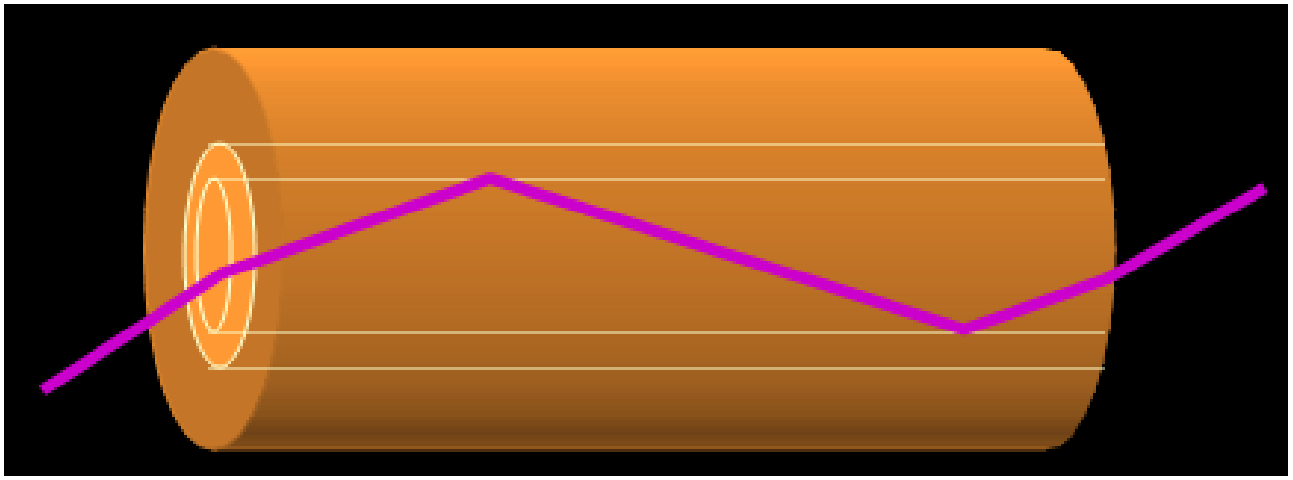
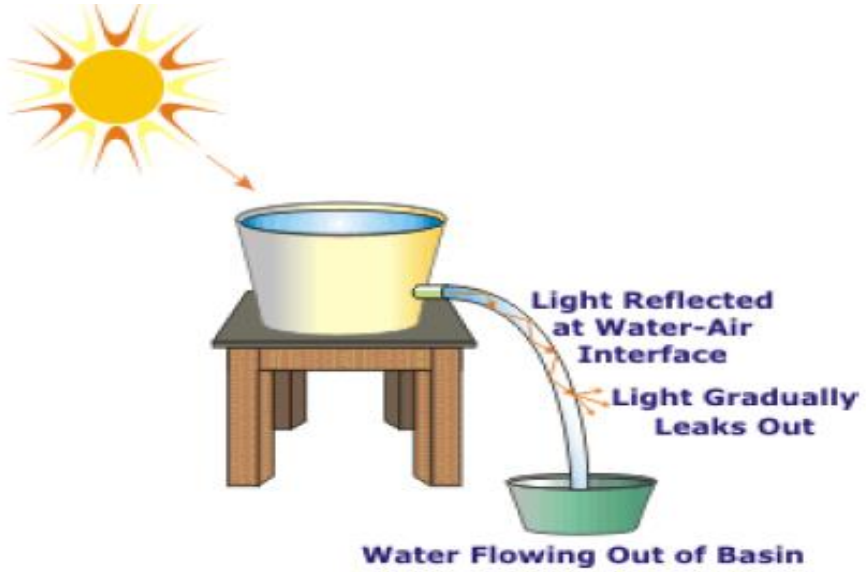
Fiber Optic Communication Fundamentals



A History of Fiber Optic Technology

The Nineteenth Century

- John Tyndall, 1870
  - water and light experiment
  - demonstrated light used internal reflection to follow a specific path
- Alexander Graham Bell, 1880
  - optical voice transmission system
  - called a photophone
  - free light space carried voice 200 meters
- Fiber-scope, 1950's

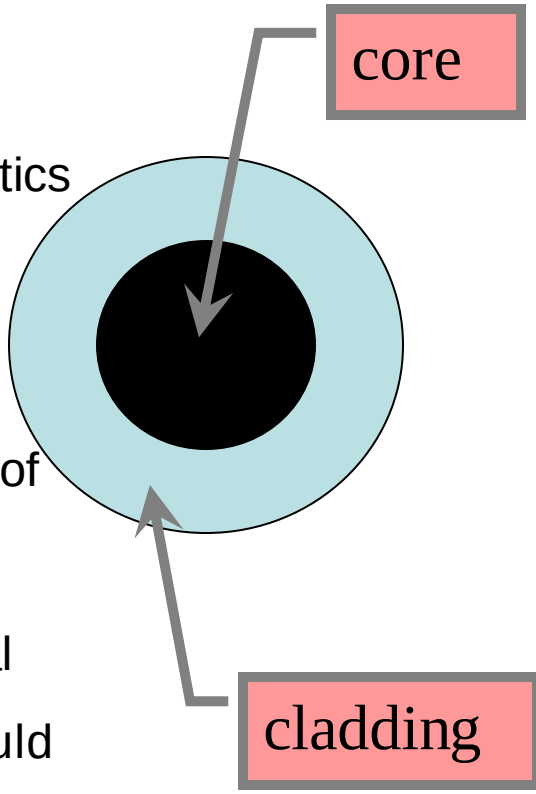






The Twentieth Century

- Glass coated fibers developed to reduce optical loss
- Inner fiber – **core** &Glass coating - **cladding**
- Development of laser technology was important to fiber optics
- Large amounts of light in a tiny spot needed
- 1960, ruby and helium-neon laser developed
- 1962, semiconductor laser introduced - most popular type of laser in fiber optics
- 1966, Charles Kao and Charles Hockman proposed optical fiber could be used to transmit laser light if attenuation could be kept under 20dB/km (optical fiber loss at the time was over 1,000dB/km)
- 1970, Researchers at Corning developed a glass fiber with less than a 20dB/km loss



Definition

Fiber-optic communication is a method of transmitting information from one place to another by sending pulses of light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated to carry information.

Optical Fibre -

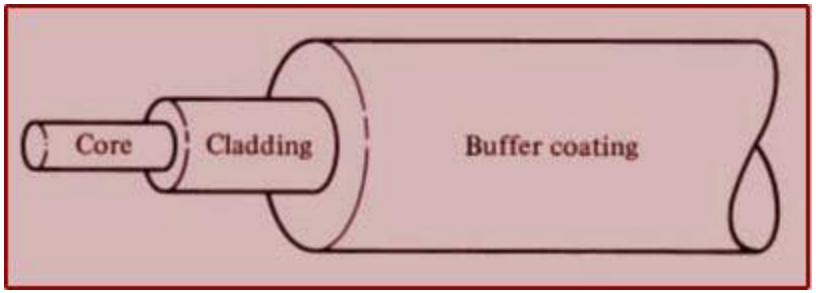
An optical fibre is a dielectric cylindrical wave guide that operates at optical frequencies.

An optical fiber is a flexible, transparent fiber made by glass (silica) or plastic to a diameter slightly thicker than that of a human hair.

Function -

It confines electro magnetic energy in the form of light to within its surfaces and guides the light in a direction parallel to its axis.

Optical Fibre Structure



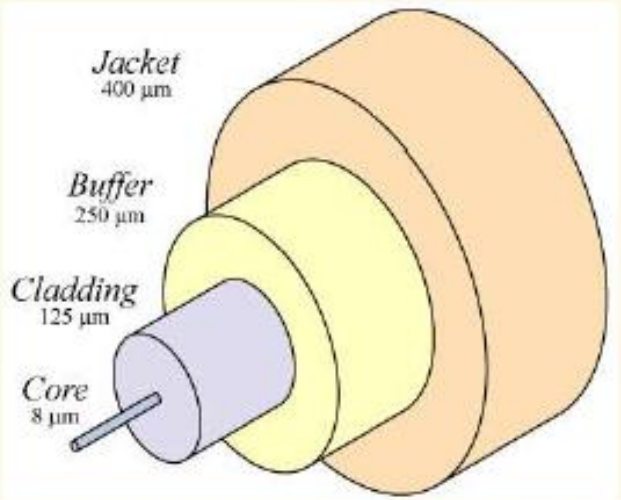
•The rod is called the **core** **and is made of highly purified glass. Most of the light energy in** confined to the core. (9 to 100 microns)

•The glass shell called **cladding**. **The cladding shields optical fields so as not to get** interfered by the outer layers of the fiber. The cladding is an essential part of an optical fiber. (125 or 140 microns)

•The cladding is surrounded by the **buffer** layers. These layers have no role in propagation of light. They are essentially use to provide the mechanical support to the glass fiber and to protect the fiber from external damage. (250, 500 and 900 microns)

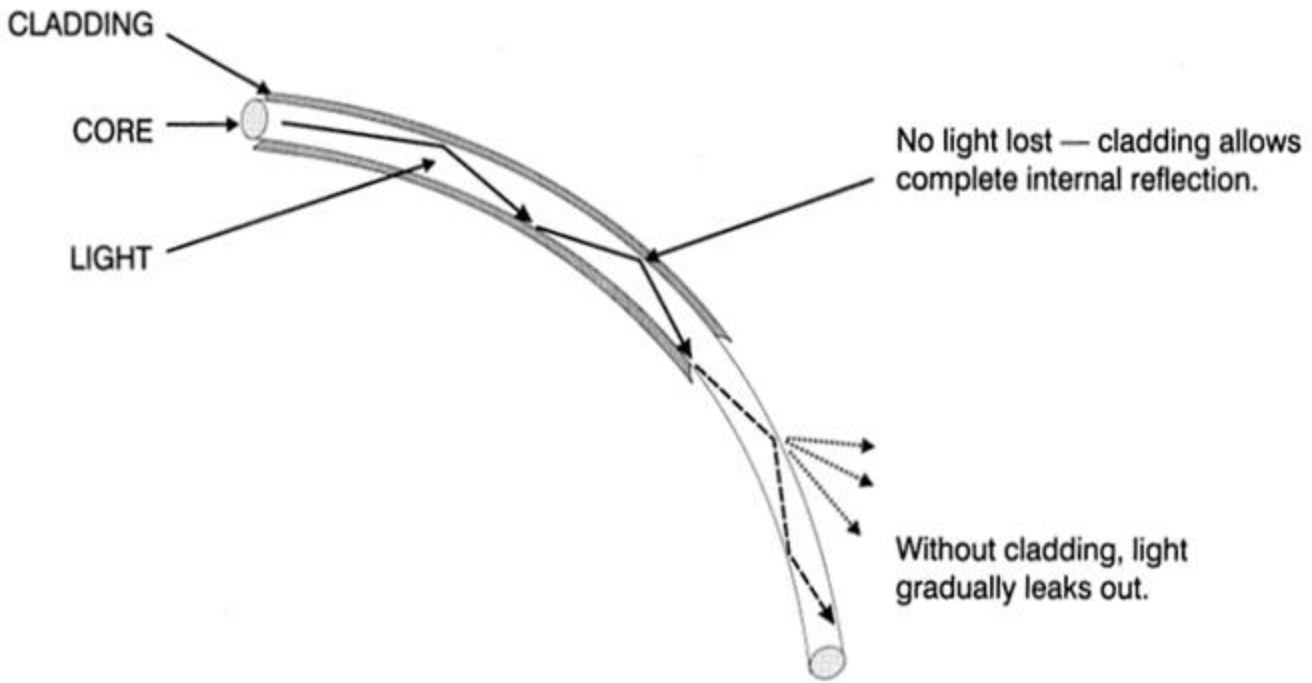
Basic structure of the Fiber Optics

- **Jacket**:
  - Determines the mechanical robustness of the cable.
  - Usually plastic, PVC etc.
- **Buffer** (or **coating**):
  - Protects the fiber optic from physical damage. Fiber identification etc.
- **Cladding**:
  - Dielectric material, with index of refraction less than the core material. Made of glass or plastic.
- **Core**:
  - Light propagation medium. Dielectric material (usually glass). Conducts no electricity.

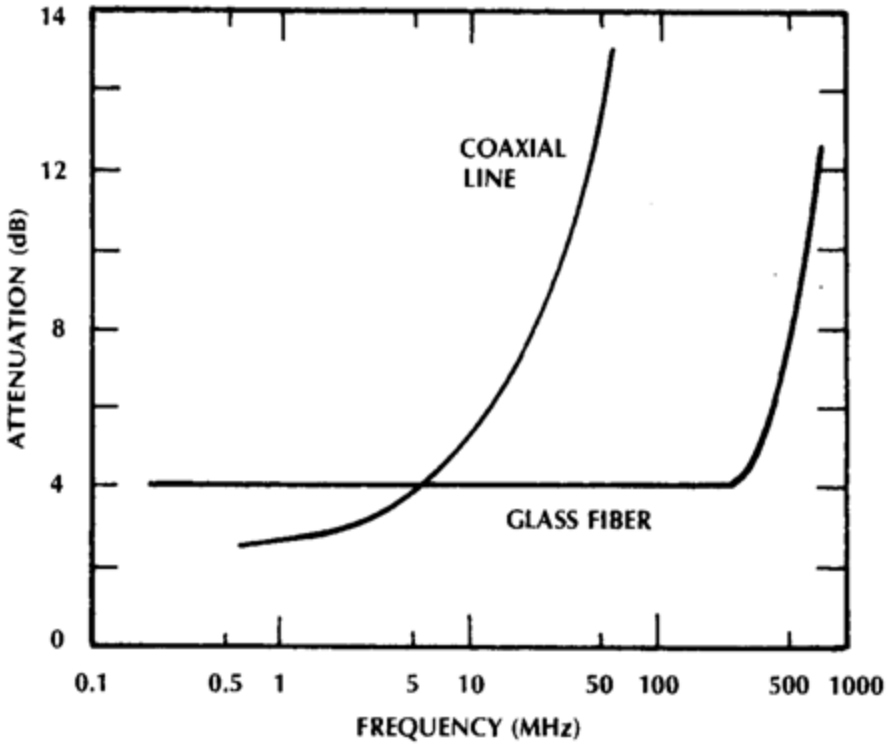




Optical Fiber with Cladding



Why Optical Fiber ???

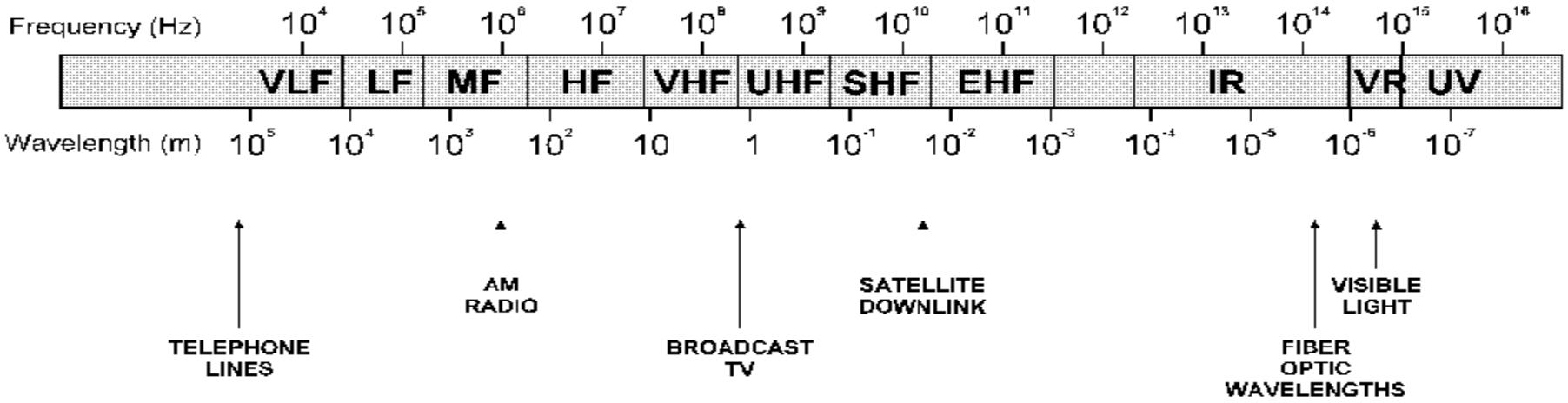


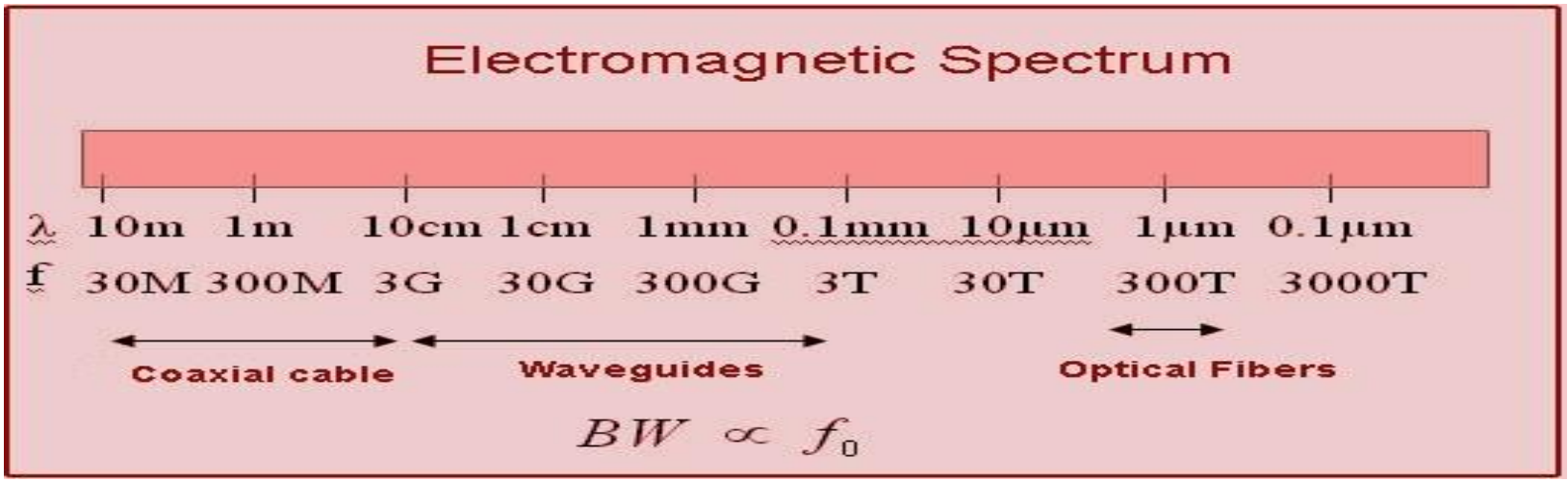
Wide bandwidth signal transmission with low delay is a key requirement in present day applications. Optical fibers provide enormous and unsurpassed transmission bandwidth with negligible latency, and are now the transmission medium of choice for long distance and high data rate transmission in telecommunication networks.

- Fiber communication promised extremely high data rates, which allow high capacity transmission quickly.
- It also had the potential for transmission over long distances without the need to amplify and retransmit along the way.
- Speed limit of electronic processing, limited bandwidth of copper/coaxial cables.
- Optical fiber has very high-bandwidth (~30 THz)
- Optical fiber has very low loss (~0.25dB/km@1550nm) suitable for long-distance transmission.

Principles of Fiber Optic Transmission

- Electronic signals converted to light & Light refers to more than the visible portion of the electromagnetic (EM) spectrum





Principles of Fiber Optic Transmission

Light wave is composed into Electromagnetic (EM) Waves.

For fiber optics applications, EM waves two categories of wavelength are used --

- Visible wavelength (400 to 700 nanometers) - limited use
- near-infrared wavelength (700 to 2000 nanometers) - used almost always in modern fiber optic systems.

For good communication a system needs to have following things.

(1) Bandwidth (BW)

(2) Good signal to noise ratio (SNR) i.e. low loss.

The BW at optical frequencies is expected to be 3 to 4 orders of magnitude higher than that at the microwave frequencies (1GHz to 100GHz).

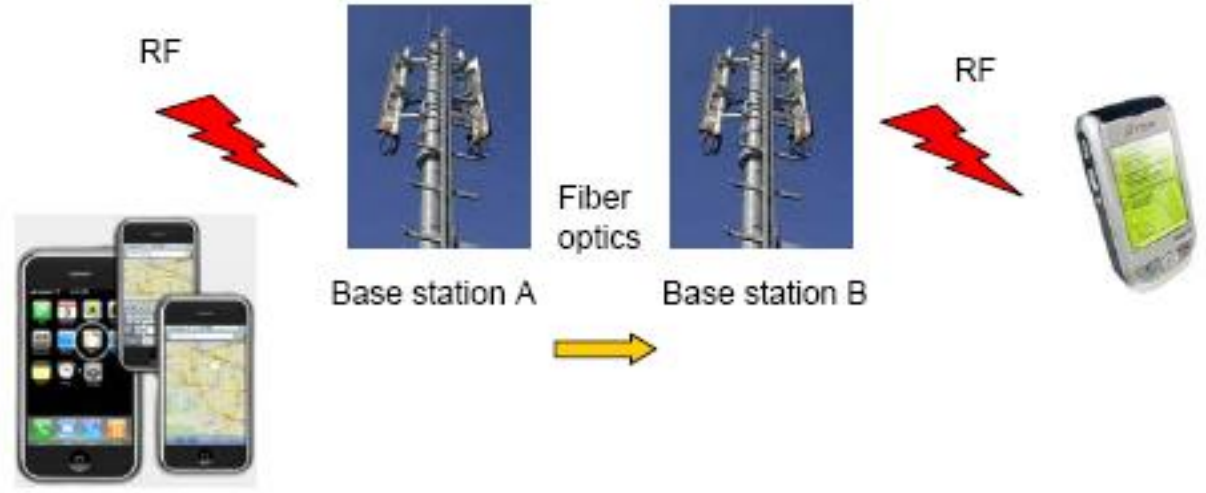
Fiber Optics Applications

- Military
  - 1970's, Fiber optic telephone link installed aboard the U.S.S. Little Rock
  - 1976, Air Force developed Airborne Light Fiber Technology (ALOF)

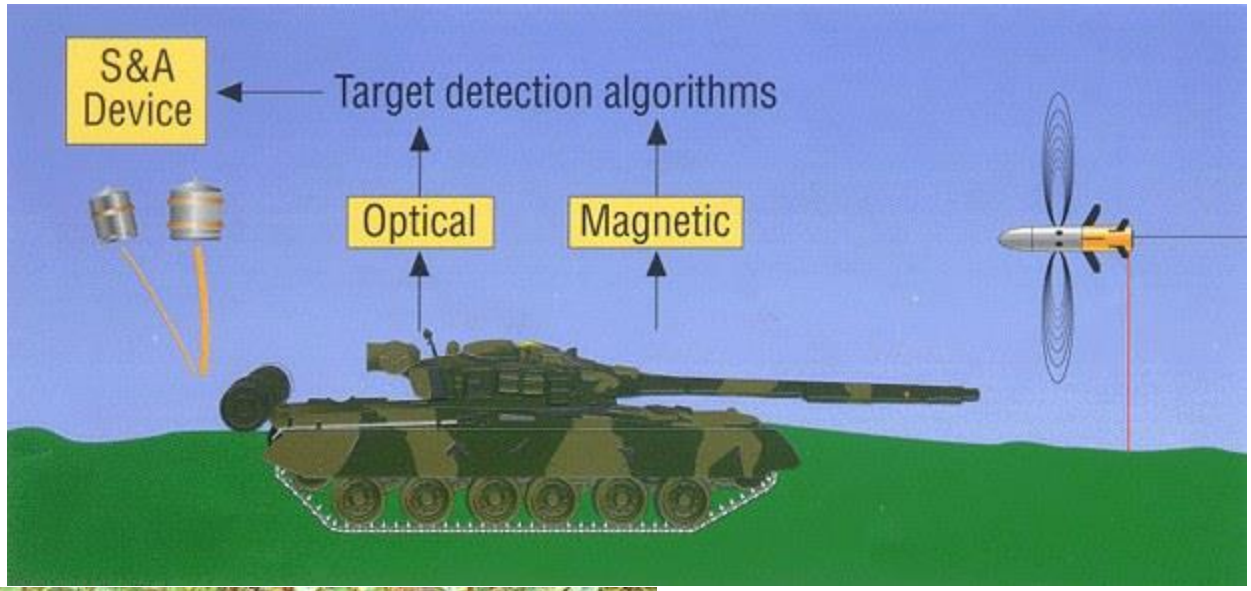
- Commercial
  - 1977, AT&T and GTE installed the first fiber optic telephone system
  - Fiber optic telephone networks are common today
  - Research continues to increase the capabilities of fiber optic transmission

Applications of Fiber Optics

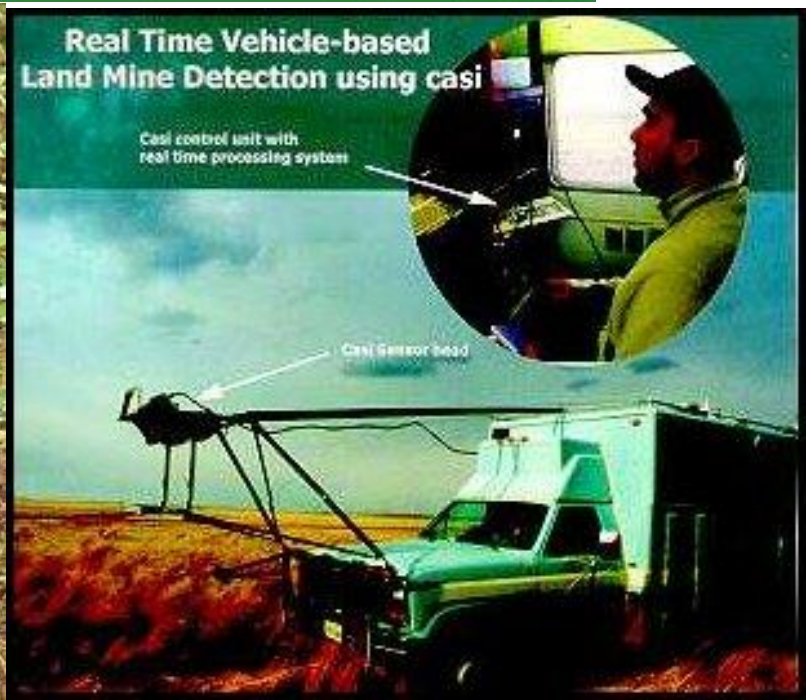
- Military
- Computer
- Medical/Optometric
- Sensor
- Communication



Military Application







Computer Application

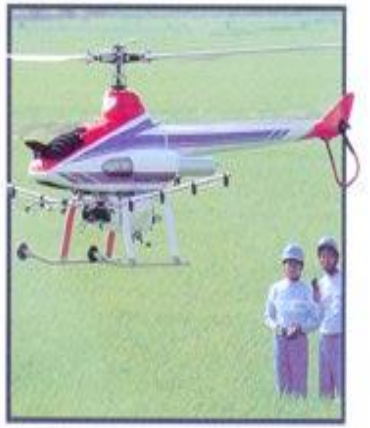


Sensors









Gas sensors
Chemical sensors
Mechanical sensors
Fuel sensors
Distance sensors
Pressure sensors
Fluid level sensors
Gyro sensors

Medical Application

- Endoscope
- Eyes surgery
- Blood pressure meter





- As fibers are very flexible, they are used in flexible digital cameras.
- Fibers are used in mechanical imaging i.e. for inspection of mechanical welds in pipes and engines of rockets, space shuttles, airplanes.
- Fibers can be used under sea communication.
- Nuclear testing applications use optical fiber phase sensors and transducers.
- Fibers are used in public utility organizations like railways, TV transmission etc.
- Fibers are used in LAN systems of offices, industrial plants and colleges etc.
- Fibers are used in telecommunication such as voice telephones, video phones, telegraph services, message services and data networks.

The Future Trends

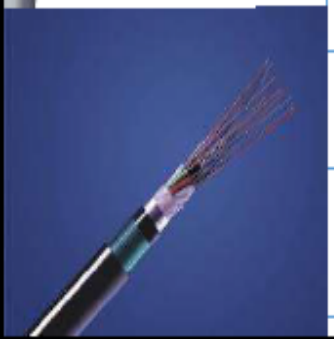
- All Optical Communication Networks **;**
- Multi – Terabit Optical Networks ;
- Intelligent Optical Transmission Network ;
- Polymer Optic Fibers ;
- Improvement in Optical Amplification Technology ;
- Improvements in Glass Fiber Design and Component Miniaturization ;
- Ultra – Long Haul Optical Transmission ;
- High – Altitude Platforms .



