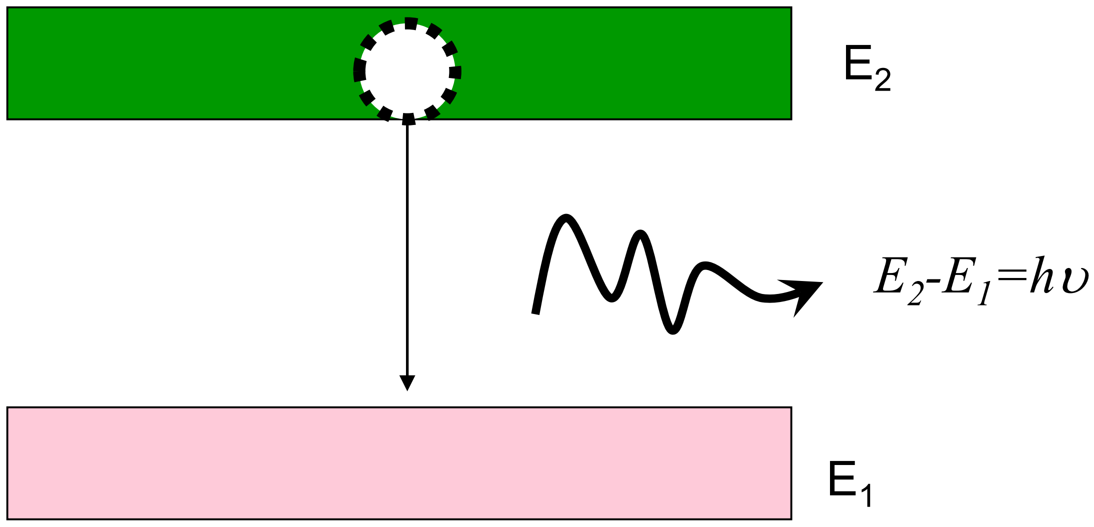
1. Absorption



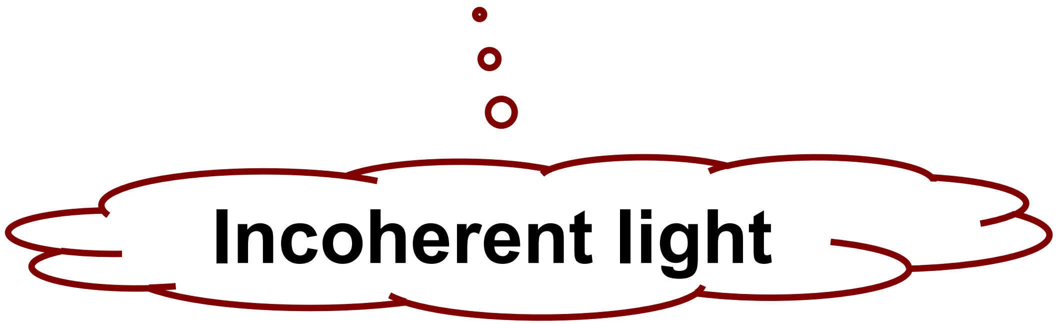
hυ + atom ➔ atom*

Attenuation

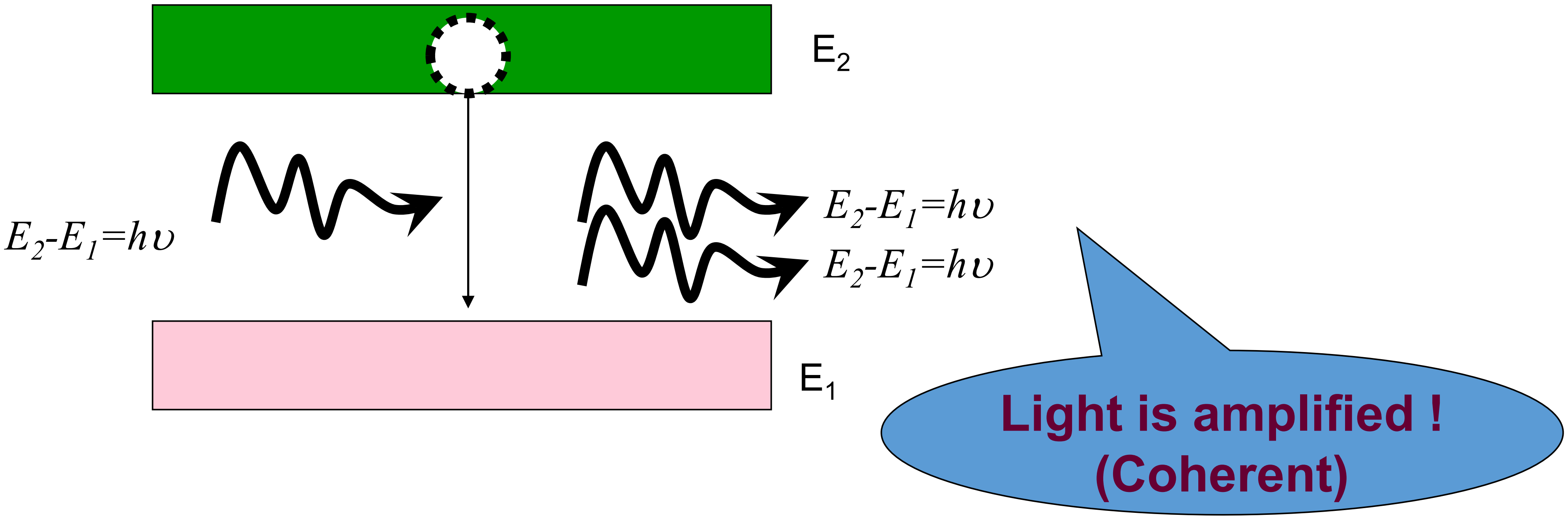
2. Spontaneous Emission



atom* → atom + hυ

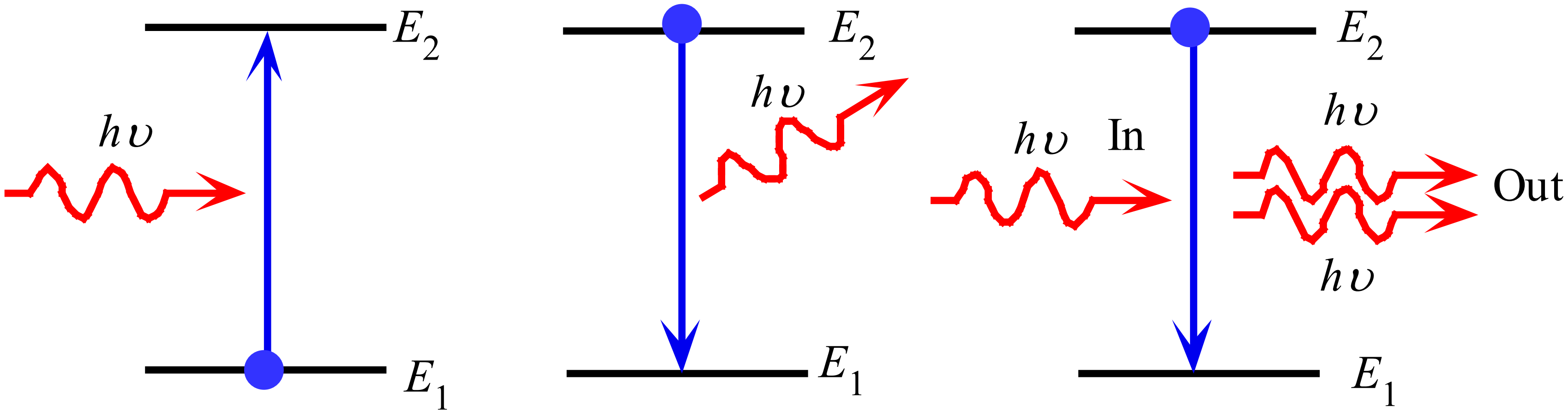


3. Stimulated Emission



Stimulated emission is the process by which an incoming photon of a specific frequency can interact with an excited atomic electron (or other excited molecular state), causing it to drop to a lower energy level. The liberated energy transfers to the electromagnetic field, creating a new photon with a phase, frequency, polarization, and direction of travel that are all identical to the photons of the incident wave.

A Recap of Three Processes



(a) Absorption (b) Spontaneous emission (c) Stimulated emission

Absorption, spontaneous (random photon) emission and stimulated emission.

Light Propagation in Optical Fibers

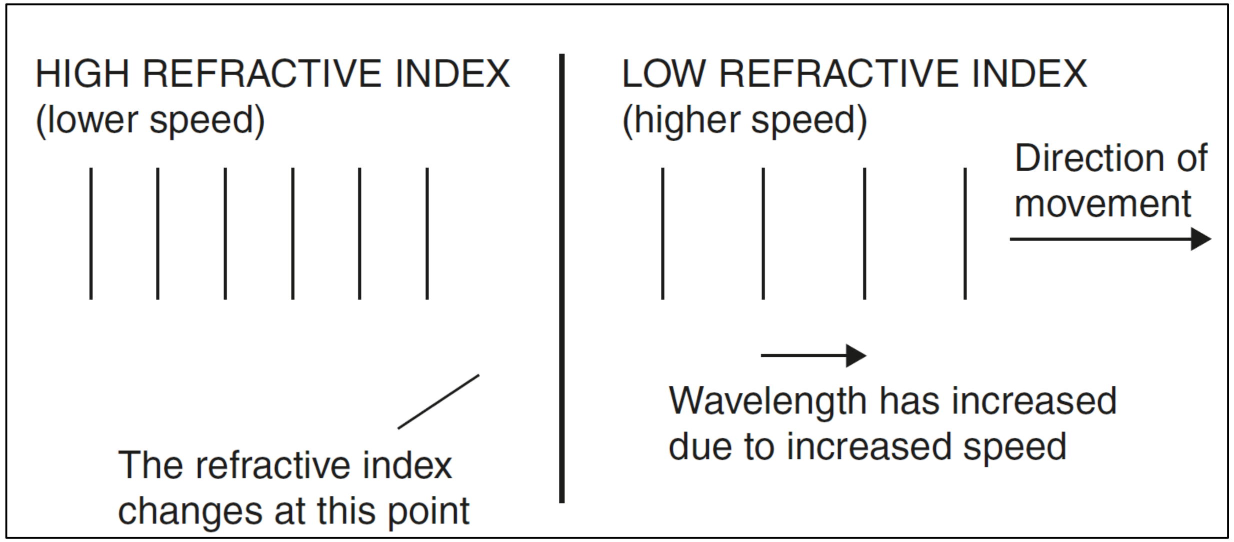
- The speed of light depends upon the material through which it is moving.
- In free space light travels at its maximum possible speed, close to 300 million meters per second
- When it passes through a clear material, it slows down by an amount dependent upon a property of the material called its ***refractive index***.
- For most materials that we use in optic fibers, the refractive index is in the region of 1.5.

Speed of light in free space / speed of light in the material = Refractive Index

- With the refractive index on the bottom line of the equation, this means that the lower the refractive index, the higher the speed of light in the material.

lower refractive index = higher speed

Light Propagation in Optical Fibers

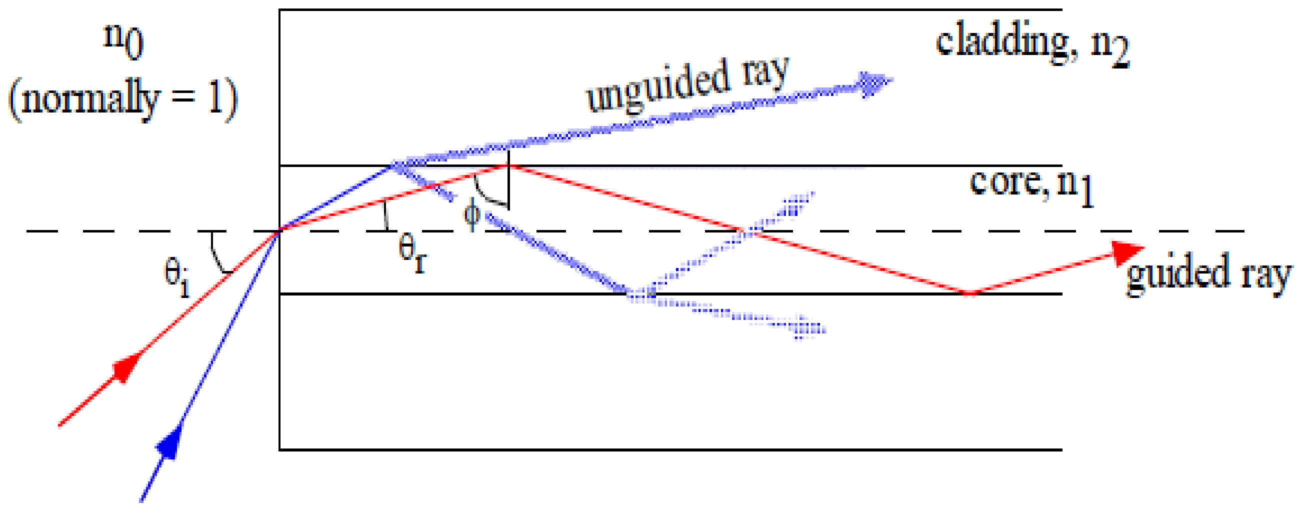


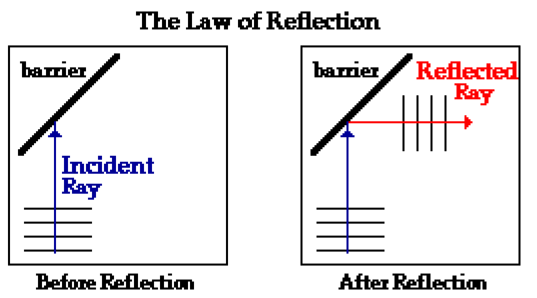
- A ray of light moving from a material of high refractive index to another material with a lower index in which it would move faster.
- The distances between the successive wave crests, or the wavelength, will increase as soon as the light moves into the second material.
- The direction that the light approaches the boundary between the two materials is very significant.

- Here, light is traveling at right angles to the boundary

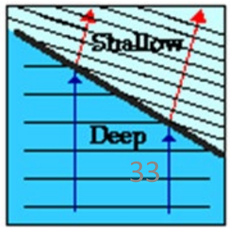
Geometrical-Optics Description

- Light is guided through the core, and the fiber acts as an optical waveguide.





Reflection involves a change in direction of waves when they bounce off a barrier.



Refraction of waves involves a change in the direction of waves as they pass from one medium to another. **Refraction**, or the bending of the path of the waves, is accompanied by a change in speed and wavelength of the waves.

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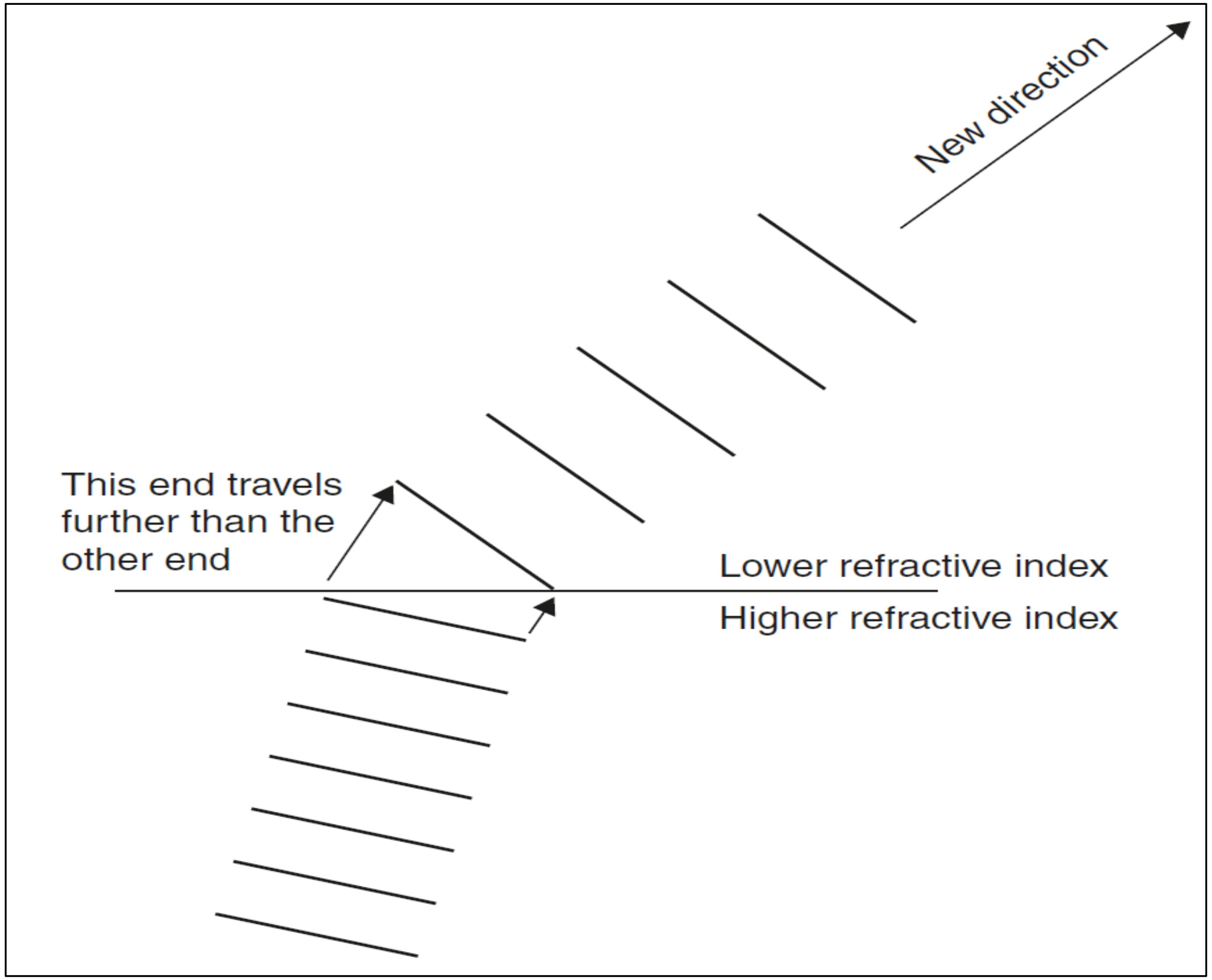
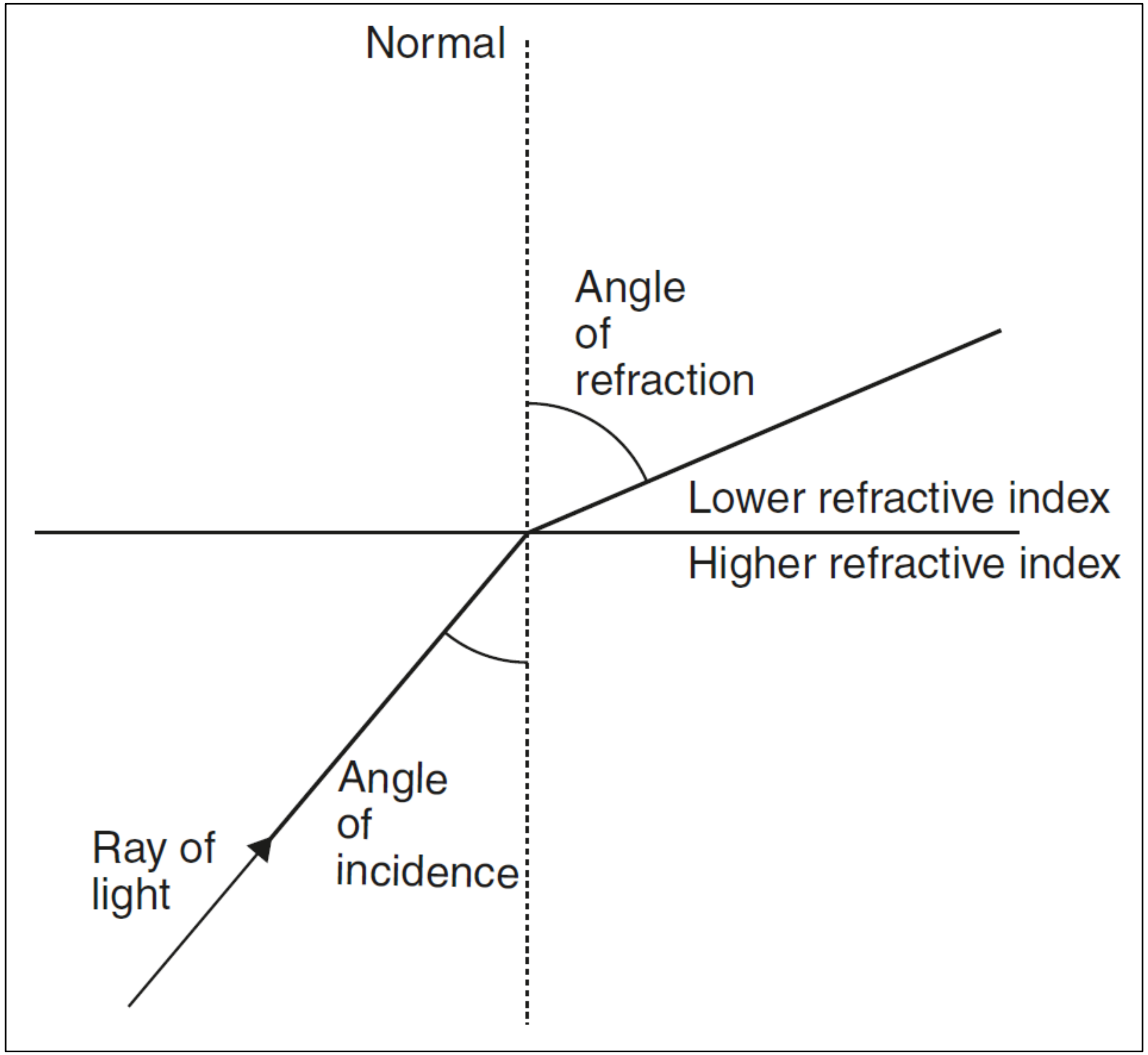
Geometrical-Optics Description



- Now, a ray approaching at another angle.
- As the ray crosses the boundary between the two materials, one side of the ray will find itself traveling in the new, high velocity material whilst the other side is still in the original material.
- The result of this is that the wavefront progresses further on one side than on the other.
- This causes the wavefront to diverge.
- The ray of light is now wholly in the new material and is again traveling in a straight line although at a different angle and speed.
- The amount by which the ray swerves and hence the new direction is determined by the relative refractive indices of the materials and the angle at which the ray approaches the boundary.

