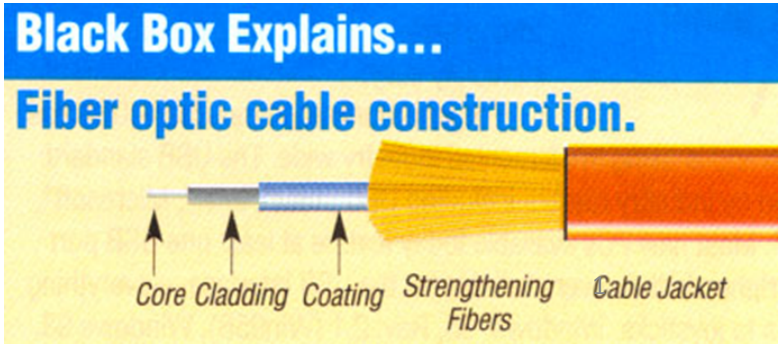
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15EC431E-PHOTONICS & OPTICAL NETWORKS

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. Though covering all light's technical applications over the whole spectrum, 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.

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Motivation

- Photonics has found increasing applications in such areas as optical communications, optical sensing, displays and printing. The course will cover the fundamentals and applications of optical communication systems.
- This module will give an overview of photonics and its applications in different areas like information technology, communications, healthcare, life sciences, optical sensing, lighting, energy and manufacturing.

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After completion of this course, the student should 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, Time division multiplexing and code division multiplexing concepts.
- Design simple optical communication link.
- Understand the main types of architectures, protocols and standards governing modern optical networks.

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Overview of Syllabus Topics:

Review of optics - The basics of optics will be covered including: Interference, diffraction, coherence and polarization.

Optical waveguides - 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, attenuation, group velocity, dispersion, and optical non-linearities.

Optical sources and transmitters- In this module the physics of light emission and amplification in a semiconductor, light emitting diodes, semiconductor lasers (edge emitting lasers and vertical cavity surface emitting lasers (VCSELs)) will be described.

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Overview of Syllabus Topics:

- **Optical detectors and receivers** - This module covers the basic concepts of light detection of light including photoconductors, photodiodes and receiver systems.
- **Lightwave systems** - A summary of important concepts of digital optical communication including time-division multiplexing (TDM) and wavelength division multiplexing (WDM) will be given.
- **Optical Devices-** Different optical devices, which are essential for an optical network like optical amplifiers, polarization control devices, optical isolators, optical filters and diffraction gratings, modulators and switches, will be discussed.

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Overview of Syllabus Topics:

- 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.
- Optical systems design This module covers the dispersion in multimode fibers, the dispersion in single mode fibers and implications for the systems designs. An overview of the design process for a point-to-point optical link should be given.

Introduction to Photonics and Optical Technologies

- Light influences our lives today in several ways that we could never have imagined just a few decades ago.
- 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 abound as well, 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.

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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.

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.

Photonics & Optics

Photonics

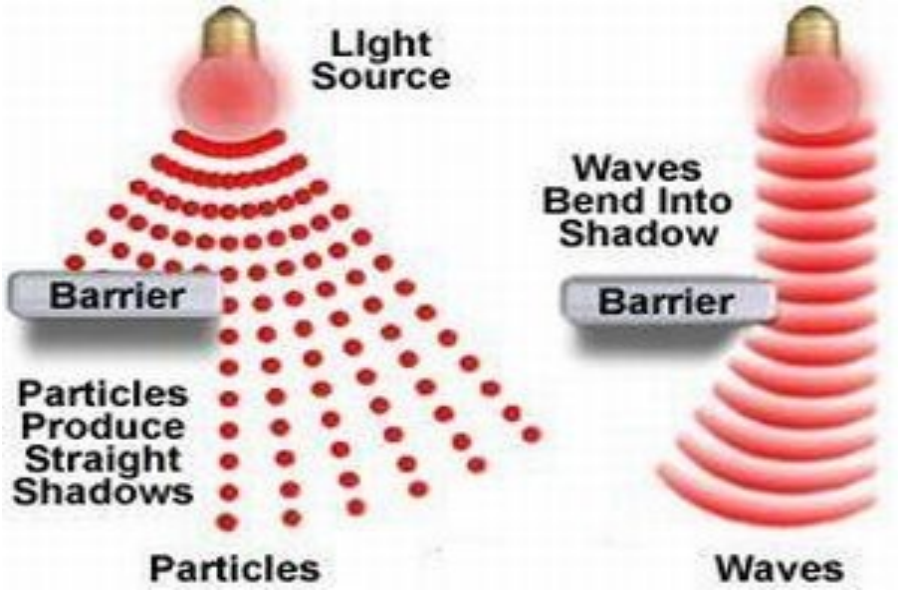
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Optics

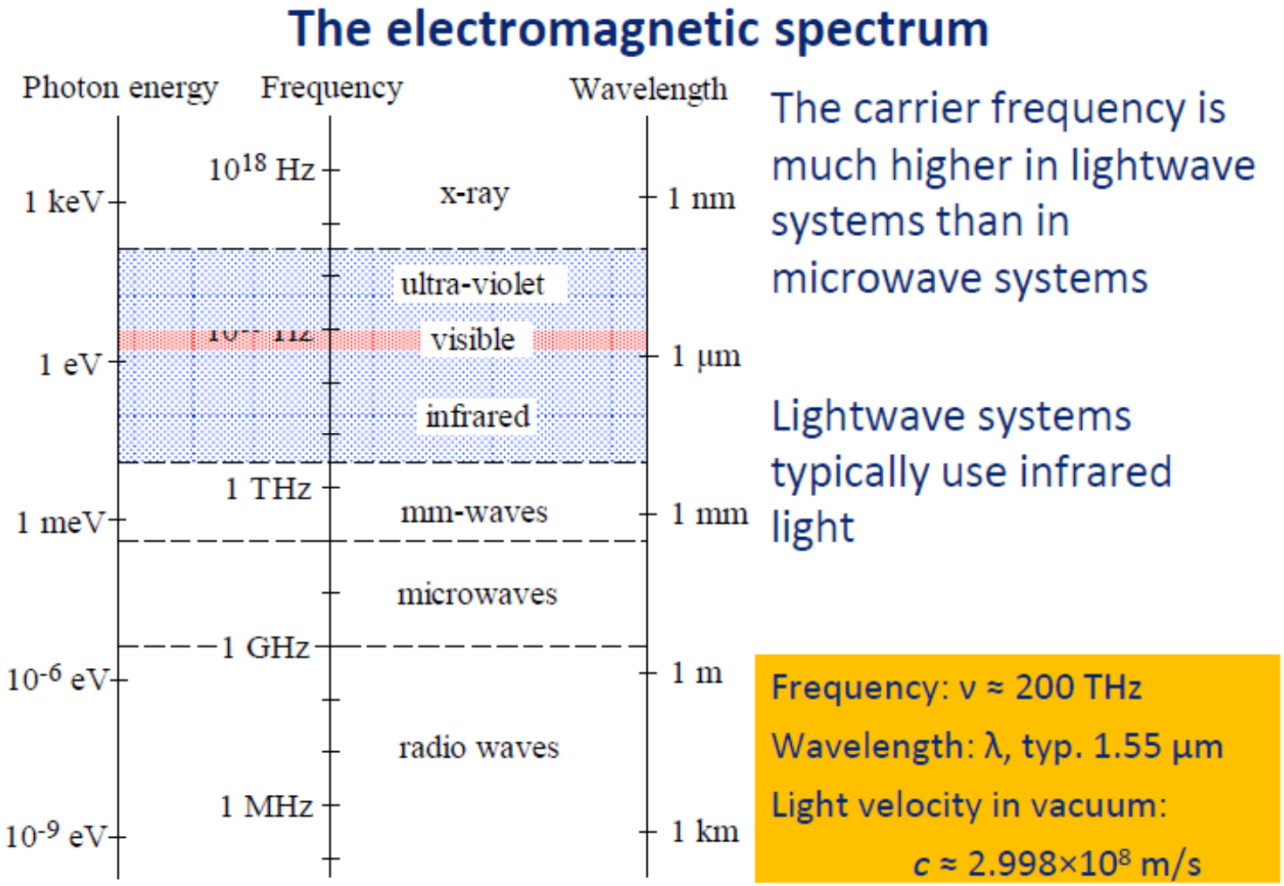
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- Because light is an electromagnetic wave, other forms of electromagnetic radiation such as X-rays, microwaves, and radio waves exhibit similar properties.