Advancements in optical cables

First generation	used GaAs semiconductor lasers, operated at a wavelength of 0·8 μm, and bit rate of 45Megabits/second with 10Km repeater spacing.
Second generation	Used InGaAsP semi-conductor lasers, operated at a wavelength of 1·3 μm, at bit rates of up to 1·7Gigabits/second on single mode fiber with 50Km repeater spacing.
Third generation	operating at a wavelength of 1·55 μm, operating at a bit rate of up to 2·5 Gigabits/second on a single longitudinal mode fiber with 100Km repeater spacing.
Fourth generation	made use of optical amplifiers replacing repeaters, utilized wavelength division multiplexing (WDM) to increase data rates, transmission of over 11,300Km at 5Gigabits/second.
Fifth generation	uses Dense Wave Division Multiplexing (DWDM)·concept of optical solitons(pulses that can preserve their shape by counteracting the negative effects of dispersion)is being explored

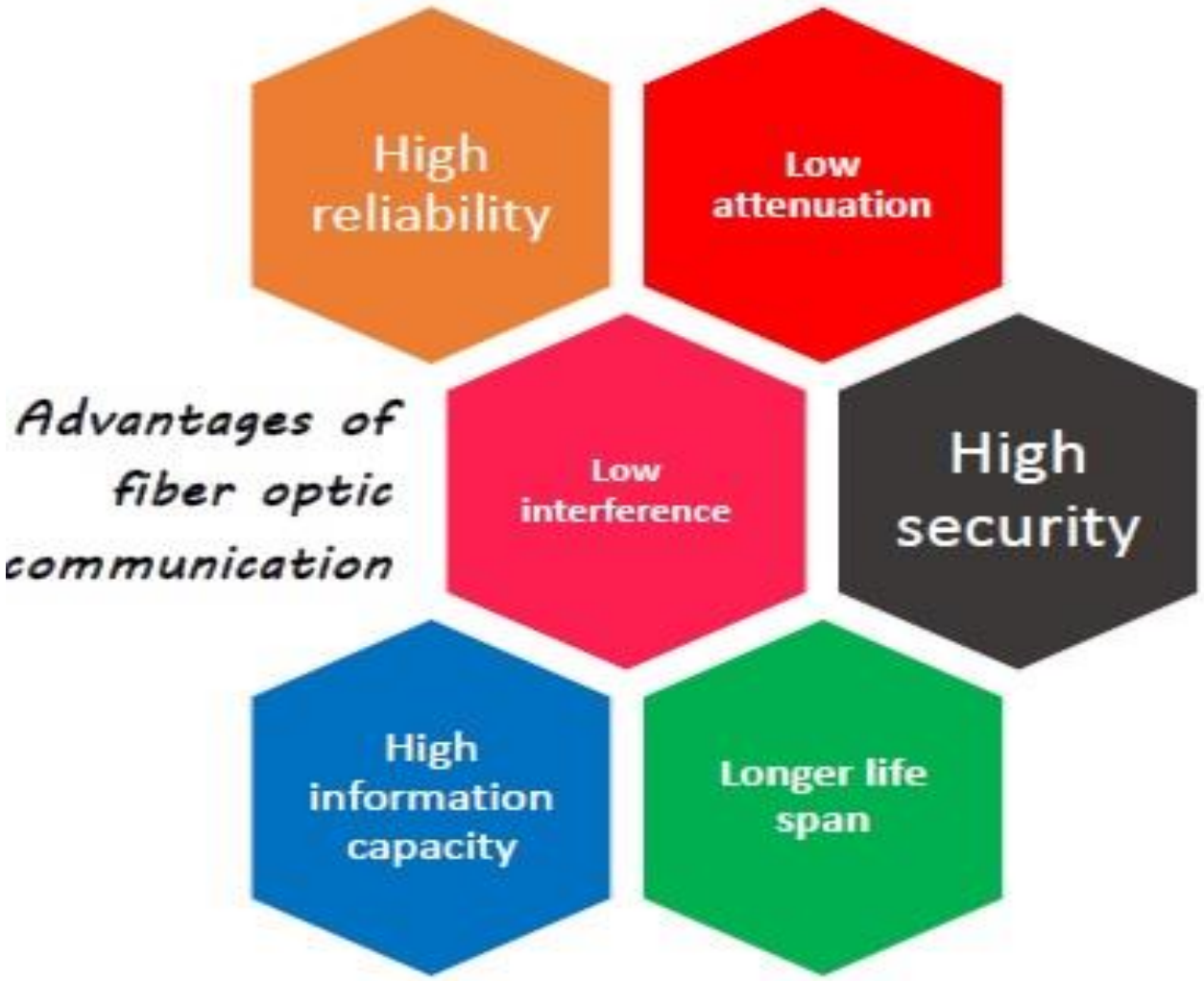




Advantages of Fiber Optics

- Immunity from Electromagnetic (EM) Radiation and Lightning
- Smaller in Size and Lighter Weight
- Higher information Bandwidth
- Better Signal Quality
- Lower Cost
- Easily Upgraded & Ease of Installation & Easy to Maintain.
- More immune to ambient electrical noise, electromagnetic interference.
- Cross talk and internal noise are eliminated in optical fibers.
- No risk of short circuit in optical fibers.

Advantages ….

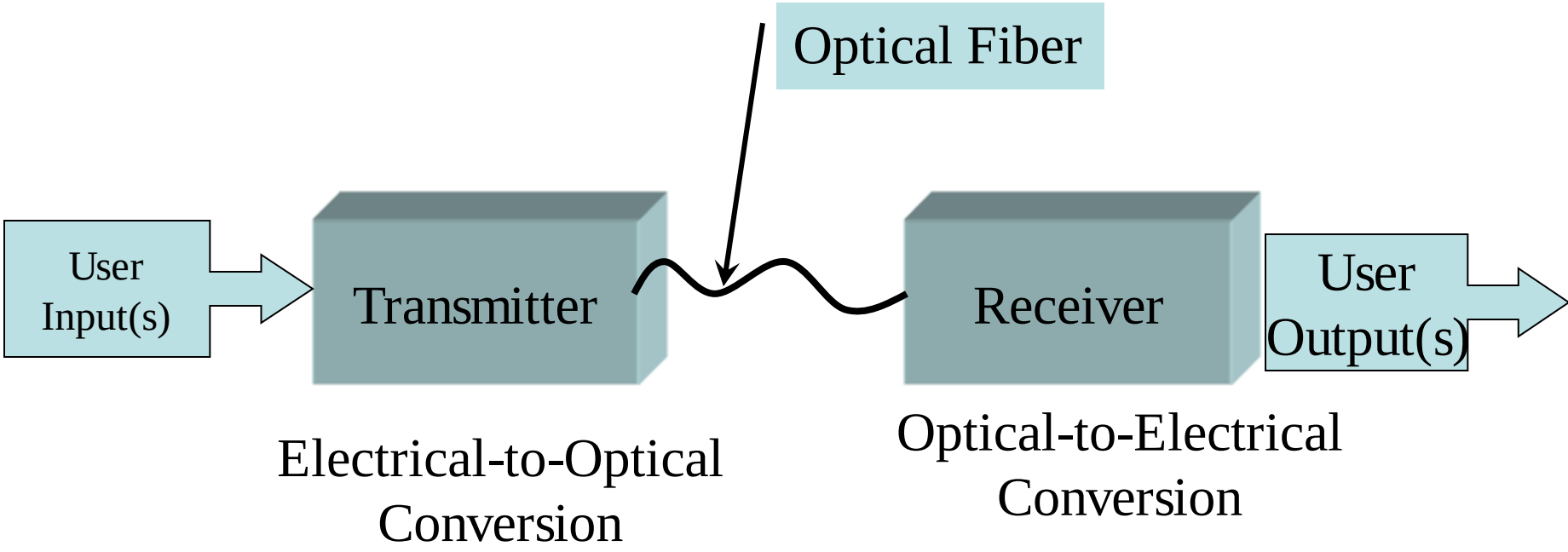

Advantages of fiber optic communication
High reliability
Low attenuation
Low interference
High security
High information capacity
Longer life span

Disadvantages

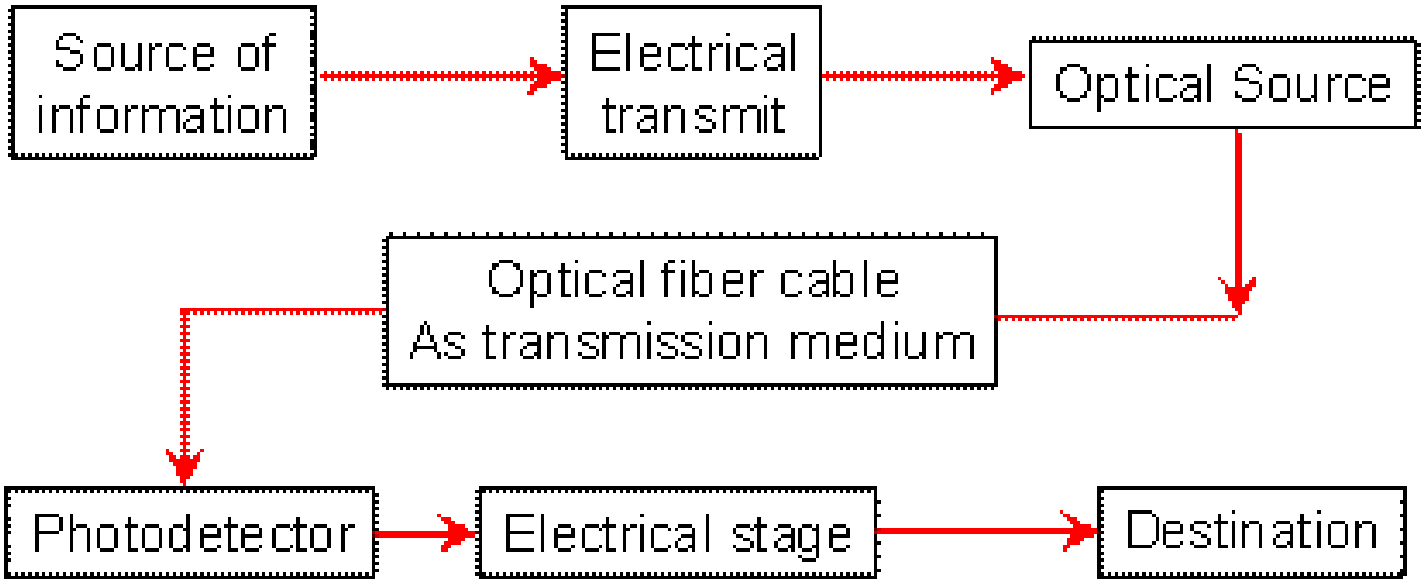
- Attenuation offered by the optical fibers depends upon the material by which it is made.
- Complex electronic circuitry is required at transmitter and receiver.
- The coupling of optical fibers is difficult.
- Skilled labors are required to maintain the optical fiber communication.
- Separated power supply is required for electronic repeaters at different stages.

Elements of an Optical Fiber communication

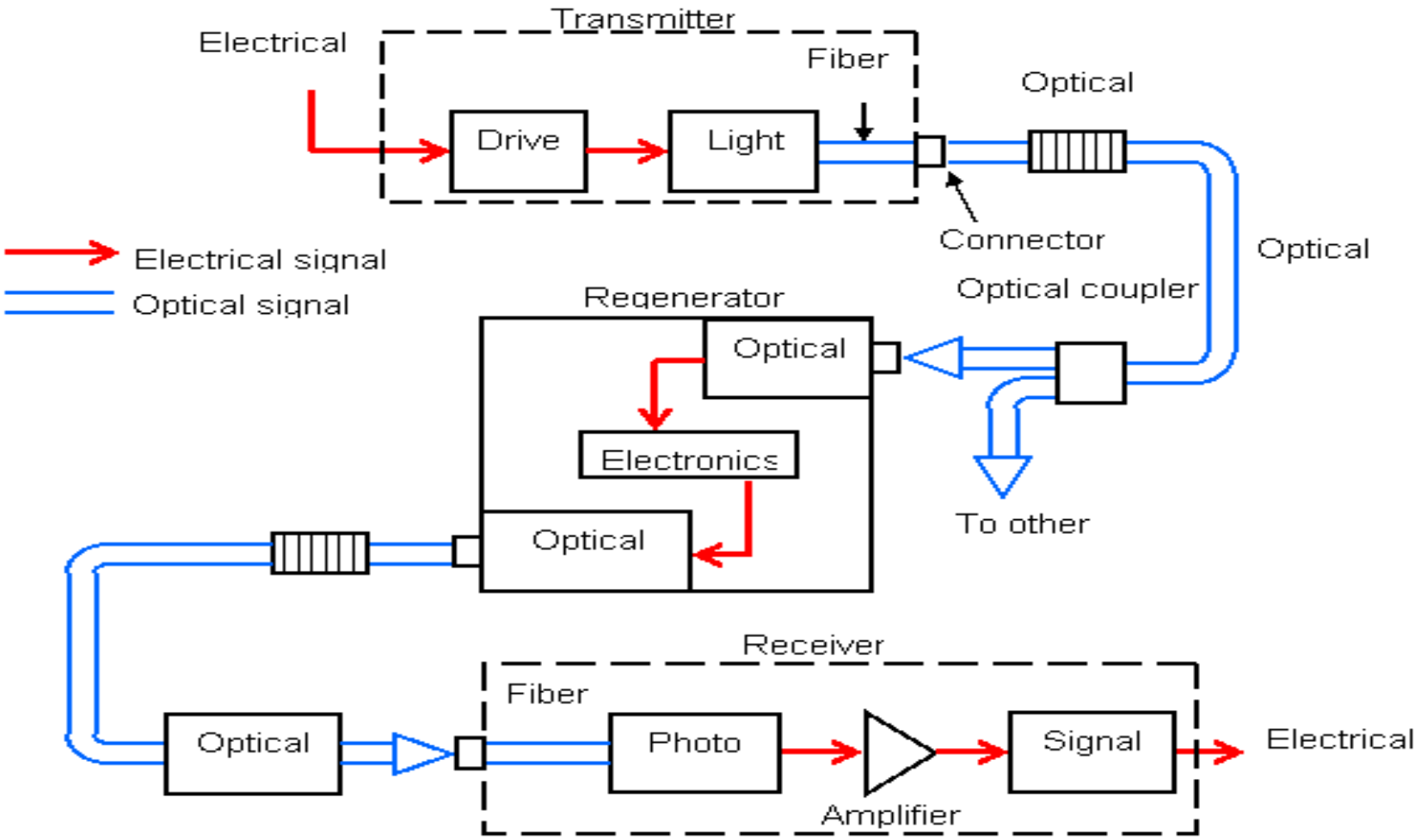
- Fiber optic links contain three basic elements
  - transmitter
  - optical fiber
  - receiver



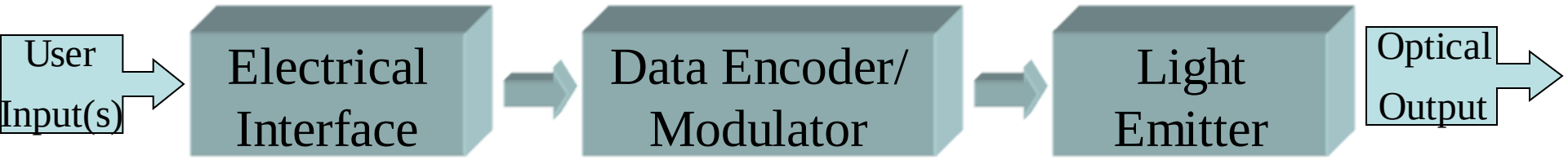
Basic Block Diagram of Optical Communication System



Basic Block Diagram of Optical Communication System



- **Transmitter (TX)**
  - Electrical interface encodes user's information through AM, FM or Digital Modulation
  - Encoded information transformed into light by means of a light-emitting diode (LED) or laser diode (LD)

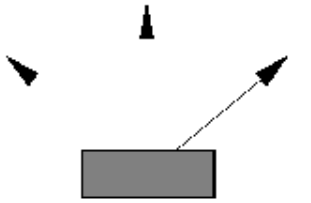


- Receiver (RX)
  - decodes the light signal back into an electrical signal
  - types of light detectors typically used
    - PIN photodiode
    - Avalanche photodiode
    - made from silicon (Si), indium gallium arsenide (InGaAs) or germanium (Ge)
  - the data decoder/demodulator converts the signals into the correct format

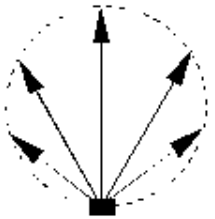


Optical Source Light Emitters

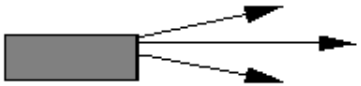
- Two types
  - Light-emitting diodes (LED's)
    - Surface-emitting (SLED): difficult to focus, low cost
    - Edge-emitting (ELED): easier to focus, faster
  - Laser Diodes (LD's)
    - narrow beam
    - fastest



SURFACE-EMITTING LED



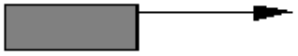
EMISSION PATTERN OF A SURFACE-EMITTING LED



EDGE-EMITTING LED



EMISSION PATTERN OF AN EDGE-EMITTING LED



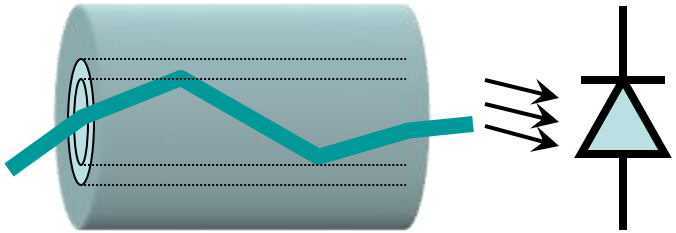
LASER



EMISSION PATTERN OF A LASER

Optical Receiver Detectors

- Two types
  - Avalanche photodiode
    - internal gain
    - more expensive
    - extensive support electronics required
  - PIN photodiode
    - very economical
    - does not require additional support circuitry
    - used more often



Principles of Light Transmission in a Fiber

Fiber optics deals with the transmission of light energy through transparent fibers.

How an optical fiber guides light depends on the **nature of light and structure of the optical fiber.**

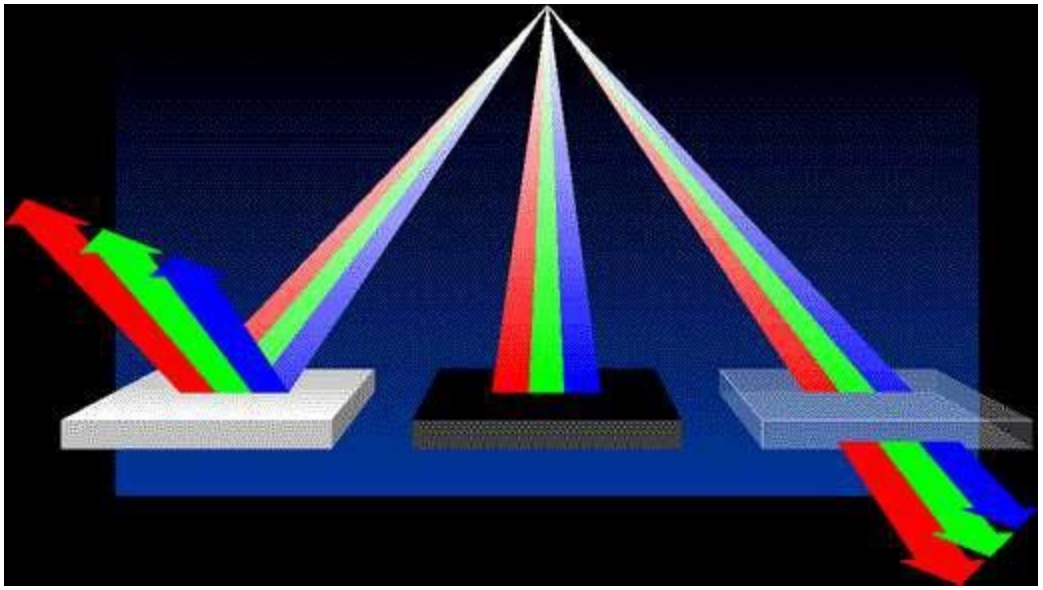
A light wave is a form of energy that is moved by wave motion.

In fiber optics, **wave motion is the movement of light energy through an optical fiber by following Law of Optics or Ray Theory.**

Properties of Light

- When light waves strike an object, some of the waves are absorbed by the object, some are reflected by it, and some might pass through it.
- When light strikes an object it is:

  1) Reflected
  2) Transmitted/ Refracted
  3) Absorbed



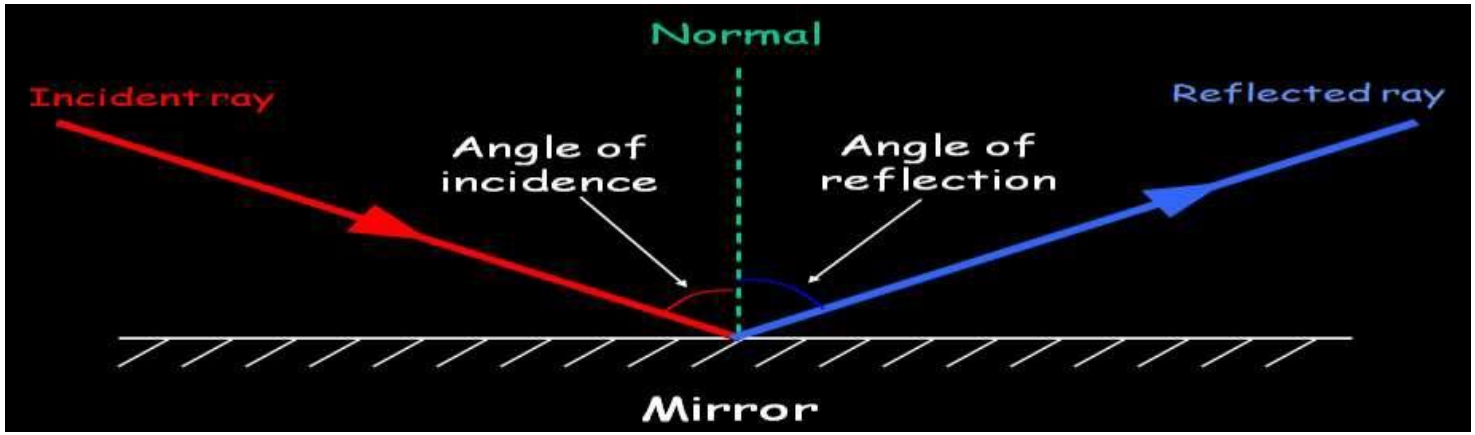
Properties of Light

Reflection—

- Reflected waves are those waves that are neither transmitted nor absorbed but are reflected from the surface of the medium.
- When a wave approaches a reflecting surface such as a mirror, the wave that strikes the surface is called ***incident wave*** and the wave that bounces back is called the ***reflected wave.***
- The amount of incident energy that is reflected from a surface depend on:

  The **nature of the surface**

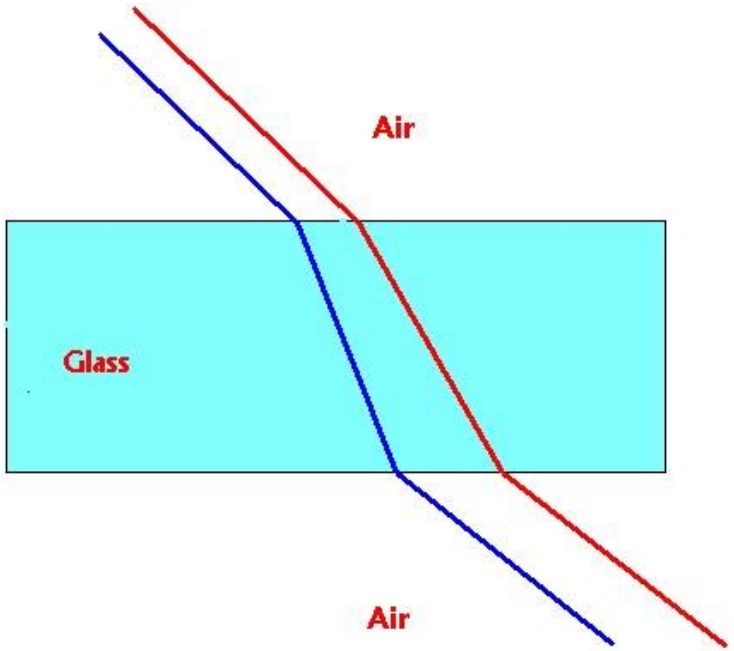
  The **angle at which the wave strikes the surface**



Properties of Light

Refraction—

- When a light wave passes from one medium to another medium having different velocity of propagation, a change in the direction of the wave will occur.
- This change of direction as the wave enters the second medium is called **refraction**.

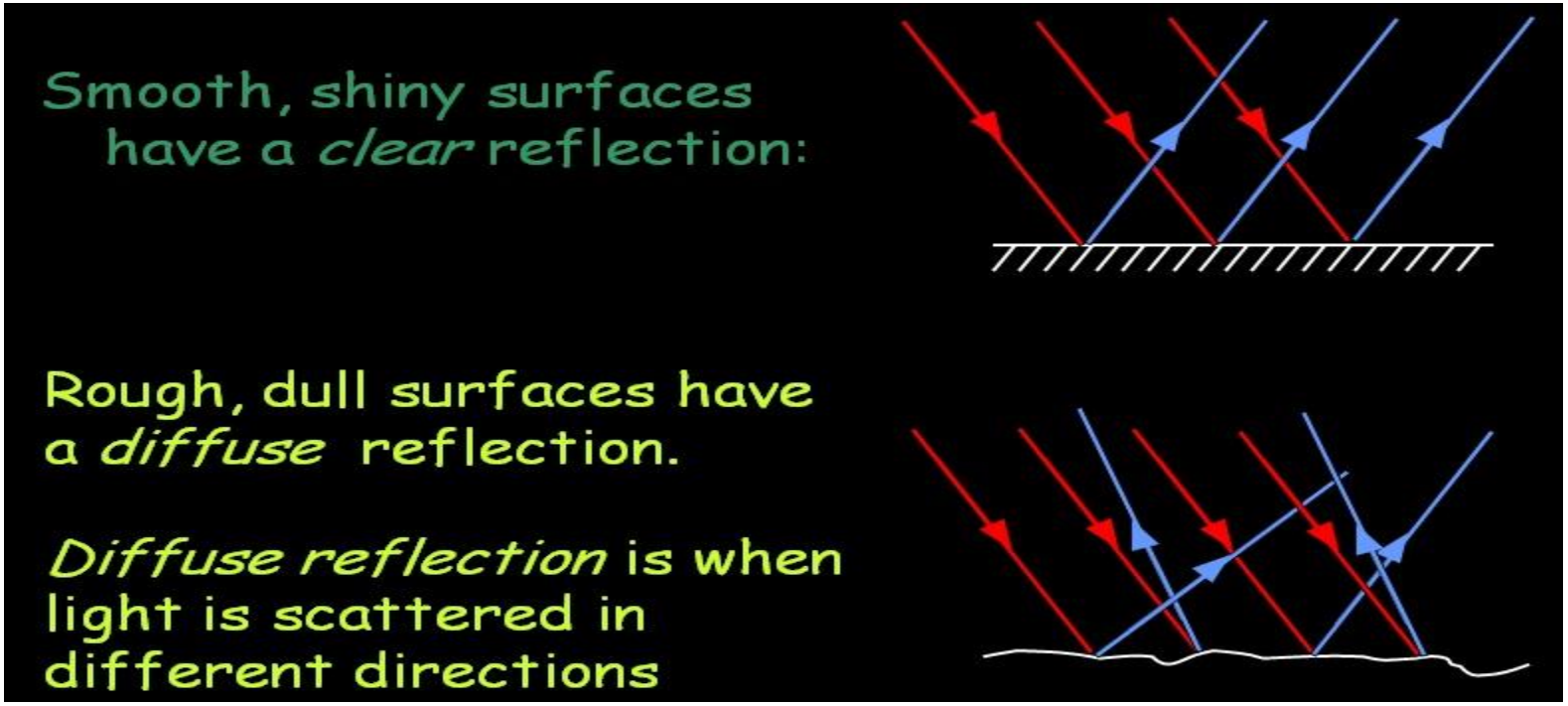




Properties of Light

Diffusion—

- When light wave is reflected from a piece of white paper, the reflected beam is scattered or diffused.
- Since the surface of paper is not smooth, the reflected light is broken up into many light beams that are reflected in all directions.

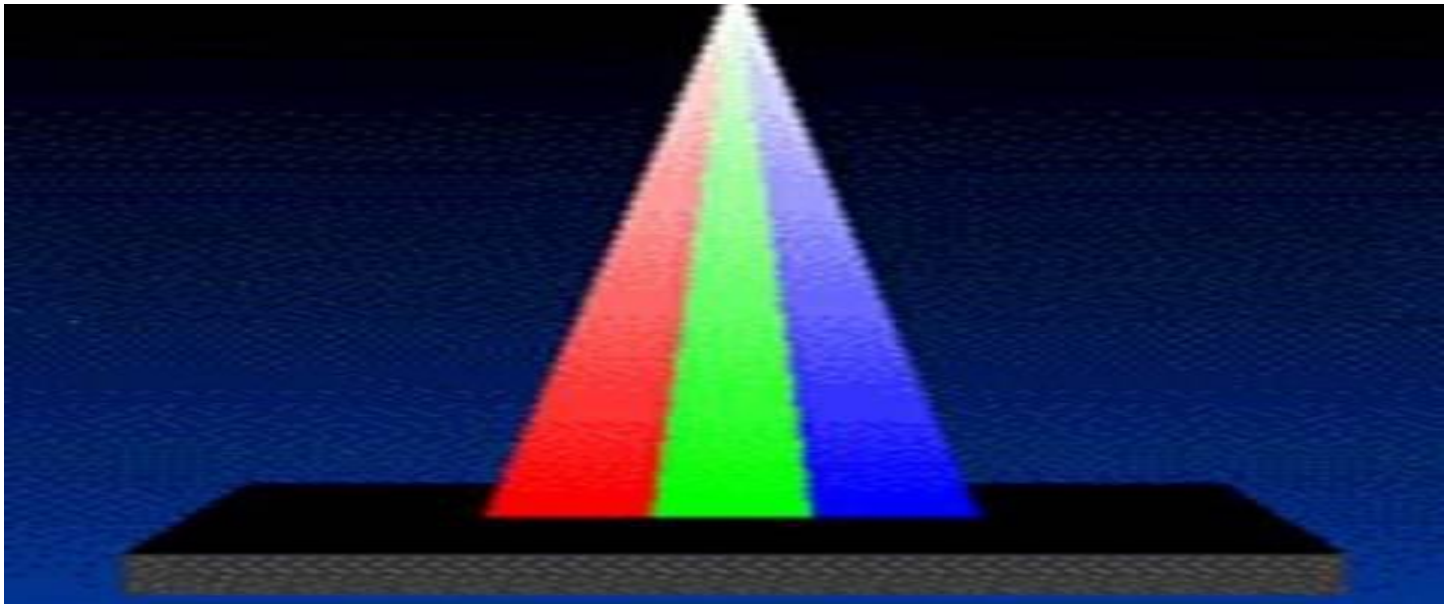


Properties of Light

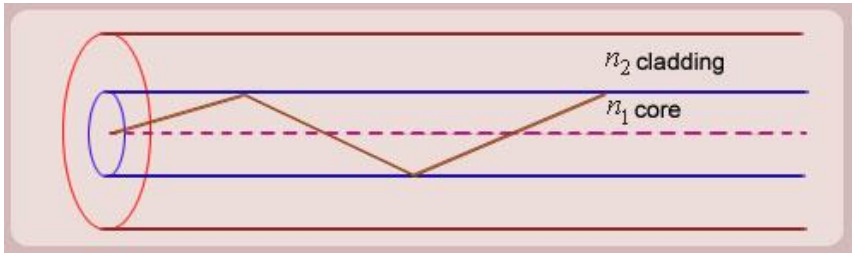
Absorption—

- A light wave is reflected and diffused from a piece of white paper.

  But if the light beam falls upon a piece of black paper, the **black paper** absorbs most of the light and very small amount of light is reflected from the paper.
- If the surface upon which the light beam falls is **perfectly black**, then there is no reflection; the light is **totally absorbed.**



Ray Model



- The light energy in the form of optical signals propagates inside the core-cladding arrangement and throughout the longer length of the fiber without attenuation by a phenomenon called the Total Internal Reflection (TIR) of light. (Guidance of Light)

- This phenomenon occurs only when the refractive index of core *n1* is greater than the refractive index of cladding *n2* and so the cladding is made from glass of lower refractive index. (core,*n1 > cladding, n2*)

- Multiple total internal Fiber Optics reflections at the core-cladding interface is necessary for the light to propagate throughout the fiber over very long distances with low attenuation.