Snell's Law

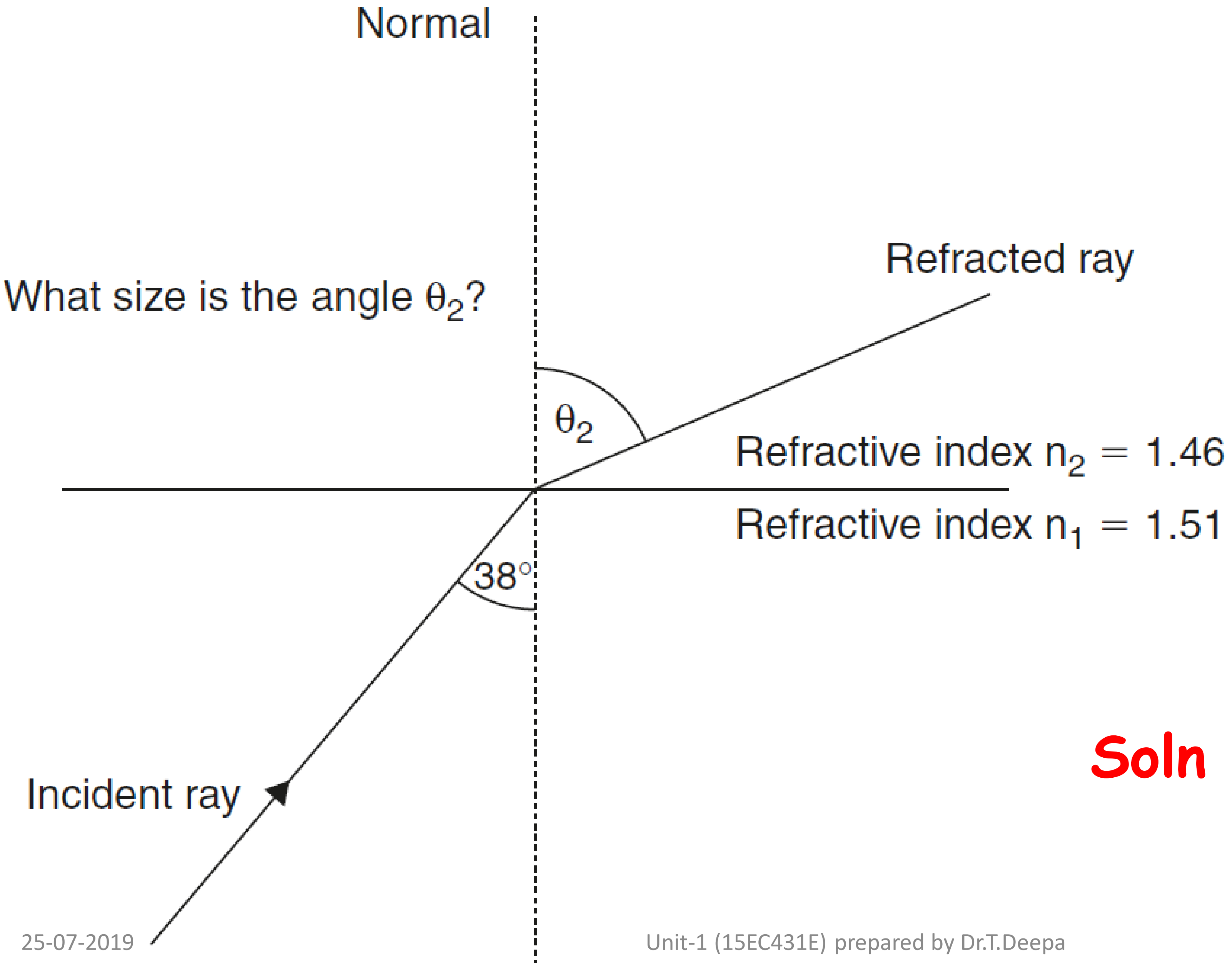


- The angle of the incoming and outgoing rays are called the angles of incidence and refraction, respectively.
- The angles are measured w.r.t. the normal
- This is a line drawn at right angles to the boundary line between the two refractive indices
- The angle increases as it crosses from the higher
- refractive index to the one with the lower refractive index

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

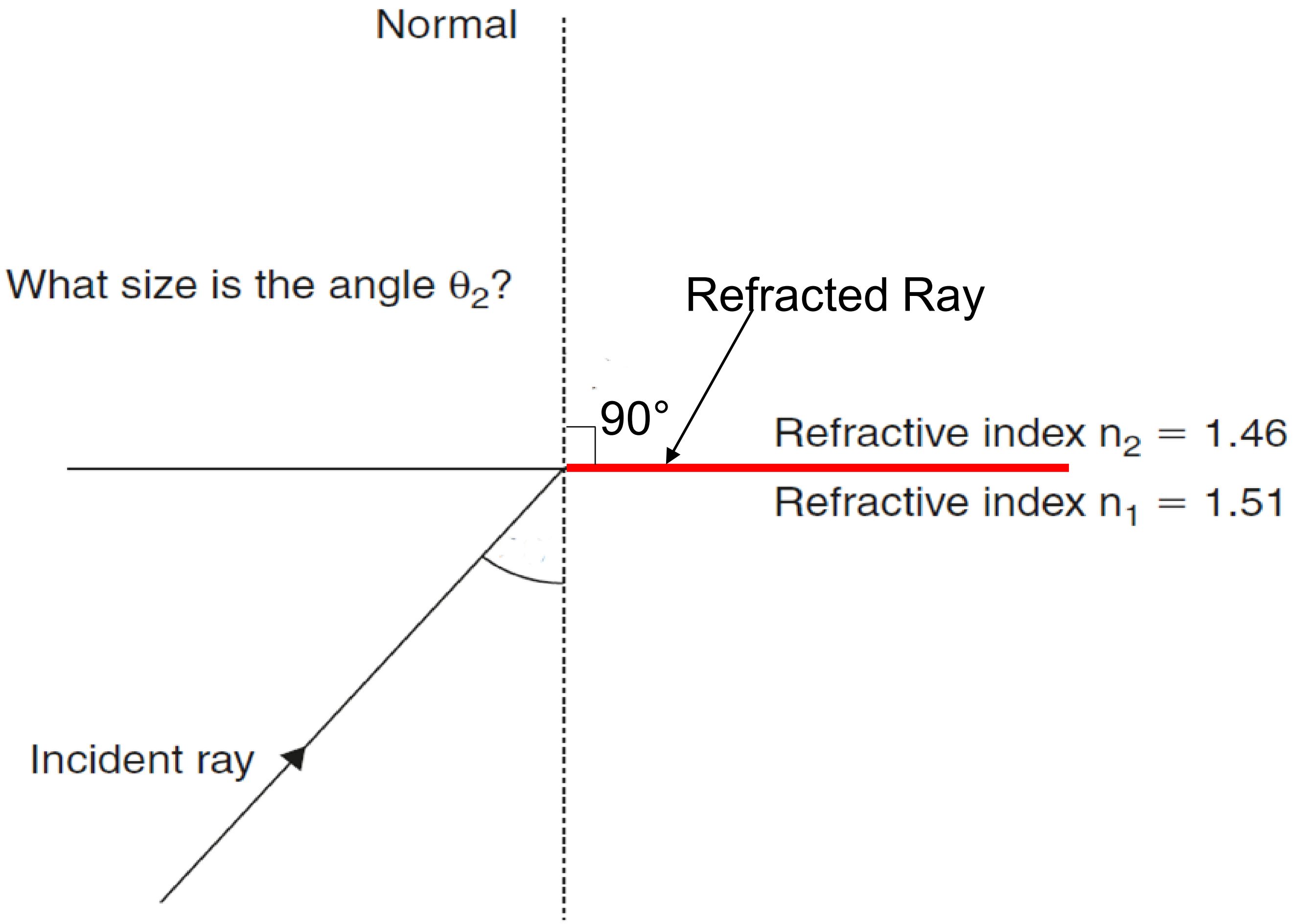
- n_1 and n_2 are the refractive indices of the two materials
- $\sin\theta_1$ and $\sin\theta_2$ are the angles of incidence and refraction respectively

Snell's Law – An Example



Soln : $\theta_2 = 39.55°$

Critical Angle



- The angle of the ray increases as it enters the material having a lower refractive index.
- **As the angle of incidence in the first material is increased, there will come a time when, eventually, the angle of refraction reaches 90° and the light is refracted along the boundary between the two materials.**
- The angle of incidence which results in this effect is called the critical angle.
- $n_1 \sin\theta_1 = n_2 \sin 90°$

$$\theta_{critical} = \sin^{-1}(n_2/n_1)$$

Critical Angle– An Example

A light ray is traveling in a transparent material of refractive index 1.51 and approaches a second material of refractive index 1.46. Calculate the critical angle.

Soln:

$\theta_{critical} = \sin^{-1} \frac{n_2}{n_1}$

$\theta_{critical} = \sin^{-1} (1.46/ 1.51)$

$\theta_{critical} = 75.2°$

Total Internal Reflection

- The propagation of light down the fiber-optic cable using the principle of total internal reflection.
- As illustrated, a light ray is injected into the fiber-optic cable on the left.
- If the light ray is injected and strikes the core-to-cladding interface at an angle greater than the critical angle with respect to the normal axis, it is reflected back into the core. Because the angle of incidence is always equal to the angle of reflection, the reflected light continues to be reflected.
- The light ray then continues bouncing down the length of the fiber-optic cable. If the angle of incidence at the core-to-cladding interface is less than the critical angle, both reflection and refraction take place.
- Because of refraction at each incidence on the interface, the light beam attenuates and dies off over a certain distance.

Definition : Total Internal Reflection

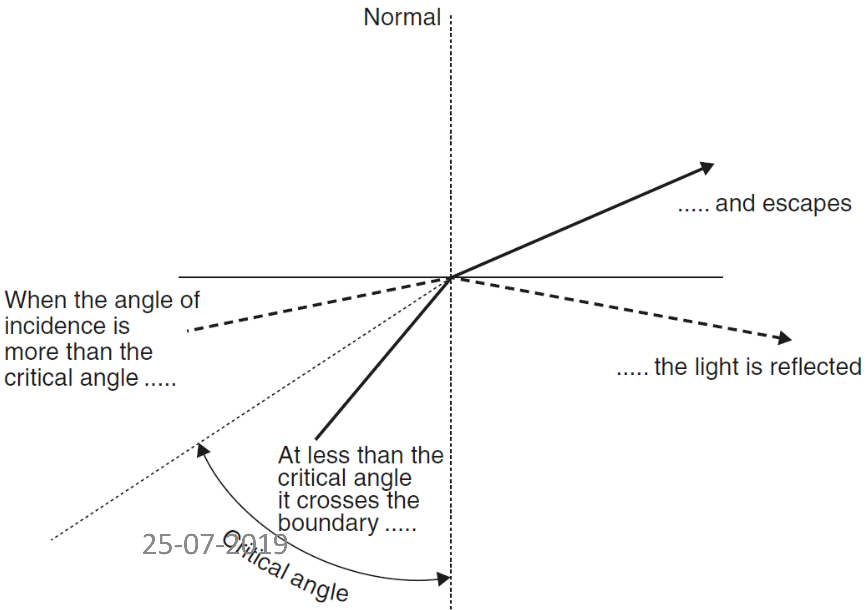
- At angles of incidence less than the critical angle, the ray is refracted.
- However, if the light approaches the boundary at an angle greater than the critical angle, the light is actually reflected from the boundary region back into the first material.
- The boundary region simply acts as a mirror.
- This effect is called total internal reflection (TIR).
- Any ray launched at an angle greater than the critical angle will be propagated along the optic fiber.

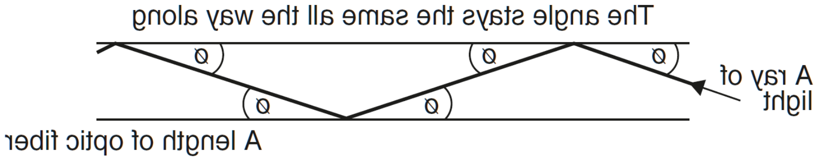
Conditions for Total Internal Reflection

Two necessary conditions for TIR to occur are :

1. **The refractive index of first medium (n_1) must be greater than the refractive index of second one (n_2) i.e. $n_1 > n_2$**

2. **The angle of incidence of the ray exceeds the critical value ($\theta_i > \theta_c$)**



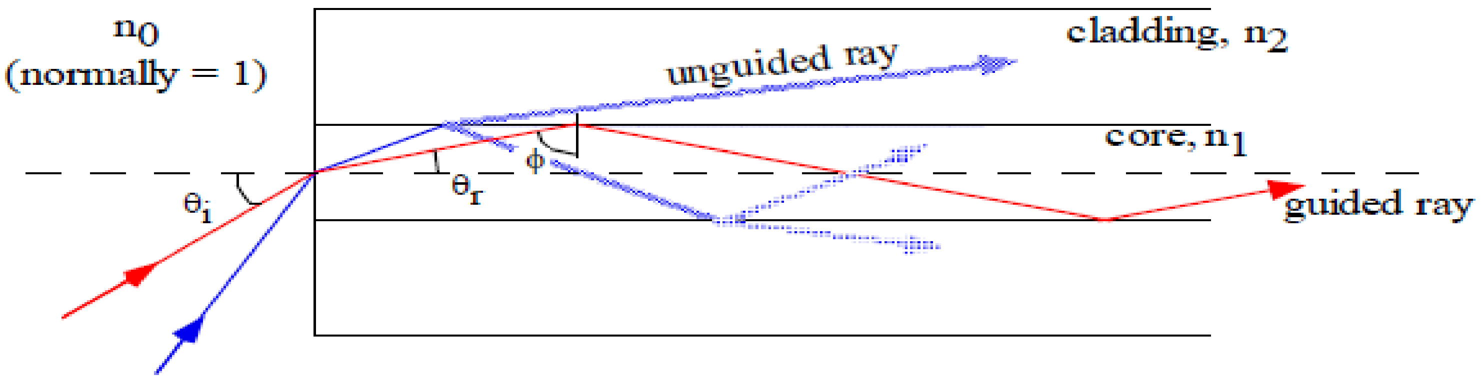


Numerical Aperture

- The ***numerical aperture*** (NA) is a measure of the light-gathering power of an optical system
  - The term originates from microscopy
- For fibers, we have

$$\mathrm{NA} = n_0 \sin\theta_{i,\max} = \sqrt{n_1^2 - n_2^2} \approx n_1\sqrt{2\Delta}$$

- Clearly, a higher NA is always better!?!
  - No, we get problems with ***dispersion***



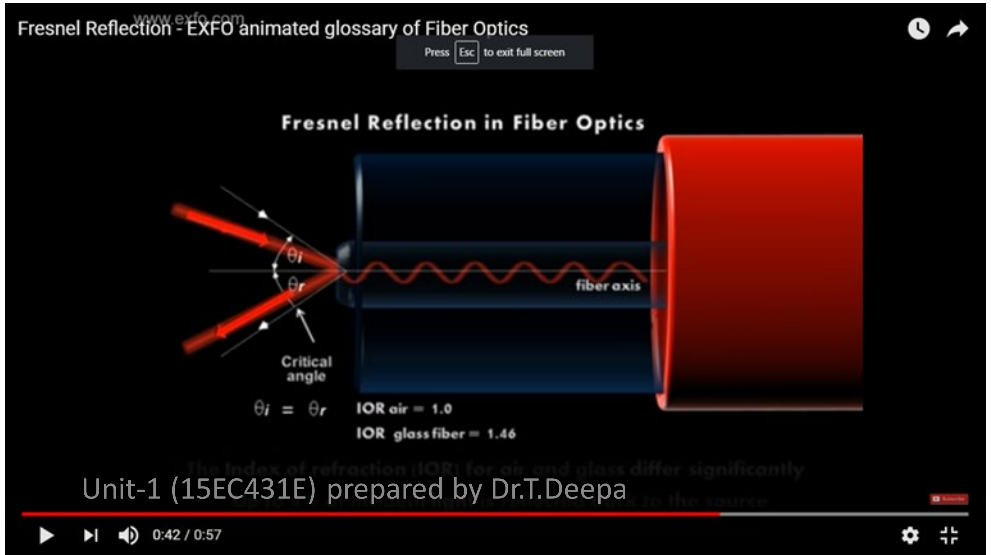
Fresnel's Equations

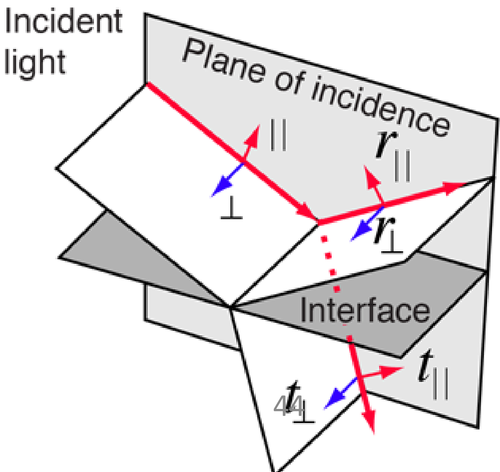
- When light strikes the interface between a medium with refractive index n_1 and a second medium with refractive index n_2, both reflection and refraction of the light may occur.
- The Fresnel equations describe the ratios of the reflected and transmitted waves' electric fields to the incident wave's electric field (the waves' magnetic fields can also be related using similar coefficients).
- Since these are complex ratios, they describe not only the relative amplitude, but phase shifts between the waves.
- The equations assume the interface between the media is flat and that the media are homogeneous and isotropic. The incident light is assumed to be a plane wave, which is sufficient to solve any problem since any incident light field can be decomposed into plane waves and polarizations.