Nature of Light

- 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



RF 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)

Introduction to Optics

- Based on the inventions the following disciplines were created:
- Electro-optics,
- Optoelectronics,
- Quantum electronics,
- Quantum Optics,
- Lightwave technology

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Introduction to Optics (Cont'd)

- **Electro-optics** is generally reserved for optical devices which electrical effects play a role (laser and electro-optic modulators and switches).
- **Optoelectronics** typically refers to devices and systems that are essentially electronics in nature but involve light (examples are light emitting devices, liquid crystal displays and sensor arrays).
- **Quantum electronics** is used in connection with devices and systems that rely principally on the interaction of light and matter (e.g. lasers and non linear devices)
- **Quantum Optics** described the studies of quantum and coherence properties of light.
- **Lightwave technology** is used to describe devices and systems in optical communication.

Some Photonics Applications



Blu-Ray disc



LED-TV



Environmental monitoring



Fiber-optic gyroscope



LED light bulb



Optical communication



Solar cell

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Some Photonic Applications (Cont'd)

- **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)
- **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)

Some Photonic Applications (Cont'd)

- 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

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

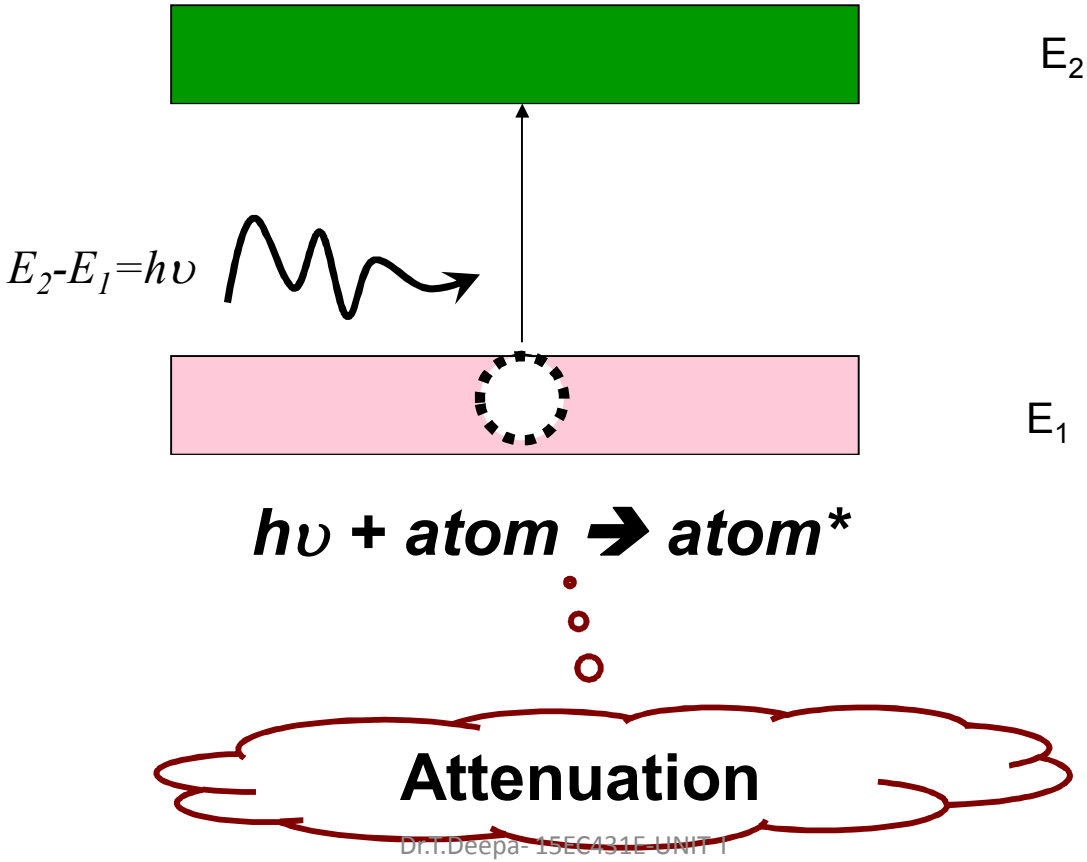
Definition of LASER

- **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.

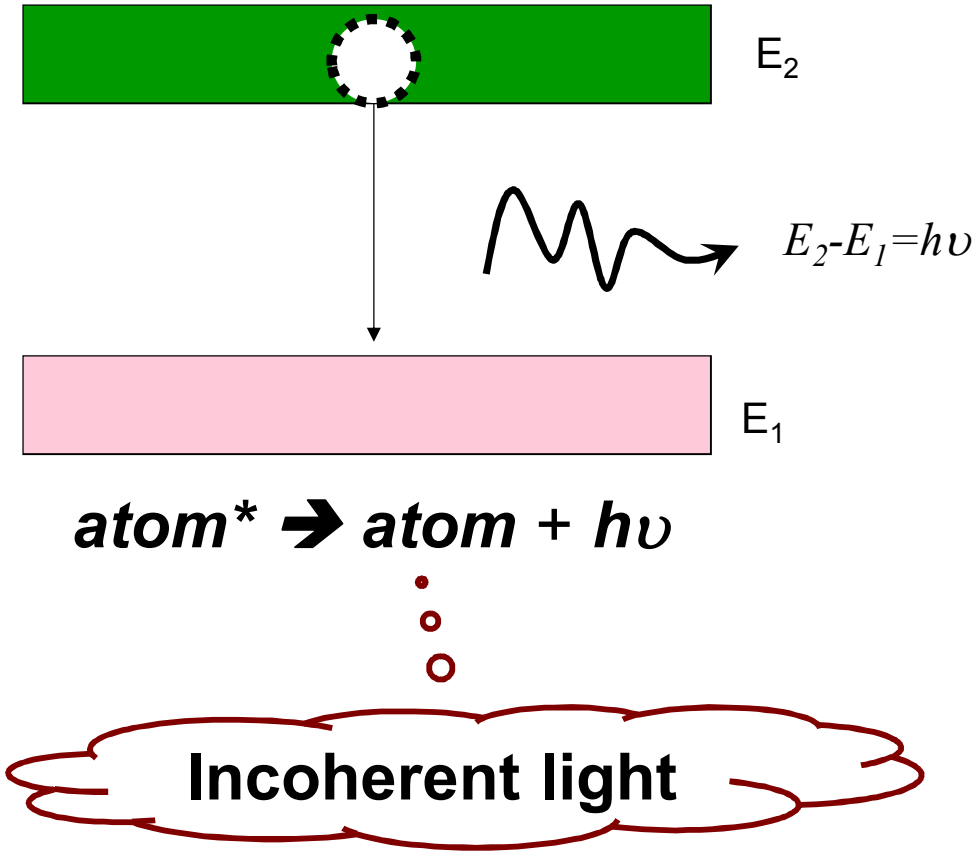
- **Inspiration for LASERS: Albert Einstein - 1917**