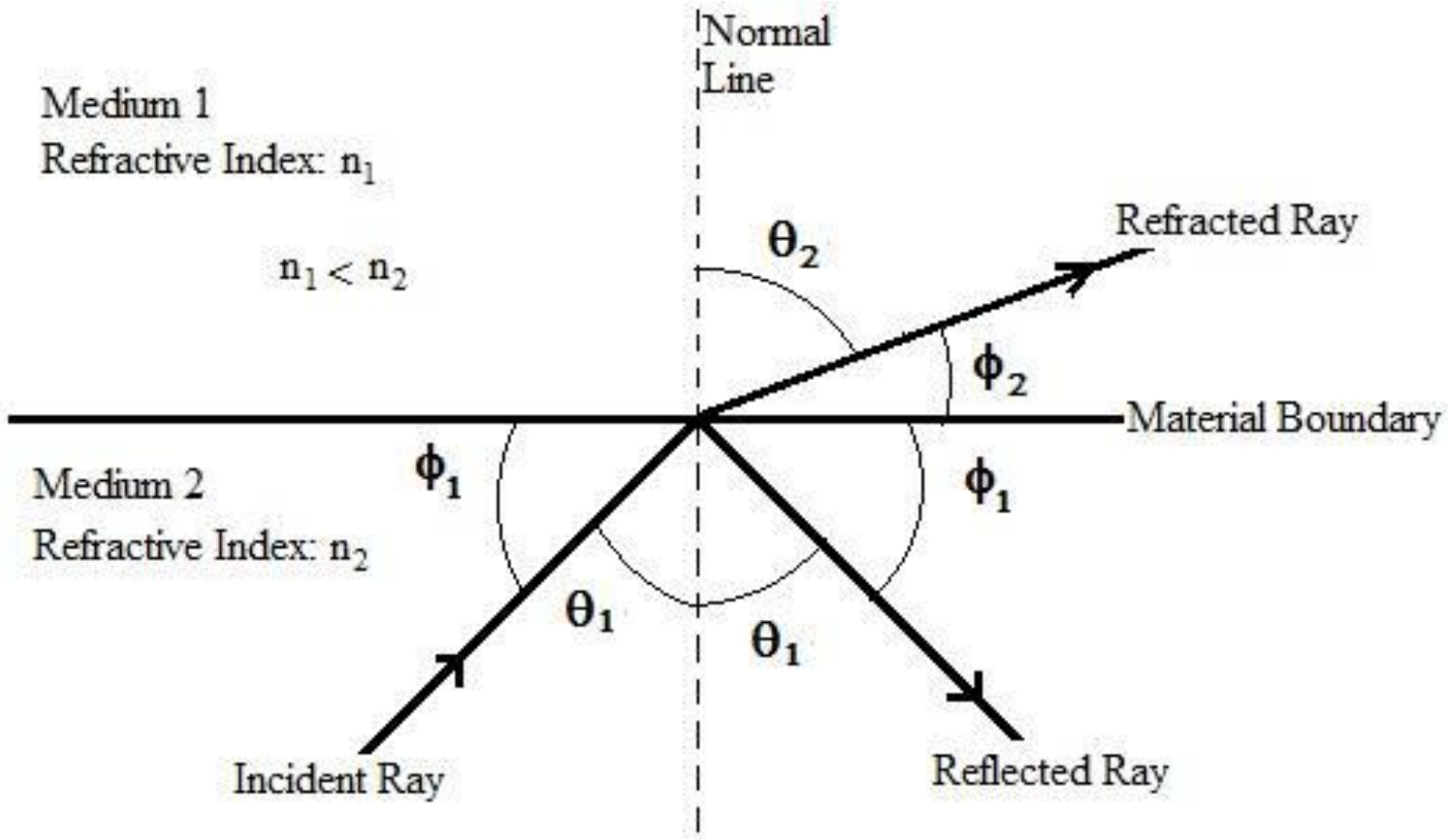
Refractive Index

- The index of refraction of a material is the ratio of the speed of light in a vacuum to the speed of light in the material

$$n = c / v$$

- The factor *n is the index of refraction (or refractive index) of the medium.*
- Glass has many compositions, each with a slightly different *n*.

Sr. No.	Medium	Refractive Index (RI)
1	Air	1.00
2	Water	1.33
3	Silica Glass	1.45
4	Diamond	2.42



$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad \text{(Snell's Law)}$$

The Ray-Model of light obeys the Snell's laws.

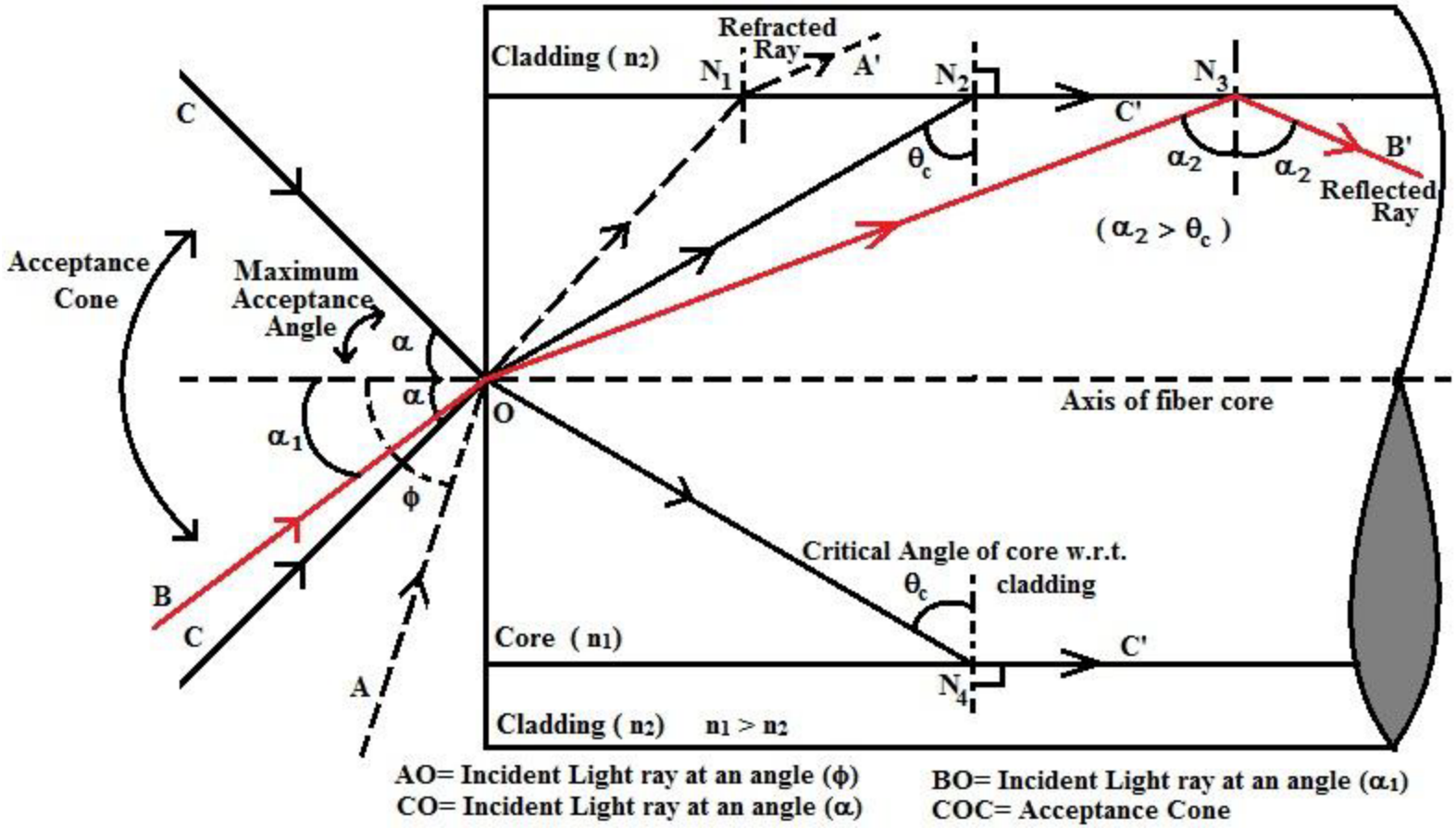
Total Internal Reflection & Critical Angle

- If the angle of incidence ($\theta 1$) is increased further, the angle of refraction ($\theta 2$) also increases in accordance with the Snell's law and at a particular angle of incidence the angle of refraction becomes 90 degree and the refracted ray grazes along the boundary of core-cladding.
- This angle of incidence is called the ***Critical Angle*** of incidence (θ_c) of medium 2
- If θ_1 is increased beyond the critical angle, there exists no refracted ray and the incident light ray is then reflected back into the same medium.
- This phenomenon is called the ***Total Internal Reflection*** of light. The word 'total' signifies that the entire light energy can be made to remain confined in the same medium when the angle of incidence is greater than the angle of reflection.

- We can see that there are two basic requirements for a TIR to occur: with respect to medium 1.

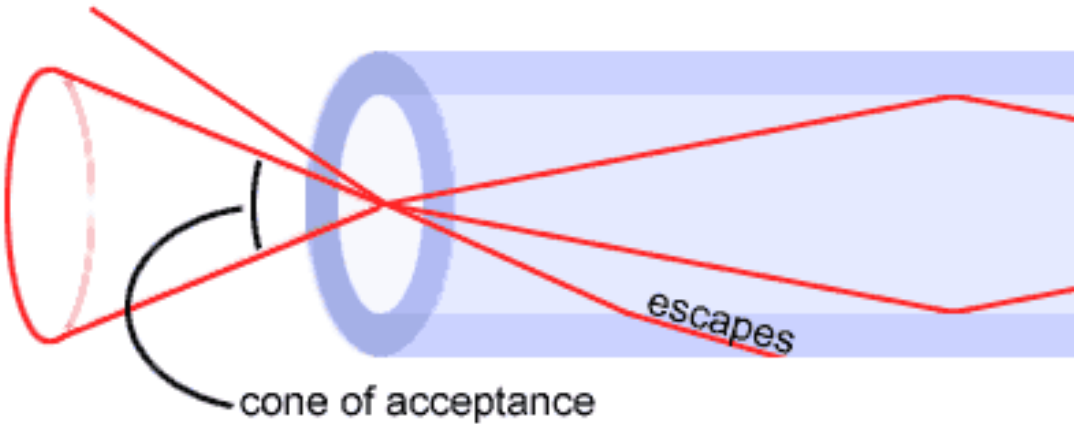
1. The medium from which light is incident, must be optically denser than the medium to which it is incident. $n_2 > n_1$.
2. The angle of incidence in the denser medium must be greater than the critical angle of the denser medium with respect to the rarer medium.

Launching of Light into Fiber for TIR



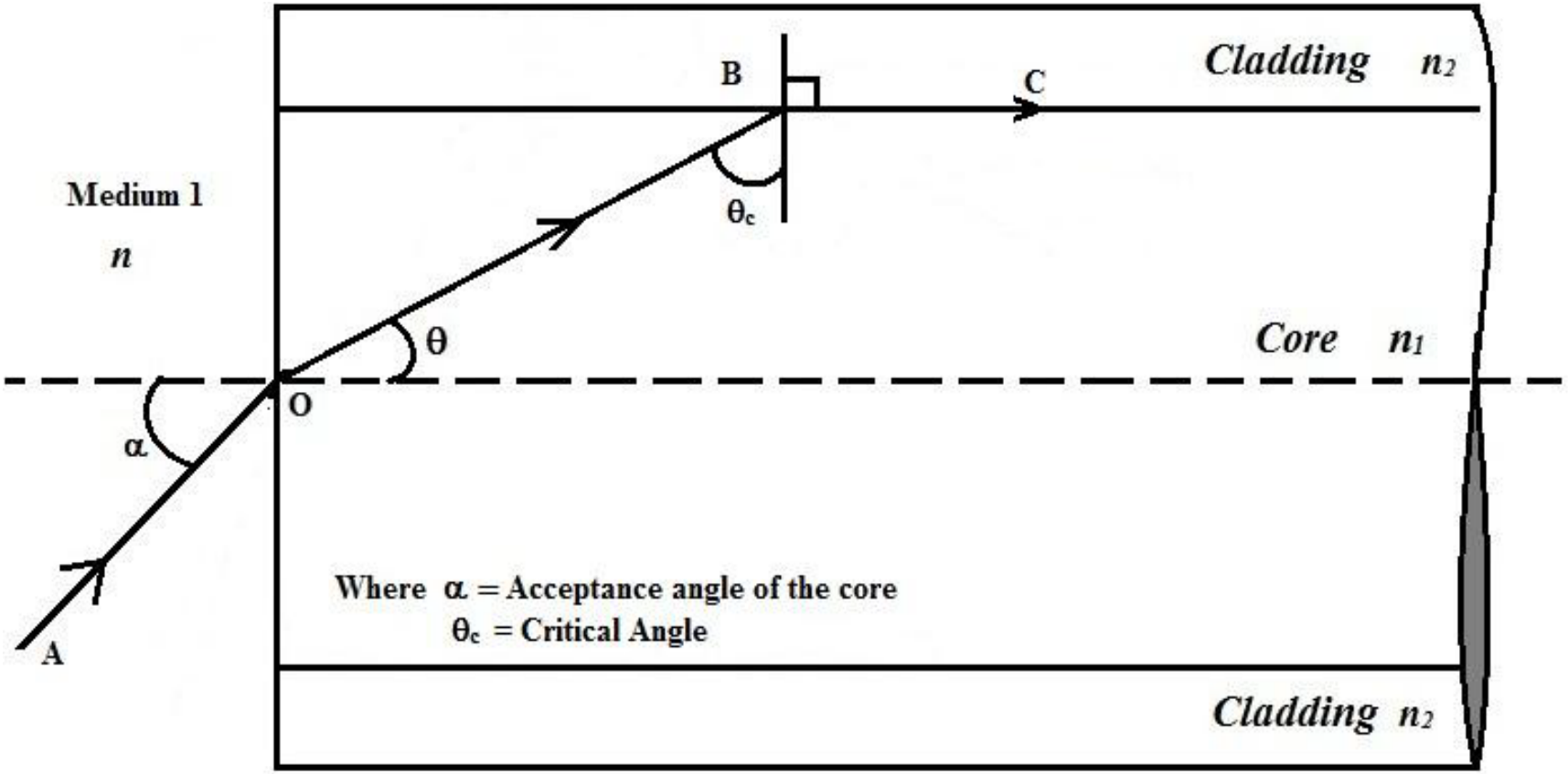
Acceptance Angle

- The angle α is indicative of the maximum possible angle of launching of a light ray that is accepted by the fiber. Consequently, the angle α is called the angle of acceptance of the fiber core.
- Since the optical fiber is symmetrical about its axis, it is very clear that all the launched rays, which make an angle α with the axis, considered together, form a sort of a cone. This cone is called the acceptance cone of the fiber as shown in the fig.
- Any launched ray that lies within this cone is accepted by the fiber and the light of this ray is guided along the fiber by virtue of multiple TIRs.

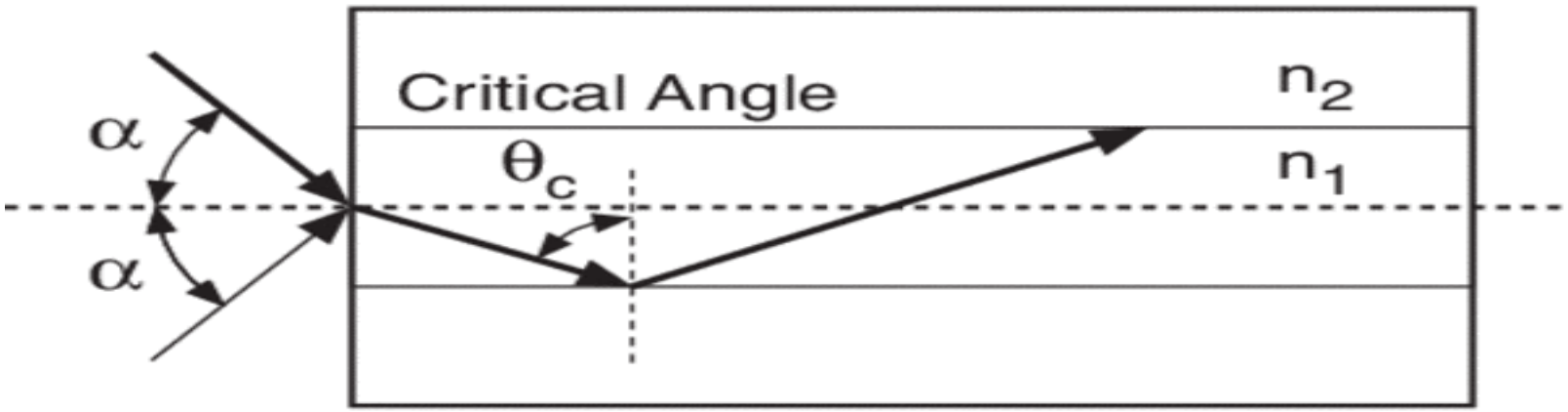


NUMERICAL APERTURE

Numerical aperture of the fiber is the light collecting efficiency of the fiber and is the measure of the amount of light rays that can be accepted by the fiber. It is equal to the sine of acceptance angle.



Numerical Aperture



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

Full Acceptance Angle $= 2\alpha$

Greater the value of α, more is the light accepted by the optical fiber

- Numerical Aperture is one of the most fundamental quantities of an optical fiber.
- It indicates the light collecting efficiency of an optical fiber.
- More the value of N.A. better is the fiber.
- For maximizing the difference, either the refractive index of the core (n_1) has to be increased or the refractive index of the cladding (n_2) has to be reduced.
- Since the core used is always glass, the value of its refractive index n_1 is thus fixed (approximately 1.5).
- The only option thus available with us is to reduce the value of n_2.
- By selecting air medium, $n_2 = 1$.

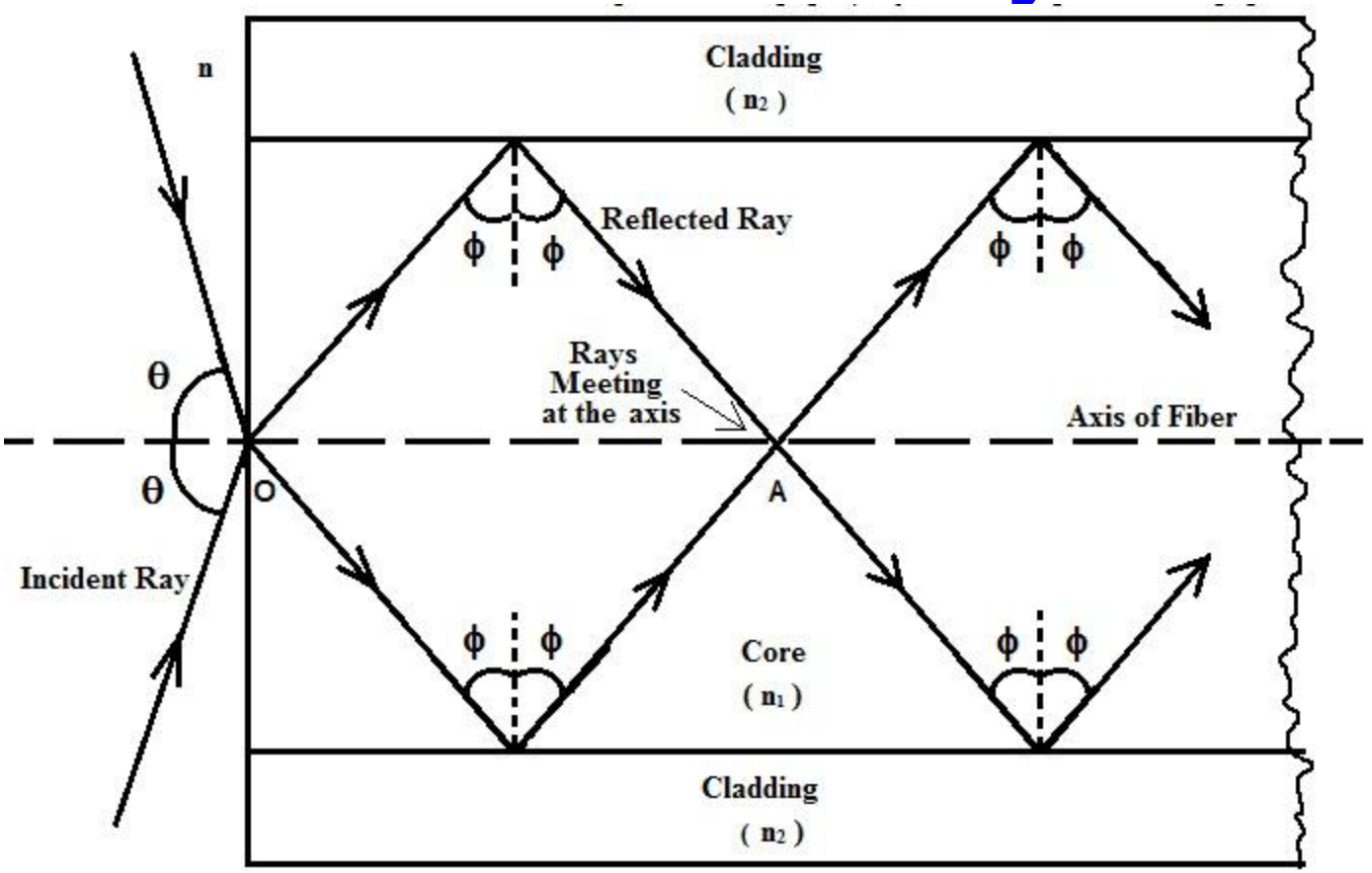
Types of Rays Transmission

- If the light is to propagate inside an optical fiber it could be through two types of rays

  a) Meridional rays: The rays which always pass through the axis of fiber giving high optical intensity at the center of the core of the fiber.

  b) Skew Rays : The rays which never intersect the axis of the fiber, giving low optical intensity at the center and high intensity towards the rim of the fiber.

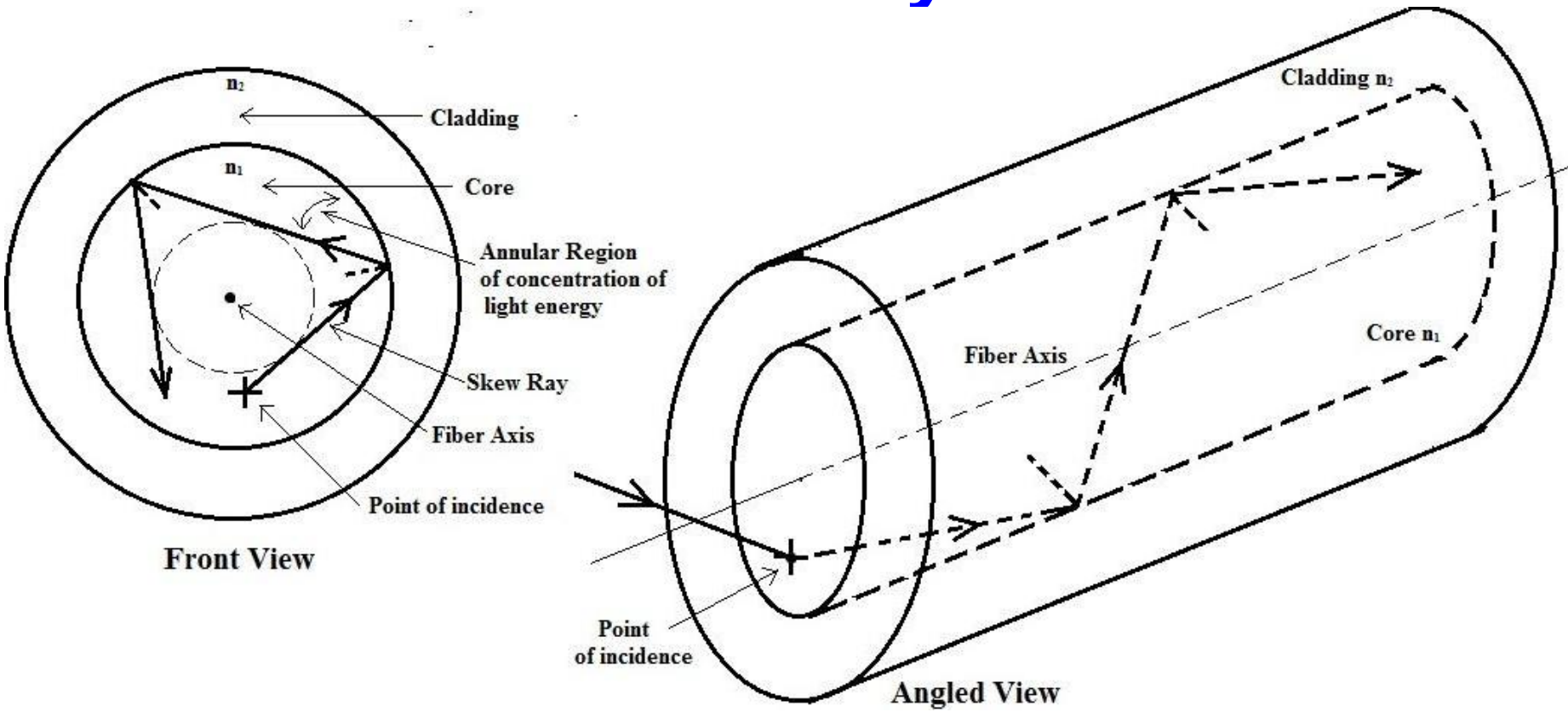
Meridional Ray



- Meridional ray strictly follows the phenomena of Total Internal Reflection.
- All the reflected rays meet repeatedly at regular interval at the same point in a region of **high** optical intensity is generated at that point (point A).

- This causes multiple regions of maximum intensity along the axis of the fiber.
- Also, different sets incident rays would have different angles of reflection at the core-cladding boundary and consequently have different points of maximum intensities along the fiber axis.
- Thus it can be visualized easily that at the output end of the optical fiber, maximum intensity will be in the axial region of the fiber core and the intensity would gradually decrease as we move away from the axis towards the periphery of the core.
- The rays that undergo TIR inside the fiber core remain inside the core at all times along the propagation and are called as bounded rays.

Skew Rays



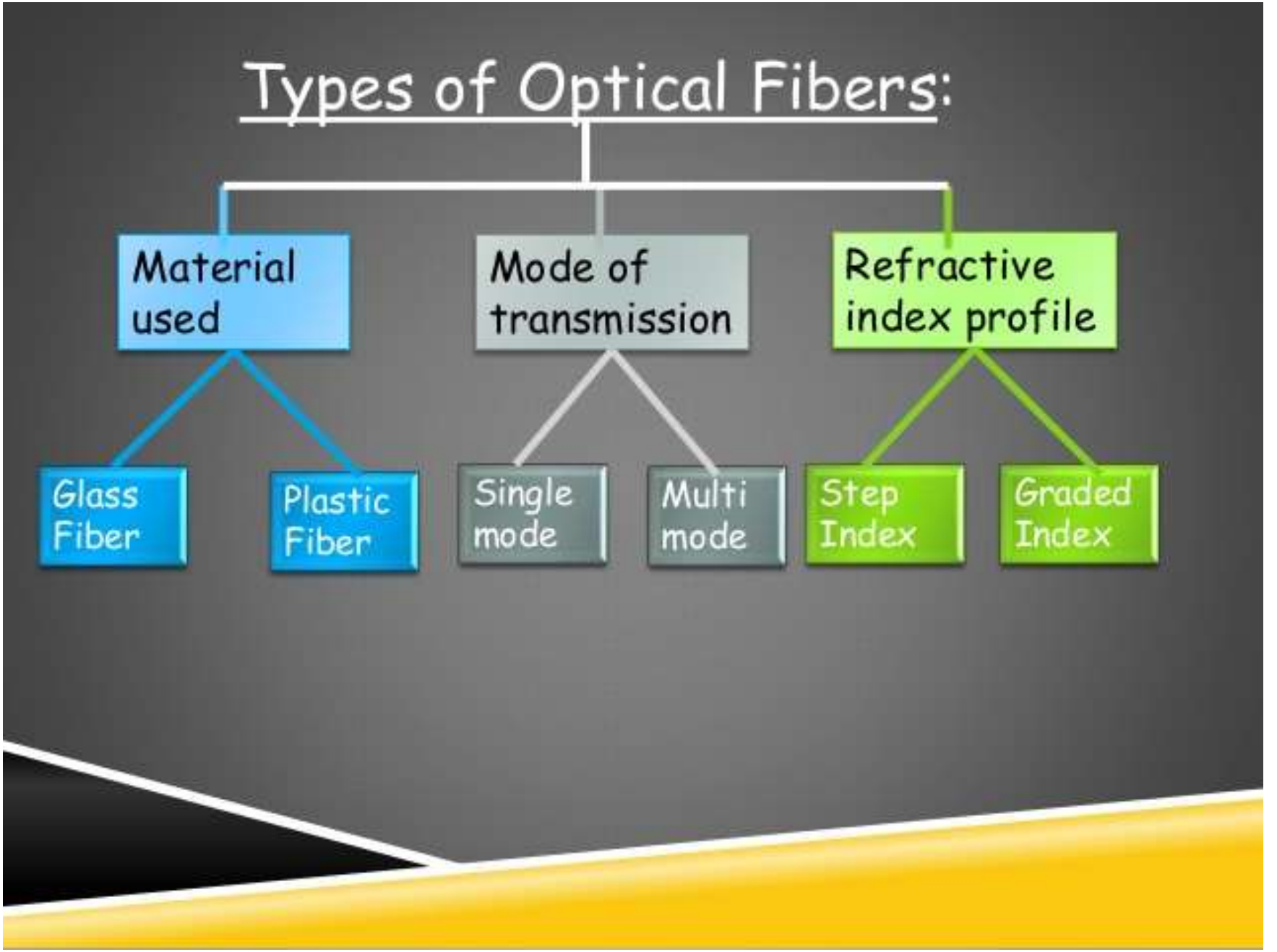
•Skew rays propagate without passing through the central axis of the fiber.
•In fact the skew rays go on spiraling around the axis of the optical fiber.
•The light energy carried by them is effectively confined to an annular region around the axis as shown in fig.
•Consequently, at the output, skew rays will have minimum energy at the axis of the optical fiber and it will gradually increase towards the periphery of the core.