Fresnel's Equations(Contd)

- Fresnel's equations describe the reflection and transmission of electromagnetic waves at an interface.
- They give the **reflection and transmission coefficients for waves parallel and perpendicular to the plane of incidence.**
- For a dielectric medium where Snell’s law can be used to relate the incident and transmitted angles, Fresnel's Equations can be stated in terms of the angles of incidence and transmission.

Fresnel equations describing reflection and refraction of light at uniform planar interfaces.
The return portion of an incident light at an interface between two media that have different refractive indices





Fresnel's equations give the reflection coefficients:

$$r_{\parallel} = \frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)} \qquad r_{\perp} = -\frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)}$$

Transmission Coefficients

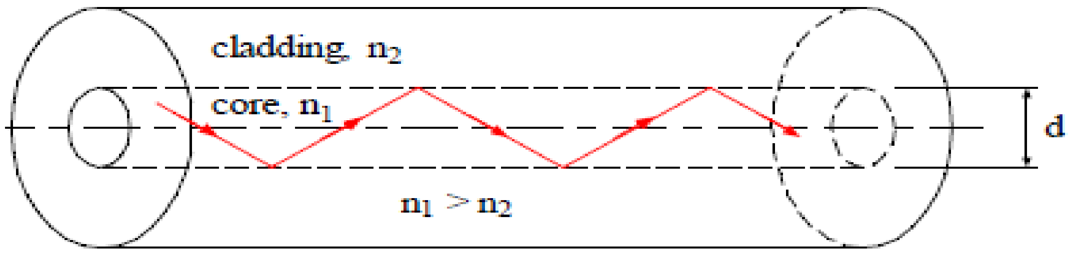
$$t_{\parallel} = \frac{2\sin\theta_t\cos\theta_i}{\sin(\theta_i + \theta_t)\cos(\theta_i - \theta_t)} \qquad t_{\perp} = \frac{2\sin\theta_t\cos\theta_i}{\sin(\theta_i + \theta_t)}$$

Fresnel's Equations (Contd)

These coefficients are fractional amplitudes, and must be squared to get fractional intensities for reflection and transmission.

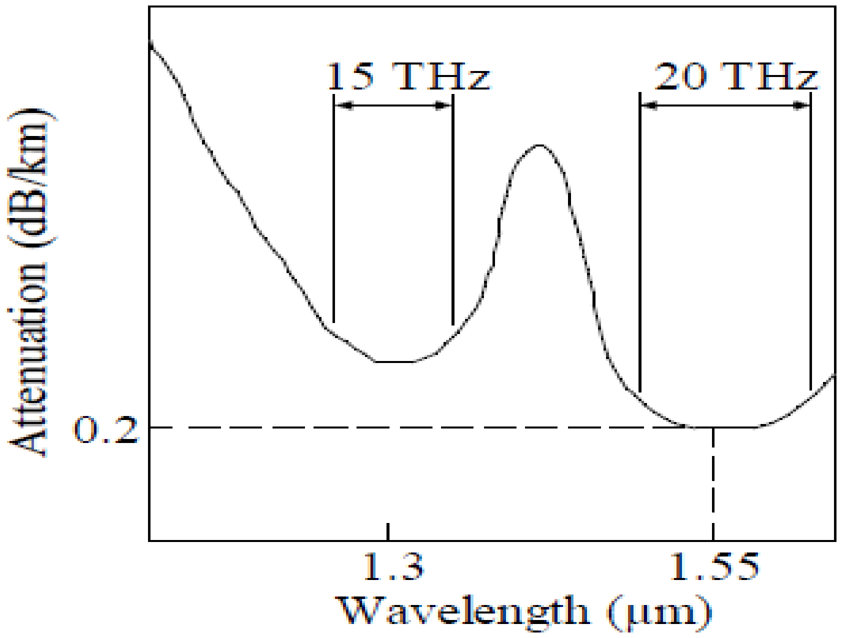
$$\boldsymbol{r^2 + t^2 \frac{n_2 \cos\theta_t}{n_1 \cos\theta_i} = 1}$$

Optical Fiber:



Typical core sizes:

- Single-mode fibers: $d \approx 5–10$ μm
- Multi-mode fibers: $d \approx 50–200$ μm



- Typical attenuation:
  - 0.2 dB/km@1.55 μm
  - 4% power loss per km@1.55 μm
- Available bandwidth:
  - >30 THz in modern fibers

Interference

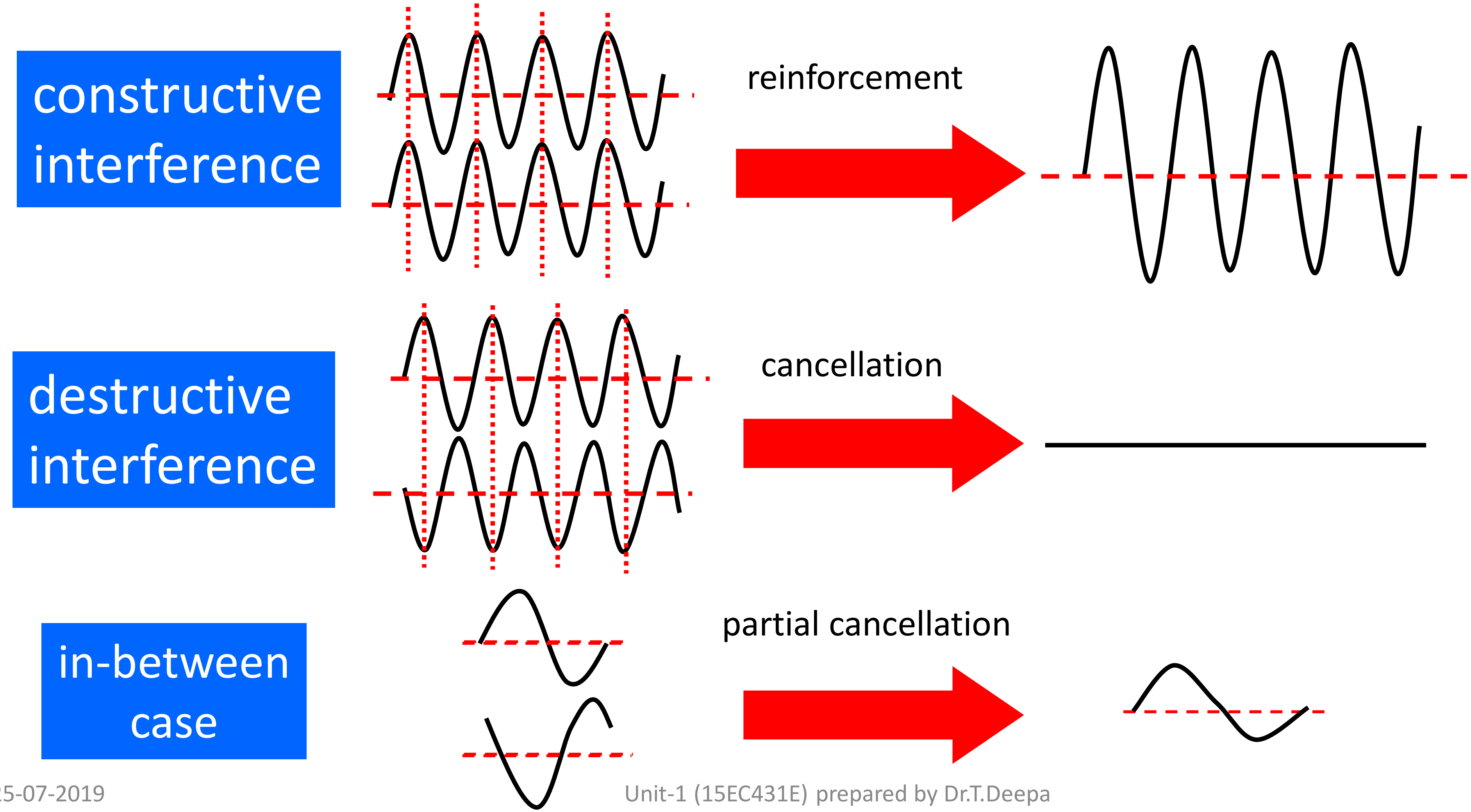
- Light waves interfere with each other much like mechanical waves do
- All interference associated with light waves arises when the electromagnetic fields that constitute the individual waves combine

Conditions for Interference

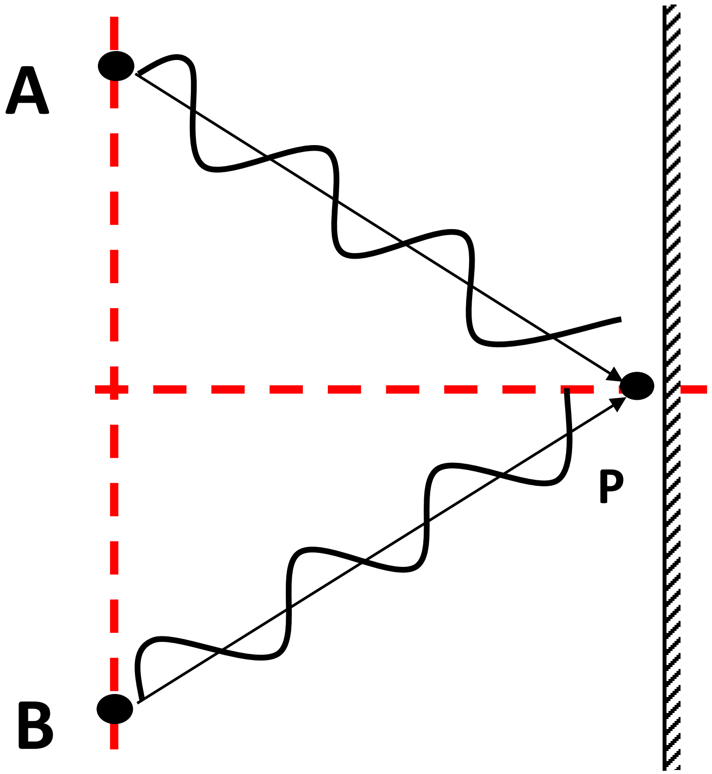
- For sustained interference between two sources of light to be observed, there are two conditions which must be met
  - The sources must be *coherent*
    - They must maintain a constant phase with respect to each other
  - The waves must have identical wavelengths

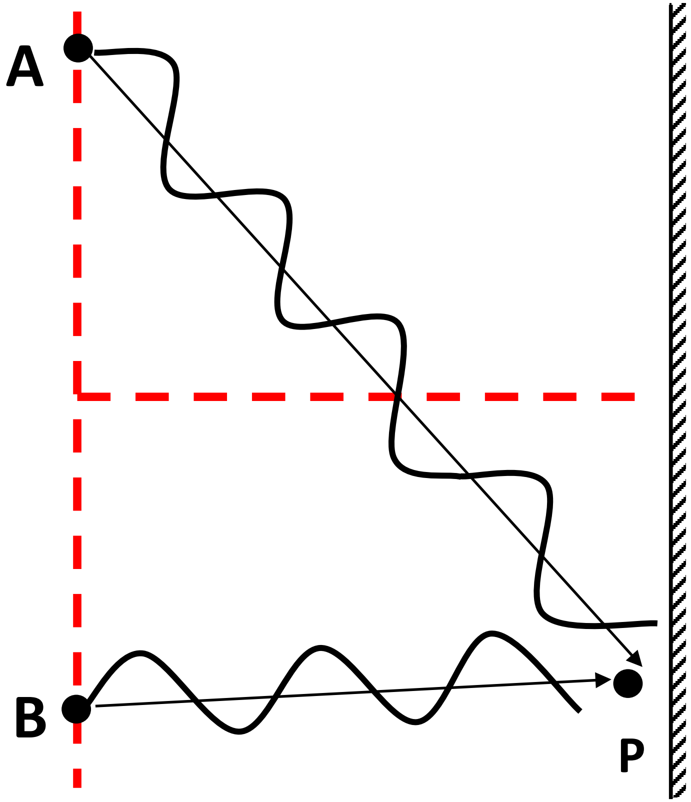
Interference of light

when two light waves are combined, interference can occur → more light intensity or less light intensity



Interference of light- Spatial Interference





Waves leave A and B in phase, travel the same distance to P, and arrive in phase. P is a bright spot → Constructive interference

Waves leave A and B in phase, but travel different distances to P, and arrive out of phase. P is a dark spot → Destructive interference

Coherent Sources

- Light from a monochromatic source is allowed to pass through a narrow slit
- The light from the single slit is allowed to fall on a screen containing two narrow slits
- The first slit is needed to insure the light comes from a tiny region of the source which is coherent
- Old method

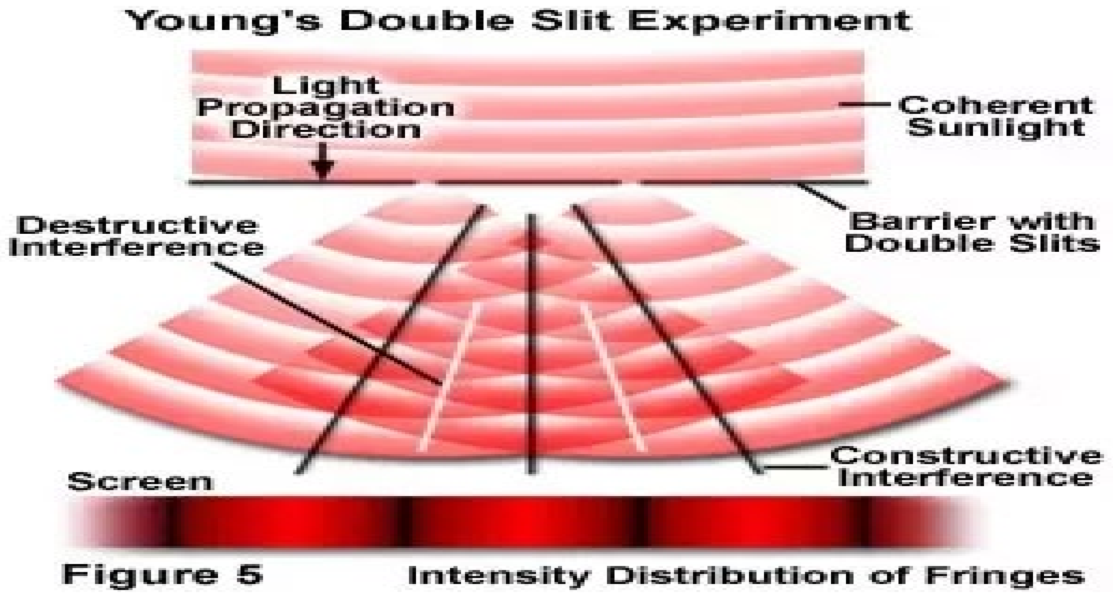
➢ Currently, it is much more common to use a laser as a coherent source

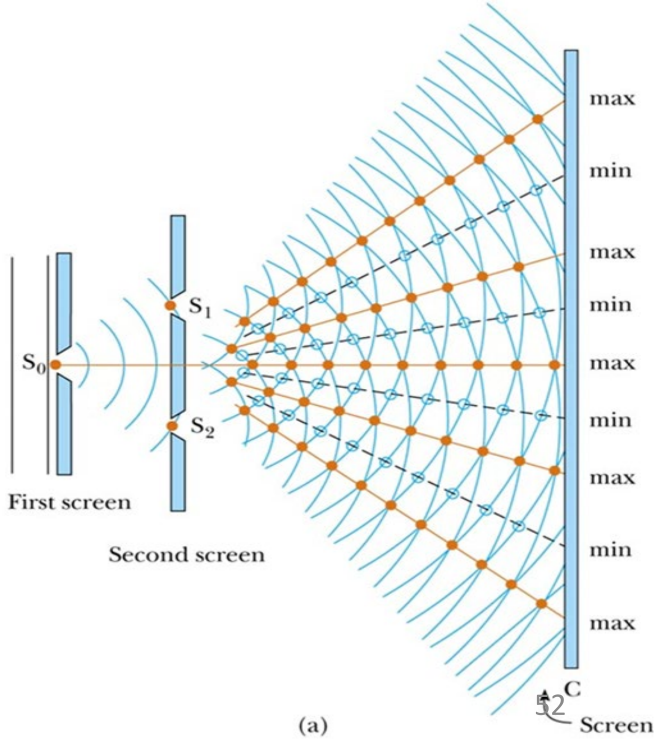
➢ The laser produces an intense, coherent, monochromatic beam over a width of several millimeters

➢ The laser light can be used to illuminate multiple slits directly

Interference of Light

- When two light waves from different coherent sources meet together, then the distribution of energy due to one wave is disturbed by the other.
- This modification in the distribution of light energy due to superposition of two light waves is called "Interference of light".





Conditions for Interference

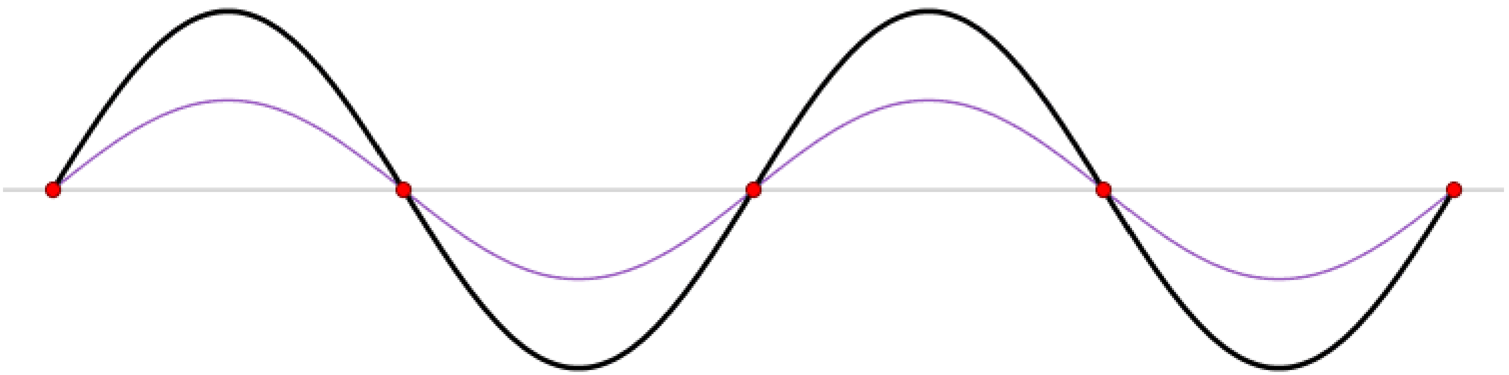
- The two sources of light should emit continuous waves of same wavelength and same time period. i.e.the source should have phase coherence.
- The two sources of light should be very close to each other.
- The waves emitted by two sources should either have zero phase difference or no
- **Coherent Sources**: Those sources of light which emit light waves continuously of same wavelength, and time period, frequency and amplitude and have zero phase difference or constant phase difference are coherent sources. phase difference.

Types of Interference

- Constructive interference –
  - when the peak of one wave merges with the peak of an identical wave, they add together and 'construct' a larger wave.
- Destructive Interference
  - the peak of one wave meets the valley of an identical wave, and they totally cancel each other out (they 'destroy' each other).

Definitions: Constructive & Destructive

In nature, the peaks and valleys of one wave will not always perfectly meet the peak or valley of another wave. Regardless of how they merge, however, the height of the wave resulting from the interference always amounts to the sum of the heights of the merging waves. When the waves don't meet up perfectly, '*partial*' constructive or destructive interference can occur. The animation below illustrates this effect. The black wave goes through a full range of heights from twice as high and deep (where total constructive interference occurs) to flat (where total destructive interference occurs) as the red and blue waves interact.