Interaction of Light with Matter

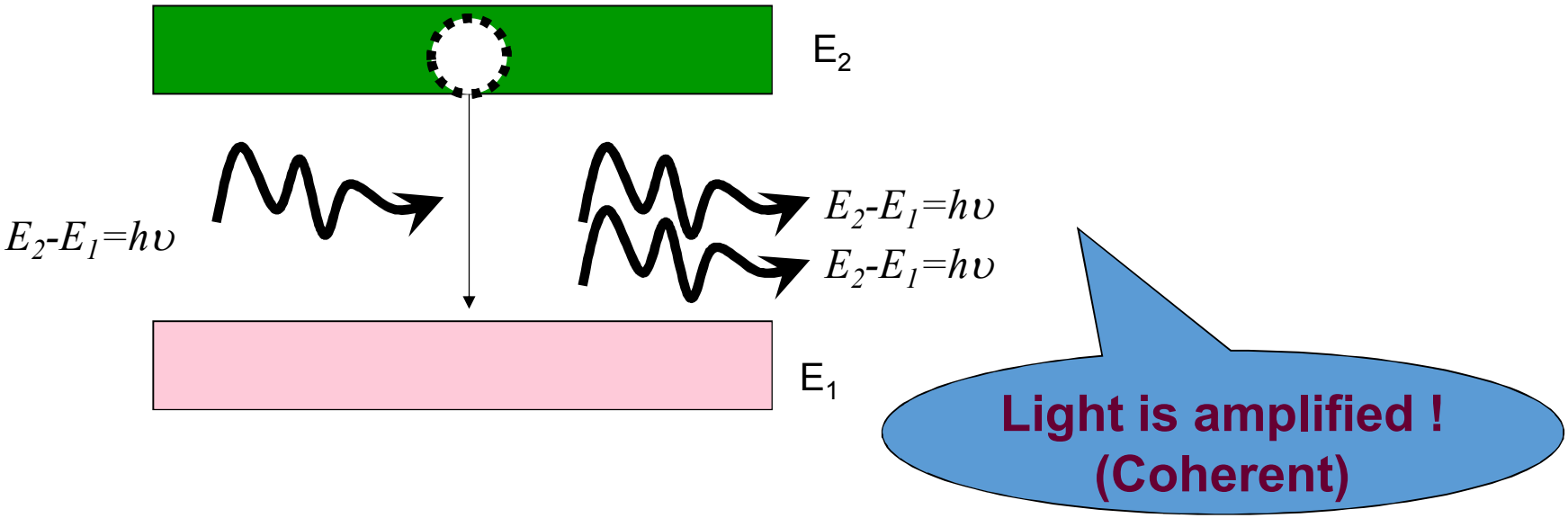
1. Absorption



2. Spontaneous Emission

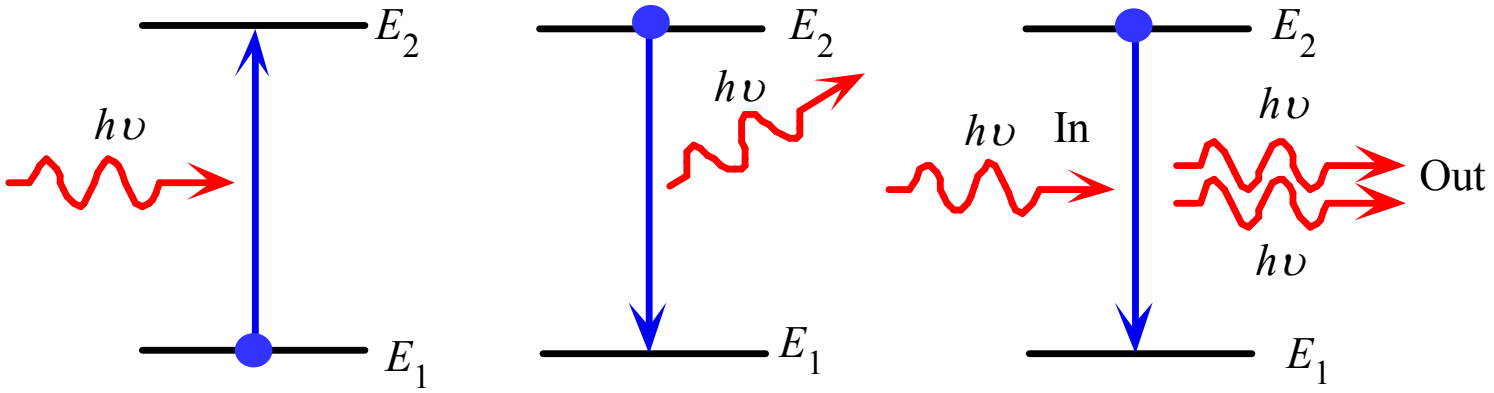


3. Stimulated Emission



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.

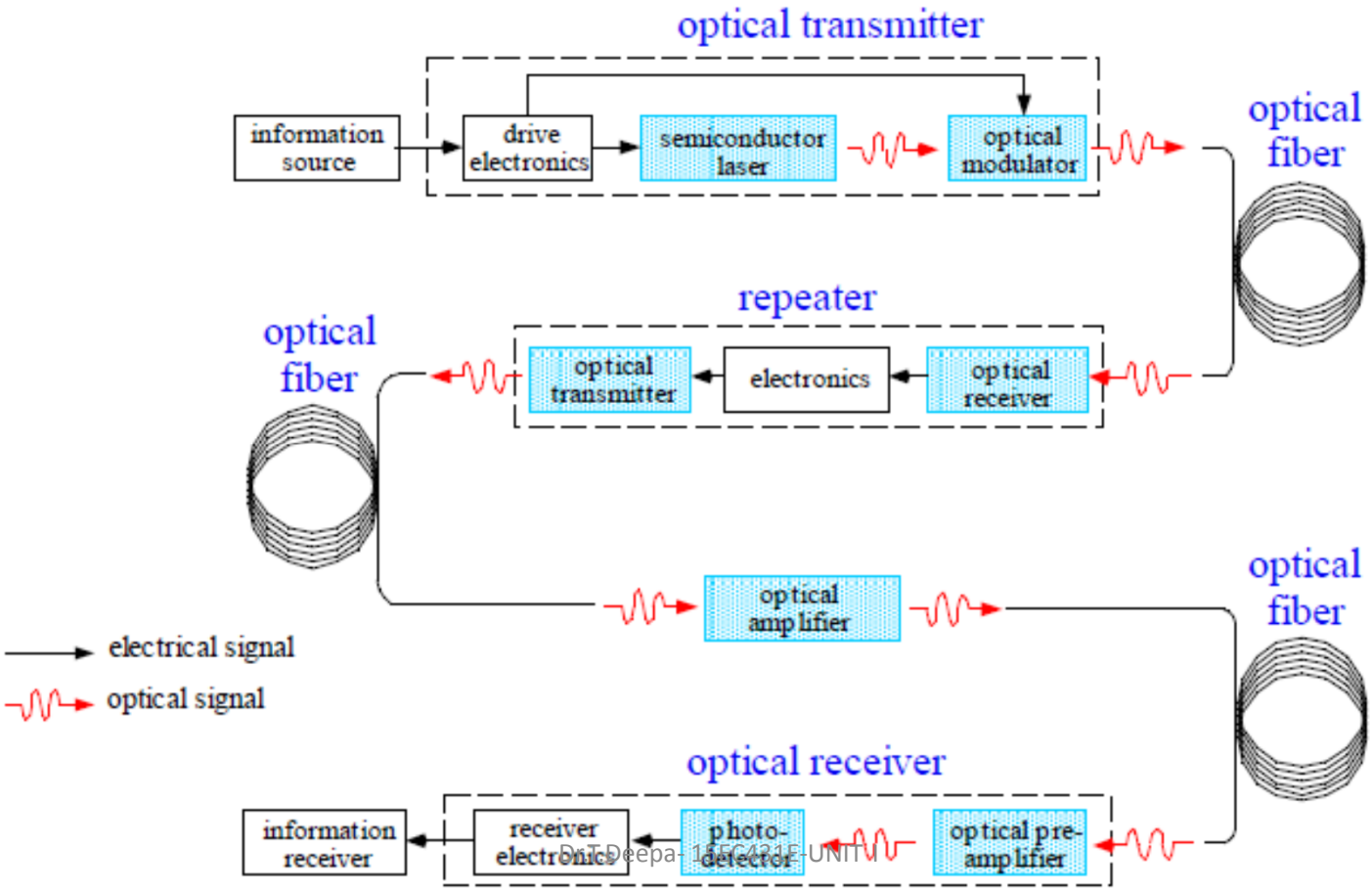
A Recap of Three Processes



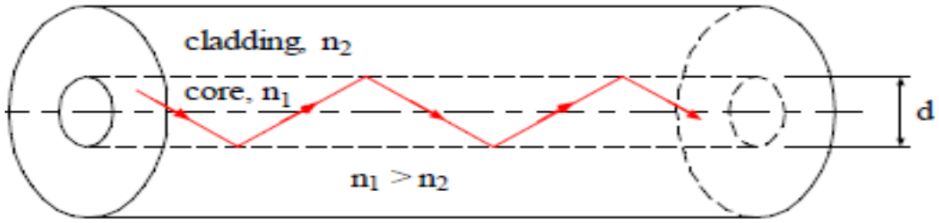
(a) Absorption (b) Spontaneous emission (c) Stimulated emission

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

A Fiber Communication Link



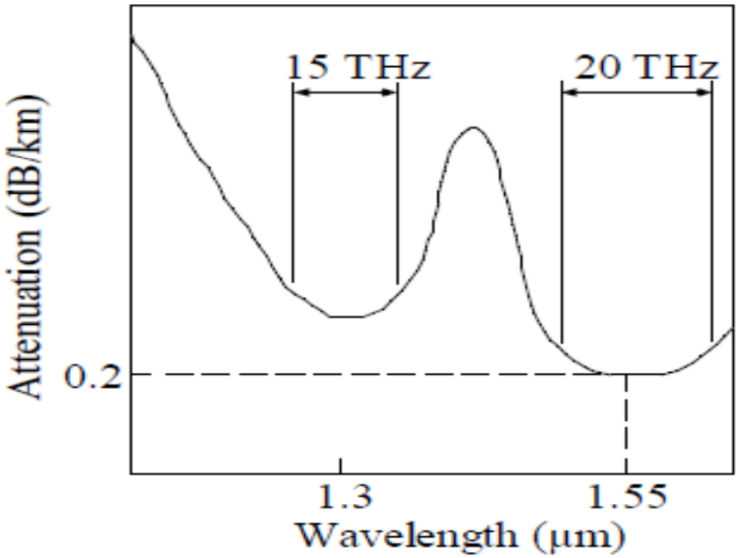
Optical Fiber:



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

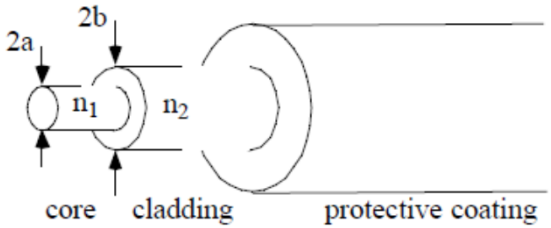
Typical core sizes:

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



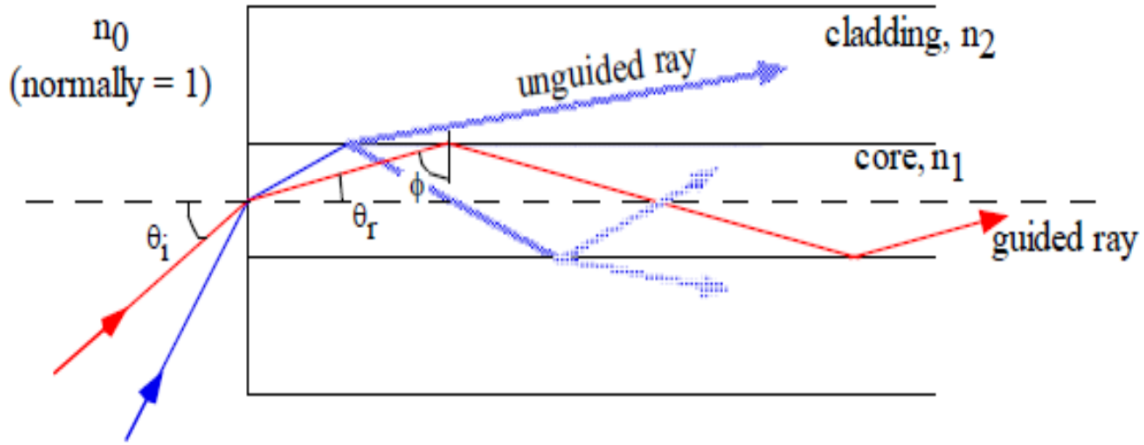
Basics of Fiber Optic Waveguide

- 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 (SiO2)
- • 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

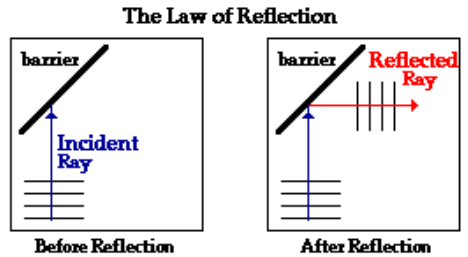


Geometrical-Optics Description

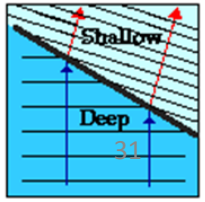
- Light is guided through the core, and the fiber acts as an optical waveguide.



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.



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.



Apply Snell's law at input

$$n_0 \sin\theta_i = n_1 \sin\theta_r$$

Minimum critical angle ϕ_c for total internal reflection

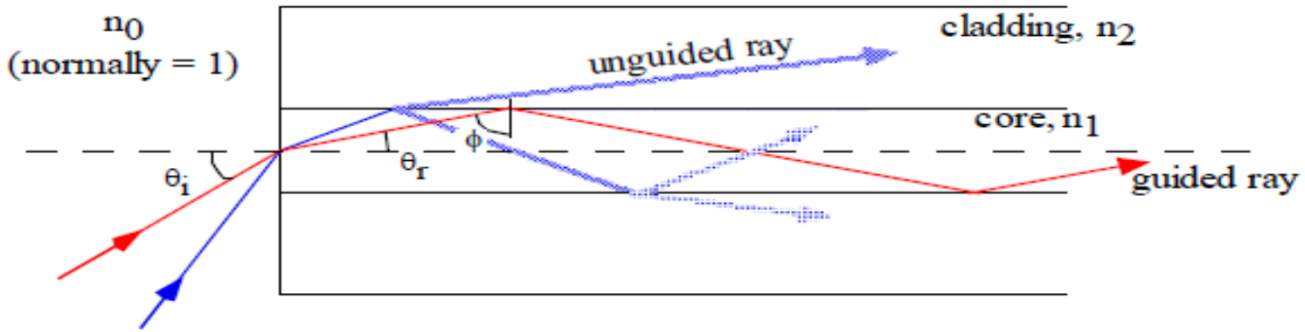
$$n_1 \sin\phi_c = n_2 \sin(\pi/2) \Rightarrow \sin\phi_c = n_2 / n_1$$

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***



Dispersion

The **dispersion of light** is the phenomenon of splitting of a beam of white light into its seven constituent colours when passed through a transparent medium.

Optical-Power Measurement

- The power level in optical communications is of too wide a range to express on a linear scale. A logarithmic scale known as decibel (dB) is used to express power in optical communications.
- The wide range of power values makes decibel a convenient unit to express the power levels that are associated with an optical system. The gain of an amplifier or attenuation in fiber is expressed in decibels.
- The decibel does not give a magnitude of power, but it is a ratio of the output power to the input power.

Decibel (dB) expresses a power ratio according to

$$10\log_{10}\left(\frac{P_1}{P_2}\right)$$

The photo current is proportional to the optical power

- $I_{det} \sim P_{opt} \Rightarrow P_{el} \sim P_{opt}^2$
- $dB_{opt} \neq dB_{el}$ (3 dB optical power diff. ⇒ 6 dB electrical power diff.)

dBm expresses the absolute power on a log scale relative to 1 mW

$$P_{dBm} = 10\log_{10}\left(\frac{P[\mathrm{W}]}{1\,\mathrm{mW}}\right)$$

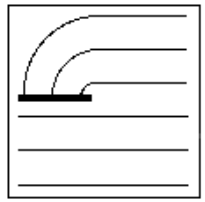
Examples:

- 1 mW = 0 dBm, 2 mW = 3 dBm, 4 mW = 6 dBm, 8 mW = 9 dBm
- 0.5 mW = –3 dBm, 1 µW = –30 dBm
- 100 mW = 20 dBm, 400 mW = 26 dBm

Diffraction

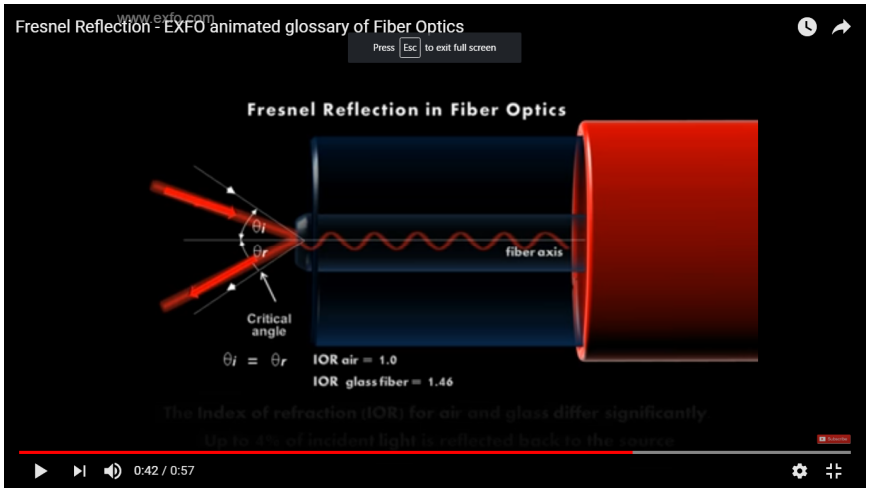
Diffraction involves a change in direction of waves as they pass through an opening or around a barrier in their path. Water waves have the ability to travel around corners, around obstacles and through openings. This ability is most obvious for water waves with longer wavelengths. Diffraction can be demonstrated by placing small barriers and obstacles in a ripple tank and observing the path of the water waves as they encounter the obstacles. The waves are seen to pass around the barrier into the regions behind it; subsequently the water behind the barrier is disturbed. The amount of diffraction (the sharpness of the bending) increases with increasing wavelength and decreases with decreasing wavelength. In fact, when the wavelength of the waves is smaller than the obstacle, no noticeable diffraction occurs.