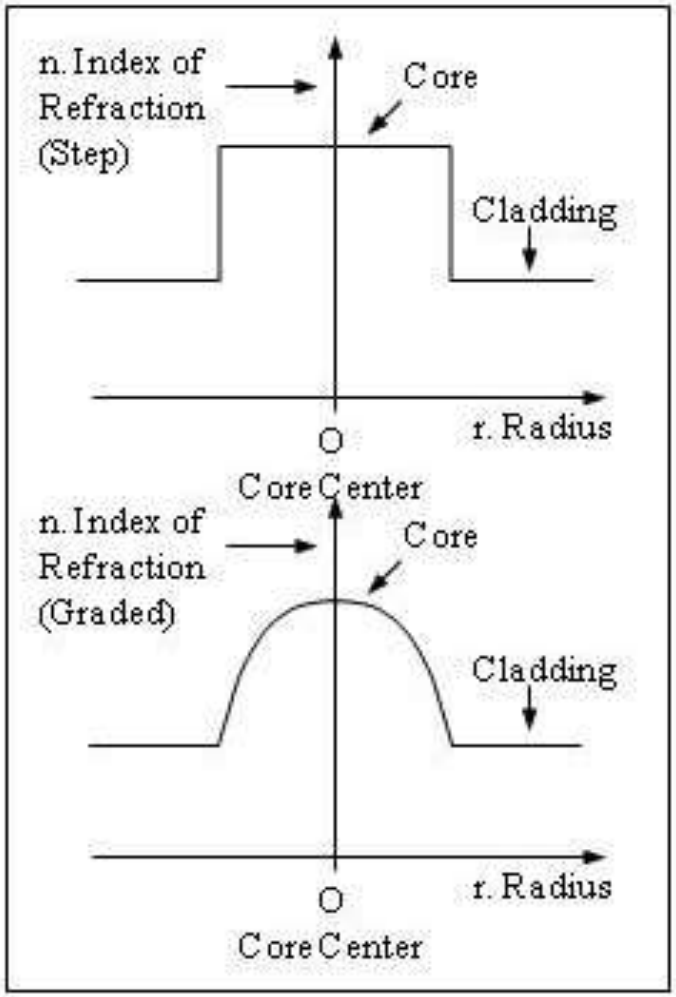
Modes of Optical Fiber

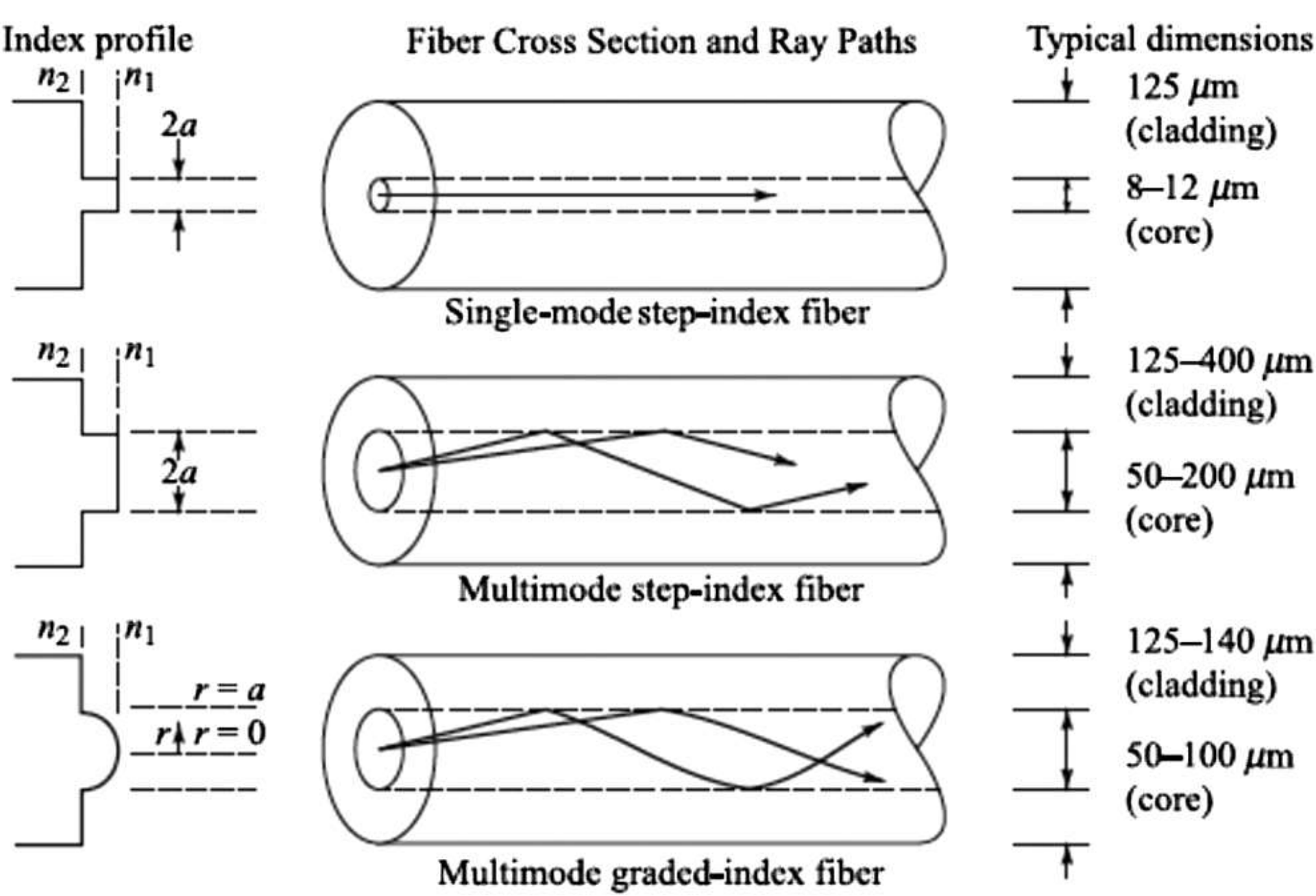
- Mode is the one which describes the nature of propagation of electromagnetic waves in a wave guide.
- i.e. it is the allowable direction whose associated angles satisfy the conditions for total internal reflection and constructive interference.

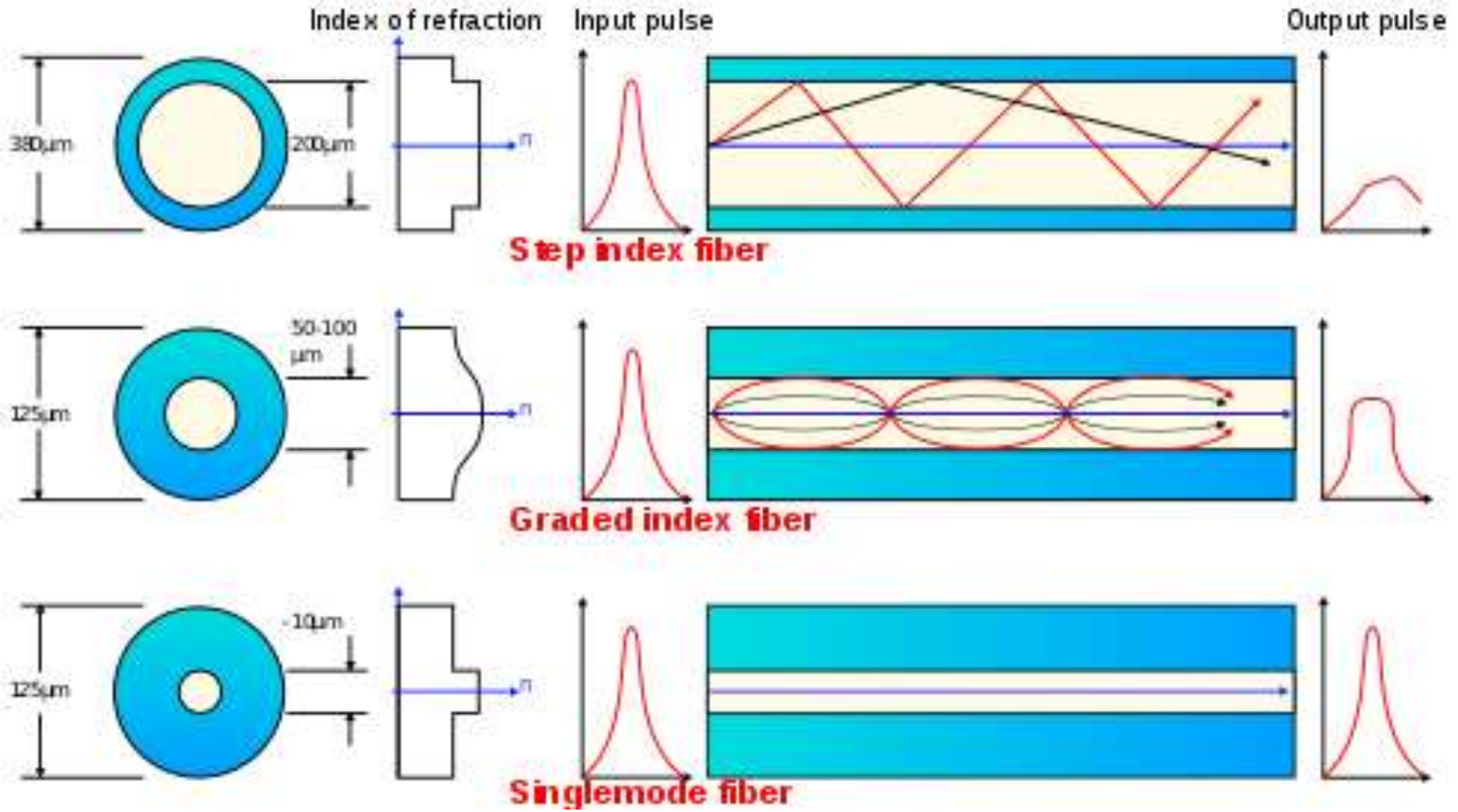
- Based on the number of modes that propagates through the optical fiber, they are classified as:
    1) Single Mode fibers
    2) Multi mode fibers

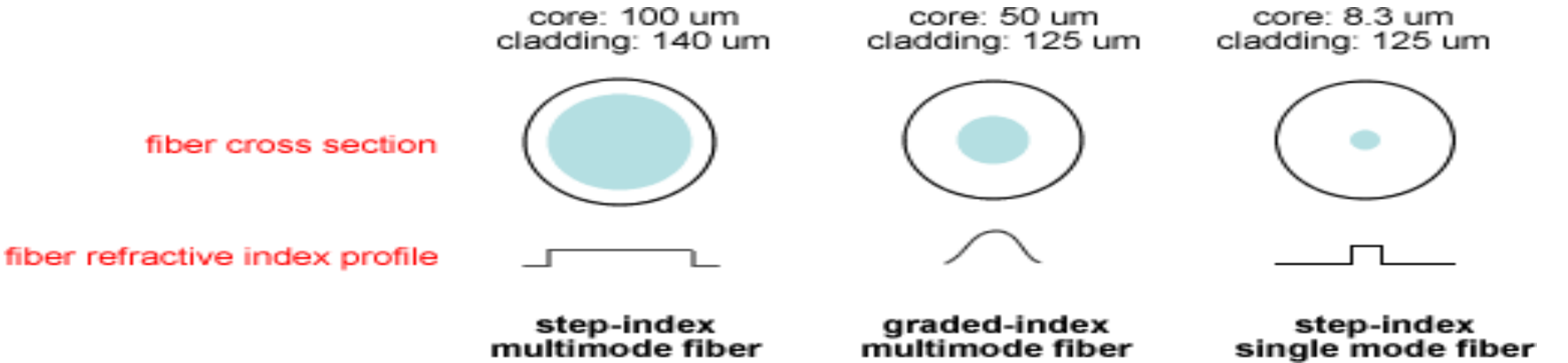
Types of Optical Fibers:




n. Index of
Refraction
(Step)
Core
Cladding
r. Radius
O
Core Center
n. Index of
Refraction
(Graded)
Core
Cladding
r. Radius
O
Core Center


Index profile
Fiber Cross Section and Ray Paths
Typical dimensions
n_2
n_1
$2a$
125 μm
(cladding)
8–12 μm
(core)
Single-mode step-index fiber
125–400 μm
(cladding)
50–200 μm
(core)
Multimode step-index fiber
$r = a$
$r = 0$
125–140 μm
(cladding)
50–100 μm
(core)
Multimode graded-index fiber


Index of refraction
Input pulse
Output pulse
380µm
200µm
n
Step index fiber
50-100 µm
125µm
n
Graded index fiber
10µm
125µm
n
Singlemode fiber


core: 100 um
cladding: 140 um
core: 50 um
cladding: 125 um
core: 8.3 um
cladding: 125 um
fiber cross section
fiber refractive index profile
step-index multimode fiber
graded-index multimode fiber
step-index single mode fiber

1. Single Mode Fiber

- Different similar technical words: *mono-mode optical fiber ; single-mode fiber ; single-mode optical waveguide; uni-mode fiber*

•**Single Mode cable** is a single stand (most applications use 2 fibers) of glass fiber with a diameter of 8.3 to 10 microns that has one mode of transmission.

• Narrow diameter, through which only one mode will propagate typically 1310 or 1550nm wavelength.

• Carries higher bandwidth.

• Requires launching of light source with a narrow spectral width (LASER).

• Fabrication Cost is more.

• The small core and single light-wave virtually eliminate any distortion that could result from overlapping light pulses, providing the least signal attenuation and the highest transmission speeds up to 50 times more distance (km) than multimode.

Single Mode Fiber

• Propagate only one mode, as the core size approaches to the operational wavelength. The light energy in a single-mode fiber is concentrated in one mode only.

• Normally, the no. of modes propagating is proportional to the value of normalized frequency 'V'

$$V = \frac{2\pi n_1 a\left(\sqrt{2\Delta}\right)}{\lambda}$$

Here, n1 = refractive index of the core;
a = radius of the core;
λ = wavelength of the light propagating through the fiber;
Δ = relative refractive indices difference.

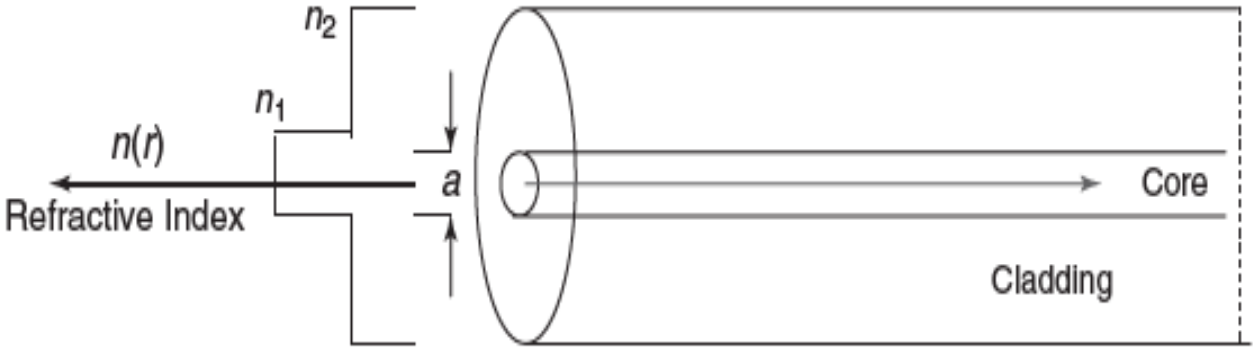
• The condition for the single mode operation , V≤ 2.405. (otherwise, power loss in cladding)

• Applications where data is sent at multi-frequency (WDM Wave-Division-Multiplexing).

• Applicable for long distance communication.

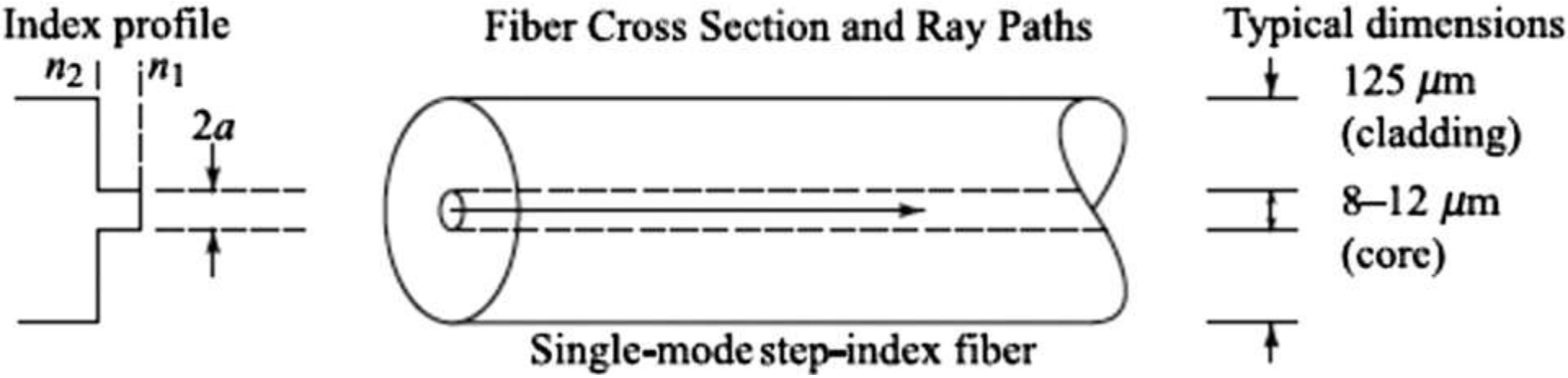
Single Mode - Step Index Fiber

- In a step index fiber, the refractive index changes in a step fashion, from the centre of the fiber i.e. from the core, to the outer shell i.e. to the cladding.
- R.I. is high in the core and lower in the cladding.
- The light in the fiber propagates by bouncing back and forth from core-cladding interface.
- The cladding is thick and has low loss.



(b)

- No intermodal dispersion exists in single mode step index fibers because only one mode exists.
- Handling and manufacturing of single mode step index fiber is more difficult.



The refractive index (*n*) profile with reference to the radial distance (*r*) from the fiber axis is given as:

when $r = 0$, $n(r) = n1$;

$r < a$, $n(r) = n1$ *(core);*

$r \geq a$, $n(r) = n2$ *(cladding).*

Designing of this fiber can be accomplished by reducing Δ and or the core diameter to a point where the V < 2.4.

2. Multimode Fiber

- Multimode fibers allow large no. of modes (over 100 Modes).
- Typical multimode fiber core diameters are 50, 62.5 and cladding diameter of 100, 125 micrometers.
- Multimode fiber gives you high bandwidth at high speeds (10 to 100MBS - Gigabit to 275m to 2km) over medium distances.
- LED/LASER source can be used.
- Light waves travelling through it get dispersed into numerous paths, or modes, typically at 850 or 1300nm wavelength.
- Multiple paths of light can cause signal distortion at the receiving end, resulting in an unclear and incomplete data transmission.
- The condition for the Multimode mode operation is given by the 'V' number of the fiber which is defined as such that V>= 2.405.
- Normalized freq.

$$V = \frac{2\pi n_1 a\left(\sqrt{2\Delta}\right)}{\lambda}$$

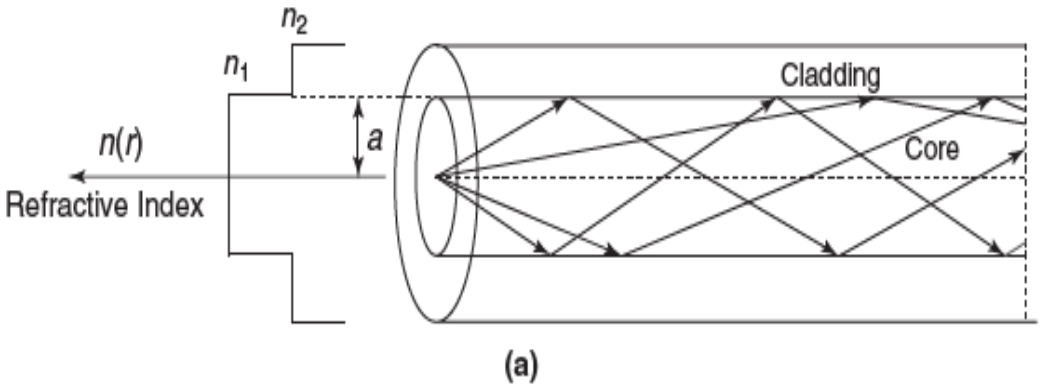
(2.a) Multimode - Step Index Fiber :

•The light rays propagating through it are in the form of Meridional rays which will cross the fiber core axis during every reflection at the core – cladding boundary and are propagating in a zig – zag manner.

• Fibers with a core diameter much larger than the wavelength of the launched light

• The wavelength of light supports many propagating modes, and the propagating conditions can be analyzed with geometric optics.

•Each of these modes carries the signal imposed on the optical wave.



• The total number of modes *Ms* increases with increase in the numerical aperture.

•For a larger number of modes, *Ms* can be approximated by

$$M_S = \frac{V^2}{2} = 4.9\left[\frac{d(n_1\sqrt{2\Delta})}{\lambda}\right]^2 = \frac{1}{2}\left[\frac{\pi d}{\lambda}(NA)\right]^2$$

Where, *a* is the fiber core radius,

d =2a is the fiber core diameter.

λ is the operating wavelength,

n1 is the core refractive index and

Δ is the relative refractive index difference.

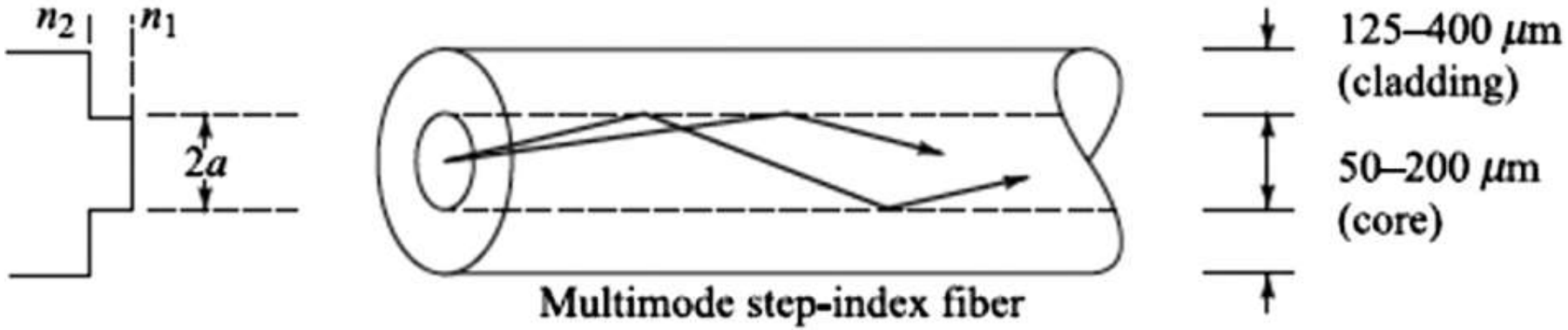
V is the Normalized Freq.

$$V = \frac{2\pi n_1 a\left(\sqrt{2\Delta}\right)}{\lambda}$$

- To reduce the dispersion, the N.A. should not be decreased beyond a certain limit for the following reasons:

- First, injecting light into fiber with low N.A becomes difficult. Lower N.A means lower acceptance angle, which requires the entering light to have a very shallow angle.

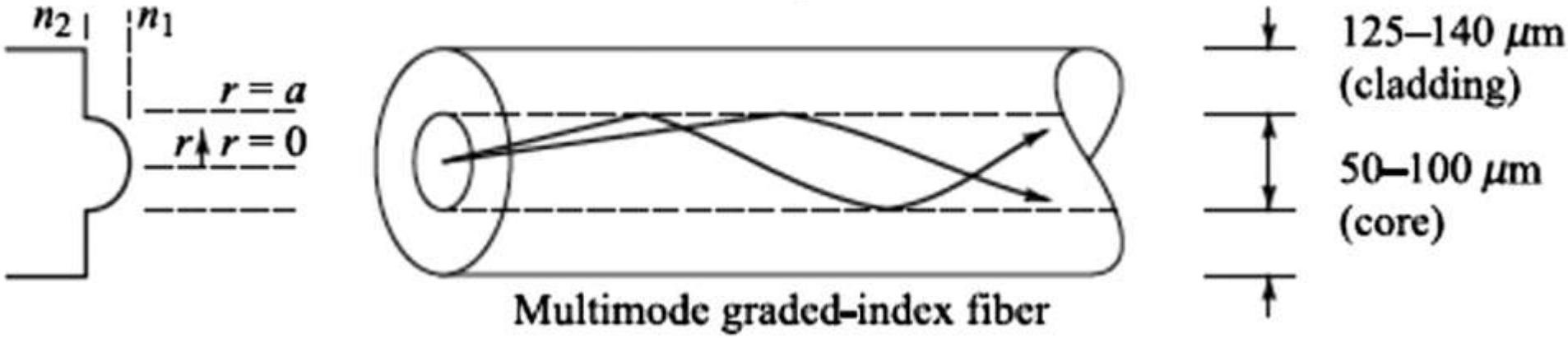
- Second, leakage of energy is more likely, and hence losses increase.



Multimode step-index fiber

(2.b) Multimode -Graded Index Fibers

- The refractive index *n* in the core varies as we move away from the centre.
- The basic concept here is to vary the R. I. from a maximum at the center of the core to a minimum at the core–cladding interface.
- The refractive index of the core is made to vary in the form of parabolic manner such that the maximum refractive index is present at the centre of the core.



Multimode graded-index fiber

•The light rays will be propagated in the form skew rays (or) helical rays which will not cross the fiber axis at any time and are propagating around the fiber axis in a helical or spiral manner. Due to this almost all the light rays reach exit end of the fiber at the same time.

• Due to the parabolic variation in R.I. profile , light rays travels with different speed in different path of the fiber.

•The effective acceptance angle of the graded-index fiber is somewhat less than that of an equivalent step-index fiber.

•This makes coupling fiber to the light source more difficult.

• Because of self focusing effect, signal distortion is less.

• Launching of light into the fiber is easy.

• Application : LAN.

The number of modes supported by a

step index multimode fiber, *Mstep, is*

$$M_{\text{step}} \approx \frac{V^2}{2}$$

And **graded index multimode fiber,** M_{graded}*, is*

$$M_{\text{graded}} \approx \left(\frac{\alpha}{\alpha+2}\right) \cdot \left(\frac{V^2}{2}\right)$$

Where, α is the refractive index profile parameter.

For a parabolic profile (α = 2),

The number of modes is $M_{graded} = \frac{V^2}{4} = \frac{M_{step}}{2}$

From such an analysis a very useful quantity emerges called **Normalized Frequency, V.**

It combines the wavelength, the physical dimensions of the fiber, and the properties of the dielectric (glass), and is given by

$$V = \frac{2\pi n_1 a\left(\sqrt{2\Delta}\right)}{\lambda} = \frac{\pi d}{\lambda}\left(NA\right)$$

Where, a is the fiber core radius,

$d = 2a$ is the fiber core diameter ,

λ is the operating wavelength,

$n1$ is the core refractive index and

Δ is the relative refractive index difference

Consider a multimode fiber operating at 1300 nm with radius 25 mm, *n1 = 1.5, and* Δ *= 2%. Then the step index fiber supports*

$$V \approx \frac{2\pi}{\lambda} \bullet a \bullet n_1 (2\Delta)^{1/2} = \frac{2 \times \pi}{1300 \times 10^{-9}} \times 25 \times 10^{-6} \times (2 \times 0.02)^{1/2} = 24$$

and

$$M_{\text{step}} \approx \frac{V^2}{2} = \frac{(24^2)}{2} = 288 \qquad \text{guided modes}$$

With a parabolic refractive index profile the same fiber will support *144* guided modes.

Numerical

Problem (1) : *Calculate the V – number and number of modes propagating through the fiber having a = 50 μm, n1 = 1. 53, n2 = 1.50 and λ = 1μm.*

Problem(2) : Find the core radius necessary for single mode operation at 850 nm of step index fiber with n1 = 1.480 and n2 = 1.465.
Hint: V – number = 2.405 (for single mode fiber)

Solved Problem (1) : Calculate the V – number and number of modes propagating through the fiber having a = 50 µm, n1 = 1. 53, n2 = 1.50 and λ = 1µm.

Solution :-

Given : n1 = 1.53 ; n2 = 1.50; λ = 1µm.

$$\text{V - Number} = \left(\frac{2\pi a}{\lambda}\right) \times \text{N.A} = \left(\frac{2\pi a}{\lambda}\right) \times (n_1^2 - n_2^2)^{\frac{1}{2}}$$

$$= \frac{2 \times 3.142 \times 50}{1} \left(1.53^2 - 1.50^2\right)^{\frac{1}{2}}$$

$$= 94.72$$

The number of modes propagating through the fiber $M_N = \frac{V^2}{2} = \frac{94.72^2}{2} = 4486$

V – number = 94.72 ; No. of modes = 4486

Problem(2) : Find the core radius necessary for single mode operation at 850 nm of step index fiber with n1 = 1.480 and n2 = 1.465.

Hint: V – number = 2.405 (for single mode fiber)

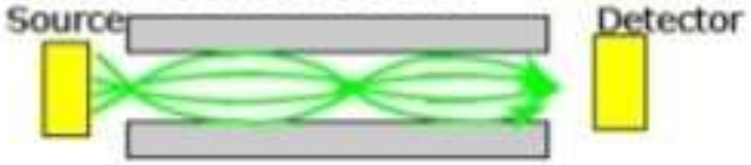
Solution :-

$$V = \left(\frac{2\pi a}{\lambda}\right) \times \text{N.A} = \left(\frac{2\pi a}{\lambda}\right) \times n_1 \times (2\Delta)^{\frac{1}{2}}$$

a **= core radius = 1.554** ***μm***

Multi-mode v/s Single mode

Multimode

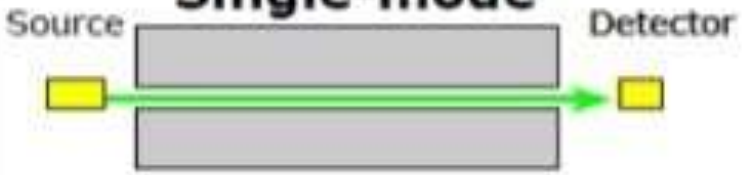


+ Low cost sources
  + 850 nm and 1310 nm LEDs
  + 850 nm lasers at 1 & 10 Gb/s
  + Low precision packaging
+ Low cost connectors
+ Lower installation cost
- Higher fiber cost
+ Lower system cost
- Higher loss, lower bandwidth
- Distance up to 2 km

Best for:

- ***LAN, SAN, Data Center, CO***

Single-mode



- High cost sources
  - 1310+ nm lasers 1 and 10 Gb/s
  - 1 Gb/s + w/ DWDM
  - High precision packaging
- Higher cost connectors
- Higher installation cost
+ Lower fiber cost
- Higher system cost
+ Lower loss, higher bandwidth
+ Distance to 60 km+

Best for:

- ***WAN, MAN, Access, Campus***

Feature	Single-Mode Fiber	Multimode Fiber
Core diameter	Small (typically 9 µm)	Large (typically 50 or 62.5 µm)
Propagation method	Only one mode of light travels through the fiber	Multiple modes of light travel through the fiber
Light source	Laser	LED or laser
Bandwidth	Higher bandwidth, typically in the gigahertz range	Lower bandwidth, typically in the megahertz range
Distance	Longer distance, typically up to tens of kilometers	Shorter distance, typically up to a few kilometers
Dispersion	Lower dispersion, resulting in less signal distortion	Higher dispersion, resulting in more signal distortion
Attenuation	Lower attenuation, resulting in less signal loss	Higher attenuation, resulting in more signal loss
System Cost	Higher cost due to more precise manufacturing requirements	Lower cost due to less precise manufacturing requirements
Applications	Long-haul telecommunications, high-speed data transmission	Local area networks, multimedia, and video applications

BASIS OF COMPARISON	STEP INDEX FIBER	GRADED INDEX FIBER
Description	Step index fiber is a fiber in which the core is of a uniform refractive index and there is a sharp decrease in the index of refraction at the cladding.	Graded index fiber is a type of fiber where the refractive index of the core is maximum at the center core and then it decreases towards core-cladding interface.
Types	Step index fiber is found in two types, that is mono mode fiber and multi mode fiber.	Graded index fiber is of only one type, that is, multi mode fiber.
Index Profiles	Index profiles are in the shape of step.	Index profiles is in the shape of a parabolic curve (for $\alpha=2$).
Light Rays Propagation	The light rays propagate in *zig–zag* manner inside the core.	The light rays propagate in the form of skew rays or helical rays. They will not cross the fiber axis.
Signal Distortion	Signal distortion is more in case of high-angle rays in multimode step index fiber. In single mode step index fiber, there is no distortion.	Signal distortion is very low even though the rays travel with different speeds inside the fiber.