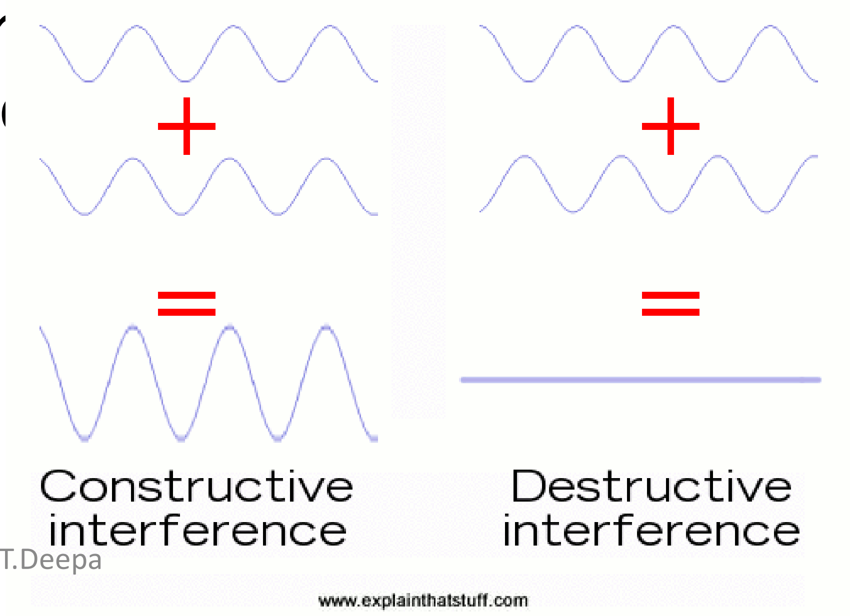
Effects- Constructive vs. Destructive Interference

Constructive

- Two waves of light reinforce each other.
- A bright fringe is obtained on the screen.

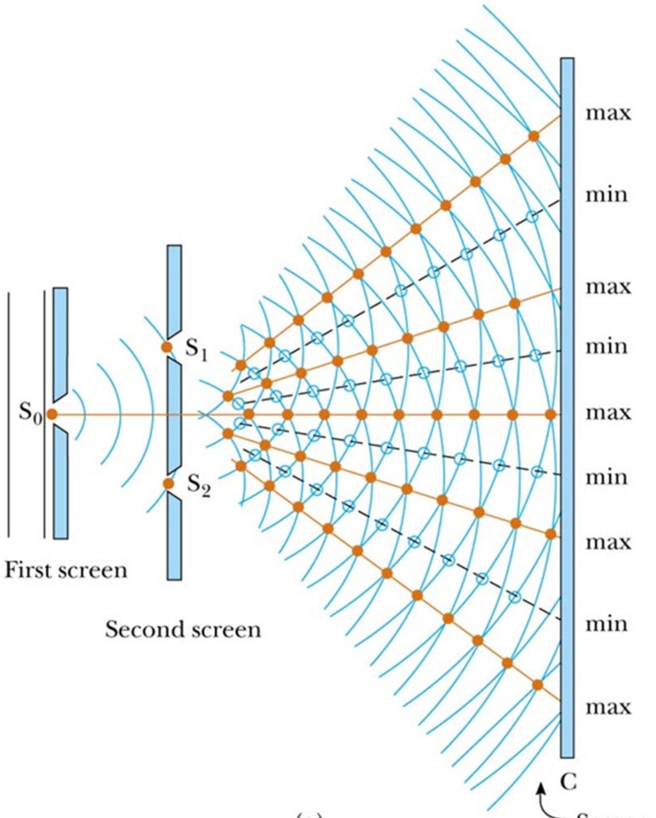
Destructive

- Two waves cancel the effects of each other
- Due to destructive interference a dar
scr



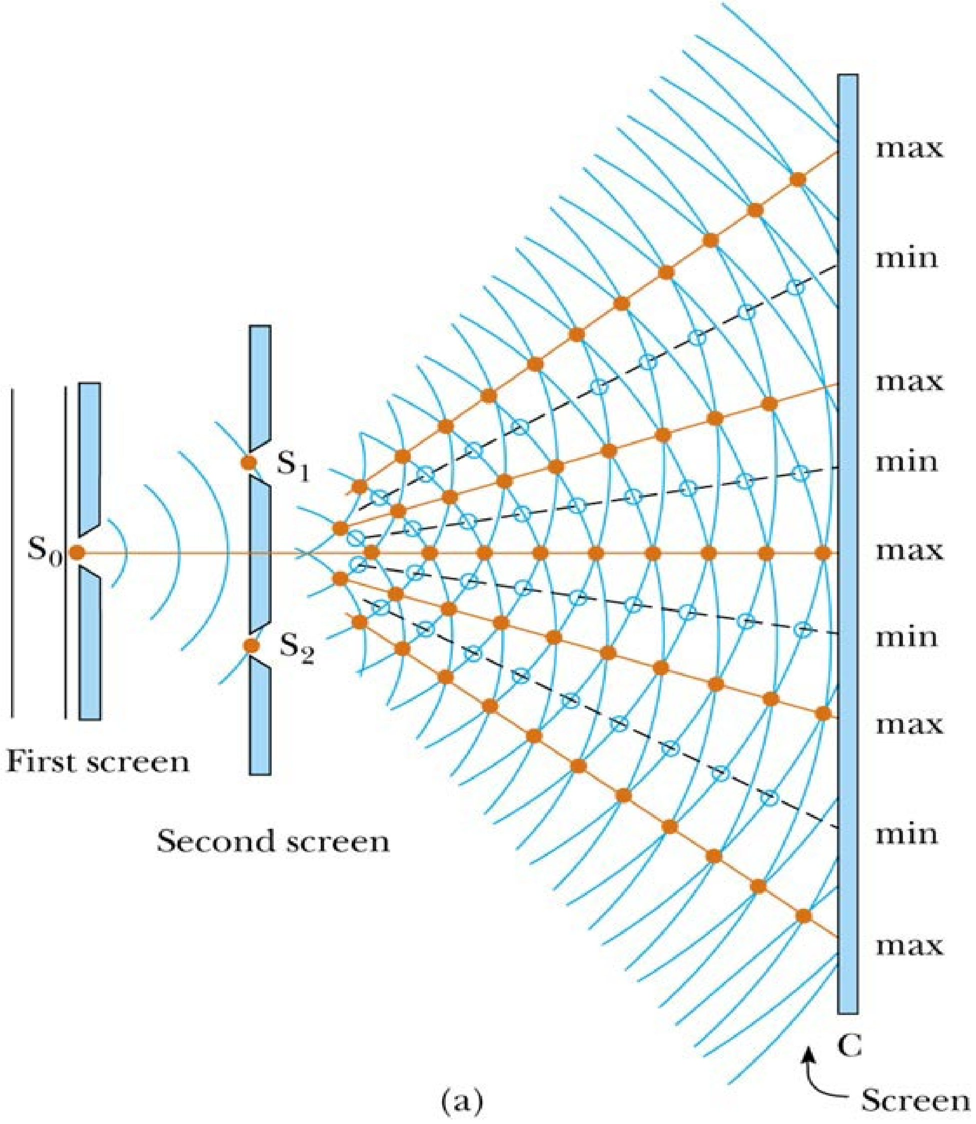
Young's Double Slit Experiment

- Thomas Young first demonstrated interference in light waves from two sources in 1801
- Light is incident on a screen with a narrow slit, S_o
- The light waves emerging from this slit arrive at a second screen that contains two narrow, parallel slits, S_1 and S_2
- The narrow slits, S_1 and S_2 act as sources of waves
- The waves emerging from the slits originate from the same wave front and therefore are always in phase



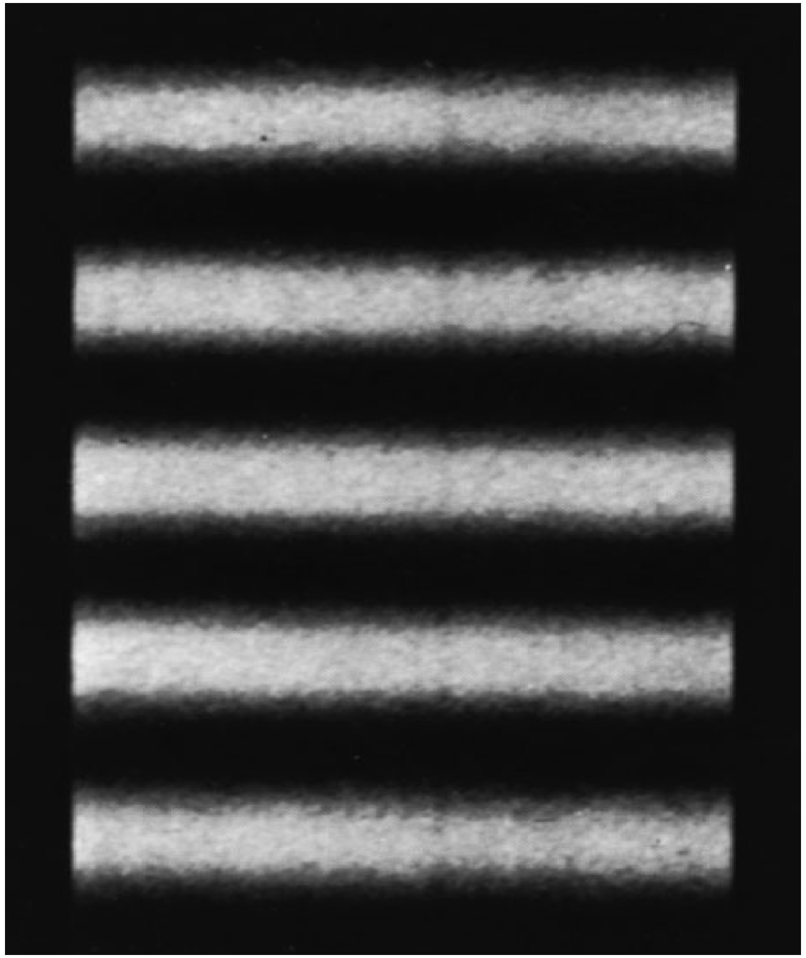
(a)

Young's Double Slit Experiment- Interference



- The light from the two slits form a visible pattern on a screen
- The pattern consists of a series of bright and dark parallel bands called **fringes**
- *Constructive interference* occurs where a bright fringe appears
- *Destructive interference* results in a dark fringe

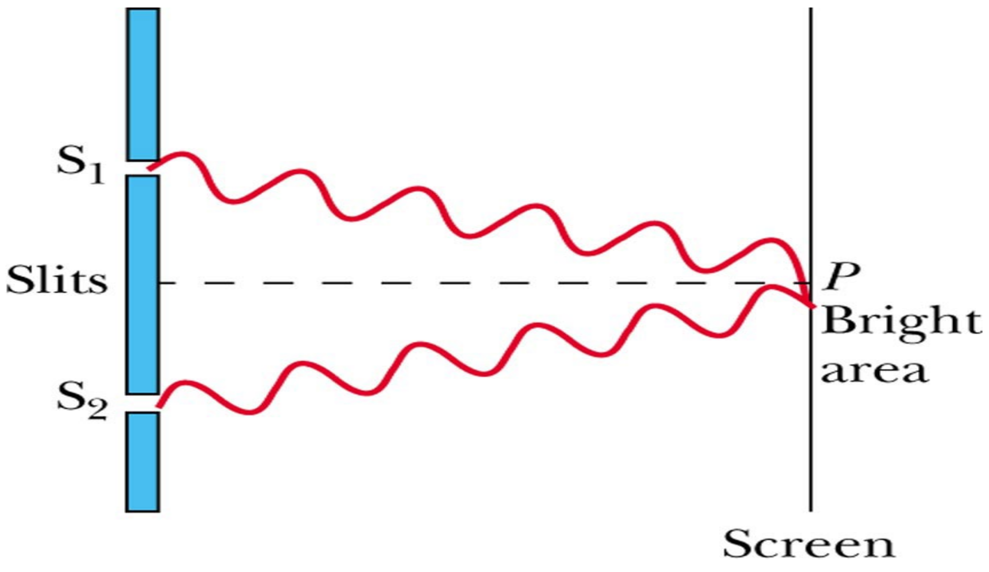
Young’s Double Slit Experiment- Interference



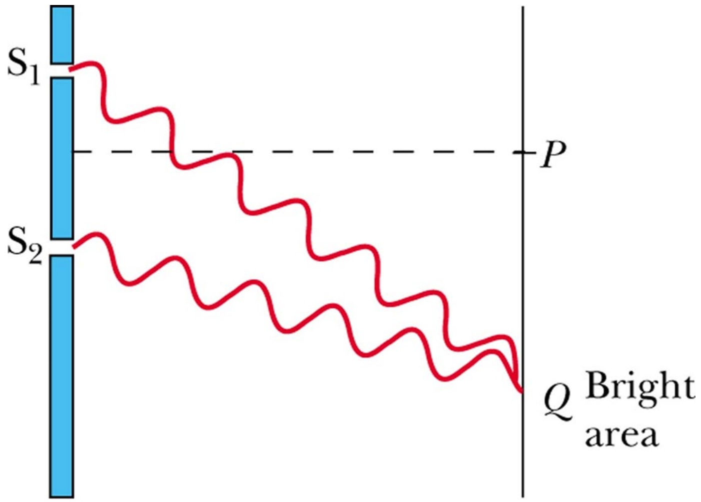
- The fringe pattern formed from a Young’s Double Slit Experiment as shown in Fig.
- The bright areas represent **constructive interference**
- The dark areas represent **destructive interference**

Interference Patterns- Constructive

- Constructive interference occurs at the center point
- The two waves travel the same distance
  - Therefore, they arrive in phase

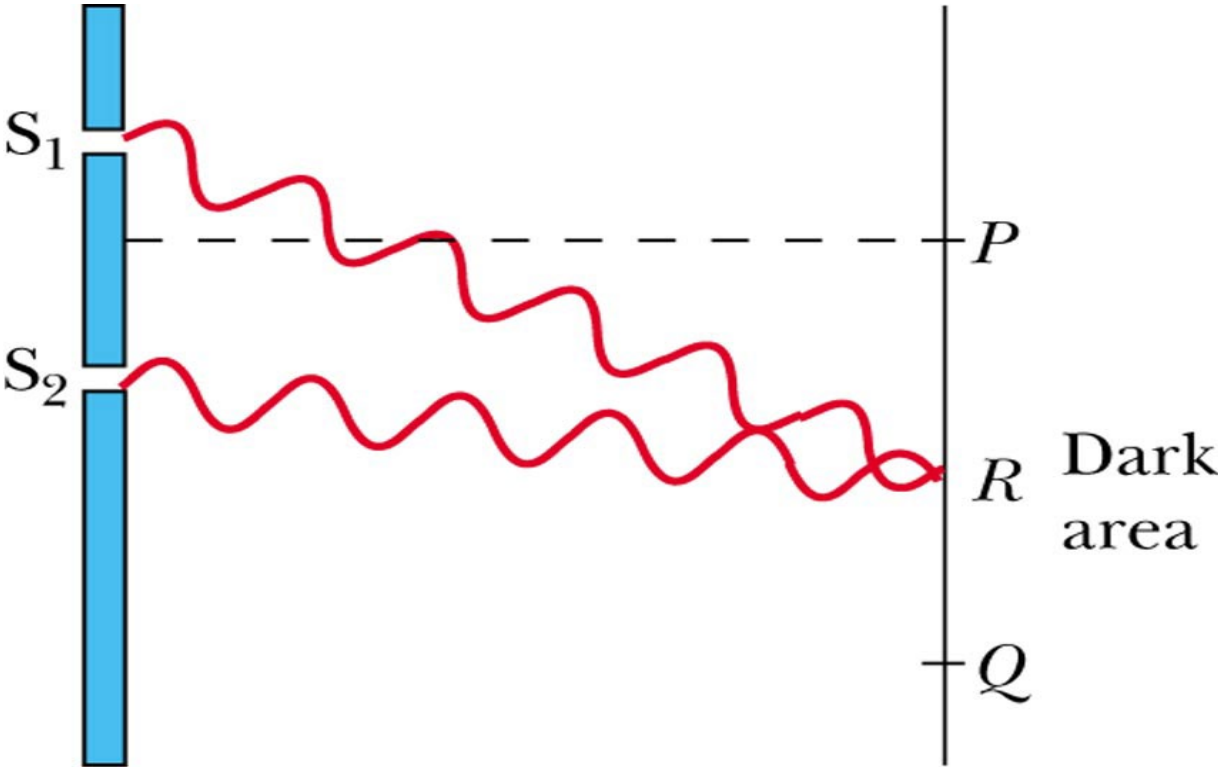


- The upper wave has to travel farther than the lower wave
- The upper wave travels one wavelength farther
  - Therefore, the waves arrive in phase
- A bright fringe occurs



Interference Patterns- Destructive

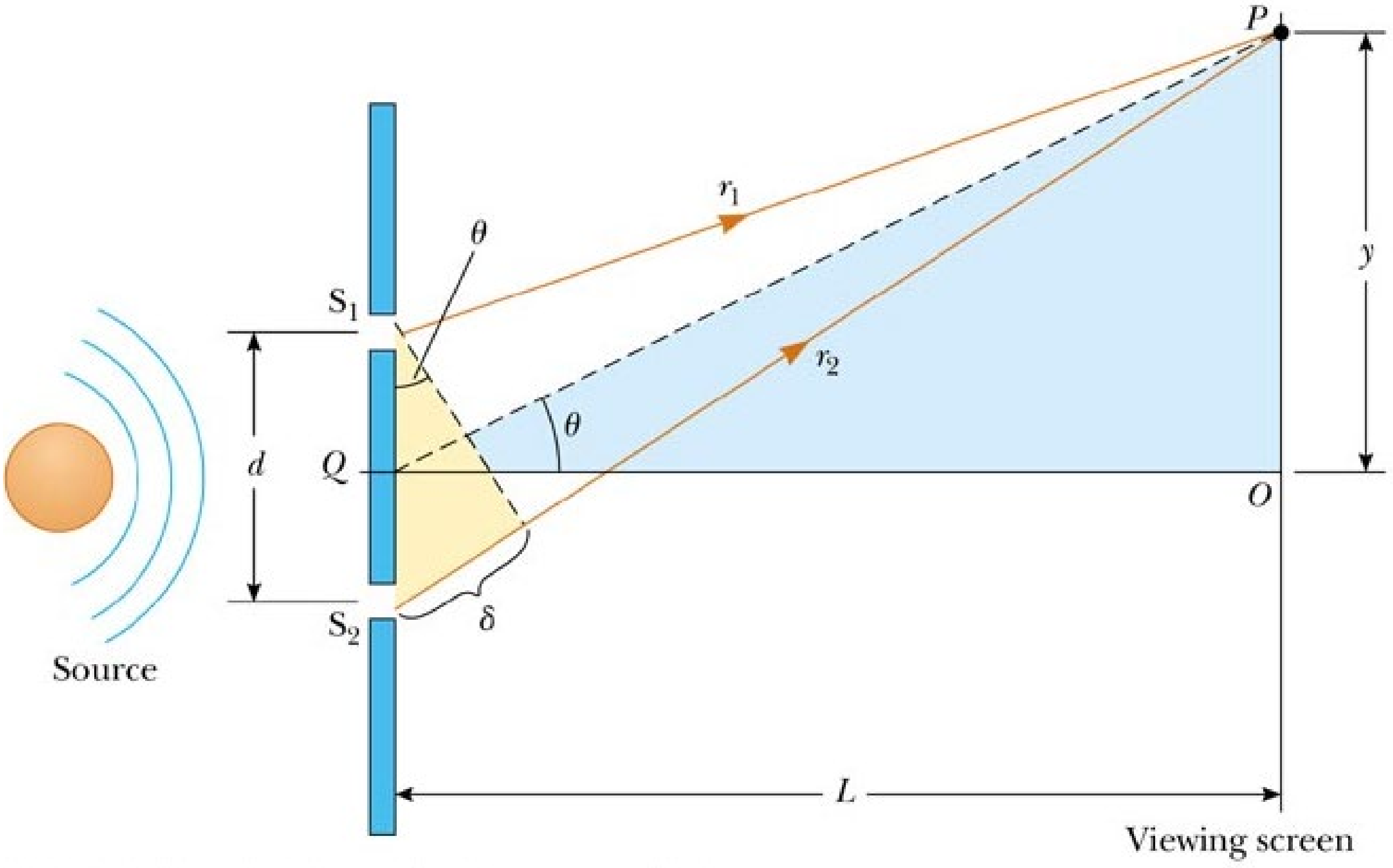
- The upper wave travels one-half of a wavelength farther than the lower wave
- The trough of the bottom wave overlaps the crest of the upper wave
- This is destructive interference
  - A dark fringe occurs