Analogy Diffraction of water waves is observed in a harbor as waves bend around small boats and are found to disturb the water behind them. The same waves however are unable to diffract around larger boats since their wavelength is smaller than the boat. Diffraction of sound waves is commonly observed; we notice sound diffracting around corners, allowing us to hear others who are speaking to us from adjacent rooms. Many forest-dwelling birds take advantage of the diffractive ability of long-wavelength sound waves. Owls for instance are able to communicate across long distances due to the fact that their long-wavelength *hoots* are able to diffract around forest trees and carry farther than the short-wavelength *tweets* of songbirds. Diffraction is observed of light waves but only when the waves encounter obstacles with extremely small wavelengths (such as particles suspended in our atmosphere). Diffraction of sound waves and of light waves will be discussed in a later unit of The Physics Classroom Tutorial.


Diffraction of Waves

Fresnel's Reflection

- *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*



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".

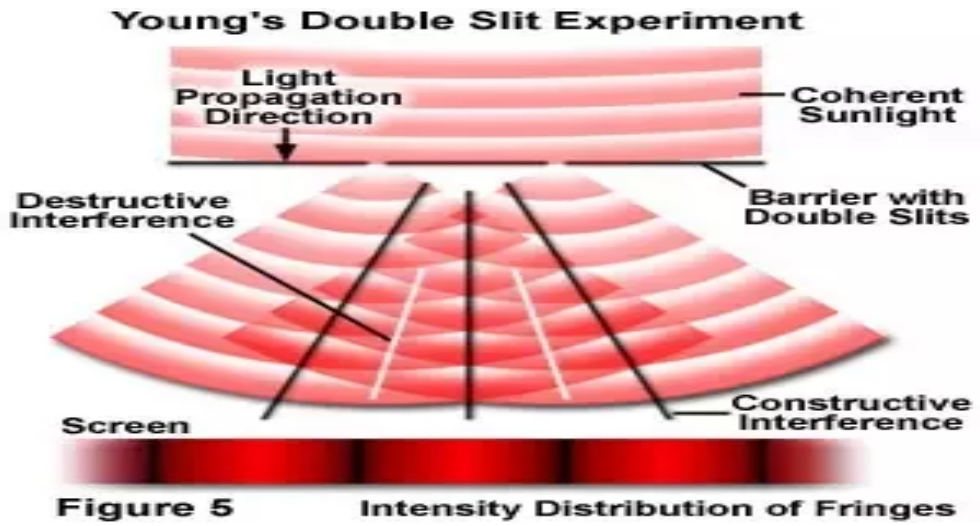


Figure 5

Conditions for Interference

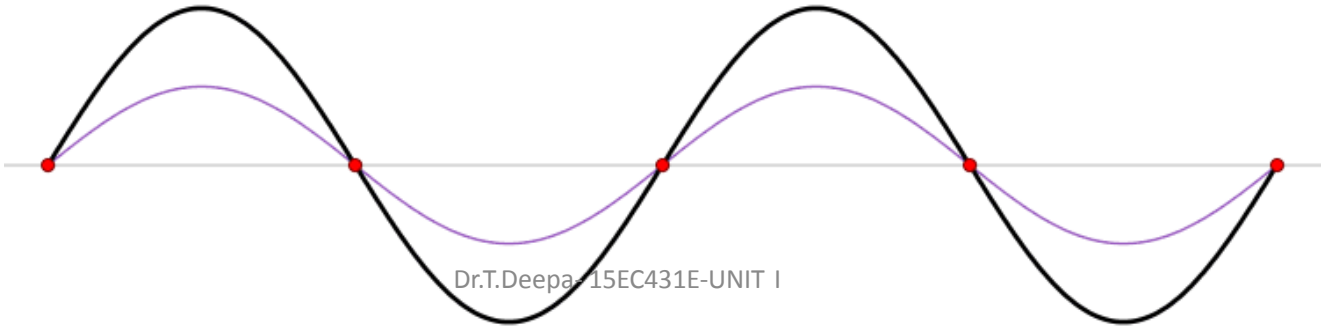
- The two sources of light should emit continuous waves of same wavelength and same time period. i.e.the source should have phase coherence.
- The two sources of light should be very close to each other.
- The waves emitted by two sources should either have zero phase difference or no
- **Coherent Sources**: 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
- Destructive Interference

Definitions: Constructive & Destructive

- In total *constructive* interference, when the peak of one wave merges with the peak of an identical wave, they add together and 'construct' a larger wave.
- In total *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).
- 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.



Constructive Interference

- When two light waves superpose with each other in such away that the crest of one wave falls on the crest of the second wave, and trough of one wave falls on the trough of the second wave, then the resultant wave has larger amplitude and it is called constructive interference
- For constructive interference, path difference between two waves is **m ƛ**

  i.e. **path difference = mƛ**

  or path difference = 0, **ƛ**, 2 **ƛ**, 3 **ƛ**, 4 **ƛ**, ...

  where m = order = 0, +_1, +_2, +_3,.....

Effects – Constructive Interference

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

https://upload.wikimedia.org/wikipedia/commons/7/7d/Standing_wave_2.gif

Destructive Interference

- When two light waves superpose with each other in such away that the crest of one wave coincides the trough of the second wave, then the amplitude of resultant wave becomes zero and it is called destructive interference.
- If the path difference between two light waves is **(m+1/2) ƛ** , then the interference between them will be destructive.

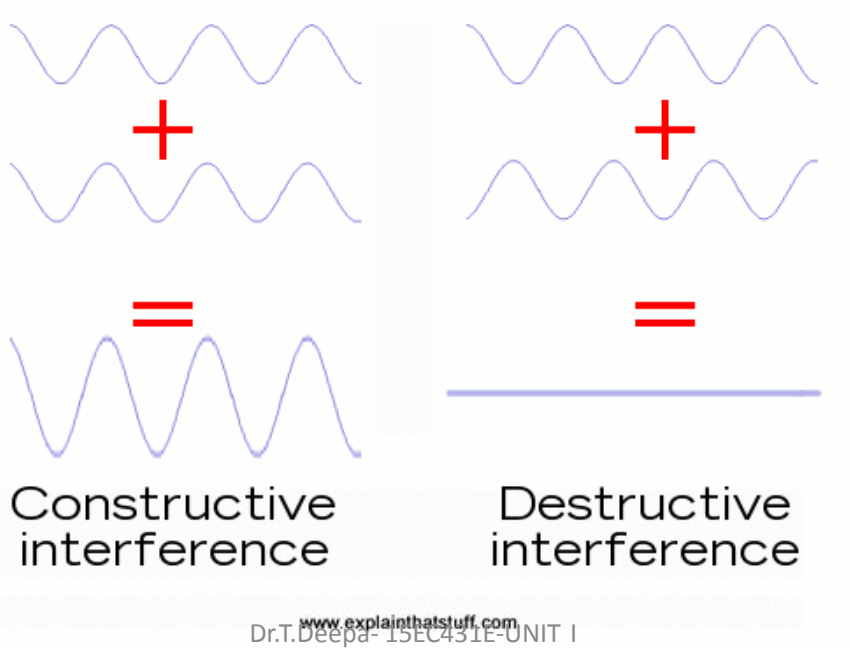
  Path difference = (m+1/2) ƛ

  i.e. path difference = 1/2**ƛ** , 3/2**ƛ** , 5/2**ƛ** , ...

  where m = order = 0, +_1, +_2, +_3,...

Effects- Destructive Interference

- Two waves cancel the effects of each other
- Due to destructive interference a dark fringe is obtained on the screen



Interferometers

- Interferometers are investigative tools used in many fields of science and engineering.
- 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 or phenomenon being studied. They are often used to make very small measurements that are not achievable any other way. This is why they are so powerful for detecting gravitational waves--LIGO's interferometers are designed to measure a distance 1/10,000th the width of a proton!