BASIS OF COMPARISON	STEP INDEX FIBER	GRADED INDEX FIBER
Bandwidth Size	The fiber has lower bandwidth.	The fiber has higher bandwidth.
Diameter Of The Core	The diameter of the core is between 50-200μm in the case of multimode fiber and 10μm in the case of single mode fiber.	The diameter of the core is about 50μm in the case of multimode fiber.
Application	Used for short distance communication.	Used for long distance communication.
Attenuation Of Light Rays	Attenuation of light rays is more in multimode step index fibers but for single mode step index fibers, it is very less.	Attenuation of light rays is less in graded index fibers.
Cost	Less expensive	Highly expensive.
NA	NA of multimode step index fiber is more whereas in single mode step index fibers, it is very less.	NA of graded index fibers is less.
Pulse Broadening	Pulse broadening and inter modal dispersion is present.	No pulse broadening and inter modal dispersion due to periodic self focusing.

UNIT II
OPTICAL SOURCES

:Dr. Sanket B. Kasturiwala

Unit 2.1

Optical Source :
Light Emitting Diode
LED

OPTICAL SOURCES

- The optical source is often considered to be the active component in an optical fiber communication system.

- Its fundamental function is to convert electrical energy in the form of current into optical energy(light) in an efficient manner.

- The light output should be effectively launched or coupled into the optical fiber.

The optical sources can be mainly divided into three categories:-

- Wideband ‘continuous spectra’ sources
  (Incandescent lamps)
- Monochromatic incoherent sources
  (LEDs)
- Monochromatic coherent sources
  (Lasers)

Wideband Sources

- Very primitive type of source
- Were used generally for Morse-code and other obsolete forms of signaling
- Consisted of Incandescent lamps
- Monochromatic incoherent and coherent sources are preferred over wideband sources now-a-days
- Not used on optical source.

Monochromatic Incoherent Sources

- Consists of Light Emitting Diodes (LEDs)
- Very widely used due to simple fabrication, low cost and high reliability
- Limitations include

  - low optical power coupling(microwatts),
  - relatively small modulation bandwidth(less than 50Mhz) and
  -high harmonic distortion

Monochromatic coherent sources

- Incoherent sources were not feasible for long distance communications
- Coherent sources include LASER which is widely used for long distance communication
- Generally used with single mode fibers as they provide low dispersion

•Bothe LED and LASER are used in single mode as well as multimode fiber with long life cycles over a longer distance.

Major Requirements of optical sources :

1. A size and configuration compatible with launching light into an optical fiber.

-Ideally, the light output should be highly directional

2. Must accurately track the electrical input signal to minimize distortion and noise.

-Ideally, the source should be linear

3. Emit light at wavelengths where the fiber has low losses and low dispersion and where the detectors are efficient to receive.

4. Capable of simple signal modulation (i.e. direct-) over a wide bandwidth extending from LF to beyond the HF i.e. gigahertz range.

5. Must couple sufficient optical power to overcome attenuation in the fiber plus additional minimize connector losses.

6. Very narrow spectral bandwidth in order to minimize dispersion in the fiber

7. Must be capable of maintaining a stable optical output irrespective of ambient conditions (e.g. temperature)

8. Comparatively cheaper and highly reliable .

Two energy bands :

- Conduction band (CB)
- Valence band (VB)

Fundamental processes

- Absorbed photon creates an electron-hole pair
- Recombination of an electron and hole can emit a photon.

Types of photon emission :

- Spontaneous emission

- Random recombination of an electron-hole pair
- Dominant emission for light emitting diodes (LED)

- Stimulated emission

- A photon excites another electron and hole to recombine
- Emitted photon has similar wavelength, direction, and phase.
- Dominant emission for laser diodes (LASER)

- Mathematically-

$$E_g = E_2 - E_1$$

$$\lambda = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)}(\mu m)$$

h = 6.636 x 10^{-34} *J s (Plank's constant)*

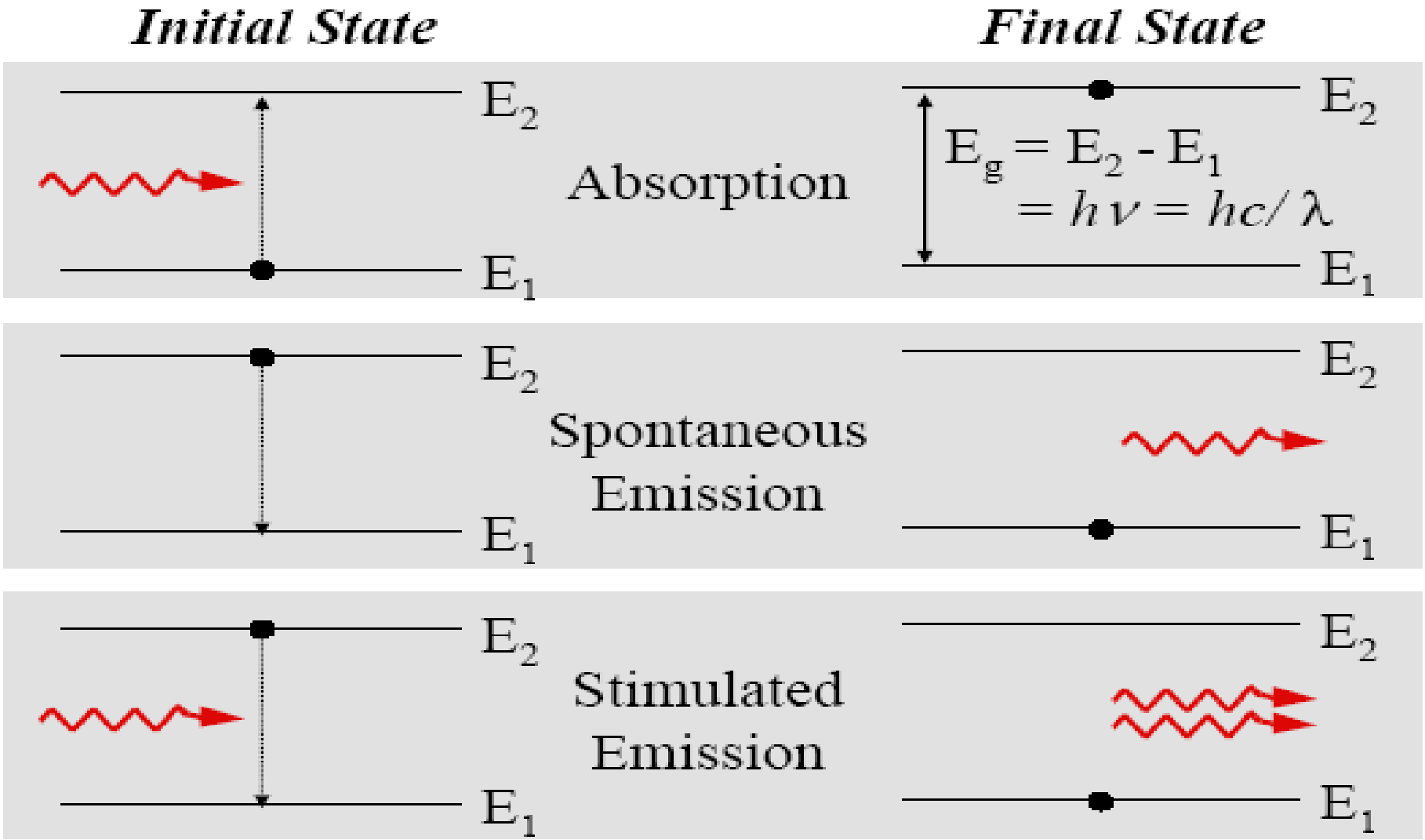
c = 3 x 10^{8} *m/s (velocity of light)*

Eg = Energy released by electron-hole recombination (approximately equal to the band gap energy)

E_2 = Higher Energy level (Excited State)

E_1 = Lower Energy Level (Ground State)

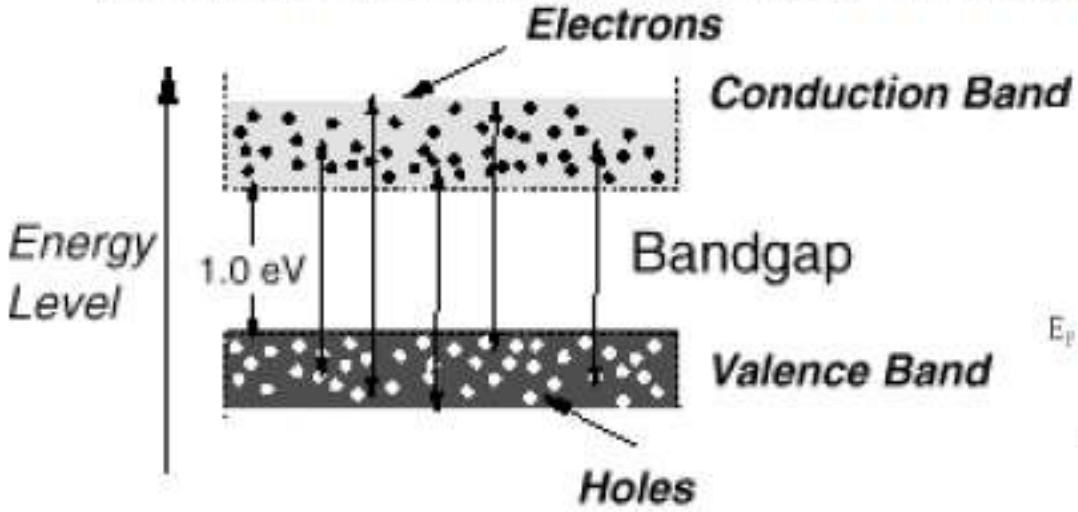
λ = *Optical Wavelength*

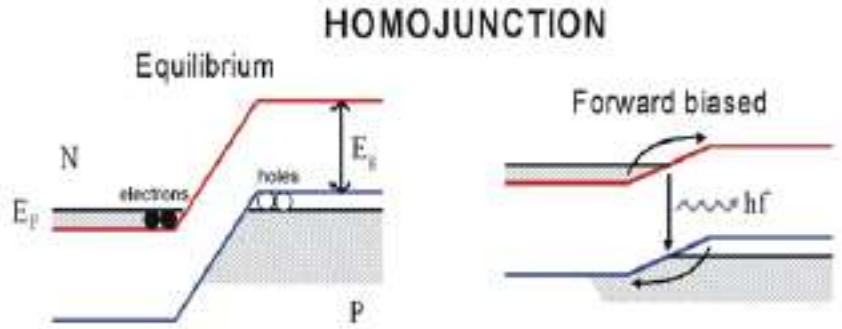


Energy state diagram showing: (a) absorption; (b) spontaneous emission; (c) stimulated emission. The black dot indicates the state of the atom before and after transition take place.

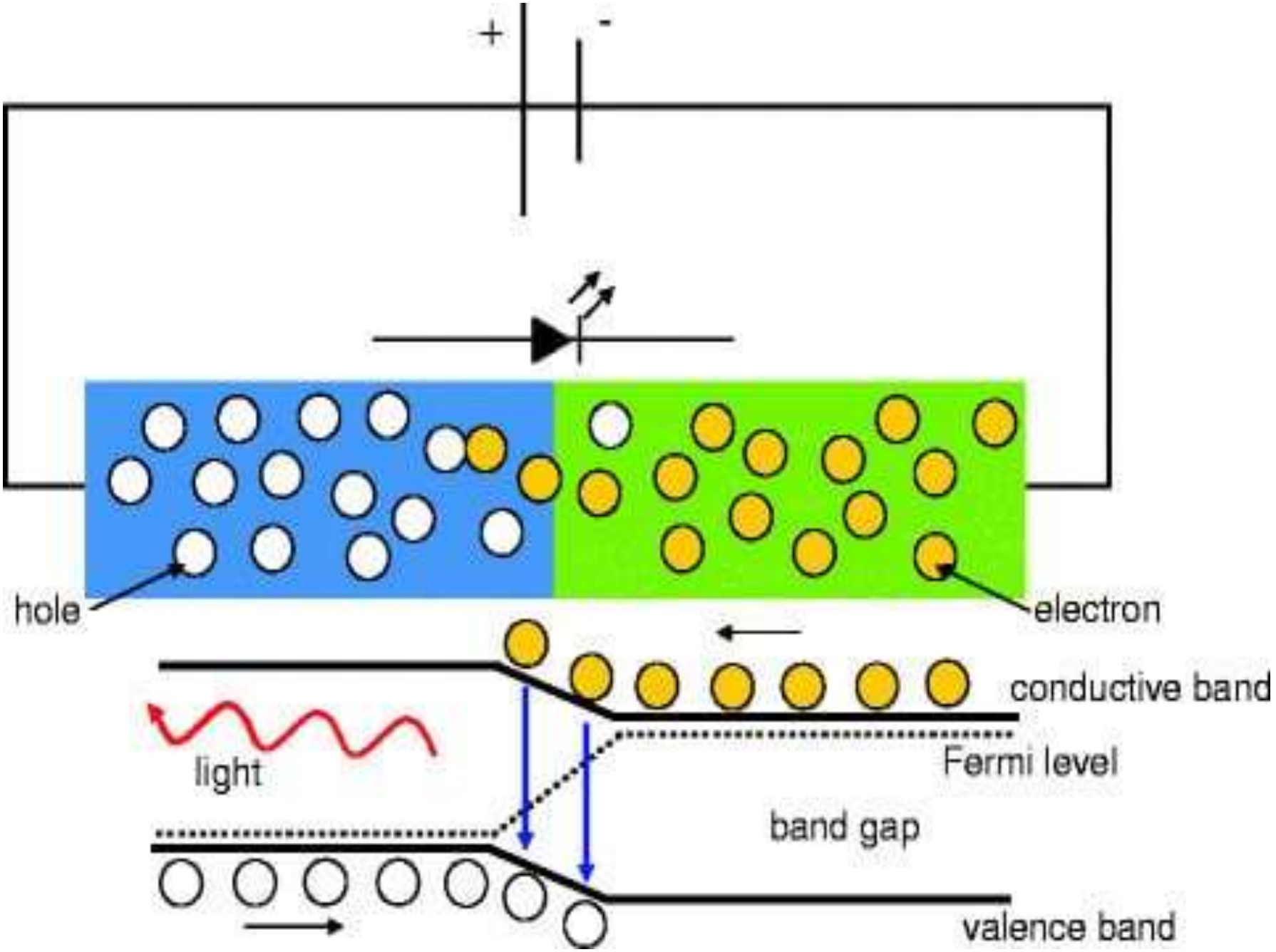
Basic LED operation

- A PN junction acts as the active or recombination region.
- When the PN junction is forward biased, electrons and holes recombine either radiatively (emitting photons) or non-radiatively (emitting heat). This is simple LED operation.

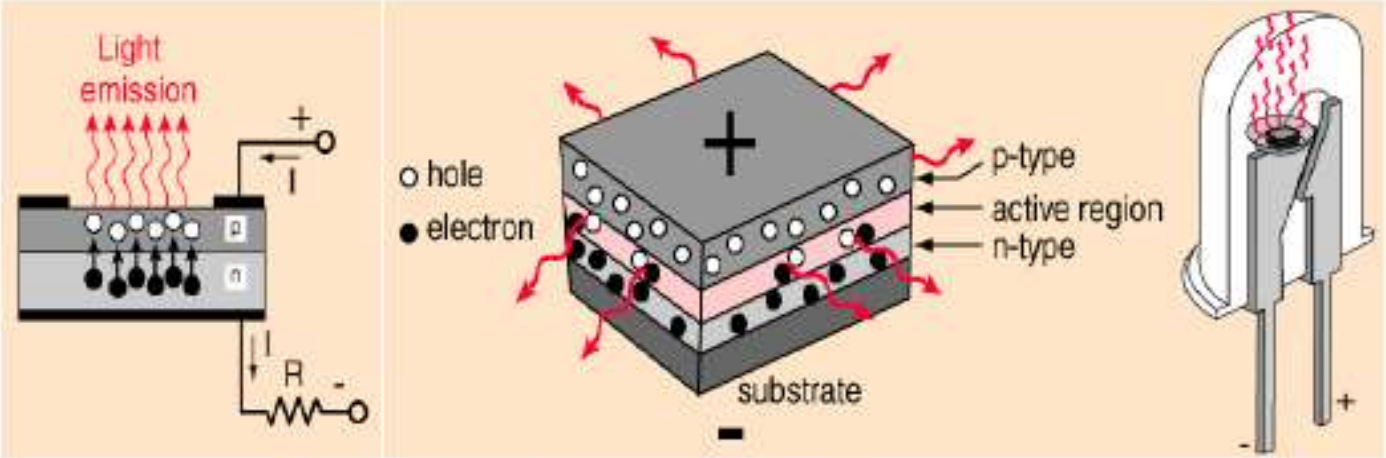


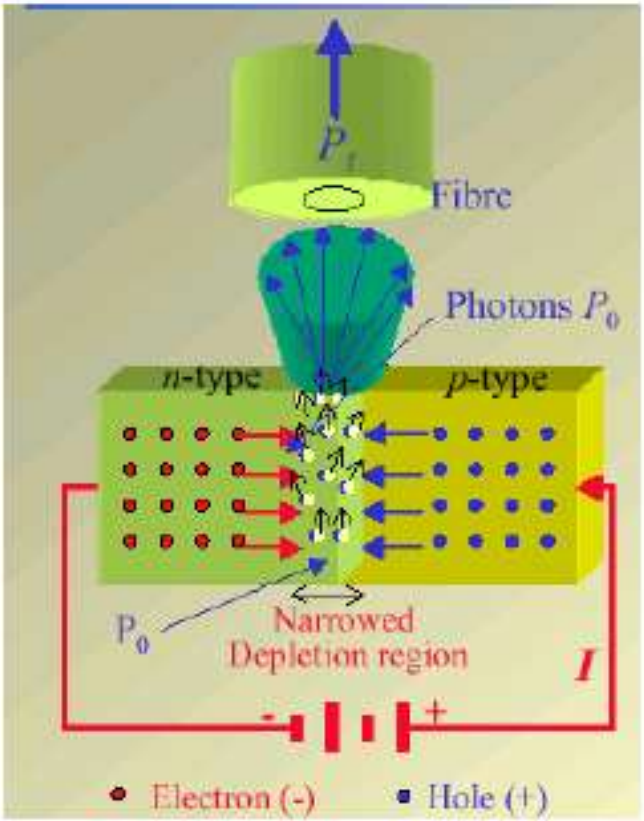


- Emitted wavelength depends on bandgap energy
- Transitions can take place from any energy state in either band to any state in the other band. This results in a range of different wavelengths produced in this spontaneous emission. This accounts for the fact that LEDs produce a range of wavelengths. Typically the range is about 80 nm or so.


+
-
hole
electron
conductive band
light
Fermi level
band gap
valence band

Working of LED





The main semiconductor materials used to manufacture LEDs :

- **Indium Gallium Nitride (InGaN):**

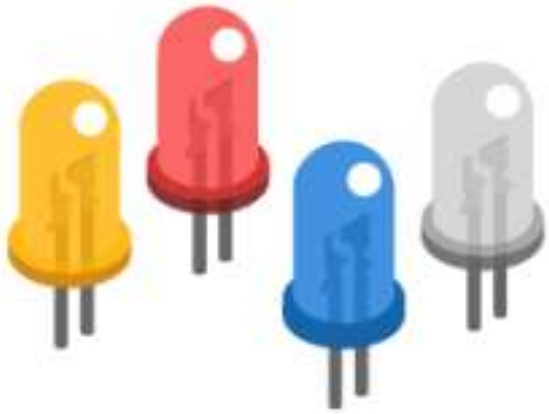
  Blue, Green and ultraviolet high-brightness LEDs.

- **Aluminum Gallium Indium Phosphide (AlGaInP):**

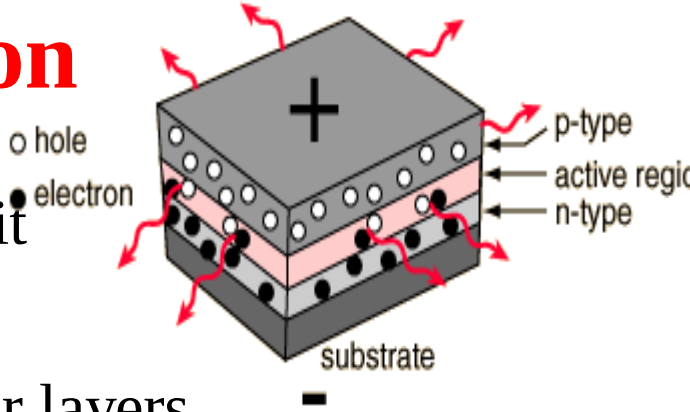
  Yellow, Orange and Red high-brightness LEDs.

- **Aluminum Gallium Arsenide (AlGaAs):**

  Red and infrared LEDs.



LED Construction



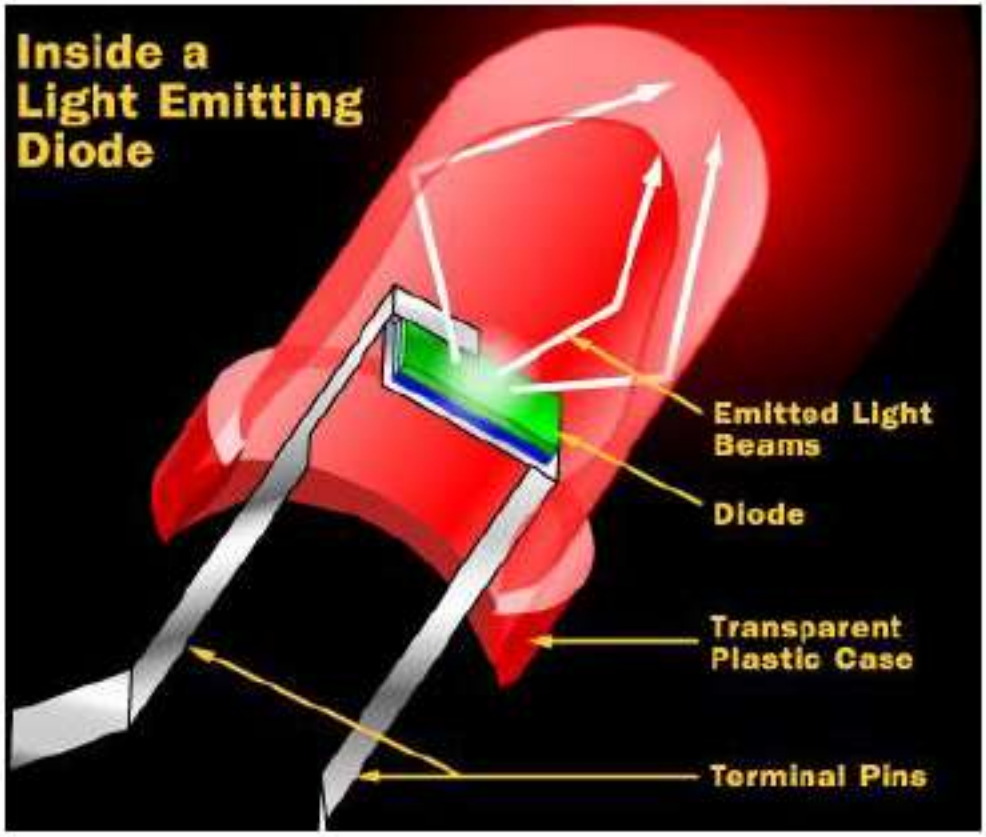
•One way to construct an LED is to deposit three semiconductor layers on a substrate.

•Between p-type and n-type semiconductor layers, an active region emits light when an electron and hole recombine.

•Considering the p-n combination to be a diode, then when the diode is forward biased, holes from the p-type material and electrons from the n-type material are both driven into the active region. The light is produced by a solid state process called electroluminescence.

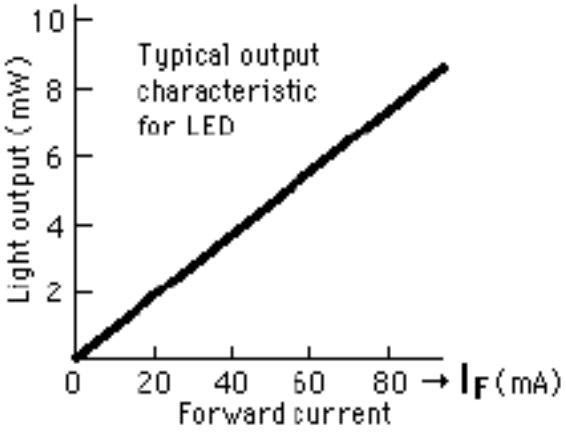
•In this particular design, the layers of the LED emit light all the way around the layered structure, and the LED structure is placed in a tiny reflective cup so that the light from the active layer will be reflected toward the desired exit direction.

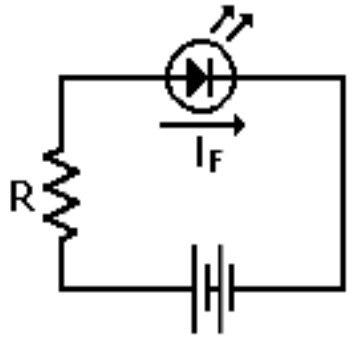
- Light is emitted at site of carrier recombination which is primarily close to the junction.
- However, the amount of radiative recombination and the emission area within the structure is dependent upon the semiconductor materials used and the fabrication of the device.

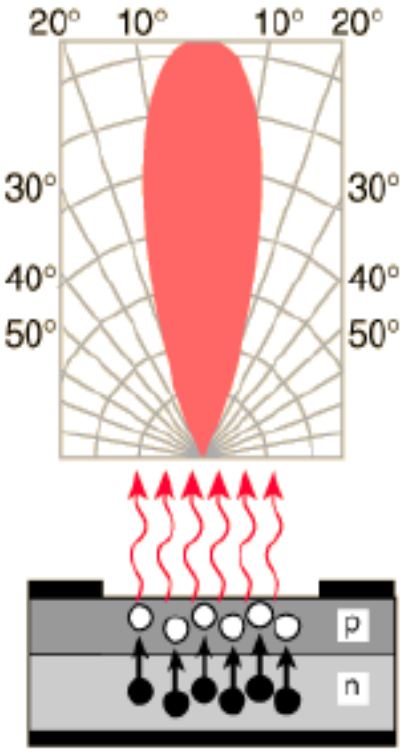


- Emits incoherent light through spontaneous emission.
- Used for Multimode systems with 100-200 Mb/s rates.
- Broad spectral width and wide output pattern.
- 850nm region: GaAs and AlGaAs
- 1300–1550nm region: InGaAsP and InP

LED Characteristics

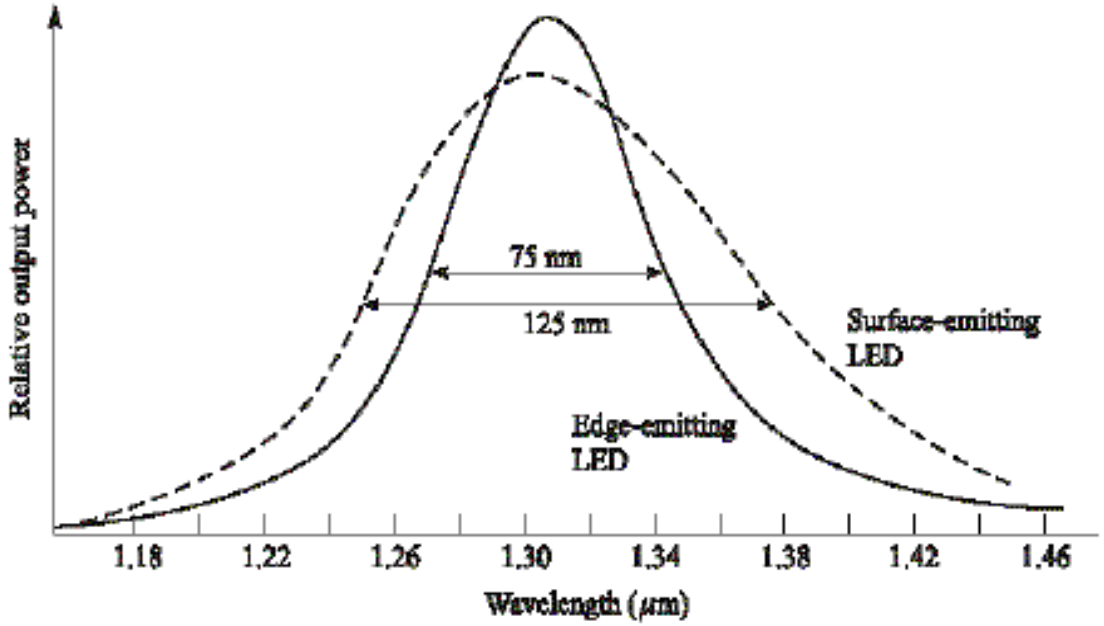






- LED is forward biased, its current increases rapidly and must be controlled to prevent destruction of the device.
- The light output is quite linearly proportional to the current, so it can be precisely modulated.
- Full Width Half Max, Peak Wavelength, Forward current, Rise time, Luminous intensity (Flux(lm)), LED radiation pattern

Spectral Linewidth

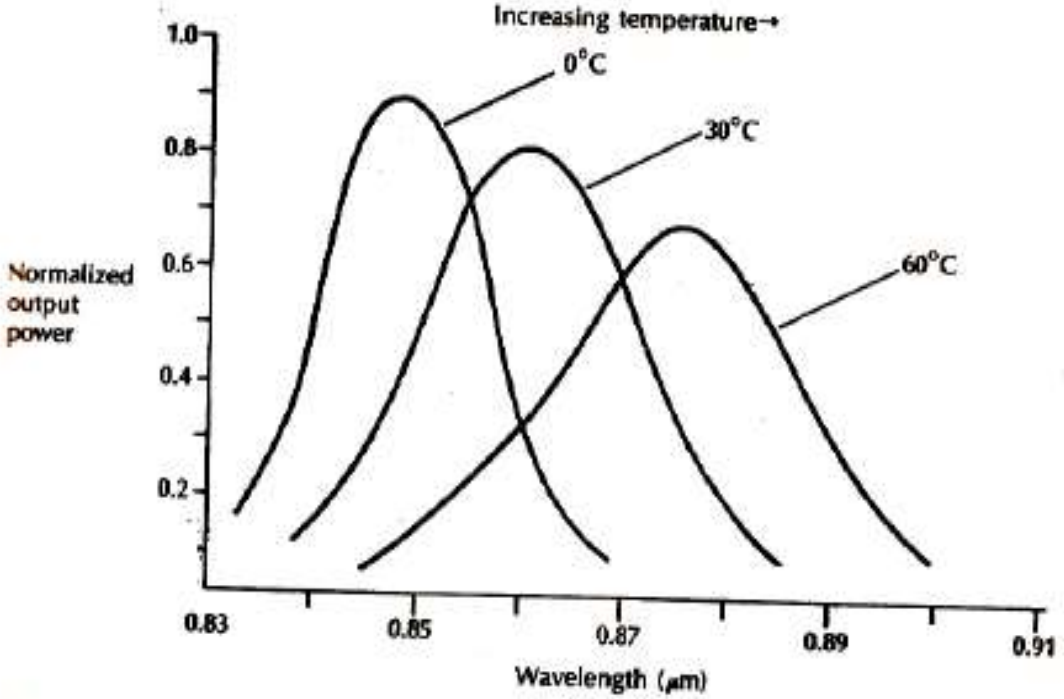


Typical spectral patterns for edge- and surface-emitting LEDs at 1310 nm.