Interference Equations

- The path difference, δ, is found from the tan triangle

- $\delta = r_2 - r_1 = d \sin \theta$
  - This assumes the paths are parallel
  - Not exactly parallel, but a very good approximation since L is much greater than d



Interference Equations (Contd)

- For a bright fringe, produced by constructive interference, the path difference must be either zero or some integral multiple of the wavelength

$$\delta = d \sin \theta_{bright} = m \lambda$$

$m = 0, \pm 1, \pm 2, \ldots$

- m is called the *order number*
  - When m = 0, it is the zeroth order maximum
  - When m = ±1, it is called the first order maximum

Interference Equations (Contd)

- The positions of the fringes can be measured vertically from the zeroth order maximum
- $y = L \tan \theta \approx L \sin \theta$
- Assumptions
  - **L>>d**
  - **d>>λ**
- Approximation
  - θ is small and therefore the approximation $\tan \theta \approx \sin \theta$ can be used

Interference Equations (Contd)

- When destructive interference occurs, a dark fringe is observed
- This needs a path difference of an odd half wavelength
- $\delta = d \sin \theta_{dark} = (m + ½)\, \lambda$
  - m = 0, ±1, ±2, …

- For bright fringes

$$y_{bright} = \frac{\lambda L}{d} m \qquad m = 0, \pm 1, \pm 2 \square$$

- For dark fringes

$$y_{dark} = \frac{\lambda L}{d}\left(m + \frac{1}{2}\right) \qquad m = 0, \pm 1, \pm 2 \square$$

Uses - Young's Double Slit Experiment

- Young's Double Slit Experiment provides a method for measuring wavelength of the light
- This experiment gave the wave model of light a great deal of credibility
  - It is inconceivable that particles of light could cancel each other

Interferometers

- Interferometers are investigative tools used in many fields of science and engineering.
- They are called interferometers because they work by merging two or more sources of light to create an interference pattern, which can be measured and analyzed; **hence "Interfere-ometer".**
- The interference patterns generated by interferometers contain information about the object.
- Often used to make very small measurements.
- Powerful for detecting gravitational waves--LIGO's interferometers are designed to measure a distance 1/10,000th the width of a proton!

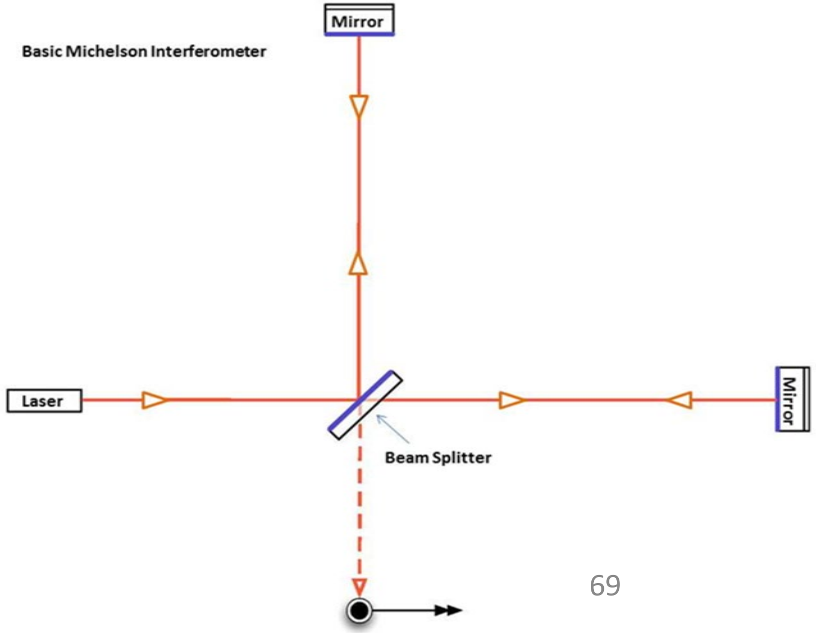
Interference Pattern

- To better understand how interferometers work, it helps to understand more about 'interference'.
- **Analogy:** Anyone who has thrown stones into a pond or a pool and watched what happened already knows a lot about interference. When the stones hit the water, they generate concentric waves that move away from the stone's point of entry. And where two or more of those concentric waves intersect (meet up), they interact and in that spot, create new waves that are sometimes larger and sometimes smaller.
- The pattern of new waves occurring where the concentric waves intersect constitutes an "interference" pattern.

Structure of Interferometer

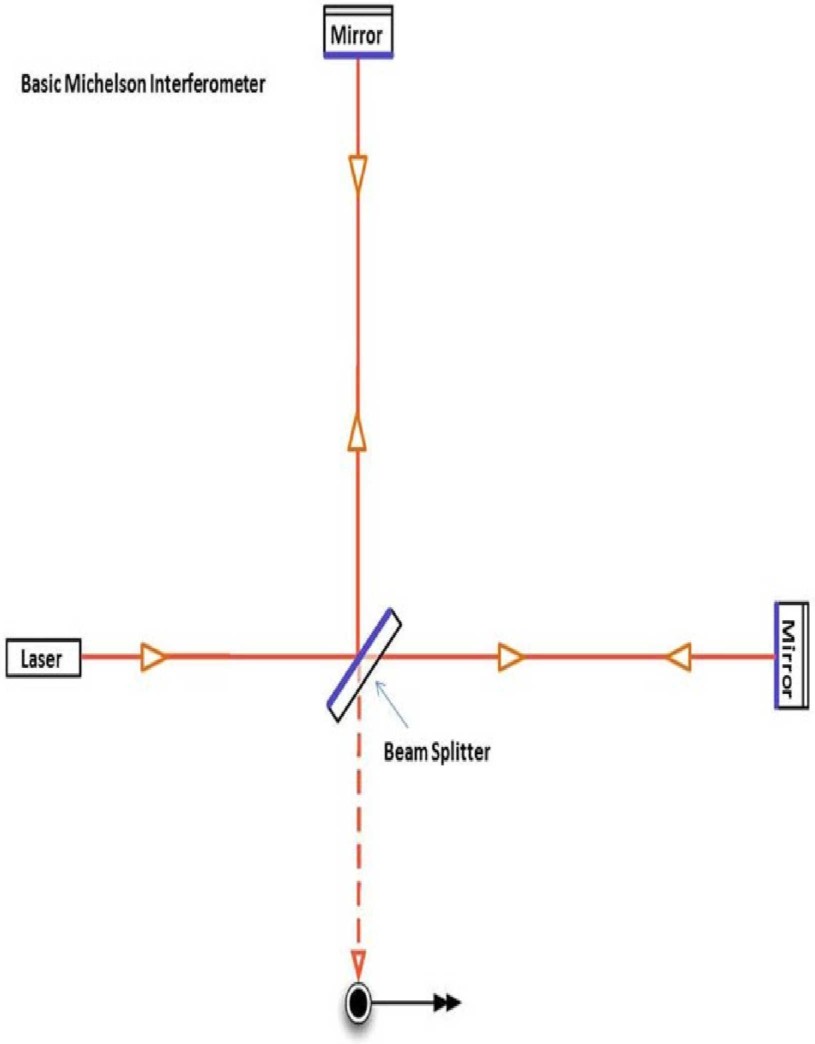
- used to measure everything from the smallest variations on the surface of a microscopic organism, to the structure of enormous expanses of gas and dust in the distant Universe, and now, to detect gravitational waves.
- Despite their different designs and the various ways in which they are used, all interferometers have one thing in common:
- Superimpose beams of light to generate an interference pattern.
- The basic configuration of a Michelson interferometer is shown.

- **It consists of a laser, a beam splitter, a series of mirrors, and a photodetector (the black dot) that records the interference pattern.**



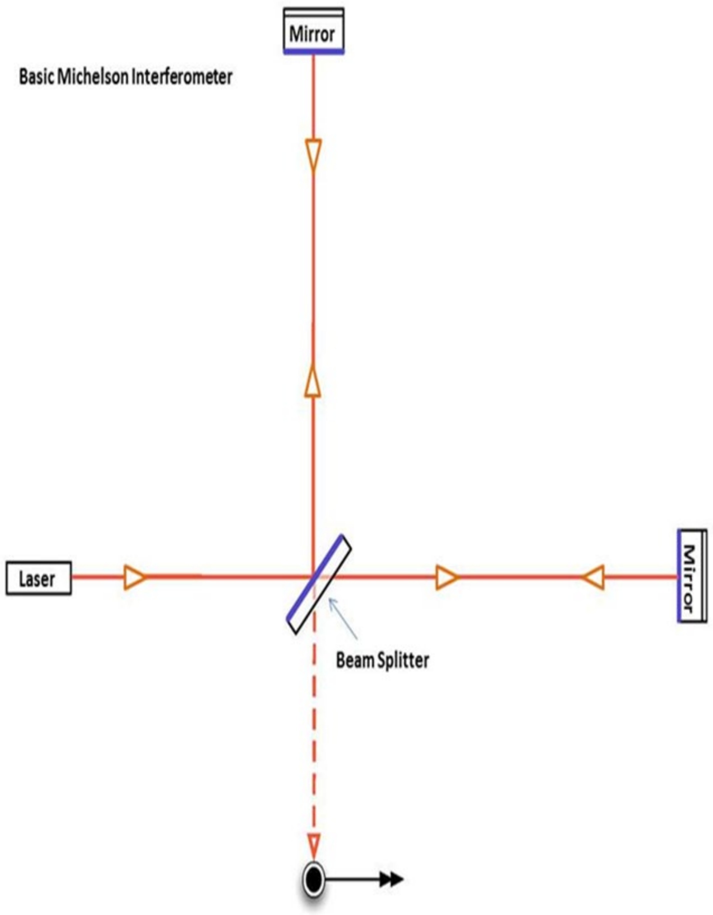
Working of Michelson Interferometer

- In a Michelson interferometer, a laser beam passes through a 'beam splitter' (a kind of mirror) which as the name suggests, splits a single beam into two identical beams.
- One beam passes straight through while the other is reflected at 90-degrees.
- Each beam then travels down an arm of the interferometer.
- At the end of each arm, a mirror reflects each beam back to the beam splitter where the two beams merge back into a single beam.



Working of Michelson Interferometer (Contd)

- In 'merging', the light waves from the two beams 'bump' into (or interfere with) each other before traveling to a photodetector, which measures the resulting beam's brightness.
- If the two beams travel exactly the same distance (i.e. the arms were exactly the same length) before recombining, the photodetector will either see a beam as bright as the pre-split beam or nothing at all, depending on how the mirrors are set up.

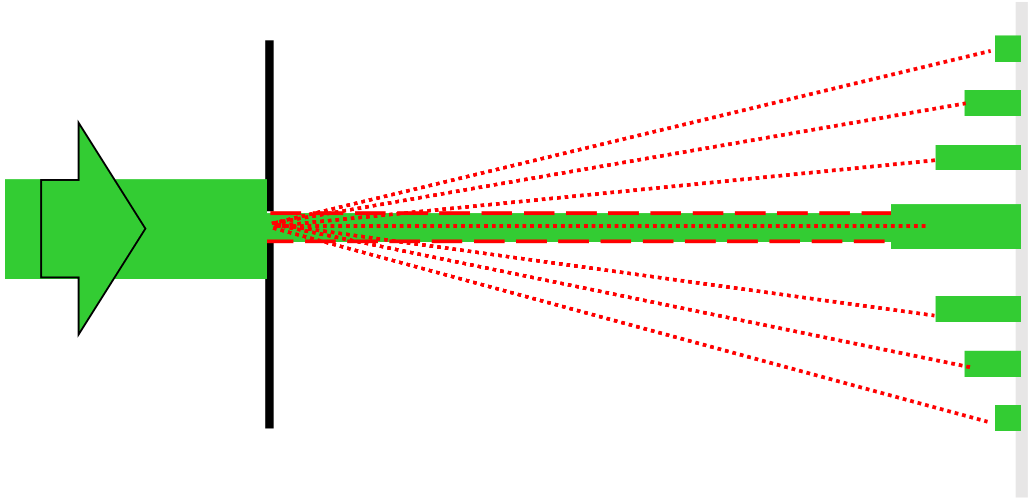


Working of Michelson Interferometer (Contd)

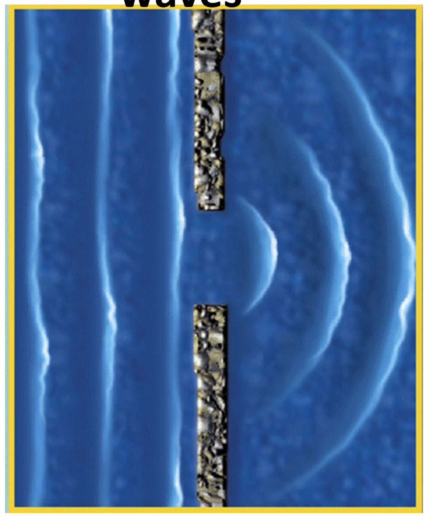
- As a result, the resulting merged beam will be brighter or dimmer than it was when the arms were the same length.
- In an interferometer, any change in light intensity (higher or lower) indicates that something happened to change the distance traveled by one or both laser beams.
- Moreover, the interference pattern can be used to calculate precisely how much change in length occurred.

Diffraction

- An important interference effect is the spreading of light as it passes through a narrow opening.
- without diffraction, light passing through a narrow slit would just produce a shadow effect.
- The effect of diffraction is to **cause the light to spread out around the edges of the slit**



Diffraction of water waves



Diffraction occurs when waves bend around small obstacles, or when waves spread out after they pass through small openings.

Diffraction occurs with all waves, including sound waves, water waves, and electromagnetic waves such as light that the eye can see.

Example - Diffraction

- The effects of diffraction are often seen in everyday life. The most striking examples of diffraction are those that involve light;
  - **for example, the closely spaced tracks on a CD or DVD act as a diffraction grating to form the familiar rainbow pattern seen when looking at a disc.**

- Diffraction can occur with any kind of wave. Ocean waves diffract around jetties and other obstacles. Sound waves can diffract around objects, which is why one can still hear someone calling even when hiding behind a tree.[7] Diffraction can also be a concern in some technical applications; it sets a fundamental limit to the resolution of a camera, telescope, or microscope.

Diffraction Vs Interference

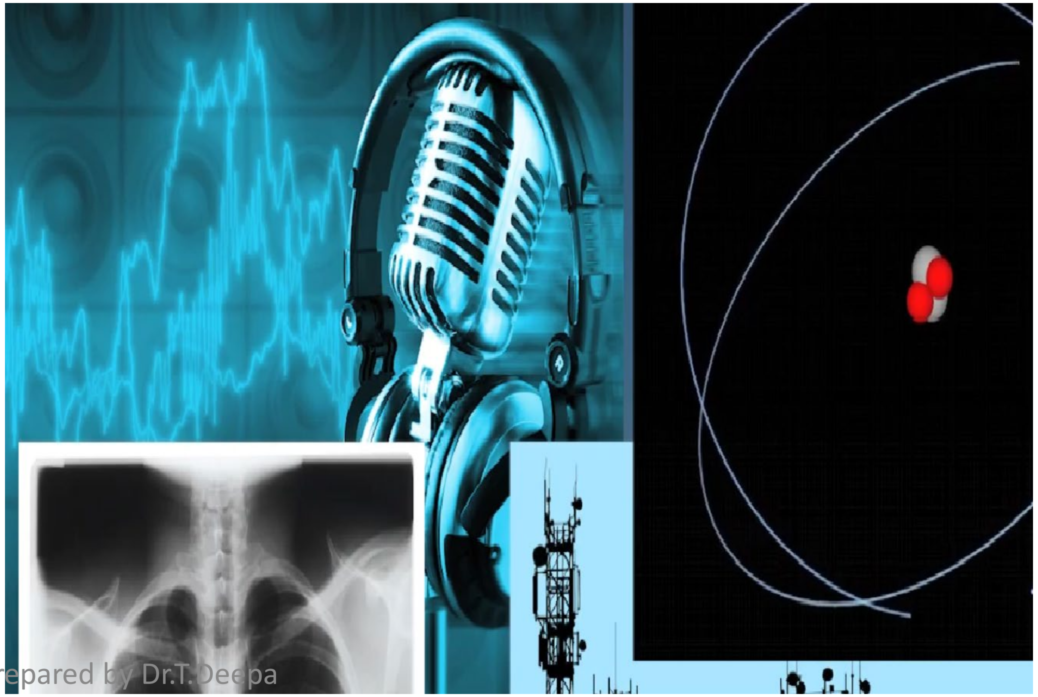
- **Diffraction** is the spreading of the light that occurs when a beam of light interacts with an object
- Just as diffraction describes the scattering of light by an object into divergent waves.

- **Interference** describes the recombination and summation of two or more superimposed waves.
- In a real sense, diffraction and interference are indications of the same process.

Diffraction and interference are closely related and are nearly – if not exactly – identical in meaning. Richard Feynman observes that "diffraction" tends to be used when referring to many wave sources, and "interference" when only a few are considered.

Diffraction (contd)

- **Diffraction**, the spreading of waves around obstacles.
- Diffraction takes place with sound; with electromagnetic radiation, such as light, X-rays, and gamma rays; and with very small moving particles such as atoms, neutrons, and electrons, which show wavelike properties.

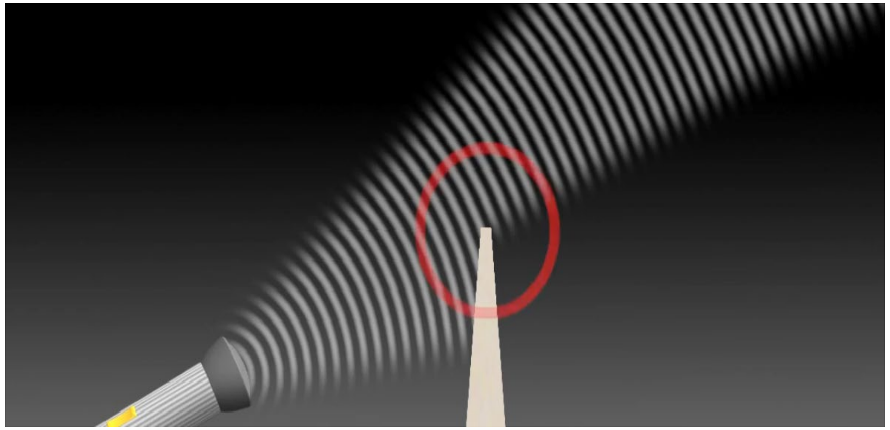


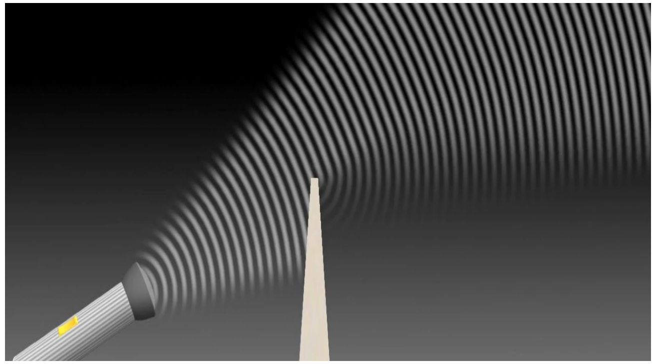
Diffraction (Cont'd)

- One consequence of diffraction is that sharp shadows are not produced. The phenomenon is the result of interference (i.e., when waves are superimposed, they may reinforce or cancel each other out) and is most pronounced when the wavelength of the radiation is comparable to the linear dimensions of the obstacle.
- When sound of various wavelengths or frequencies is emitted from a loudspeaker, the loudspeaker itself acts as an obstacle and casts a shadow to its rear so that only the longer bass notes are diffracted there.