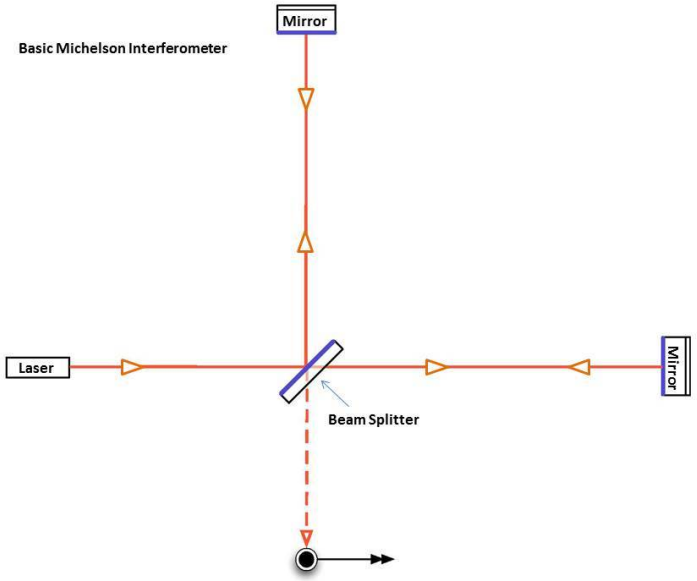
Interference Pattern

- 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.



How does Interferometer look like

- Because of their wide application, interferometers come in a variety of shapes and sizes.
- 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: they superimpose beams of light to generate an interference pattern.
- The basic configuration of a Michelson interferometer is shown at right. It consists of a laser, a beam splitter, a series of mirrors, and a photodetector (the black dot) that records the interference pattern.



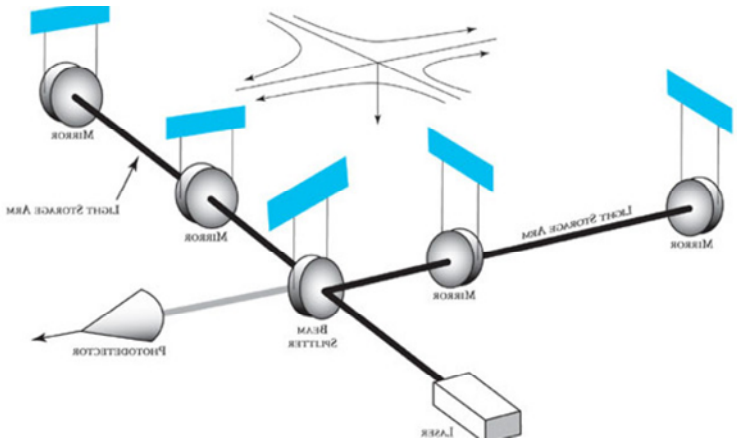
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Working Principle : Interferometer

- In a Michelson interferometer, a laser beam passes through a 'beam splitter' (a kind of mirror) which 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.
- 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.

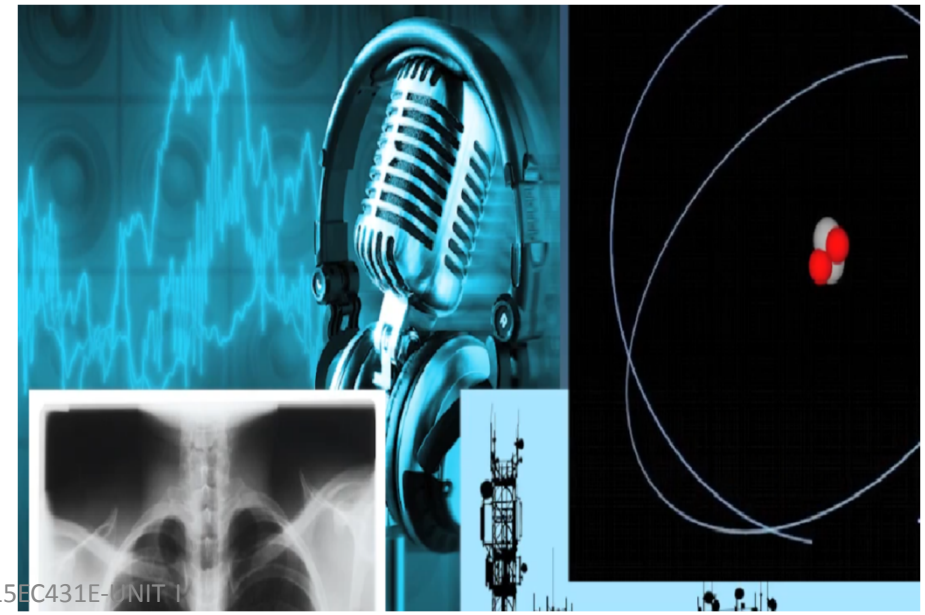
Working Principle : Interferometer (Cont'd)

- Since they don't arrive at the same time, the beams' waves will be slightly offset when they merge, which causes the light waves to interfere in a different way than they did when they travelled the same distance.
- 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

- **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.

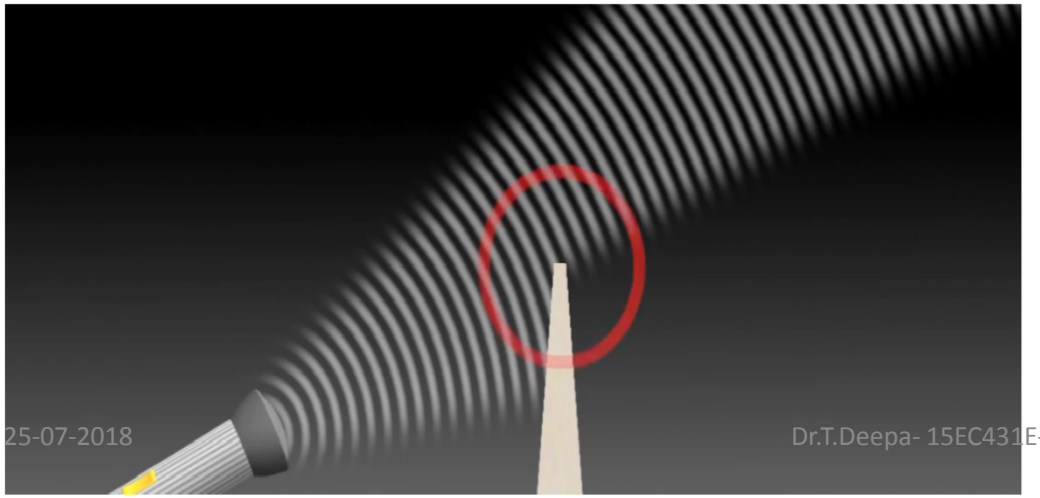


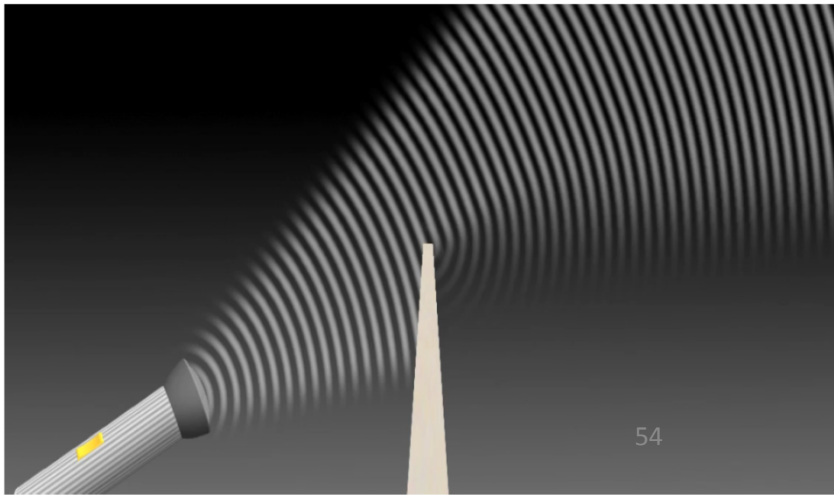
Diffraction (Cont'd)

- 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)