- FWHM about 1.6 times smaller for ELED than SLED.
- Further narrowed by the Superluminescent operation; linewidth far smaller ≅ 30 nm
- The patterns broaden with increasing wavelength and are wider for surface emitters.

Temperature dependence

- Spectra tend to broaden with increase in temperature due to greater energy spread in carrier distributions at higher temperatures.
- Increase in temperature affect the peak emission wavelength as well.



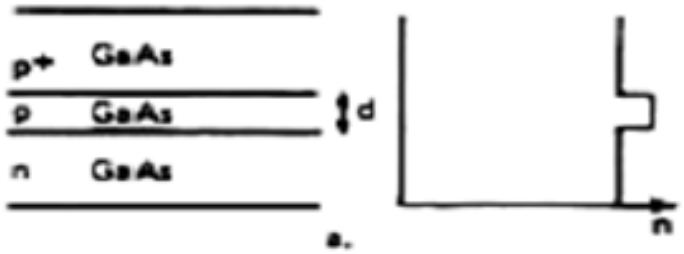
Spectral variation with temperature for AlGaAs SLED

Advantages of LED

- Cost: Simple construction of LED leads to much reduced cost
- Reliability : The LED does not exhibit catastrophic degradation & has proved far less sensitive to gradual degradation, it is also immune to self pulsation & modal noise problems.
- Simpler drive circuitry: This is due to lower drive currents and reduced temperature dependence
- Linearity: Ideally LED has linear light output against current
- Less temperature dependence: Light output against current is less affected by temperature

- **Homojunctions**: P- type and N-type from same material

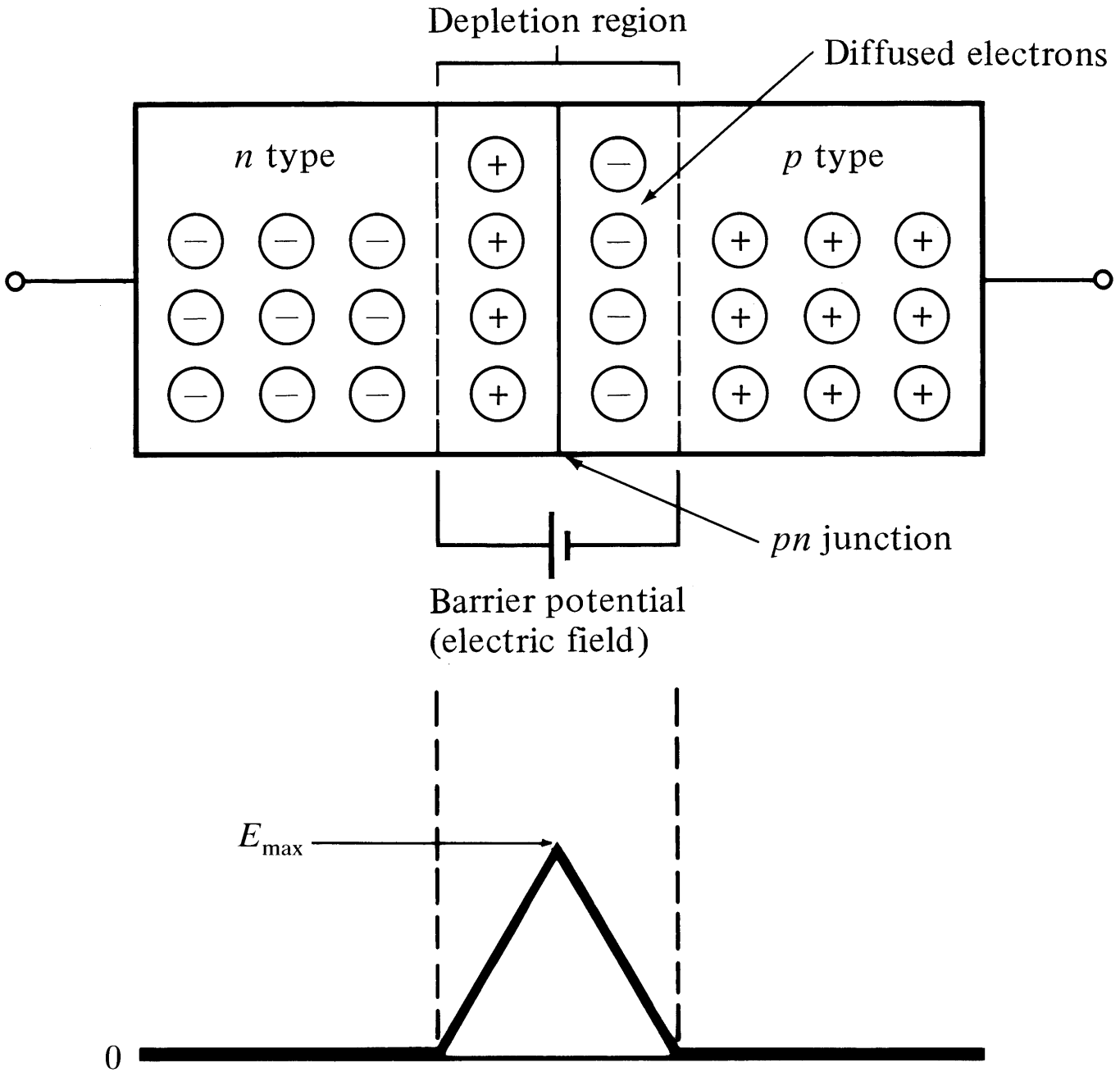




- Carriers are not confined
- Light is not confined

Structure and index of refraction n in gallium arsenide with a junction width d

- LED should have a high radiance (light intensity), fast response time and a high quantum efficiency for FO system

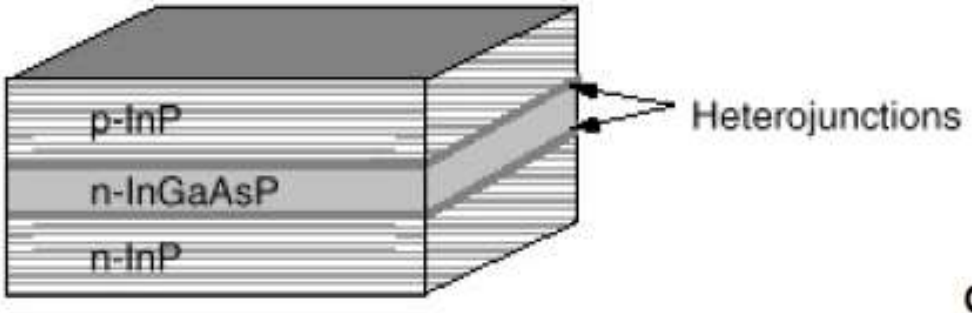

Depletion region
Diffused electrons
n type
p type
pn junction
Barrier potential
(electric field)
E_{max}
0

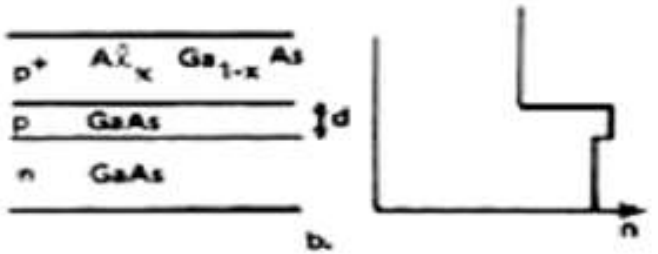
Heterojunctions: Different p- and n- materials

- Carriers are confined
- Light is also confined
- Single Heterojunction, Double Heterojunction.

- A heterojunction is a junction between two different semiconductors with different bandgap energies.

- The difference in bandgap energies creates a one-way barrier. Charge carriers (electrons or holes) are attracted over the barrier from the material of higher bandgap energy to the one of lower bandgap energy.



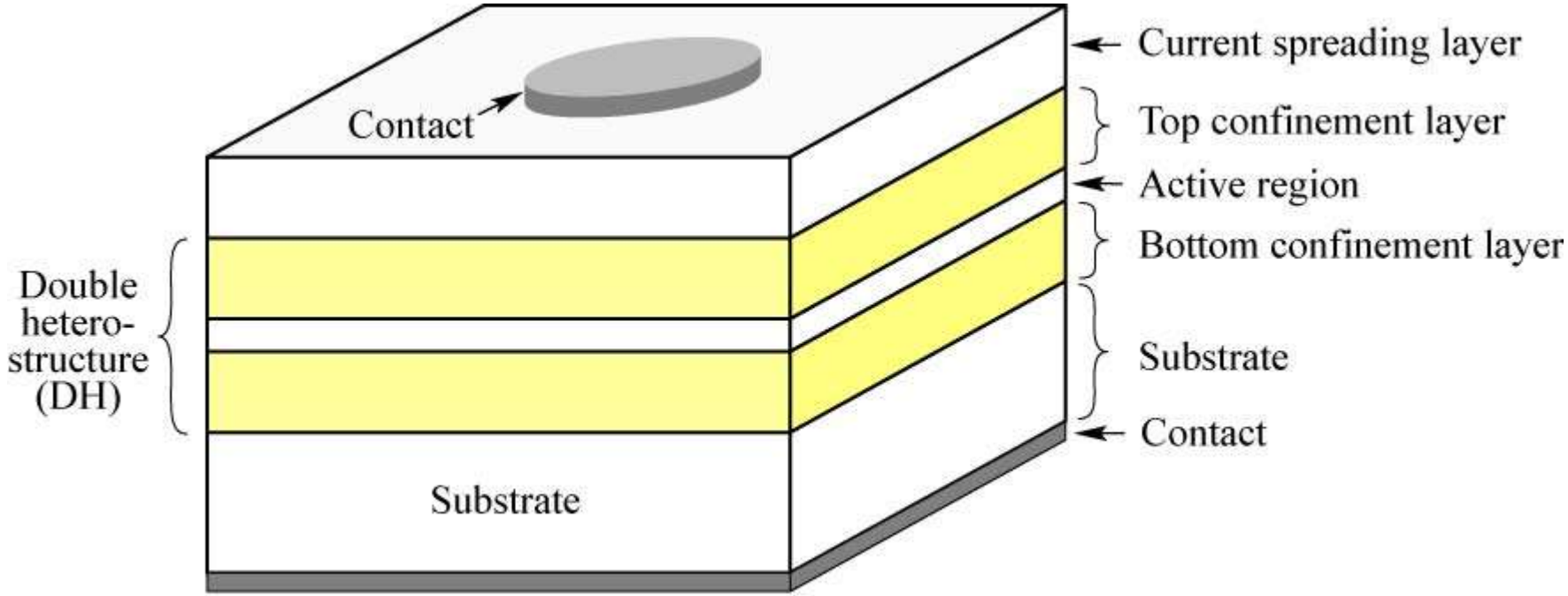


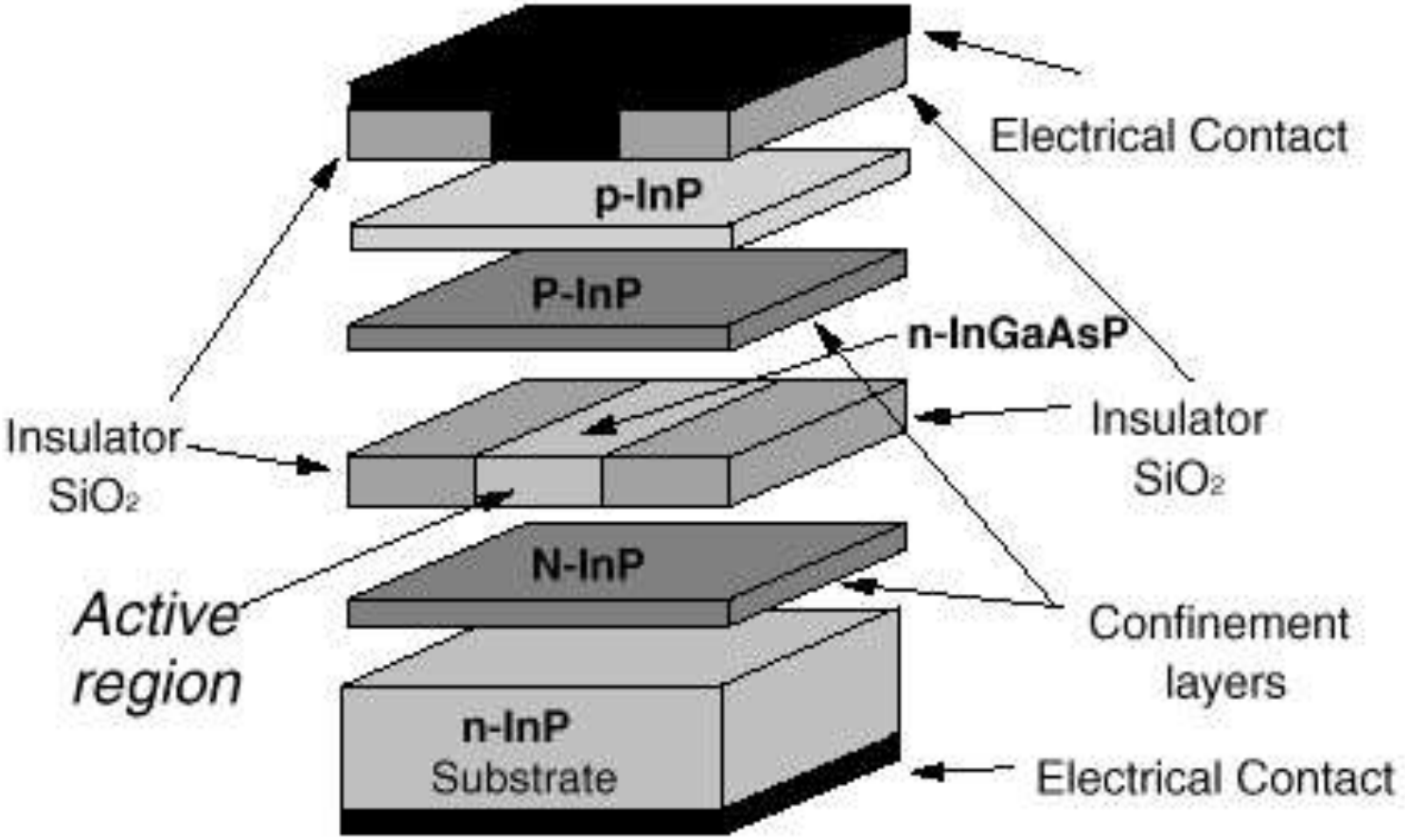
Gallium Arsenide-Aluminum Gallium Arsenide single heterojunction

Double Heterojunction

- When a layer of material with a lower bandgap energy is sandwiched between layers of material with a higher energy bandgap a *double heterojunction* is formed. This is called a double heterojunction because there are two heterojunctions present - one on each side of the active material.

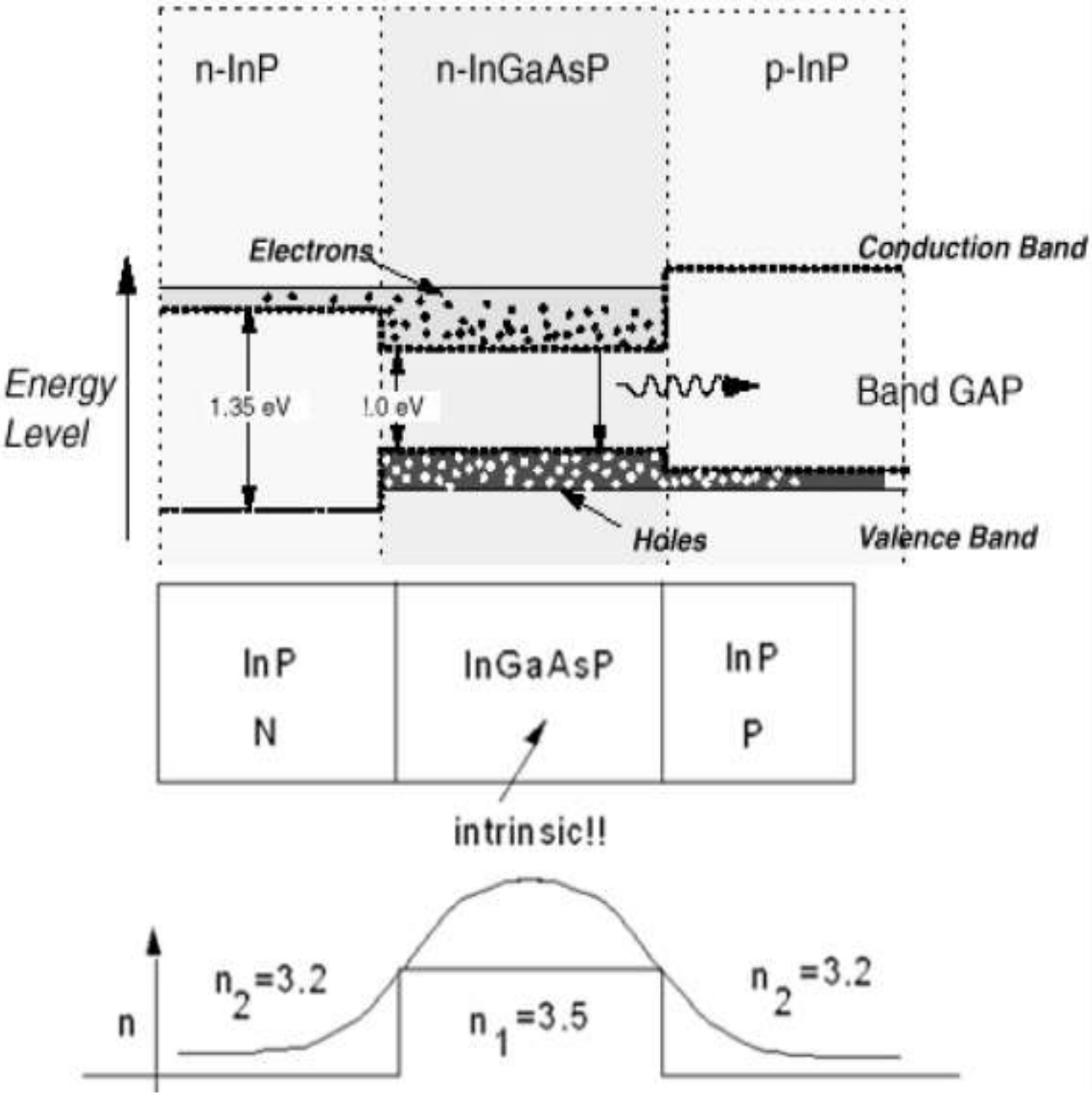
- The double heterojunction forms a barrier which restricts the region of electron-hole recombination to the lower bandgap material. This region is then called the "active" region

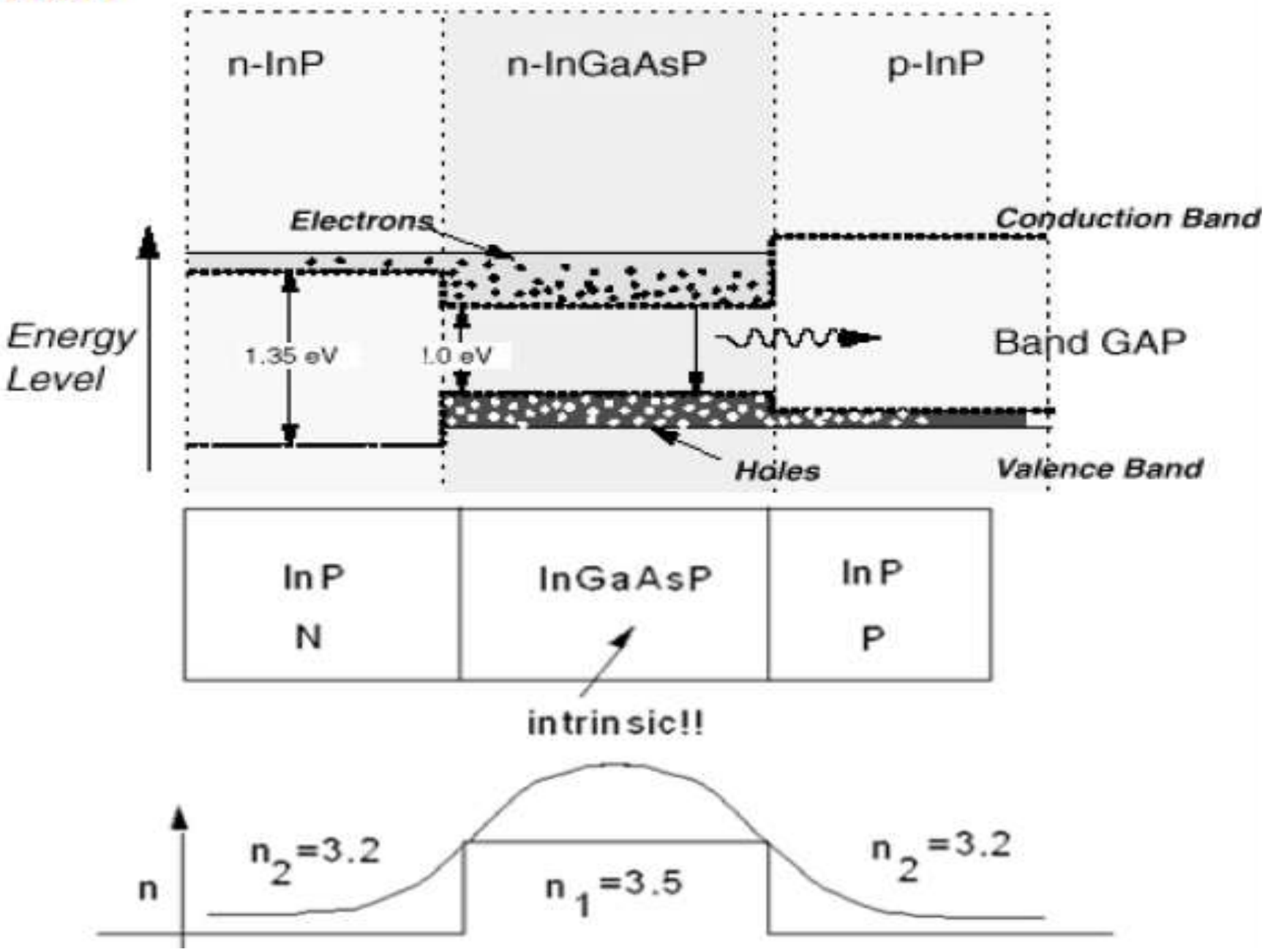



Electrical Contact
p-InP
P-InP
n-InGaAsP
Insulator
SiO2
Insulator
SiO2
N-InP
Active
region
Confinement
layers
n-InP
Substrate
Electrical Contact

Double Heterojunction

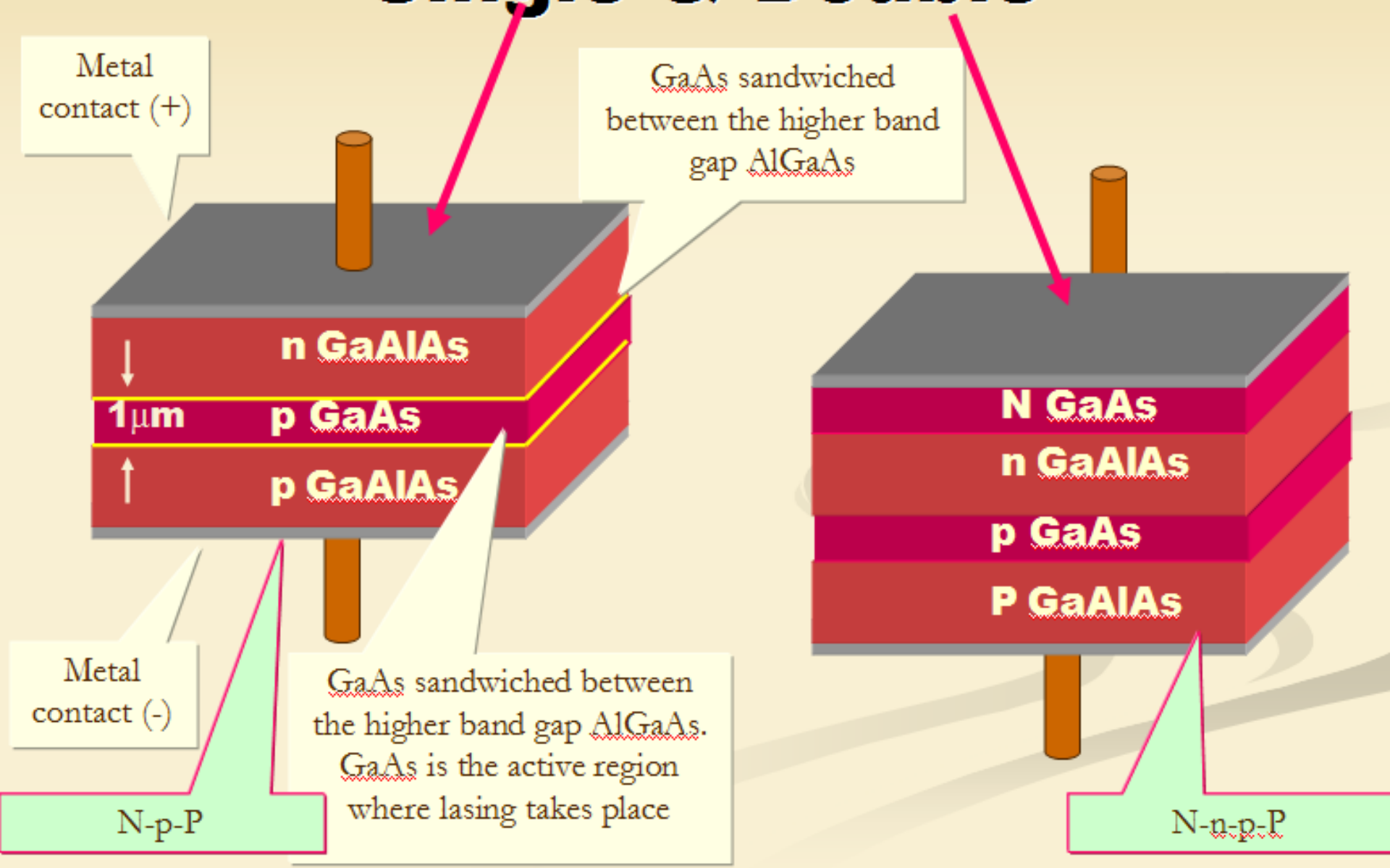
- The valence band of n-InGaAsP is at a higher energy than the valence band of the adjacent n-InP. The conduction band is at a lower energy level.
- p-InP has higher energy levels than n-InP but the bandgap is the same




n-InP
n-InGaAsP
p-InP
Electrons
Conduction Band
Energy Level
1.35 eV
1.0 eV
Band GAP
Holes
Valence Band
InP
N
InGaAsP
InP
P
intrinsic!!
n
n2=3.2
n1=3.5
n2=3.2

- Electrons are attracted across the left-hand junction from the n-InP to n-InGaAsP.
- Holes are attracted across the right-hand junction from the p-InP into the n-InGaAsP.
- Recombination takes place in the n-InGaAsP and spontaneous emission occurs.
- The heterojunction allows to have a small active region where the light is produced.
- The material in the active region has a higher refractive index than that of the material surrounding it. This means that a mirror surface effect is created at the junction which helps to confine and direct the light emitted.

The Heterojunction Laser Single & Double



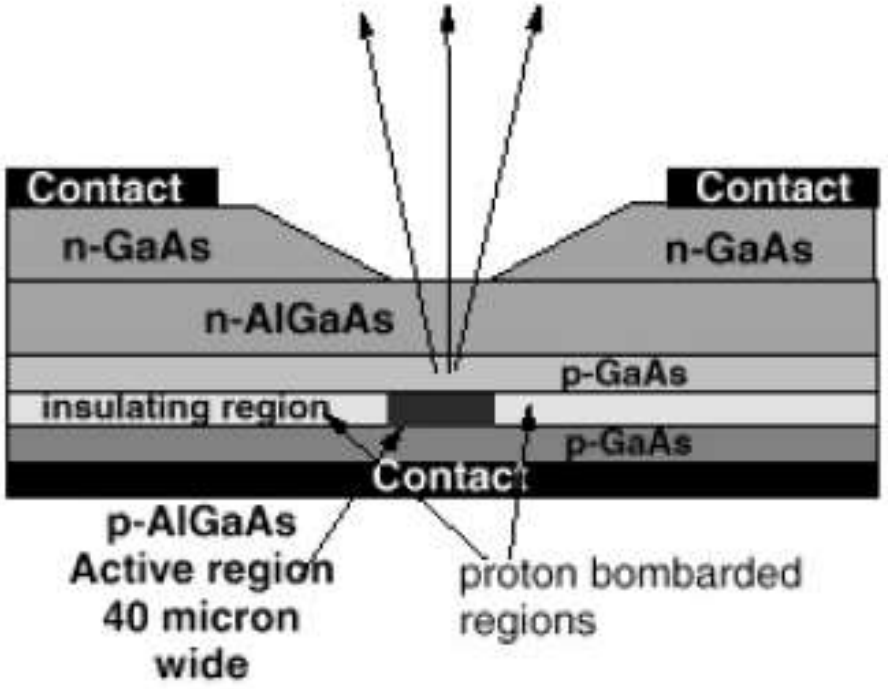
TYPES OF LED STRUCTURES

- Surface Emitting LED (S-LED) ;
- Edge Emitting LED (E-LED) .