Diffraction (Cont'd)

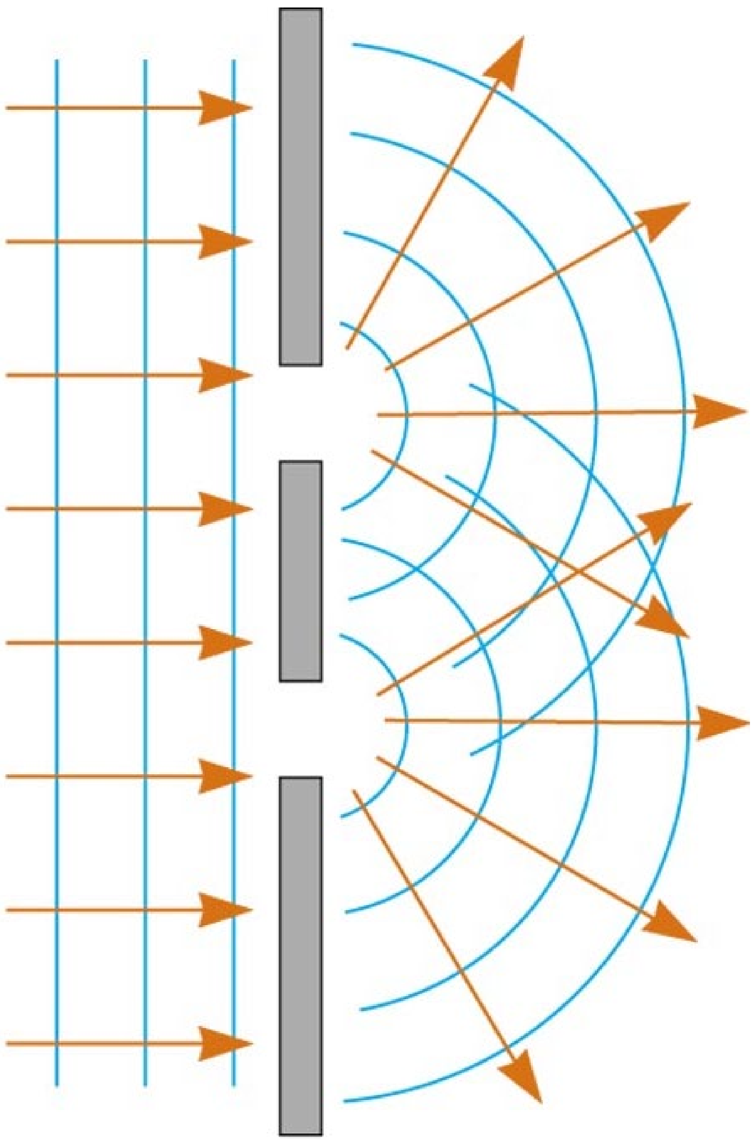
- Example 1 : When a beam of light falls on the edge of an object, it will not continue in a straight line but will be slightly bent by the contact, causing a blur at the edge of the shadow of the object; the amount of bending will be proportional to the wavelength.
- Example 2 : When a stream of fast particles impinges on the atoms of a crystal, their paths are bent into a regular pattern, which can be recorded by directing the diffracted beam onto a photographic film.





Diffraction (contd)

- Huygen's principle requires that the waves spread out after they pass through slits
- This spreading out of light from its initial line of travel is called *diffraction*
  - In general, diffraction occurs when waves pass through small openings, around obstacles or by sharp edges



Polarization

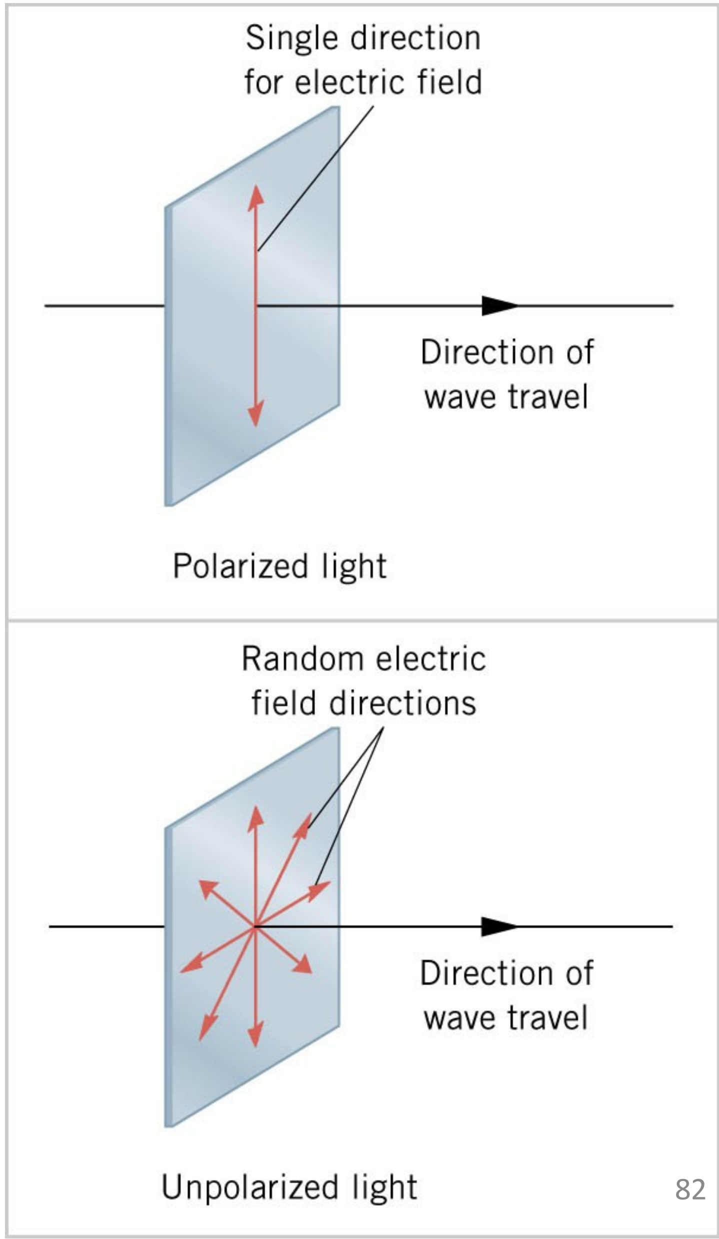
- An **electromagnetic** wave such as light consists of a coupled oscillating electric field and magnetic field which are always perpendicular; by convention, the "**polarization**" of **electromagnetic** waves refers to the direction of the electric field. In linear **polarization**, the fields oscillate in a single direction.

Polarized Light Vs Unpolarized light

- the direction in which the electric field vibrates is the direction of polarization

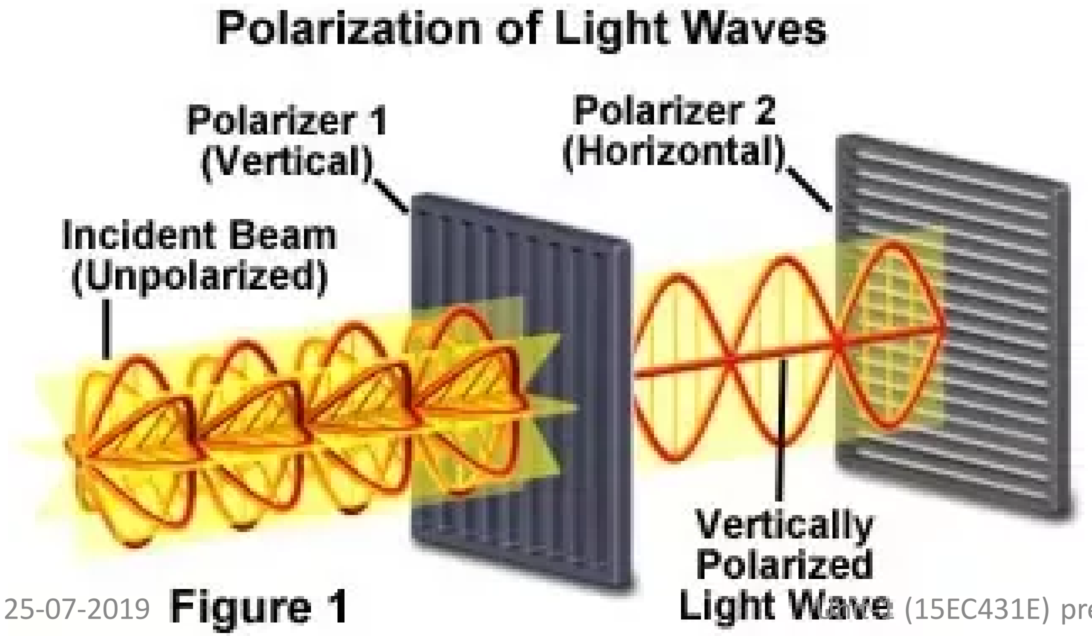
- with *polarized* light the electric field always vibrates in one direction

- ordinary light is *unpolarized* so that the electric field is randomly oriented about the direction of travel
    - **All directions of the electric field vector are equally possible and lie in a plane perpendicular to the direction of propagation**

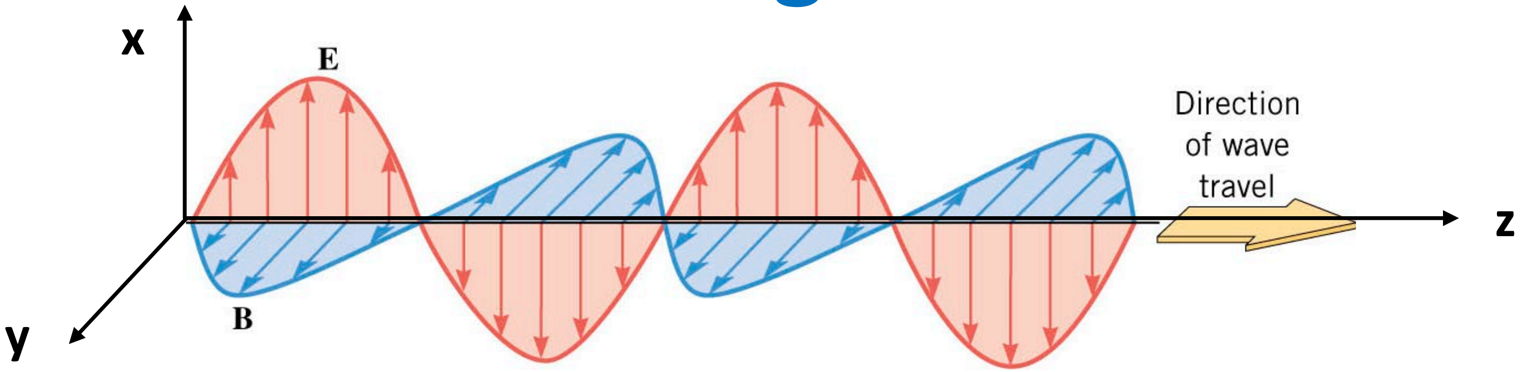


Polarized versus Unpolarized

- **Light** in which wave oscillate only in one angle. Then it is called **polarized light**
- . If it oscillate in all the angles then it is called **unpolarized light**. Non **polarized light** have the ability that the photons **in the** waves can oscillates in many **different** angles.



Polarization of Light



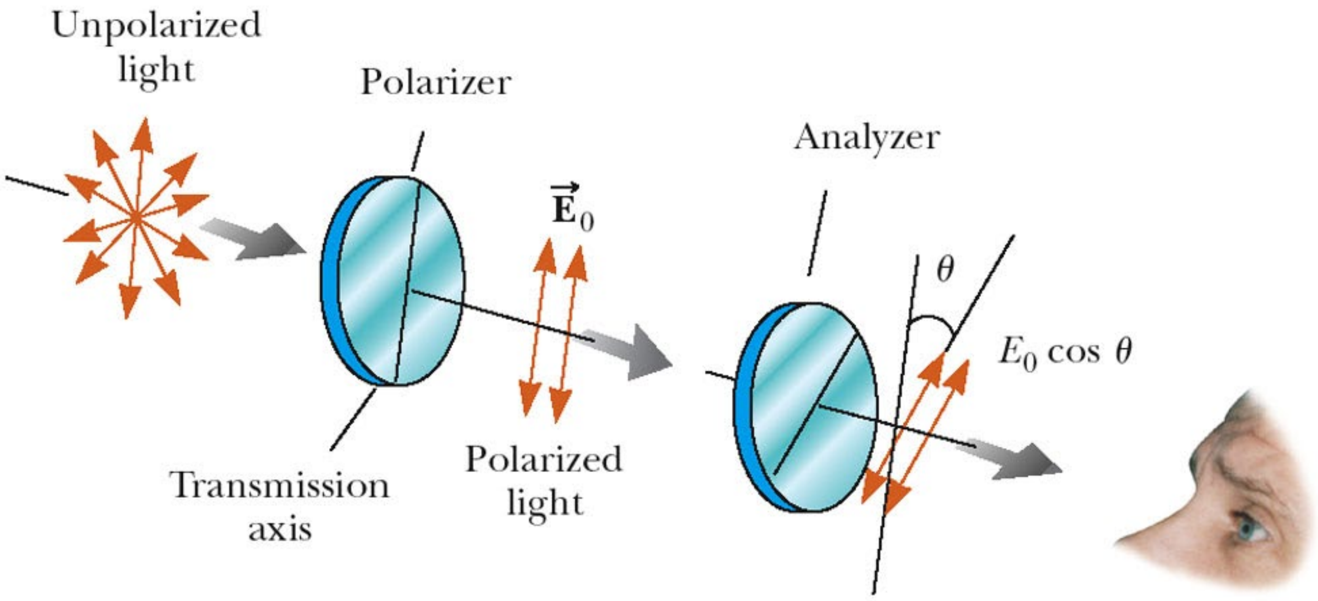
- Light is an electromagnetic wave with the electric and magnetic field having very specific orientations
- A light wave in which the electric field always vibrates along one direction is called a ***linearly polarized* wave**
- The direction of polarization is the axis along which the electric field vibrates
- In the diagram above, the wave polarization is x

Polarization of Light, cont

- A wave is said to be *linearly polarized* if the resultant electric field vibrates in the same direction at all times at a particular point

- Polarization can be obtained from an unpolarized beam by
  - **selective absorption**
  - **reflection**

Polarization by Selective Absorption



- The most common technique for polarizing light
- Uses a material that transmits waves whose electric field vectors in the plane are parallel to a certain direction and absorbs waves whose electric field vectors are perpendicular to that direction

Polarization by Selective Absorption (Contd)

- E. H. Land discovered a material that polarizes light through selective absorption
  - He called the material **Polaroid**
  - The molecules readily absorb light whose electric field vector is parallel to their lengths and transmit light whose electric field vector is perpendicular to their lengths

Polarization by Selective Absorption (Contd)

- The intensity of the polarized beam transmitted through the second polarizing sheet (the analyzer) varies as
  - $I = I_o \cos^2 \theta$
    - I_o is the intensity of the polarized wave incident on the analyzer
    - This is known as **Malus' Law** and applies to any two polarizing materials whose transmission axes are at an angle of θ to each other

Polarization by Reflection

- When an unpolarized light beam is reflected from a surface, the reflected light is
  - Completely polarized
  - Partially polarized
  - Unpolarized
- It depends on the angle of incidence
  - If the angle is 0° or 90°, the reflected beam is unpolarized
  - For angles between this, there is some degree of polarization
  - For one particular angle, the beam is completely polarized

Polarization by Reflection, cont

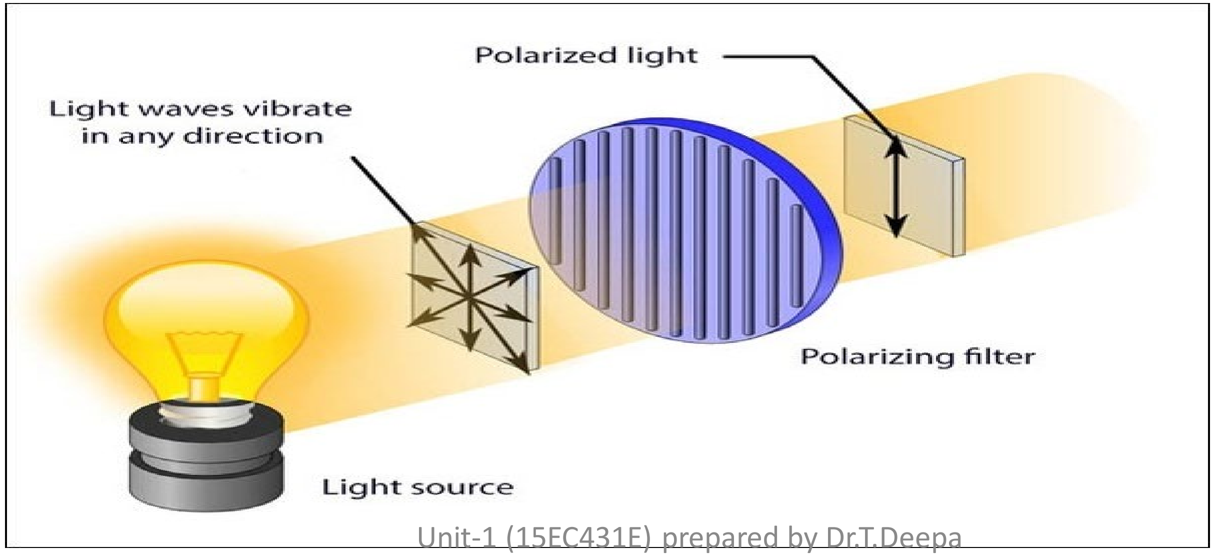
- The angle of incidence for which the reflected beam is completely polarized is called the *polarizing angle*, θ_p
- Brewster's Law relates the polarizing angle to the index of refraction for the material

$$n = \frac{\sin\theta_p}{\cos\theta_p} = \tan\theta_p$$

- θ_p may also be called Brewster's Angle

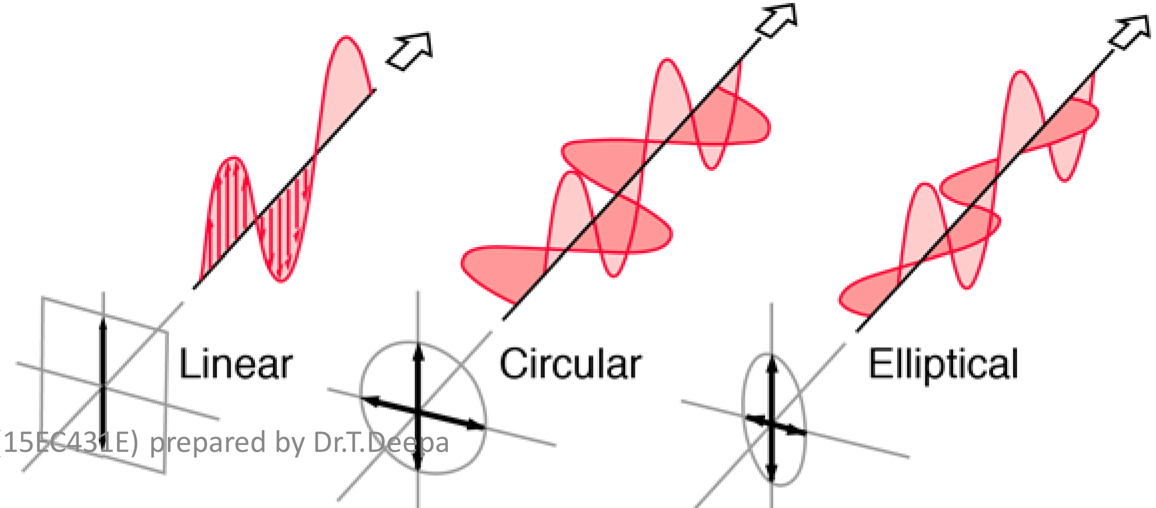
Difference between the plane polarized light and ordinary light

- In plane **polarized light**, the vibrations of the particles are confined to a single plane perpendicular to the direction of propagation of **light** while in **ordinary light**, the vibrations of the particles is in all planes.