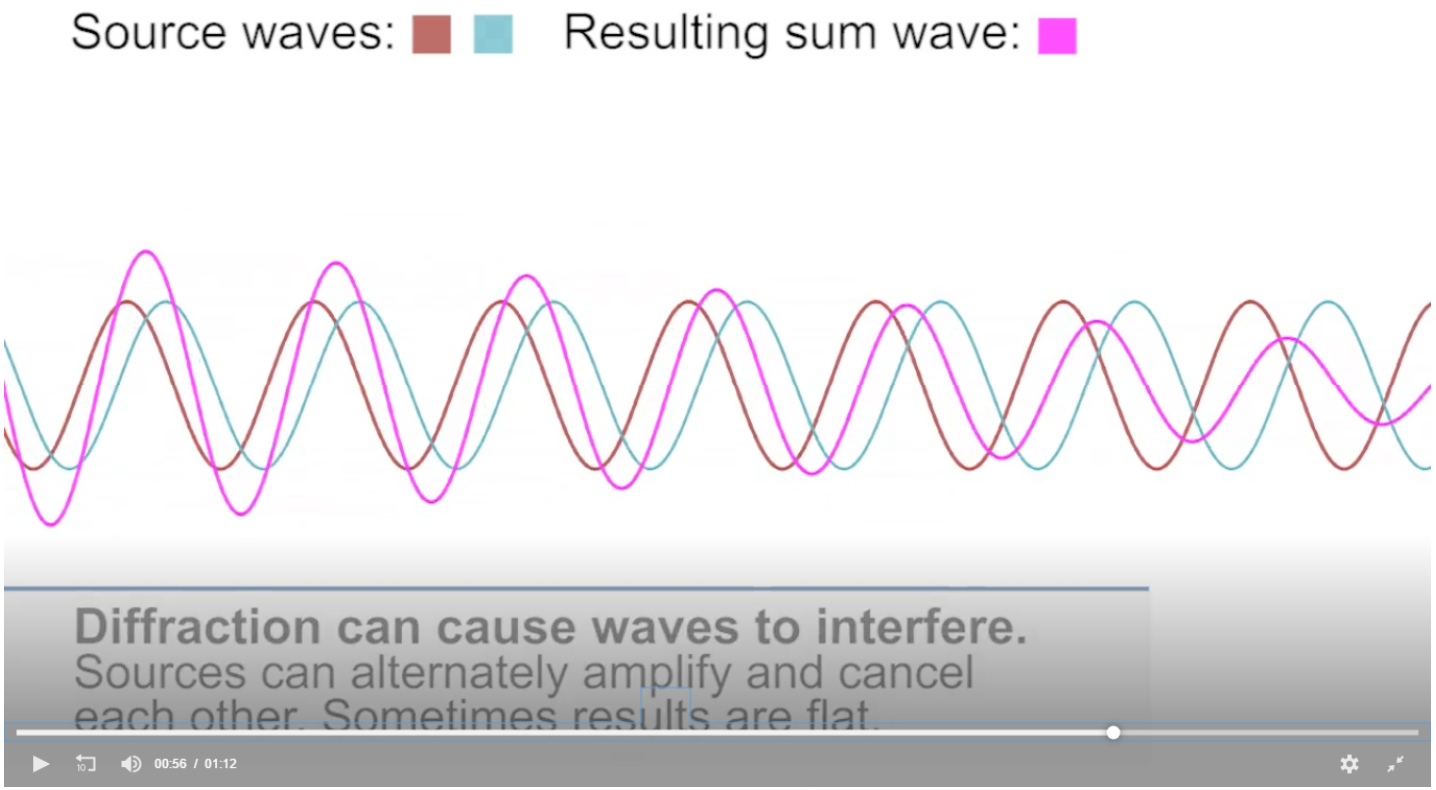
- Example 1 : When a beam of light falls on the edge of an object, it will not continue in a straight line but will be slightly bent by the contact, causing a blur at the edge of the shadow of the object; the amount of bending will be proportional to the wavelength.
- Example 2 : When a stream of fast 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.



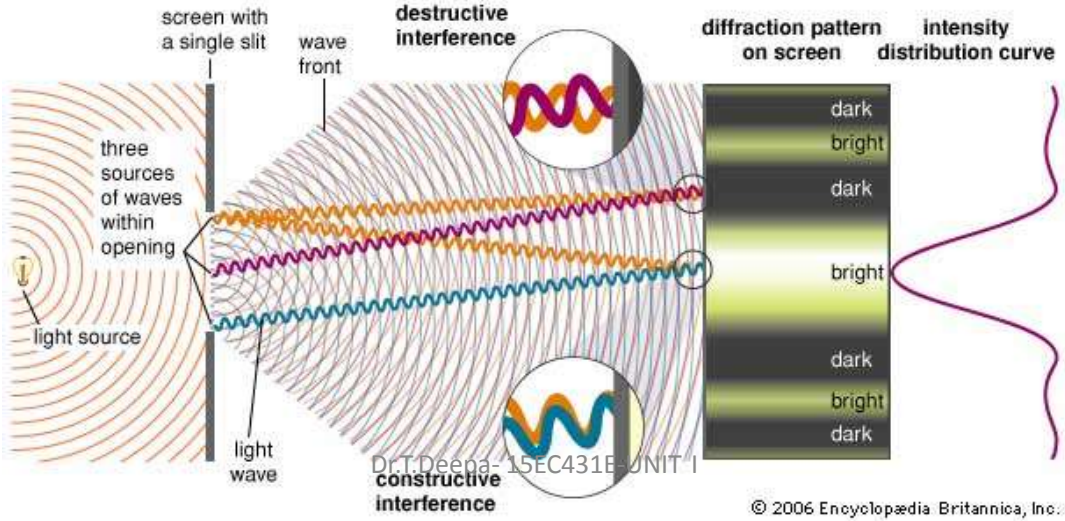


Diffraction (Cont'd)

Diffraction can cause waves to interfere



- Single-slit diffractionWhen monochromatic light passing through a single slit illuminates a screen, a characteristic diffraction pattern is observed. Diffraction is a product of the superposition of waves—i.e., it is an interference effect. The detailed pattern of constructive and destructive interference fringes can be derived by treating every point on the wave front passing through the slit as a secondary source of spherical waves. The paths from three representative secondary sources to the viewing screen are shown here. The central bright fringe in a single-slit diffraction pattern is produced by the constructive interference of all of the secondary sources. The width of the central fringe is inversely proportional to the width of the slit. Diffraction effects become pronounced only when the width of the slit is an appreciable fraction of the wavelength of the light.



Polarization of Light

- 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 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.

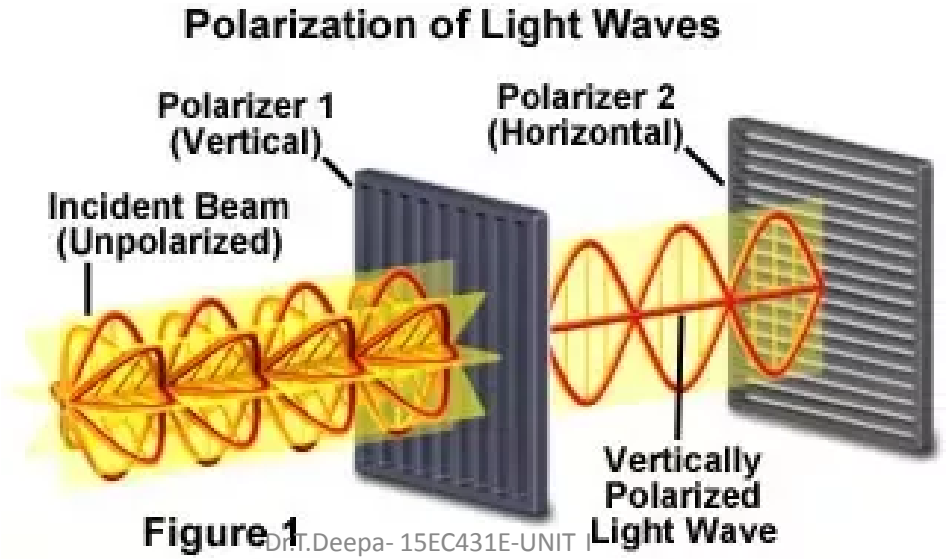
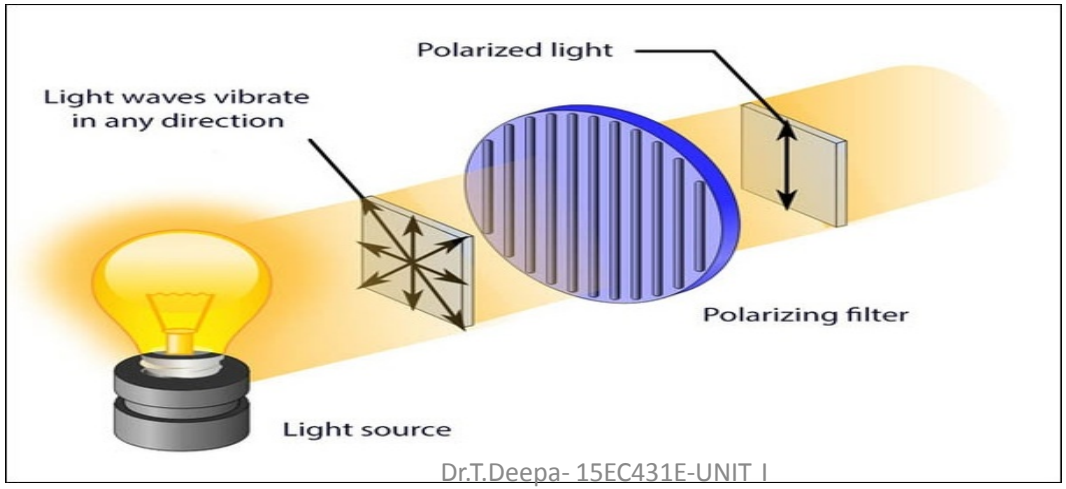