Surface Emitting LED (SLED)

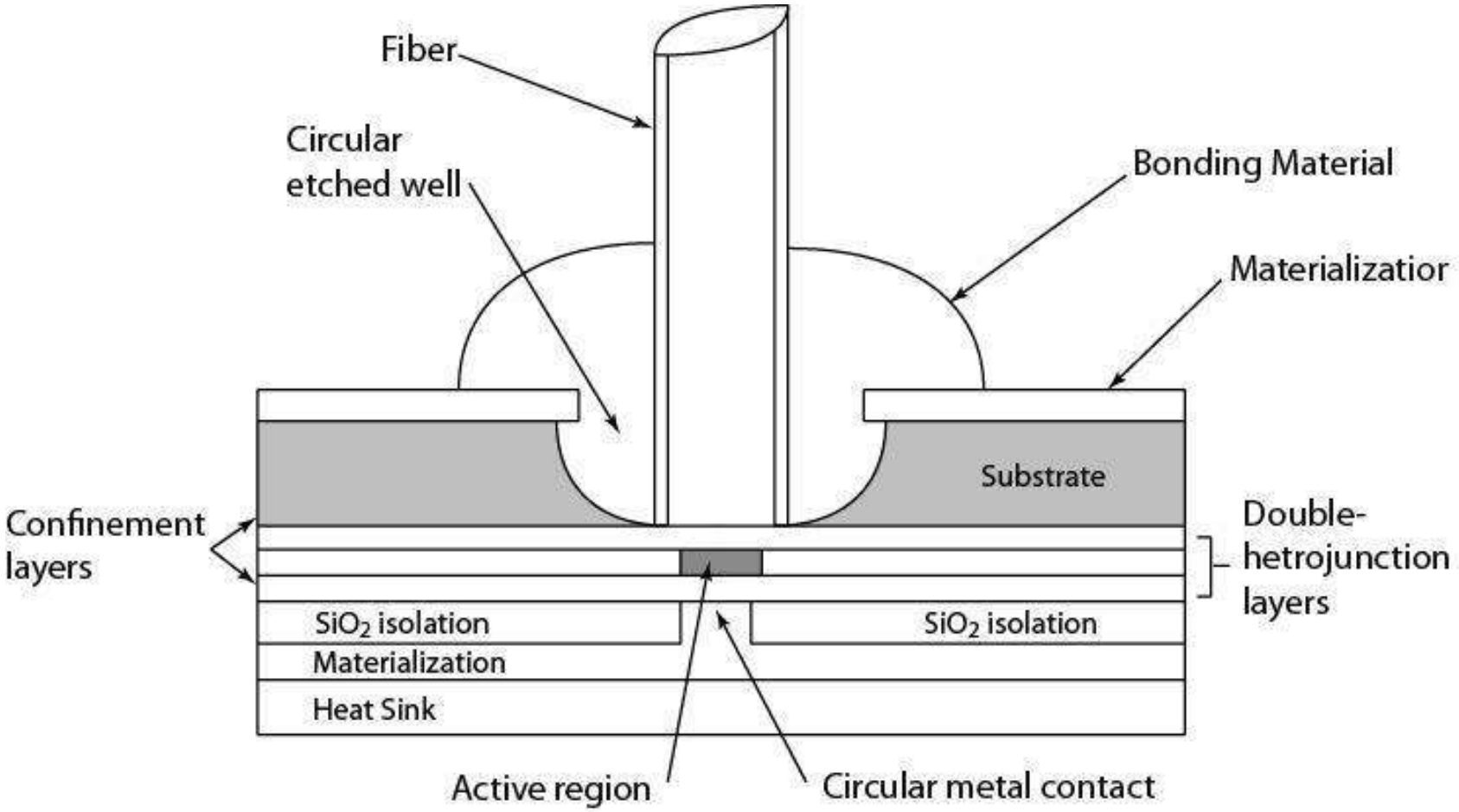
- Method for obtaining high radiance is to restrict the emission to a small active region within the device – Burrus & Dawson (1970)

- Power coupled into the fiber is dependent on many factors; *distance and alignment between emission area and fiber, emission pattern and interfacing medium*
  - More Power
  - Poor Radiance



- Coupling lens used to increase efficiency.
- Short optical Links with Large NA fibers.
- Data rates less than 20 Mbps.

S-LED Coupling with Fiber



The active region is limited to a circular section that has an area compatible with the fiber-core end face.

Surface Emitting LED

- The surface-emitting LED is also known as the Burrus LED in honor of C. A. Burrus, its developer.
- In SLEDs, the size of the primary active region is limited to a small circular area of 20micron to 50micron in diameter.
- The primary active region is below the surface of the semiconductor substrate perpendicular to the axis of the fiber.
- A well is etched into the substrate to allow direct coupling of the emitted light to the optical fiber. The etched well allows the optical fiber to come into close contact with the emitting surface.

Working of S-LED

• When the SLED is forward-biased, photons are generated in the p-GaAs layer.

• The emission from the top surface is ensured by the upper n+ AlGaAS and lower p+ AlGaAs layers of the hetero-structure.

• Therefore, radiance of the device in the forward direction is very high.

• Although the fiber is properly aligned to optimize the coupling of the emitted radiation with the fiber, there is some loss due to the Lambertian distribution of radiation intensity.

• Difference between refractive index of adjacent layers confines the optical power in the central GaAs.

Emission Pattern

- Emission pattern is isotropic with a 120^{o} half-power beam width.
- This isotropic pattern from the SLED is called a Lambertian pattern.
- Power distribution is described by $PD = P \cos \theta$
- Where θ is the angle between the direction of the observation and the line orthogonal to the radiating surface
- This implies that the source is equally bright when viewed from any direction but the power diminishes as $\cos \theta$.
- Thus the power is down to 50% of its peak when $\theta = 60^{o}$ so that half power beam width is 120^{o}

Edge Emitter LED (E-LED)

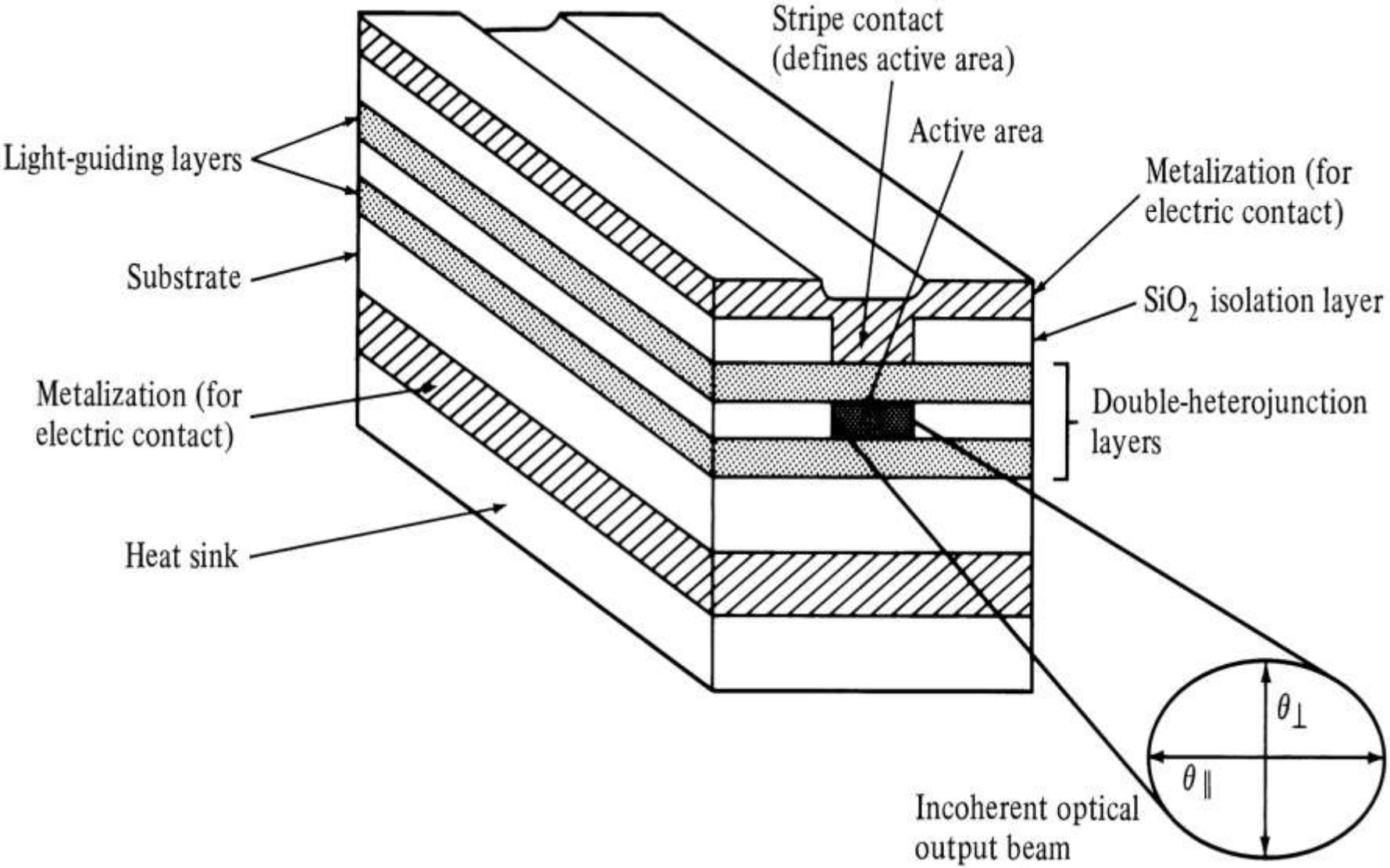
•The demand for optical sources for longer distance, & higher bandwidth system led to the development of edge-emitting LEDs.

• It shows the different layers of semiconductor material. The primary active region of the ELED is a narrow stripe, which lies below the surface of the semiconductor substrate.

•The semiconductor substrate is cut or polished so that the stripe runs between the front and back of the device.

•The polished or cut surfaces at each end of the stripe are called facets.

E-LED


Stripe contact
(defines active area)
Active area
Light-guiding layers
Metalization (for
electric contact)
Substrate
SiO_2 isolation layer
Metalization (for
electric contact)
Double-heterojunction
layers
Heat sink
$\theta_\perp$
$\theta_\parallel$
Incoherent optical
output beam

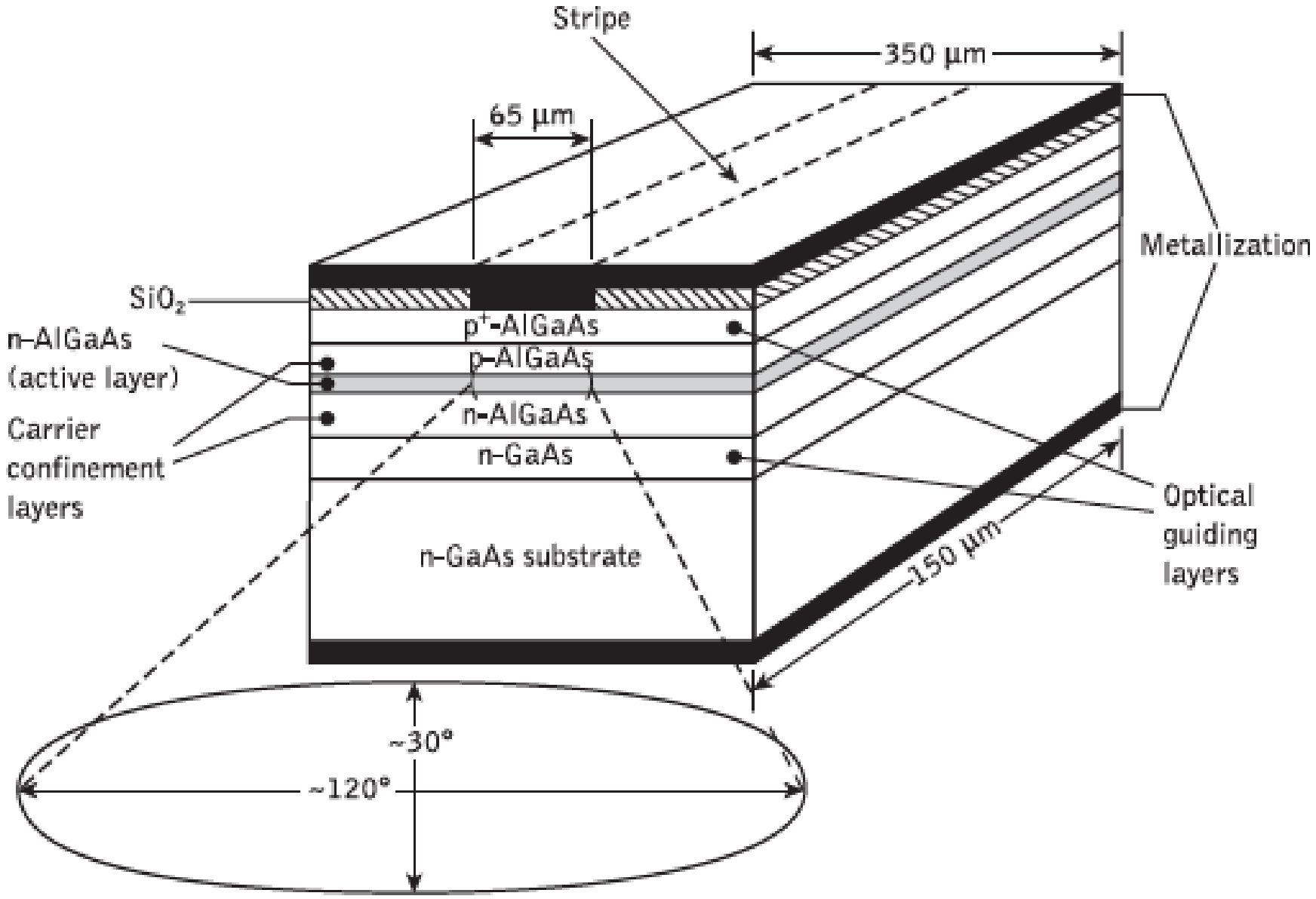


Figure 7.7 Schematic Illustration of the structure of a stripe geometry DH AlGaAs edge-emitting LED

Working of E-LED

- In an ELED the rear facet is highly reflective and the front facet is antireflection-coated.
- The rear facet reflects the light propagating toward the rear end-face back toward the front facet.
- By coating the front facet with antireflection material, the front facet reduces optical feedback and allows light emission.
- ELEDs emit light only through the front facet & in a narrow emission angle allowing for better source-to-fiber coupling.
- Edge-emitting double-heterojunction LED. The output be a mislambertian in the plane of the pn-junction and highly directional perpendicular to the pn-junction.

Edge-emitting LED

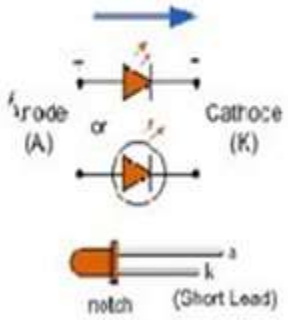
- Have advantage of transparent guiding layers with a very thin active layer (50 to 100μm). This reduces self absorption and narrows the beam divergence.
- Light is emitted at one end face only.
- Couple more power to small NA fibers
- Higher data rates>100Mbps, better modulation
- Multimode and Single Mode fibers
- ELEDs provide narrower linewidth than SLED
- High radiance

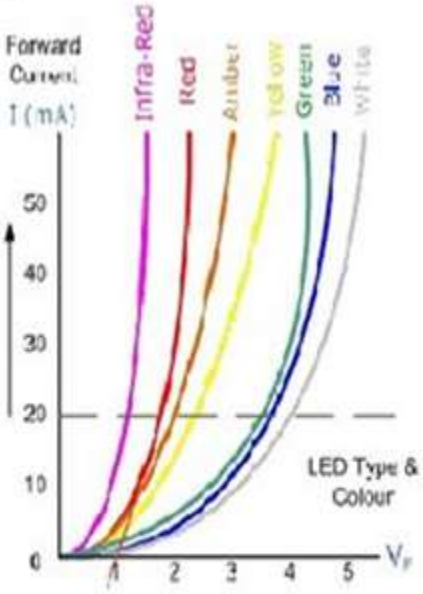
SR. No.	SLED	ELED
1.	Easy to fabricate	Difficult to fabricate
2.	Easy to mount and handle	Difficult to mount and handle
3.	Require less critical tolerances	Need critical tolerance on fabrication
4.	Less Reliable	Highly reliable
5.	Low system performance	High system performance
6.	Less modulation Bandwidth	Better Modulation, Bandwidth of the order of hundreds of MHz
7.	Couple less optical power into low NA fiber	Couple more optical power into low NA fiber
8.	Light is emitted from the surface of active Layer	Light is emitted from edge of active Layer
9.	Wider spectral width	Narrow spectral width
10.	Maximum quantum efficiency is up to 60%	Internal quantum efficiency is in the range of 60% to 80%

LED

- Inorganic semi-conductor junction
- AC rectifier character due to PN junction
- Excitons (e^--holes) are delocalised in the crystal: Energy bands
- Electrical mobility decreases with temperature
- Doping is necessary for getting free carriers
- Hetero-structures are limited due to crystal mesh mismatch
- Almost monochromatic emission linked to the energy gap





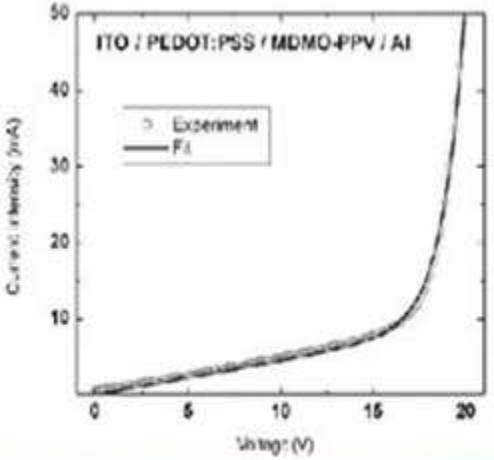


LED and its
I-V Characteristics

OLED

- Organic semi-conductor stack
- AC rectifier character due to work function difference between the two electrodes used for the carrier injection
- Excitons (e^--holes) are localized to single molecule
- Electrical mobility increases with temperature but stays very low
- Doping is not necessary for getting free carriers: they are injected from electrodes
- Structures choices are almost unlimited
- Large emission covering visible spectrum (molecular bands, mixing…)





Quantum Efficiency and Power

- The internal quantum efficiency (η_{int}) is defined as the ratio of radiative recombination rate to the total recombination rate.

$$\eta_{int} = \frac{R_r}{R_r + R_{nr}}$$

Where,

R_r is radiative recombination rate.

R_{nr} is non-radiative recombination rate.

If n are the excess carriers, then radiative life time, $\tau_r = \frac{n}{R_r}$ and

non-radiative life time, $\tau_r = \frac{n}{R_{nr}}$

- The internal quantum efficiency is given as –

$$\eta_{int} = \frac{1}{1 + \frac{R_{nr}}{R_r}}$$

$$\eta_{int} = \frac{1}{1 + \frac{\tau_r}{\tau_{nr}}}$$

- The recombination time of carriers in active region is τ. It is also known as bulk recombination life time.

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

Therefore internal quantum efficiency is given as –

$$\eta_{int} = \frac{\tau}{\tau_r}$$

- If the current injected into the LED is I and q is electron charge then total number of recombinations per second is –

$$R_r = R_{nr} = \frac{I}{q}$$

$$\eta_{int} = \frac{R_r}{I / q}$$

$$R_r = \eta_{int} \times \frac{I}{q}$$

- Optical power generated internally in LED is given as –

$$P_{int} = R_r . h\nu$$

$$P_{int} = \left(\eta_{int} \times \frac{I}{q}\right) . h\nu$$

$$P_{int} = \left(\eta_{int} \times \frac{I}{q}\right) . h\frac{c}{\lambda}$$

$$P_{int} = \eta_{int} \cdot \frac{hc\, I}{q\lambda}$$

- Not all internally generated photons will available from output of device. The external quantum efficiency is used to calculate the emitted power. The external quantum efficiency is defined as the ratio of photons emitted from LED to the number of photons generated internally. It is given by equation

$$\eta_{ext} = \frac{1}{n(n+1)^2}$$

- The optical output power emitted from LED is given as –

$$P = \eta_{ext} \cdot P_{int}$$

$$\boxed{P = \frac{1}{n\,(n+1)^2} \cdot P_{int}}$$

Example : The radiative and non radiative recombination life times of minority carriers in the active region of a double heterojunction LED are 60 nsec and 90 nsec respectively. Determine the total carrier recombination life time and optical power generated internally if the peak emission wavelength si 870 nm and the drive currect is 40 mA

Solutions : Given : $\lambda = 870$ nm 0.87×10^{-6} m

$\tau_r = 60$ nsec.

$\tau_{nr} = 90$ nsec.

$I = 40$ mA $= 0.04$ Amp.

i) Total carrier recombination life time:

$$\boxed{\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}}$$

$$\frac{1}{\tau} = \frac{1}{60} + \frac{1}{90}$$

$$\frac{1}{\tau} = \frac{150}{5400}$$

$\therefore$ $\tau = \mathbf{36\ nsec.}$

ii) Internal optical power:

$$\boxed{P_{int} = \eta_{int} \cdot \frac{hc\,I}{q\lambda}}$$

$$P_{int} = \left(\frac{\tau}{\tau_r}\right)\left(\frac{hc\,I}{q\lambda}\right)$$

$$P_{int} = \left(\frac{30}{60}\right)\left[\frac{(6.625 \times 10^{-34})(3 \times 10^{8}) \times 0.04}{(1.602 \times 10^{-19})(0.87 \times 10^{-6})}\right]$$

$$P_{int} = 34.22\ \text{mW}$$

UNIT II
OPTICAL SOURCES

:Dr. Sanket B. Kasturiwala

Unit 2.1

Optical Source :
Light Emitting Diode
LED

OPTICAL SOURCES

- The optical source is often considered to be the active component in an optical fiber communication system.

- Its fundamental function is to convert electrical energy in the form of current into optical energy(light) in an efficient manner.

- The light output should be effectively launched or coupled into the optical fiber.

The optical sources can be mainly divided into three categories:-

- Wideband ‘continuous spectra’ sources
  (Incandescent lamps)
- Monochromatic incoherent sources
  (LEDs)
- Monochromatic coherent sources
  (Lasers)

Wideband Sources

- Very primitive type of source
- Were used generally for Morse-code and other obsolete forms of signaling
- Consisted of Incandescent lamps
- Monochromatic incoherent and coherent sources are preferred over wideband sources now-a-days
- Not used on optical source.

Monochromatic Incoherent Sources

- Consists of Light Emitting Diodes (LEDs)
- Very widely used due to simple fabrication, low cost and high reliability
- Limitations include

  - low optical power coupling(microwatts),
  - relatively small modulation bandwidth(less than 50Mhz) and

  -high harmonic distortion

Monochromatic coherent sources

- Incoherent sources were not feasible for long distance communications
- Coherent sources include LASER which is widely used for long distance communication
- Generally used with single mode fibers as they provide low dispersion

•Bothe LED and LASER are used in single mode as well as multimode fiber with long life cycles over a longer distance.

Major Requirements of optical sources :

1. A size and configuration compatible with launching light into an optical fiber.

-Ideally, the light output should be highly directional

2. Must accurately track the electrical input signal to minimize distortion and noise.

-Ideally, the source should be linear

3. Emit light at wavelengths where the fiber has low losses and low dispersion and where the detectors are efficient to receive.

4. Capable of simple signal modulation (i.e. direct-) over a wide bandwidth extending from LF to beyond the HF i.e. gigahertz range.

5. Must couple sufficient optical power to overcome attenuation in the fiber plus additional minimize connector losses.

6. Very narrow spectral bandwidth in order to minimize dispersion in the fiber

7. Must be capable of maintaining a stable optical output irrespective of ambient conditions (e.g. temperature)

8. Comparatively cheaper and highly reliable .

Two energy bands :

- Conduction band (CB)
- Valence band (VB)

Fundamental processes

- Absorbed photon creates an electron-hole pair
- Recombination of an electron and hole can emit a photon.

Types of photon emission :

- **Spontaneous emission**
  - •Random recombination of an electron-hole pair
  - •Dominant emission for light emitting diodes (LED)
- **Stimulated emission**
  - •A photon excites another electron and hole to recombine
  - •Emitted photon has similar wavelength, direction, and phase.
  - • Dominant emission for laser diodes (LASER)

- Mathematically-

$$E_g = E_2 - E_1$$

$$\lambda = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)}(\mu m)$$

h = 6.636 x 10^{-34} *J s (Plank's constant)*

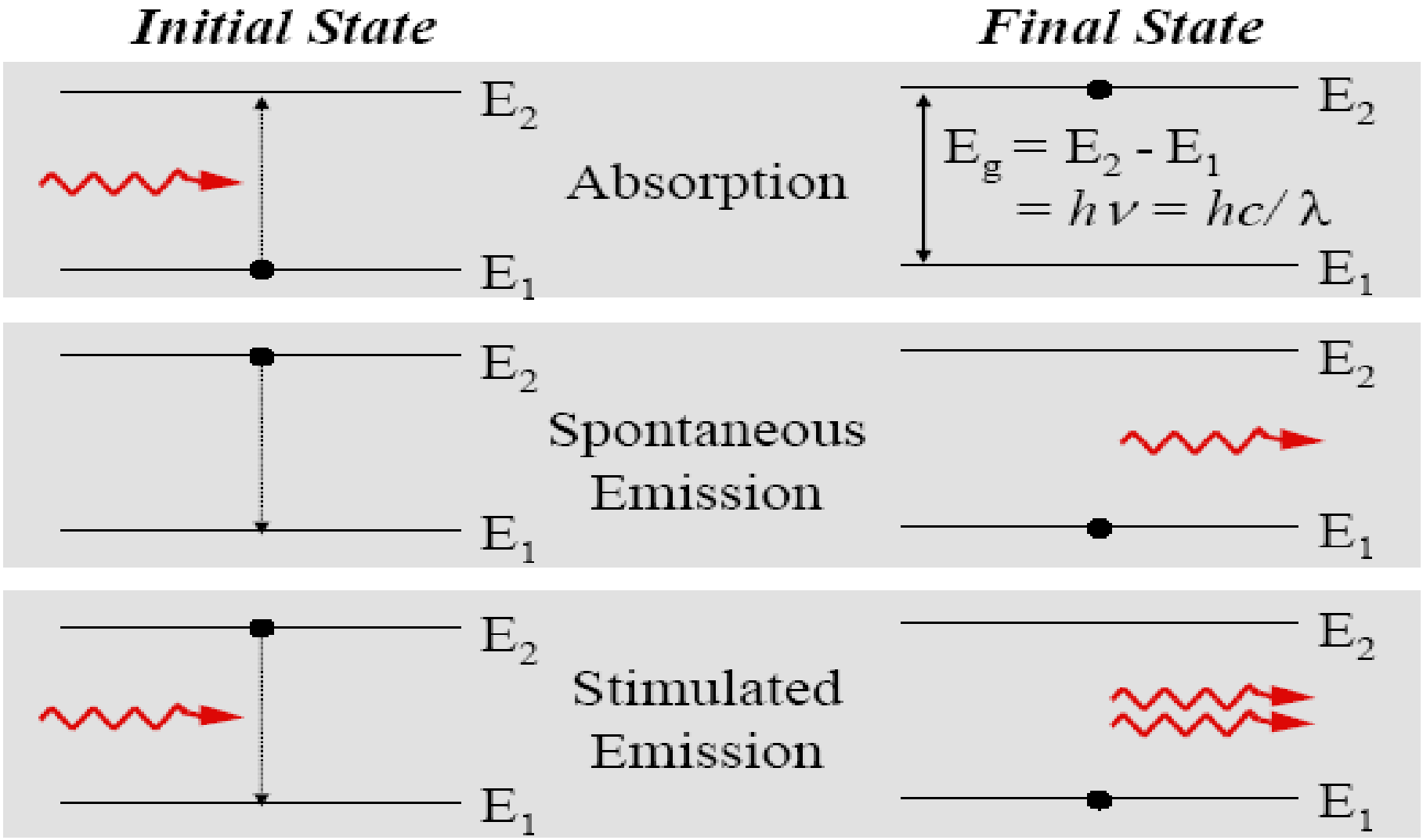
c = 3 x 10^{8} *m/s (velocity of light)*

Eg = Energy released by electron-hole recombination (approximately equal to the band gap energy)

E_2 = Higher Energy level (Excited State)

E_1 = Lower Energy Level (Ground State)

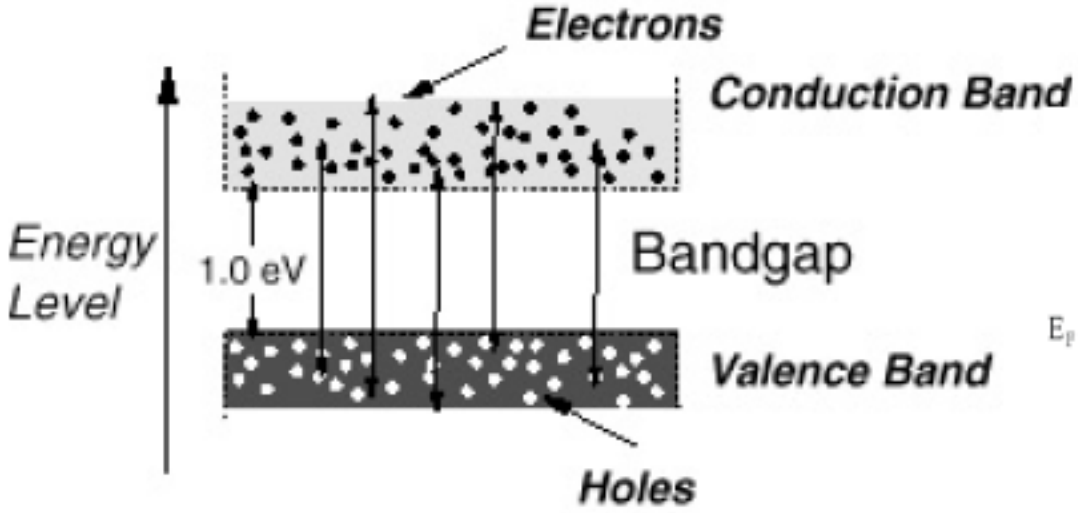
λ = *Optical Wavelength*

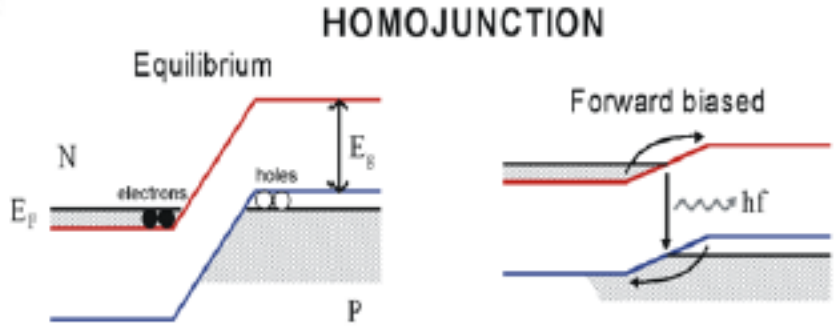


Energy state diagram showing: (a) absorption; (b) spontaneous emission; (c) stimulated emission. The black dot indicates the state of the atom before and after transition take place.