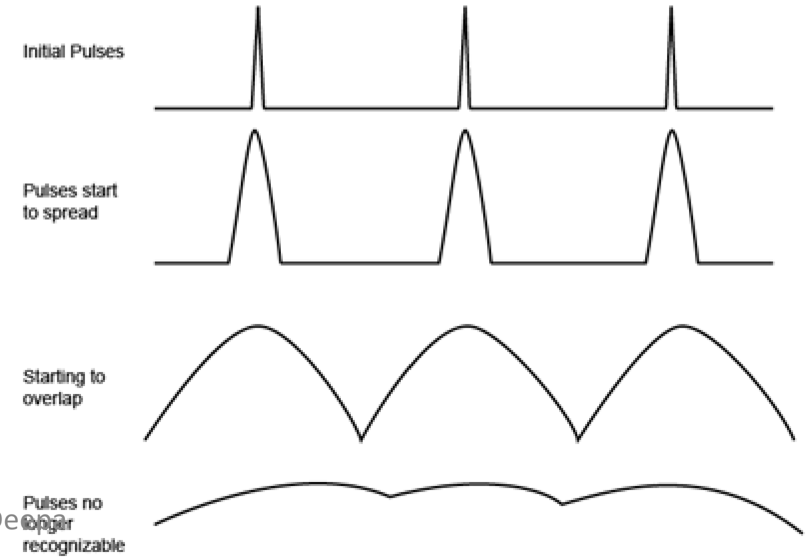
Classification of Polarization

- Light in the form of a plane wave in space is said to be **linearly polarized.**
- If light is composed of two plane waves of equal amplitude by differing in phase by 90°, then the light is said to be **circularly polarized.**
- If two plane waves of differing amplitude are related in phase by 90°, or if the relative phase is other than 90° then the light is said to be **elliptically polarized.**



Optical Fiber Dispersion

- In digital communication systems, information is encoded in the form of pulses and then these light pulses are transmitted from the transmitter to the receiver.
- The larger the number of pulses that can be sent per unit time and still be resolvable at the receiver end, the larger is the capacity of the system.
- However, when the light pulses travel down the fiber, the pulses spread out, and this phenomenon is called **Pulse Dispersion**. Pulse dispersion is shown in the following figure.

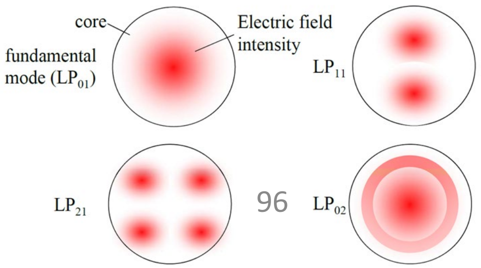


Optical Fiber Dispersion (Contd)

- Pulse dispersion is one of the two most important factors that limit a fiber's capacity (the other is fiber's losses). Pulse dispersion happens because of four main reasons:
- ***A) Intermodal Dispersion*** *(also called* ***Modal Dispersion*** *or* ***Group Delay****)*
- ***B) Material Dispersion*** *(also called* ***Chromatic Dispersion****)*
- ***C) Waveguide Dispersion***
- ***C) Polarization Mode Dispersion (PMD)***

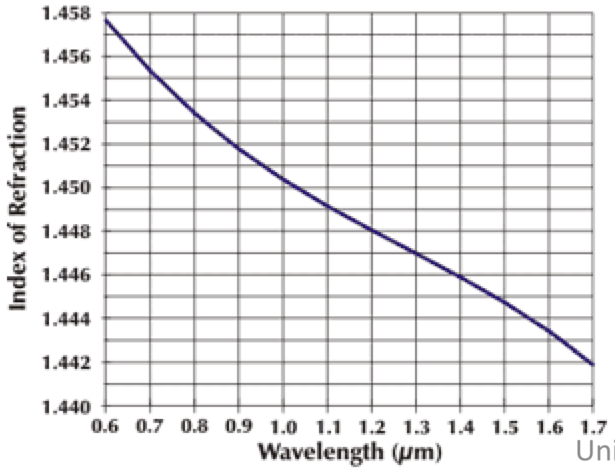
Material Dispersion and Waveguide Dispersion

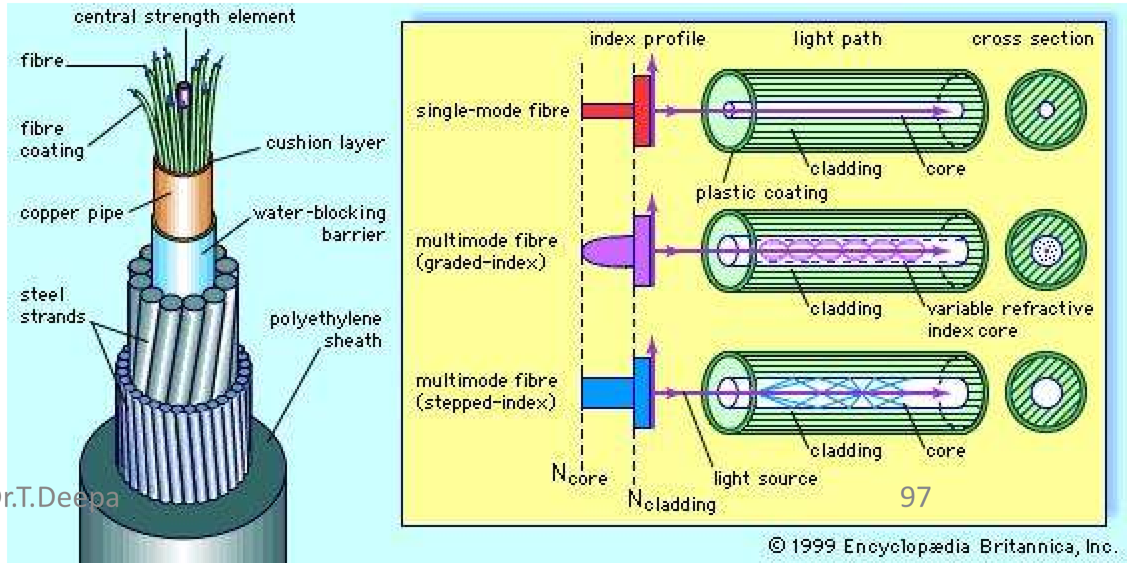
- Other important causes of signal distortion in optical fibres are material dispersion and waveguide dispersion.
- **Material dispersion is a phenomenon in which different optical wavelengths propagate at different velocities, depending on the refractive index of the material used in the fibre core.**
- **Waveguide dispersion depends not on the material of the fibre core but on its diameter; it too causes different wavelengths to propagate at different velocities.**
- As is the case in multimode dispersion, material and waveguide dispersion cause spreading of the received light pulses and can lead to inter-symbol interference.



Material Dispersion

- Arises due to the variations of the refractive index of the core material as a function of wavelength.
- Also called chromatic dispersion
- *caused by the velocity of light (or its refractive index) being a function of wavelength. Each wavelength takes different amounts of time to propagate the same path.*
- *The following figure shows refractive index versus wavelength in silica.*
-





Material Dispersion (Contd)

- Pulse broadening due to material dispersion results from the different group velocities of the various spectral components launched into the fiber form the optical source

Group Velocity:

- The group velocity (Vg) of a mode is a function of the index of refraction, the various spectral components of a given mode will travel at different speeds, depending on the wavelength.

Material dispersion D_m is usually specified in units of picoseconds per kilometer (fiber length) per nanometer (spectral width of the source) as given by

$$D_m = \frac{\Delta\tau}{L\,\Delta\lambda} = -\frac{1}{\lambda c}\left(\lambda^2 \frac{d^2 n}{d\lambda^2}\right) x10^9 \,(ps/km*nm)$$

where λ is in micrometers (um).
The quantity ($\lambda^2 d^2n/d\lambda^2$) characterizes the material dispersion of the fiber and is grouped in the equation.
Here is the plot of ($\lambda^2 d^2n/d\lambda^2$) for fused silica (the material for current glass fibers).

https://www.fiberoptics4sale.com/blogs/archive-posts/95047942-optical-fiber-dispersion

Waveguide Dispersion

- Causes pulse spreading because only part of the optical power propagation along a fiber is confined to the core.
- So the light travelling in different velocity which leads dispersion
- Waveguide dispersion results from the propagation constant of a mode (its group velocity) being a function of a/λ (a is fiber's core radius, λ is light's vacuum wavelength). Waveguide dispersion is negligible in multimode fibers and in single mode fibers operated at wavelengths below 1um, but it becomes important for single mode fibers operated in above 1.27um.

Waveguide Dispersion (Contd)

The normalized propagation constant **b** of a mode is defined by

$$b = \frac{\frac{\beta^2}{k_0^2} - n_2^2}{n_1^2 - n_2^2}$$

Since, for guided modes β/k_0 lies between n_1 and n_2, b lies between 0 and 1.

For step-index fibers, b depends only on the V value of the fiber, the above equation can be rewritten as

$$b = \frac{\frac{\beta}{k_0} - n_2}{n_1 - n_2} \frac{\frac{\beta}{k_0} + n_2}{n_1 + n_2} \approx \frac{\frac{\beta}{k_0} - n_2}{n_1 - n_2}$$

In the above equation, the ≈ step is concluded based on that n_1 is very close to n_2 which is true for all practical fibers. Thus we can conclude

$$\beta = \frac{\omega}{c}[n_2 + (n_1 - n_2) b(V)]$$

The group velocity is given by

$$\frac{1}{v_g} = \frac{d\beta}{d\omega} = \frac{1}{c}[n_2 + (n_1 - n_2) b(V)] + \frac{\omega}{c}(n_1 - n_2) \frac{db}{dV} \frac{dV}{d\omega}$$

In the above equation, n_1 and n_2 are assumed to be independent of λ.

Since

$$V = \frac{2\pi}{\lambda} a \sqrt{n_1^2 - n_2^2} = \frac{\omega}{c} a \sqrt{n_1^2 - n_2^2}$$

we have

$$\frac{dV}{d\omega} = \frac{V}{\omega}$$

So

$$\frac{1}{v_g}=\frac{1}{c}[n_2+(n_1-n_2)b(V)]+\frac{1}{c}(n_1-n_2)V\frac{db}{dV}$$

So the time taken by a pulse to traverse length L of the fiber is given by

$$\tau=\frac{L}{v_g}=\frac{L}{c}n_2[1+\Delta\frac{d}{dV}(bV)]$$

where

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

So for a light source with a spectral width of $\Delta\lambda$, the waveguide dispersion is

$$\Delta\tau_w\approx-\frac{L}{c}n_2\,\Delta(\frac{\Delta\lambda}{\lambda})(V\frac{d^2(bV)}{dV^2})$$

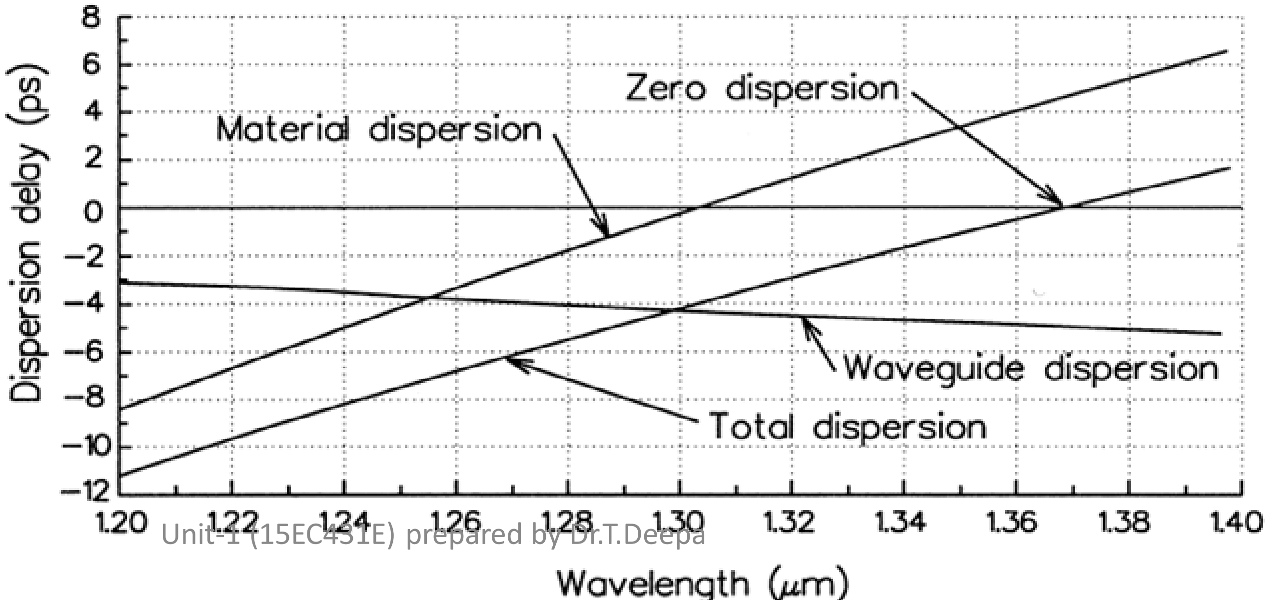
This is our desired expression for the waveguide dispersion.

For the lowest-order mode(the HE_{11} mode), our have b(V) as

$$b(V) = 1-\left(\frac{(1+\sqrt{2})^2}{\sqrt{1+(4+V^4)}}\right)$$

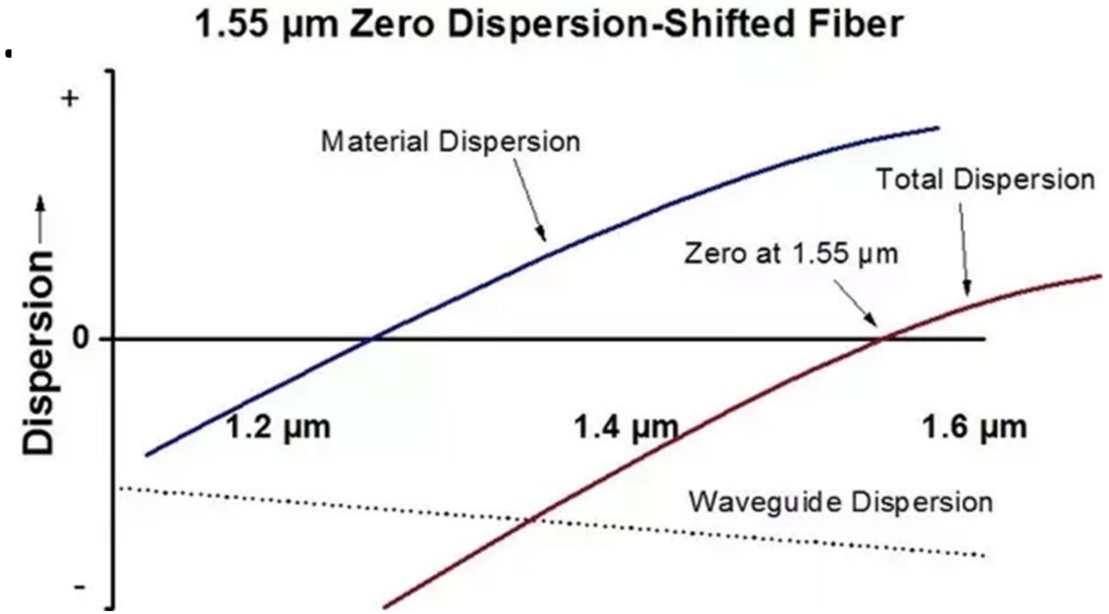
Total Dispersion

- It can be seen that the waveguide dispersion is negative in the single mode region. Since the material dispersion is positive for λ greater than the zero material dispersion wavelength, there is a wavelength at which the negative waveguide dispersion will compensate the positive material dispersion.
- At this wavelength, the net dispersion of the single mode fiber is zero. This is shown below.



Material Dispersion and Waveguide Dispersion (Cont'd)

- Therefore the total dispersion (the change of the effective index with wavelength has a material contribution- i.e, the refractive indices of the slightly different core and cladding indices) and a "structural" or "geometric" contribution (i.e., the fact that each wavelength "sees" a slightly different wave guiding structure).



Material Dispersion and Waveguide Dispersion (Cont'd)

- Since a transmitted signal always contains components at different wavelengths, material dispersion and waveguide dispersion are problems that affect not only SI and GI fibres but also SM fibres.
- For SM fibres, however, there exists a transmission wavelength at which the material dispersion exactly cancels the waveguide dispersion.
- This "zero dispersion" wavelength can be adjusted by modifying the material composition (and hence the refractive index) as well as the diameter of the fibre core. In this way SM fibres are designed to exhibit their zero dispersion wavelength near the intended optical carrier wavelength.

Dispersion shifted fiber

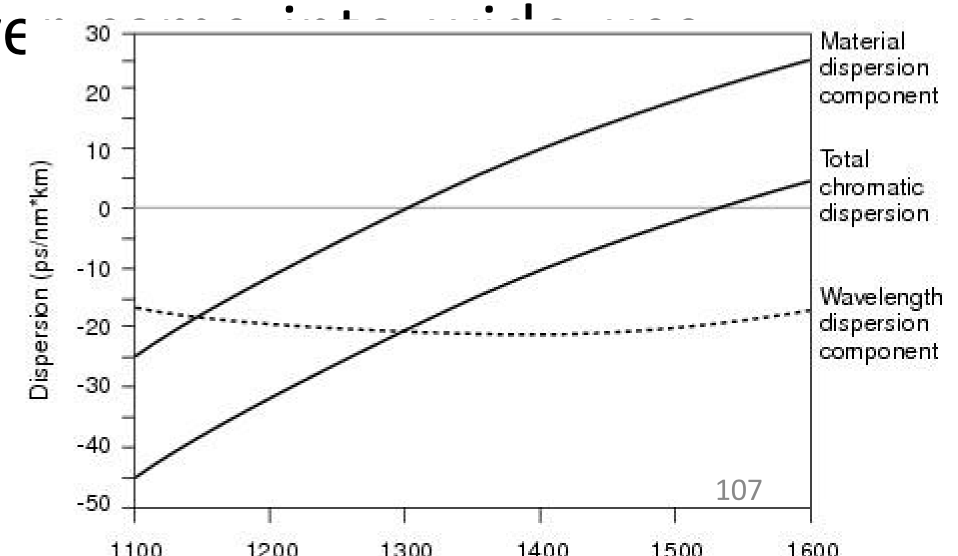
- **Dispersion-shifted fiber** (**DSF**) is a type of optical fiber made to optimize both low dispersion and low attenuation.
- DSF is a type of SM optical fiber with a core-clad index profile tailored to shift the zero-dispersion wavelength from the natural 1300 nm in silica-glass fibers to the minimum-loss window at 1550 nm.
- The group velocity or *intramodal* dispersion which dominates in single-mode fibers includes both material and waveguide dispersion.
- It allows a communication system to possess both low dispersion and low attenuation.
- However, when used in wavelength division multiplexing systems, dispersion-shifted fibers can suffer from four-wave mixing which causes intermodulation of the independent signals. As a result, nonzero dispersion shifted fiber is often used.