Figure 1

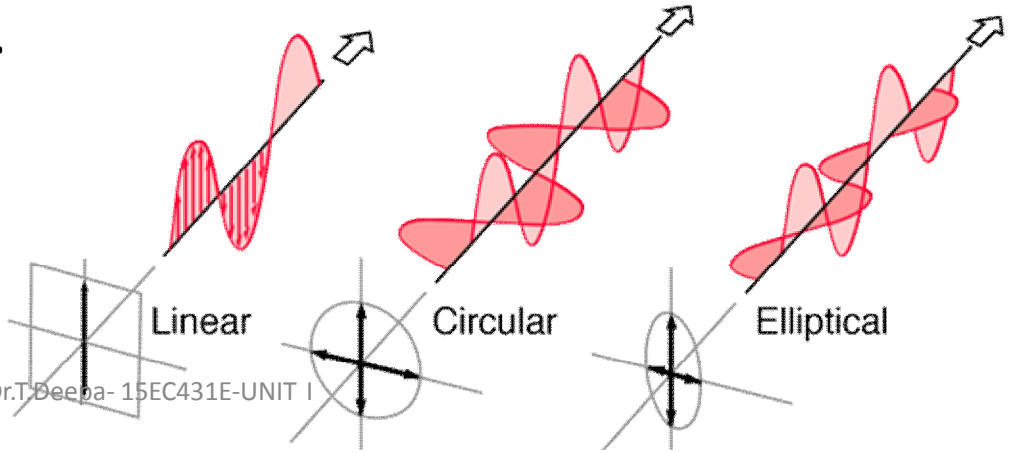
Difference between the plane polarized light and ordinary light

- 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

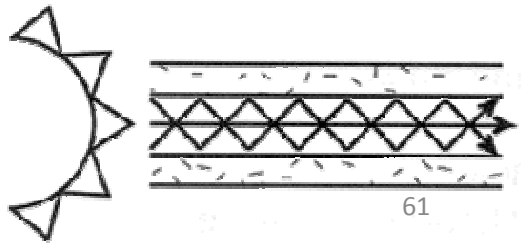
- Light in the form of a plane wave in space is said to be linearly polarized.
- Light is a transverse electromagnetic wave, but natural light is generally unpolarized, all planes of propagation being equally probable.
- If light is composed of two plane waves of equal amplitude by differing in phase 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.



Introduction –Dispersion

- **Multi-mode optical fiber** is a type of optical fiber mostly used for communication over short distances, such as within a building or on a campus.
- Typical multi-mode links have data rates of 10 Mbit/s to 10 Gbit/s over link lengths of up to 600 meters (2000 feet).
- Multi-mode fiber has a fairly large core diameter that enables multiple light modes to be propagated and limits the maximum length of a transmission link because of modal dispersion.

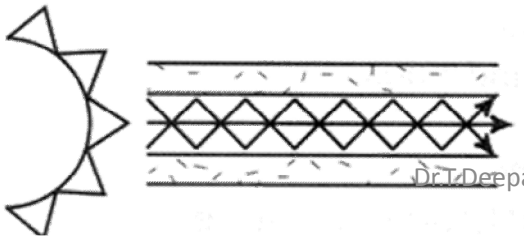
"Multimode fiber"
multiple paths through the fiber

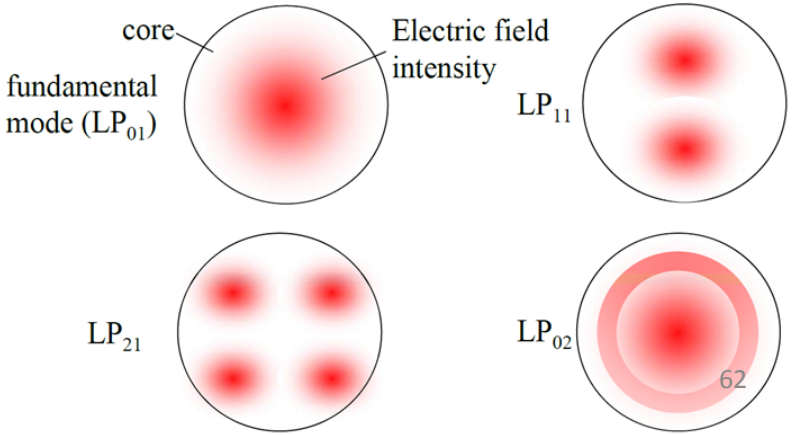


Multimode Dispersion

- The bandwidth of an optical fibre is limited by a phenomenon known as multimode dispersion.
- **What is Multimode dispersion?**
- Different reflection angles within the fibre core create different propagation paths for the light rays. Rays that travel nearest to the axis of the core propagate by what is called the zeroth order mode; other light rays propagate by higher-order modes. It is the simultaneous presence of many modes of propagation within a single fibre that creates multimode dispersion.

"Multimode fiber"
multiple paths through the fiber





Multimode Fiber Causes

- Multimode dispersion causes a signal of uniform transmitted intensity to arrive at the far end of the fibre in a complicated spatial "interference pattern," and this pattern in turn can translate into pulse "spreading" or "smearing" and intersymbol interference at the optoelectronic receiver output.
- Pulse spreading worsens in longer fibres.

Types of Multimode fiber

- When the index of refraction is constant within the core, the fibre is called a stepped-index (SI) fibre. Graded-index (GI) fibre reduces multimode dispersion by grading the refractive index of the core so that it smoothly tapers between the core centre and the cladding.

Single mode fiber

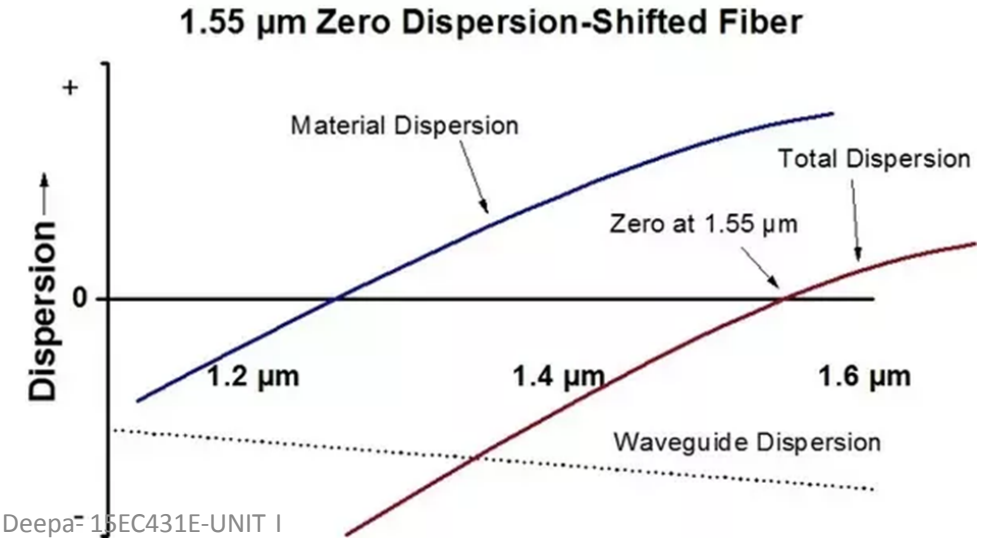
- Another type of fibre, known as single-mode (SM) fibre, eliminates multimode dispersion by reducing the diameter of the core to a point at which it passes only light rays of the zeroth order mode.
- Typical SM core diameters are 10 micrometres or less, while standard SI core diameters are in the range of 50 micrometres.
- Single-mode fibres have become the dominant medium in long-distance optical fibre links.

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 intersymbol interference.

Material Dispersion and Waveguide Dispersion (Cont'd)

- Therefore the total dispersion (the change of the effective index with wavelength has a material contribution (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.
- Waveguide dispersion can be made more negative by changing the index profile and thus be used to offset the fixed material dispersion, shifting or flattening the overall intramodal dispersion.
- This is advantageous because 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.

Signal Attenuation

- 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

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

Dispersions