Dispersion shifted fiber (Contd)

- From the above discussion, we know the conventional single mode fiber has zero total dispersion around 1300nm.
- However, the minimum fiber loss is at 1550nm. If the zero dispersion wavelength could be shifted to the 1550nm region, we could have both minimum loss and very low dispersion. This would lead to very high bandwidth systems with very long (~100km) repeaterless transmission.
- The size of the waveguide dispersion has been found to be sensitive to the doping levels as well as the values of Δ and a (core radius). Indeed, we have achieved this by changing the fiber parameters. The resulted fiber is called **dispersion-shifted fiber**.
- The first dispersion-shifted fibers had zero dispersion shifted to 1550nm to match their minimum absorption wavelength.

Dispersion shifted fiber (Contd)

- Although this type of fiber (zero dispersion-shifted fiber) worked well for single channel systems, it proved to be unusable for WDM (wavelength-division multiplexing) systems.
- When multiple optical channels pass through the same fiber at wavelengths where dispersion is very close to zero, they suffer from a type of crosstalk called four-wave mixing. The degradation is so severe that zero dispersion-shifted fiber cannot be used for dense-WDM systems.
- ZDSF were installed in some systems but neve because of four-wave mixing problem.



Non-Zero Dispersion-Shifted Fiber (NZDSF)

- In order to avoid four-wave mixing problem in WDM systems, non-zero dispersion-shifted fibers were invented. The idea is to move the zero-dispersion wavelength outside the band used for erbium-fiber doped amplifiers.
- The name Non-Zero Dispersion-Shifted comes from the fact that the dispersion is shifted to a value that is low – but not zero – in the 1550nm bad of erbium-fiber amplifiers. But you can shift the dispersion to a positive or negative value.
- This small dispersion is enough to keep signals at closely spaced wavelengths from staying in phase over long distances and thus preventing four-wave mixing.
- The following figure shows two NZDSF fibers, one with plus sign at 1550nm and one with negative sign at 1550nm (both in light blue color).

Signal Attenuation

- **Attenuation** is a general term that refers to any reduction in the strength of a **signal**. **Attenuation**occurs with any type of **signal**, whether digital or analog. Sometimes called loss, **attenuation** is a natural consequence of **signal** transmission over long distances.

Attenuation in Fiber Optics

- Also known as transmission loss, is the reduction in intensity of the light beam (or signal) with respect to distance travelled through a transmission medium.
- Attenuation coefficients in fiber optics usually use units of dB/km through the medium due to the relatively high quality of transparency of modern optical transmission media.
- The medium is typically a fiber of silica glass that confines the incident light beam to the inside.
- Attenuation is an important factor limiting the transmission of a digital signal across large distances. Thus, much research has gone into both limiting the attenuation and maximizing the amplification of the optical signal.
- Empirical research has shown that attenuation in optical fiber is caused primarily by both scattering and absorption.

Attenuation in fiber optics can be quantified using the following equation

$$\text{Attenuation (dB)} = 10 \times \log_{10}\left(\frac{\text{Input intensity (W)}}{\text{Output intensity (W)}}\right)$$

Attenuation in Fiber Optics (contd)

- The attenuation of an optical fiber measures the amount of light lost between input and output. Total attenuation is the sum of all losses.
- Optical losses of a fiber are usually expressed in ***decibels per kilometer (dB/km)***. The expression is called the ***fiber's attenuation coefficient α*** and the expression is

$$\alpha = -\frac{10}{z[\mathrm{km}]}\log\left(\frac{P(z)}{P(0)}\right)$$

where P(z) is the optical power at a position z from the origin,
P(0) is the power at the origin.
For a given fiber, these losses are wavelength-dependent which is shown in the figure below. The value of the attenuation factor depends greatly on the fiber material and the manufacturing tolerances, but the figure below shows a typical optical fiber's attenuation spectral distribution.
The typical fused silica glass fibers we use today has a minimum loss at 1550nm.

Optical Fiber Loss Mechanisms

- Absorption
  - Intrinsic Material Absorption
  - Extrinsic Ions Absorption
  - Hydrogen Effects
- Scattering
  - Linear
  - Nonlinear
- Radiative losses of energy
  - Macroband
  - Microband loss

Absorption

- Absorption is uniform. The same amount of the same material always absorbs the same fraction of light at the same wavelength. If you have three blocks of the same type of glass, each 1-centimeter thick, all three will absorb the same fraction of the light passing through them.
- Absorption also is cumulative, so it depends on the total amount of material the light passes through. If the absorption is 1% per centimeter, it absorbs 1% of the light in the first centimeter, and 1% of the *remaining* light the next centimeter, and so on.

Intrinsic Material Absorption

- Intrinsic absorption is caused by interaction of the propagating lightwave with one more more major components of glass that constitute the fiber's material composition. These looses represent a fundamental minimum to the attainable loss and can be overcome only by changing the fiber material.
- An example of such an interaction is the **infrared absorption band** of SiO_2 shown in the above figure. However, in the wavelength regions of interest to optical communication (0.8-0.9um and 1.2-1.5um), infrared absorption tails make negligible contributions.

Extrinsic Impurity Ions Absorption

- Extrinsic impurity ions absorption is caused by the presence of minute quantity of metallic ions (such as Fe^{2+}, Cu^{2+}, Cr^{3+}) and the OH^- ion from water dissolved in glass. The attenuation from these impurity ions is shown in the following table.

Impurity Ion	Loss due to 1ppm of impurity (dB/km)	Absorption Peak Wavelength (um)
Fe^{2+}	0.68	1.1
Fe^{2+}	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

Hydrogen Effects

- When fused silica glass fiber is exposed to hydrogen gas, attenuation of the fiber also increases.
- The hydrogen can interact with the glass to produce hydroxyl ions and their losses.
- Hydrogen can also infiltrate the fiber and produce its own losses near 1.2um and 1.6um.
- The fibers can come into contact with hydrogen which is produced by corrosion of steel-cable strength members or by certain bacteria. The way to solve this problem is to add a coating to the fiber that is impermeable to hydrogen.

Scattering

- Scattering losses occur when a wave interacts with a particle in a way that removes energy in the directional propagating wave and transfers it to other directions.
- The light isn’t absorbed, just sent in another direction.
- However, the distinction between scattering and absorption doesn’t matter much because the light is lost from the fiber in either case.
- There are two main types of scattering: **linear scattering** and **nonlinear scattering**.

Scattering (Contd)

- For **linear scattering**, the amount of light power that is transferred from a wave is proportional to the power in the wave. It is characterized by having no change in frequency in the scattered wave.
- On the other hand, **nonlinear scattering** is accompanied by a frequency shift of the scattered light. Nonlinear scattering is caused by high values of electric field within the fiber (modest to high amount of optical power). Nonlinear scattering causes significant power to be scattered in the forward, backward, or sideways directions.

https://www.fiberoptics4sale.com/blogs/archive-posts/95048006-optical-fiber-loss-and-attenuation

Rayleigh Scattering (Linear Scattering)

- Rayleigh scattering (named after the British physicist Lord Rayleigh) is the main type of linear scattering.
- It is caused by small-scale (small compared with the wavelength of the lightwave) inhomogeneities that are produced in the fiber fabrication process.
- Examples of inhomogeneities are glass composition fluctuations (which results in minute refractive index change) and density fluctuations (fundamental and not improvable). Rayleigh scattering accounts for about 96% of attenuation in optical fiber.
- As light travels in the core, it interacts with the silica molecules in the core. These elastic collisions between the light wave and the silica molecules result in Rayleigh scattering. If the scattered light maintains an angle that supports forward travel within the core, no attenuation occurs.
- If the light is scattered at an angle that does not support continued forward travel, the light is diverted out of the core and attenuation occurs. Depending on the incident angle, some portion of the light propagates forward and the other part deviates out of the propagation path and escapes from the fiber core.

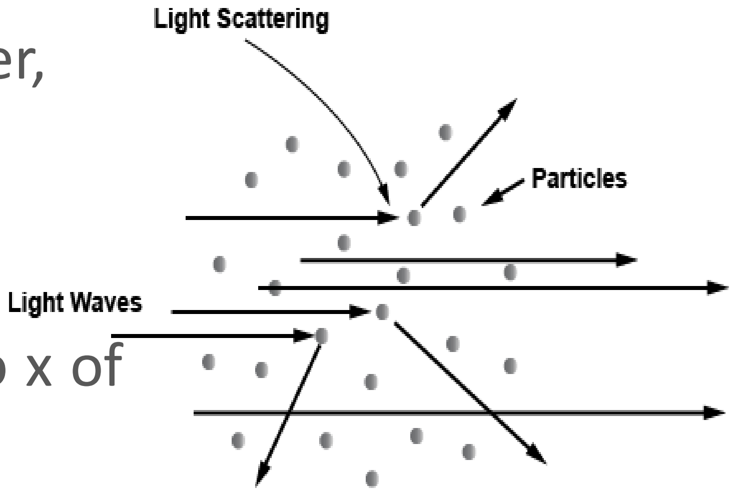
Rayleigh Scattering (Contd)

- Some scattered light is reflected back toward the light source. This is a property that is used in an OTDR (Optical Time Domain Reflectometer) to test fibers.
- Rayleigh scattering describes the elastic scattering of light by particles which are much smaller than the wavelength of light. The intensity of the scattered radiation is given by

$$I = I_0 \left(\frac{1+\cos^2\theta}{2R^2}\right)\left(\frac{2\pi}{\lambda}\right)^4\left(\frac{n^2-1}{n^2+2}\right)^2\left(\frac{d}{2}\right)^6,$$

where R is the distance between the particle and the observer,
θ is the scattering angle,
n is the refractive index of the particle, and
d is the diameter of the particle.
The size of a scattering particle is parameterized by the ratio x of its characteristic dimension r and wavelength λ:

$$x = \frac{2\pi r}{\lambda}.$$



Rayleigh Scattering (Contd)

- Rayleigh scattering is defined as scattering in the small size parameter regime $x \ll 1$.
- It can be seen from the above equation that Rayleigh scattering is strongly dependent upon the size of the particle and the wavelengths.
- The intensity of the Rayleigh scattered radiation increases rapidly as the ratio of particle size to wavelength increases. Furthermore, the intensity of Rayleigh scattered radiation is identical in the forward and reverse directions. The Rayleigh scattering model breaks down when the particle size becomes larger than around 10% of the wavelength of the incident radiation.
- Rayleigh scattering depends not on the specific type of material but on the size of the particles relative to the wavelength of light. The loss due to Rayleigh scattering is proportional to λ^{-4} and obviously decreases rapidly with increase in wavelength (see the first figure above – Loss vs. Wavelength).
- Short wavelengths are scattered more than longer wavelengths. Any wavelength that is below 800nm is unusable for optical communication because attenuation due to Rayleigh scattering is too high.

Rayleigh Scattering (Contd)

- The attenuation coefficient due to Rayleigh scattering in (pure) fused silica is given by the following approximate formula

$$\alpha(\lambda) = \alpha_0 \left(\frac{\lambda_0}{\lambda}\right)^4$$

where

$\alpha_0 = 1.7$ dB/km   at $\lambda_0 = 0.85$um

The above formula predicts the Rayleigh scattering loss to be 0.31 dB/km at 1.3um and 0.15 dB/km at 1.55um wavelengths.

Mie Scattering (Linear Scattering)

- Mie scattering is named after German physicist Gustav Mie. This theory describes scattering of electromagnetic radiation by particles that are comparable in size to a wavelength (larger than 10% of wavelength).
- For particles much larger, and much smaller than the wavelength of scattered light there are simple and excellent approximations that suffice.
- For glass fibers, Mie scattering occurs in inhomogeneities such as core-cladding refractive index variations over the length of the fiber, impurities at the core-cladding interface, strains or bubbles in the fiber, or diameter fluctuations.
- Mie scattering can be reduced by carefully removing imperfections from the glass material, carefully controlling the quality and cleanliness of the manufacturing process.
- In commercial fibers, the effects of Mie scattering are insignificant. Optical fibers are manufactured with very few large defects. (larger than 10% of wavelength)

Brillouin Scattering (Nonlinear Scattering)

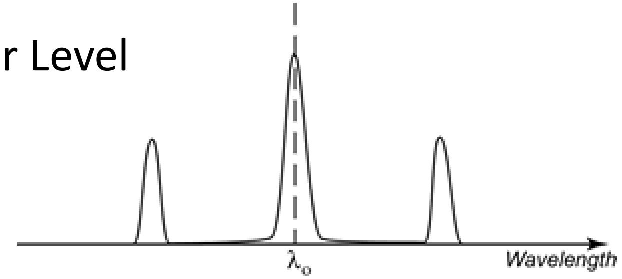
- Brillouin scattering is caused by the nonlinearity of a medium.
- In glass fibers, Brillouin scattering shows as a modulation of the light by the thermal energy in the material.
- An incident photon can be converted into a scattered photon of slightly lower energy, usually propagating in the backward direction, and a phonon (vibrational energy).
- This coupling of optical fields and acoustic waves occurs via electrostriction.
- The frequency of the reflected beam is slightly lower than that of the incident beam; the frequency difference v_B corresponds to the frequency of emitted phonons. This is called Brillouin Frequency Shift. This phenomenon has been used for fiber optic sensor applications.

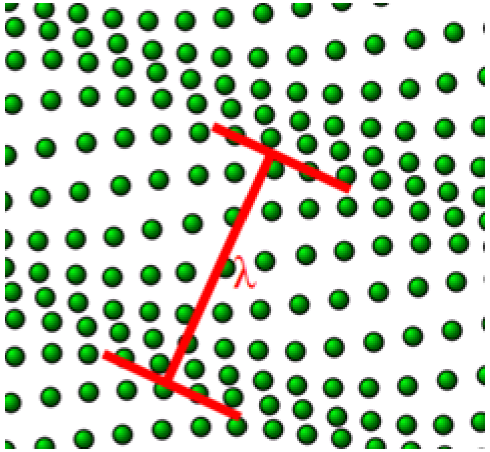
Brillouin Scattering (Contd)

Brillouin scattering can occur spontaneously even at low optical powers. This is different than Stimulated Brillouin Scattering which requires optical power to meet a threshold high enough to happen.
Above a certain threshold power, stimulated Brillouin scattering can reflect most of the power of an incident beam. The optical power level at which stimulated Brillouin scattering becomes significant in a single mode fiber is given by the empirical formula below.

$$P_B = (17.6 \times 10^{-3})\, a'^2 \lambda'^2 \alpha \Delta\nu'$$

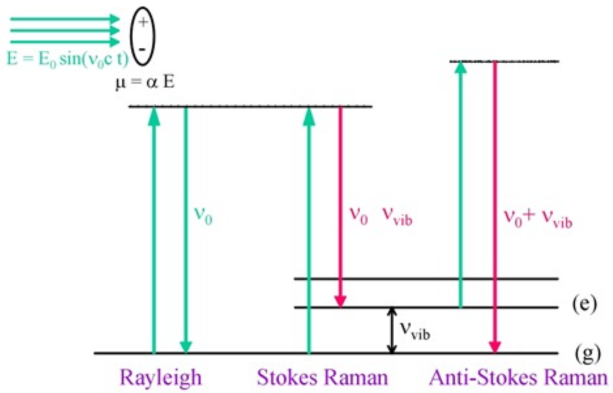
where
P_B = Stimulated Brillouin Scattering Optical Power Level Threshold (watts)
a' = Fiber radius (um)
λ' = Light source wavelength (um)
α = Fiber loss (dB/km)
△v' = Light source linewidth (GHz)





Stimulated Raman Scattering (Nonlinear Scattering)

- Stimulated Raman scattering is a nonlinear response of glass fibers to the optical intensity of light. This is caused by vibrations of the crystal (or glass) lattice.
- Stimulated Raman scattering produces a high-frequency optical phonon, as compared to Brillouin scattering, which produces a low-frequency acoustical phonon, and a scattered photon.
- When two laser beams with different wavelengths (and normally with the same polarization direction) propagate together through a Raman-active medium, the longer wavelength beam can experience optical amplification at the expense of the shorter wavelength beam. This phenomenon has been used for Raman amplifiers and Raman lasers.



Stimulated Raman Scattering (Contd)

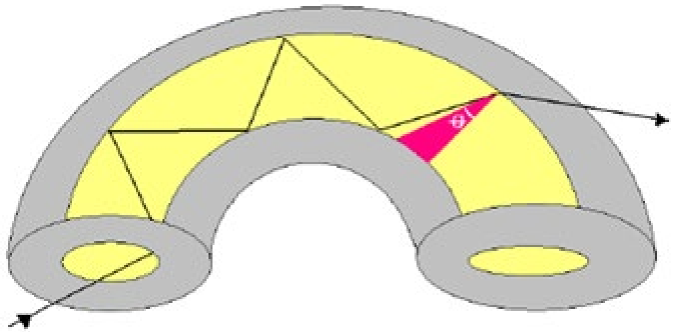
- In Stimulated Raman scattering, the scattering is predominately in the forward direction, hence the power is not lost to the receiver.
- Stimulated Raman Scattering also requires optical power to be higher than a threshold to happen. The formula below gives the threshold

$$P_R = (23.6 \times 10^{-2}) a'^2 \lambda' \alpha$$

where
P_R = Stimulated Raman Scattering Optical Power Level Threshold (watts)
a' = Fiber radius (um)
λ' = Light source wavelength (um)
α = Fiber loss (dB/km)

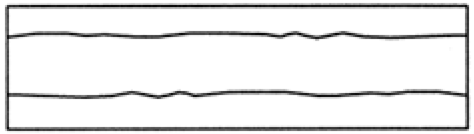
Macrobending Loss

- Macrobending happens when the fiber is bent into a large radius of curvature relative to the fiber diameter (large bends). These bends become a great source of power loss when the radius of curvature is less than several centimeters.
- Macrobend may be found in a splice tray or a fiber cable that has been bent. Macrobend won't cause significant radiation loss if it has large enough radius.
- However, when fibers are bent below a certain radius, radiation causes big light power loss as shown in the figure below.



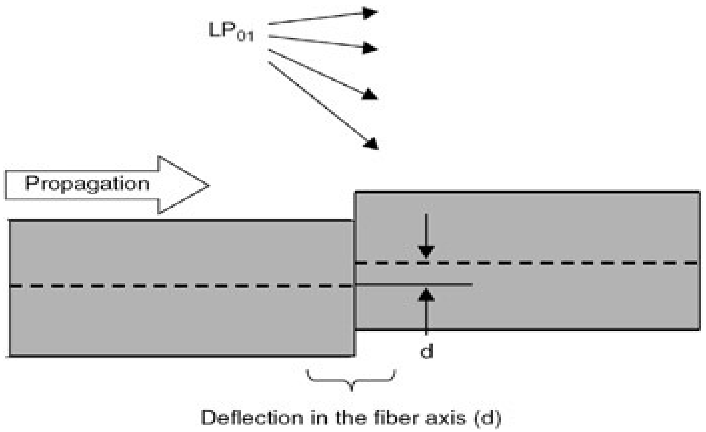
Microbending Loss

- Microbendings are the small-scale bends in the core-cladding interface. These are localized bends can develop during deployment of the fiber, or can be due to local mechanical stresses placed on the fiber, such as stresses induced by cabling the fiber or wrapping the fiber on a spool or bobbin.
- Microbending can also happen in the fiber manufacturing process. It is sharp but microscopic curvatures that create local axial displacement of a few microns (um) and spatial wavelength displacement of a few millimeters.
- Microbends can cause 1 to 2 dB/km losses in fiber cabling process.



Microbending Loss (Contd)

- The impact of a single microbend, at which, analogous to a splice, power can be coupled from the fundamental mode into higher order leaky modes as shown in Fig.
- Because external forces are transmitted to the glass fiber through the polymer coating material, the coating material properties and dimensions, as well as external factors, such as temperature and humidity, affect the microbending sensitivity of a fiber.
- Microbending sensitivity is also affected by coating irregularities such as variations in coating dimensions, the presence of particles such as those in the pigments of color coatings, and inhomogeneities in the properties of the coating materials that vary along the fiber axis.



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