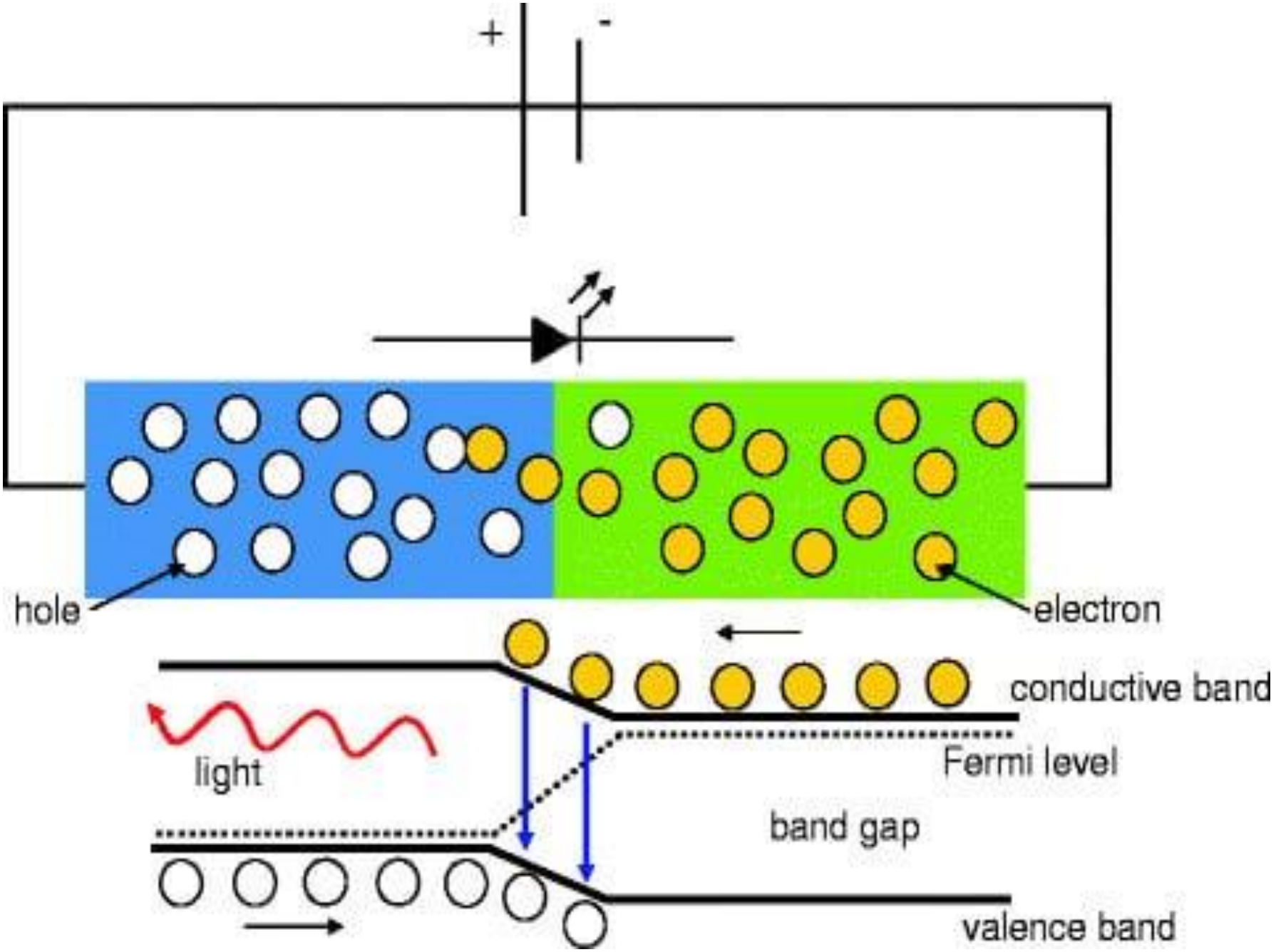
Basic LED operation

- A PN junction acts as the active or recombination region.
- When the PN junction is forward biased, electrons and holes recombine either radiatively (emitting photons) or non-radiatively (emitting heat). This is simple LED operation.

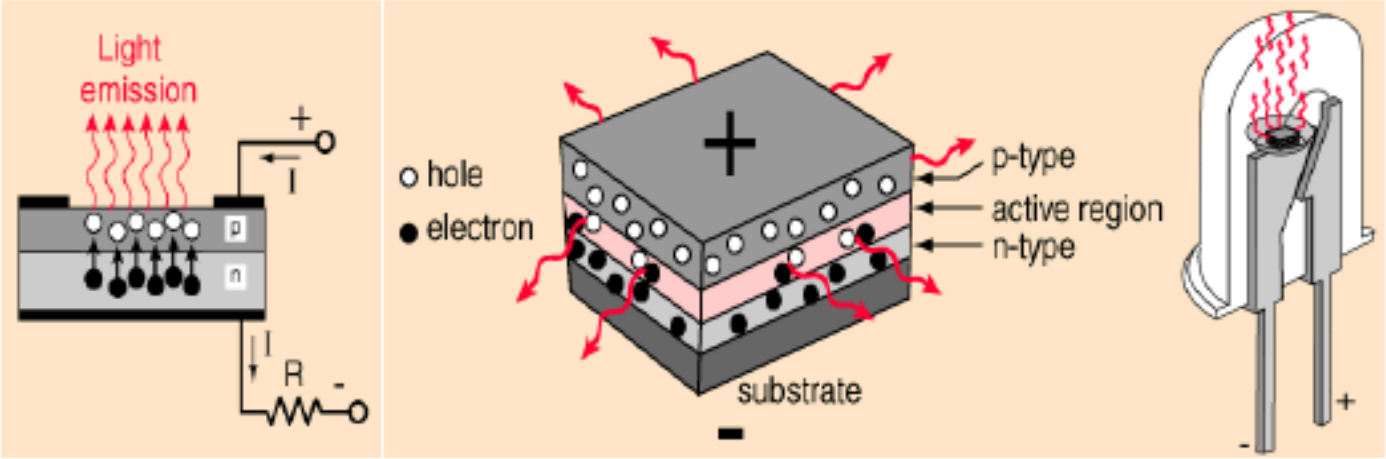


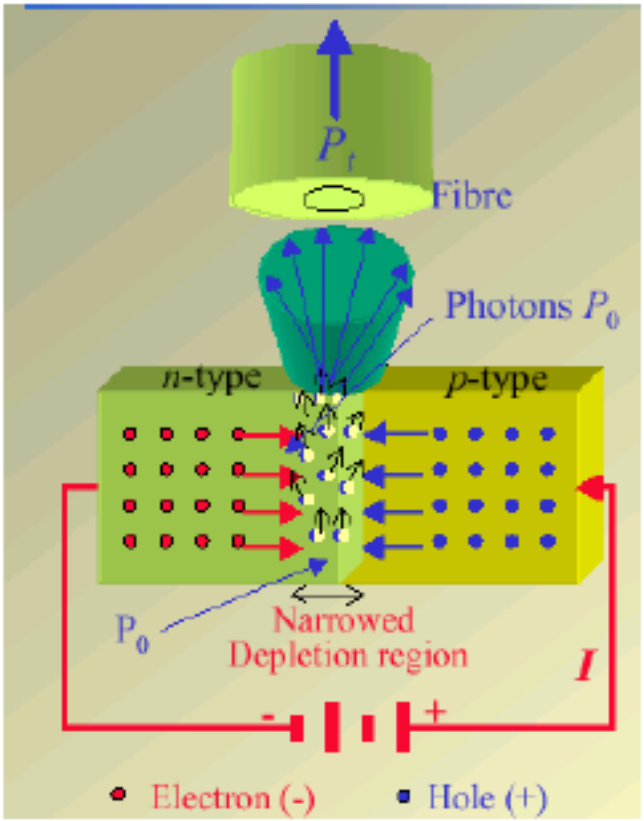


- Emitted wavelength depends on bandgap energy
- Transitions can take place from any energy state in either band to any state in the other band. This results in a range of different wavelengths produced in this spontaneous emission. This accounts for the fact that LEDs produce a range of wavelengths. Typically the range is about 80 nm or so.


+
-
hole
electron
conductive band
light
Fermi level
band gap
valence band

Working of LED





The main semiconductor materials used to manufacture LEDs :

- **Indium Gallium Nitride (InGaN):**

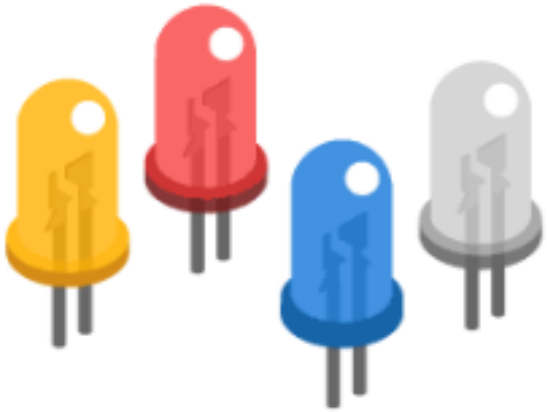
  Blue, Green and ultraviolet high-brightness LEDs.

- **Aluminum Gallium Indium Phosphide (AlGaInP):**

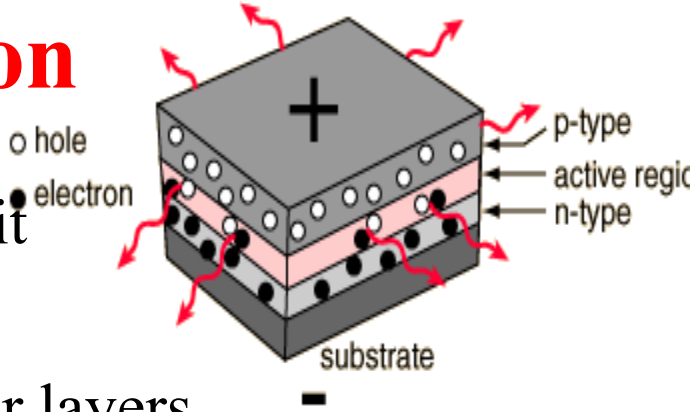
  Yellow, Orange and Red high-brightness LEDs.

- **Aluminum Gallium Arsenide (AlGaAs):**

  Red and infrared LEDs.



LED Construction



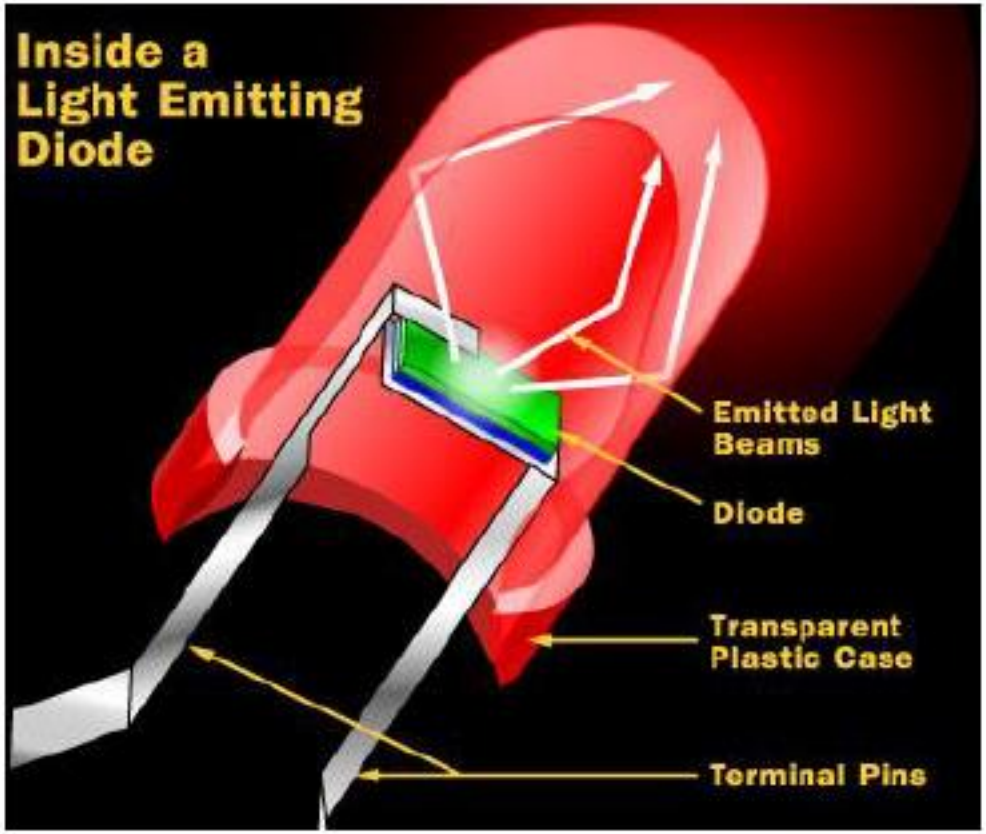
•One way to construct an LED is to deposit three semiconductor layers on a substrate.

•Between p-type and n-type semiconductor layers, an active region emits light when an electron and hole recombine.

•Considering the p-n combination to be a diode, then when the diode is forward biased, holes from the p-type material and electrons from the n-type material are both driven into the active region. The light is produced by a solid state process called electroluminescence.

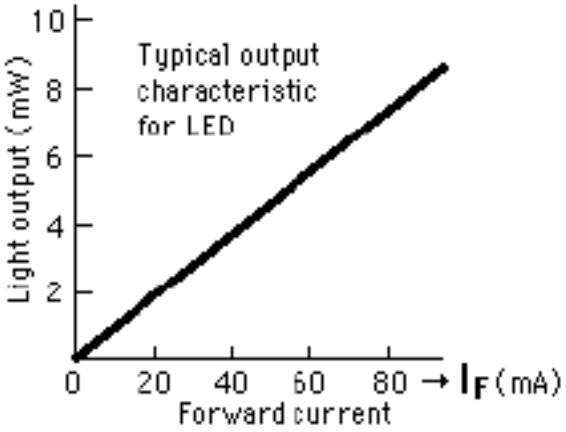
•In this particular design, the layers of the LED emit light all the way around the layered structure, and the LED structure is placed in a tiny reflective cup so that the light from the active layer will be reflected toward the desired exit direction.

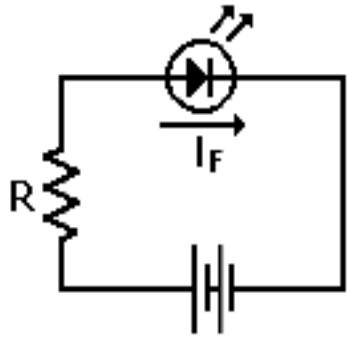
- Light is emitted at site of carrier recombination which is primarily close to the junction.
- However, the amount of radiative recombination and the emission area within the structure is dependent upon the semiconductor materials used and the fabrication of the device.

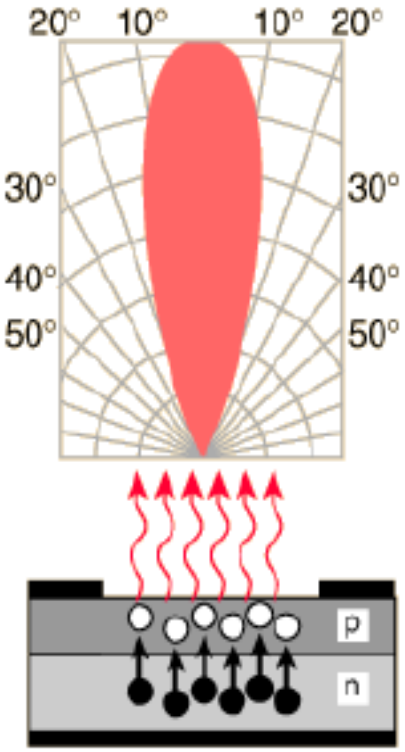


- Emits incoherent light through spontaneous emission.
- Used for Multimode systems with 100-200 Mb/s rates.
- Broad spectral width and wide output pattern.
- 850nm region: GaAs and AlGaAs
- 1300–1550nm region: InGaAsP and InP

LED Characteristics







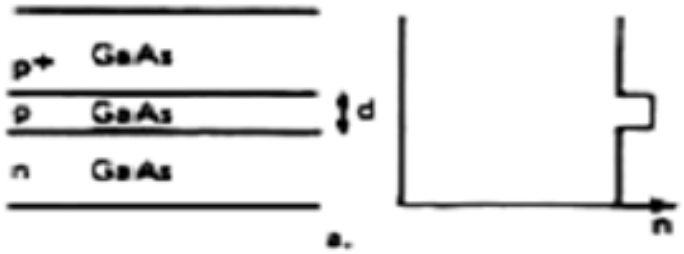
- LED is forward biased, its current increases rapidly and must be controlled to prevent destruction of the device.
- The light output is quite linearly proportional to the current, so it can be precisely modulated.
- Full Width Half Max, Peak Wavelength, Forward current, Rise time, Luminous intensity (Flux(lm)), LED radiation pattern

Advantages of LED

- Cost: Simple construction of LED leads to much reduced cost
- Reliability : The LED does not exhibit catastrophic degradation & has proved far less sensitive to gradual degradation, it is also immune to self pulsation & modal noise problems.
- Simpler drive circuitry: This is due to lower drive currents and reduced temperature dependence
- Linearity: Ideally LED has linear light output against current
- Less temperature dependence: Light output against current is less affected by temperature

- **Homojunctions**: P- type and N-type from same material

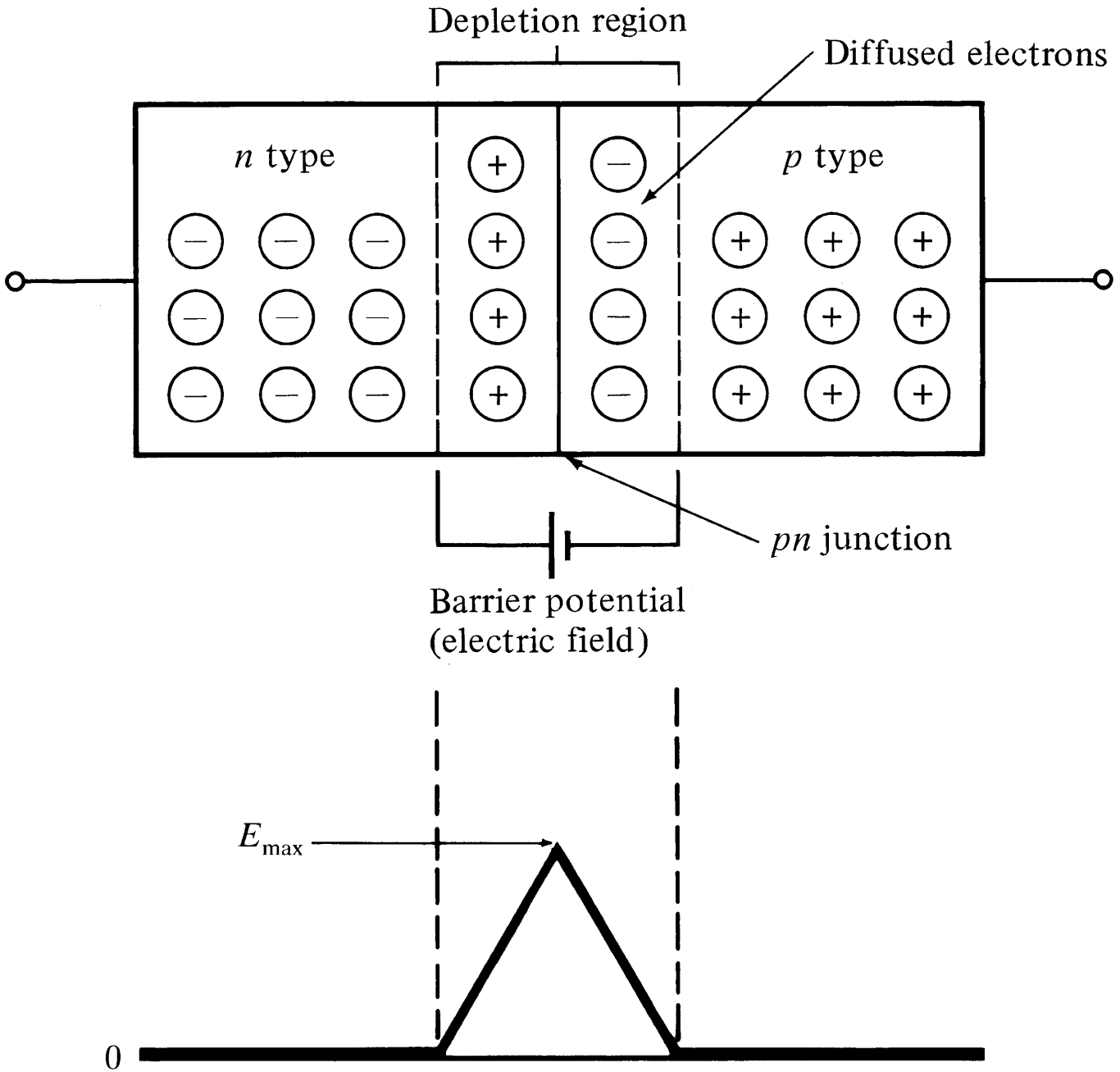




- Carriers are not confined
- Light is not confined

Structure and index of refraction n in gallium arsenide with a junction width d

- LED should have a high radiance (light intensity), fast response time and a high quantum efficiency for FO system

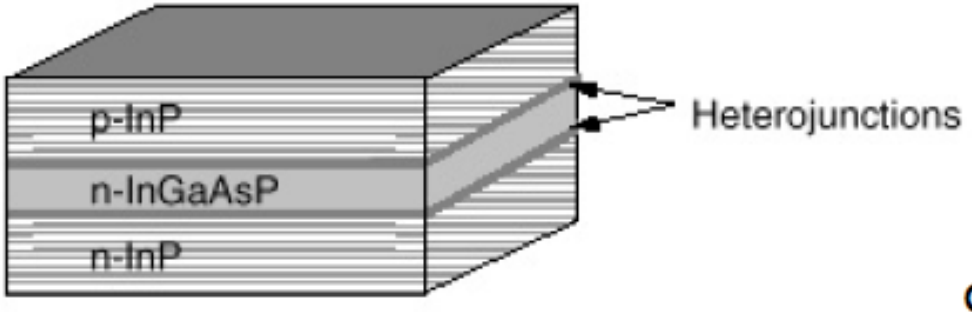

Depletion region
Diffused electrons
n type
p type
pn junction
Barrier potential
(electric field)
E_{max}
0

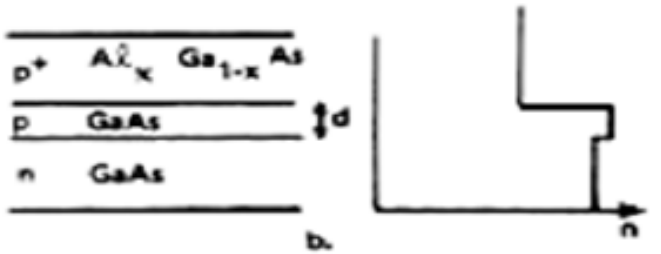
Heterojunctions: Different p- and n- materials

- Carriers are confined
- Light is also confined
- Single Heterojunction, Double Heterojunction.

- A heterojunction is a junction between two different semiconductors with different bandgap energies.

- The difference in bandgap energies creates a one-way barrier. Charge carriers (electrons or holes) are attracted over the barrier from the material of higher bandgap energy to the one of lower bandgap energy.



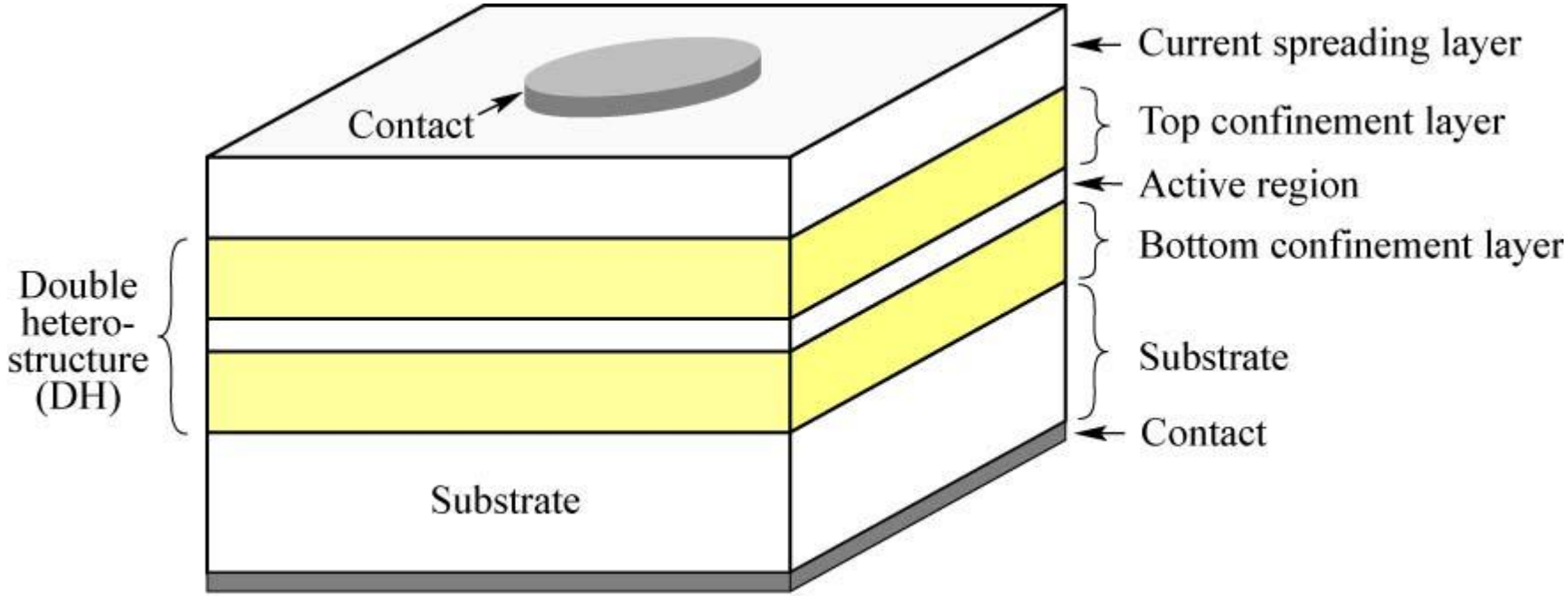


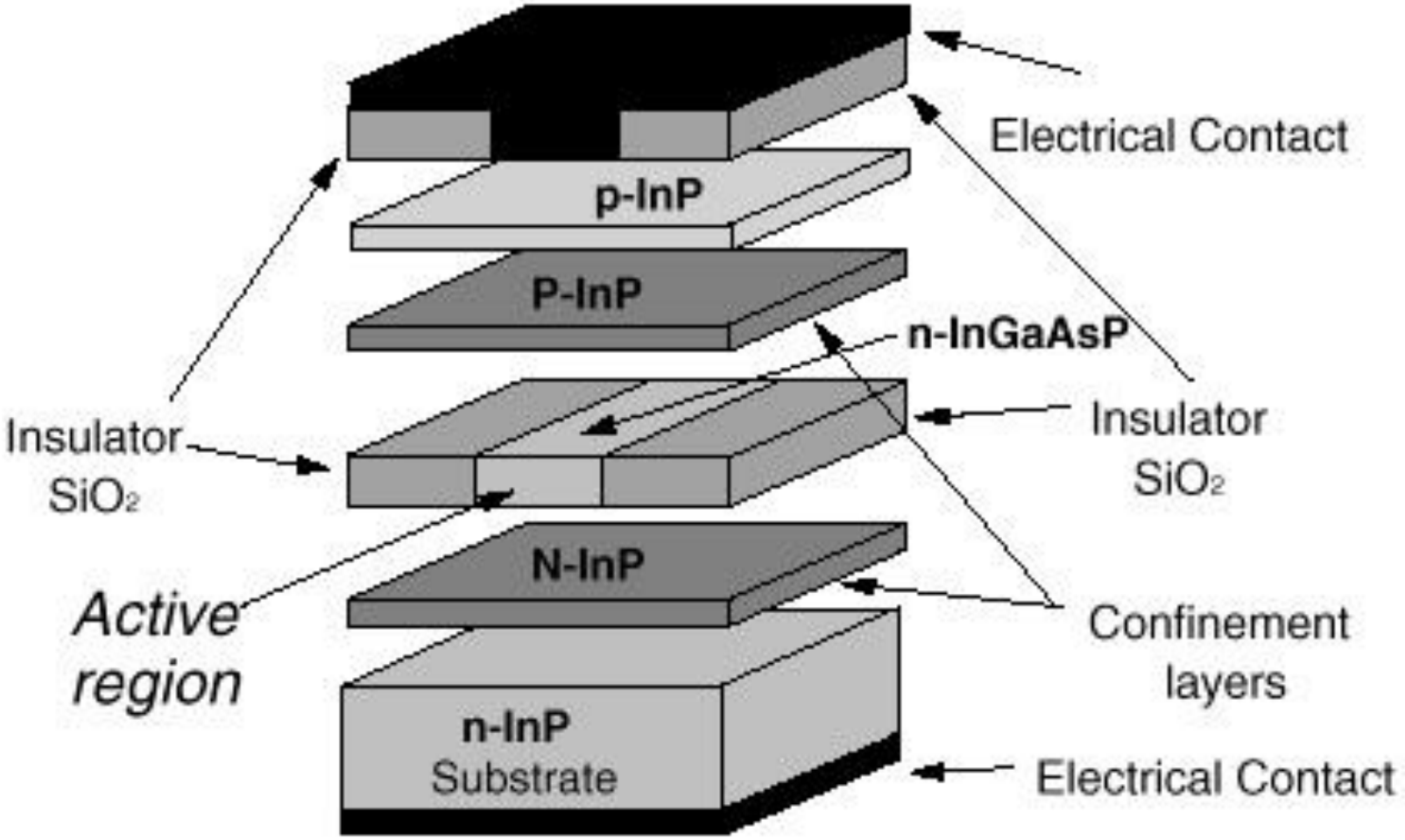
Gallium Arsenide-Aluminum Gallium Arsenide single heterojunction

Double Heterojunction

- When a layer of material with a lower bandgap energy is sandwiched between layers of material with a higher energy bandgap a *double heterojunction* is formed. This is called a double heterojunction because there are two heterojunctions present - one on each side of the active material.

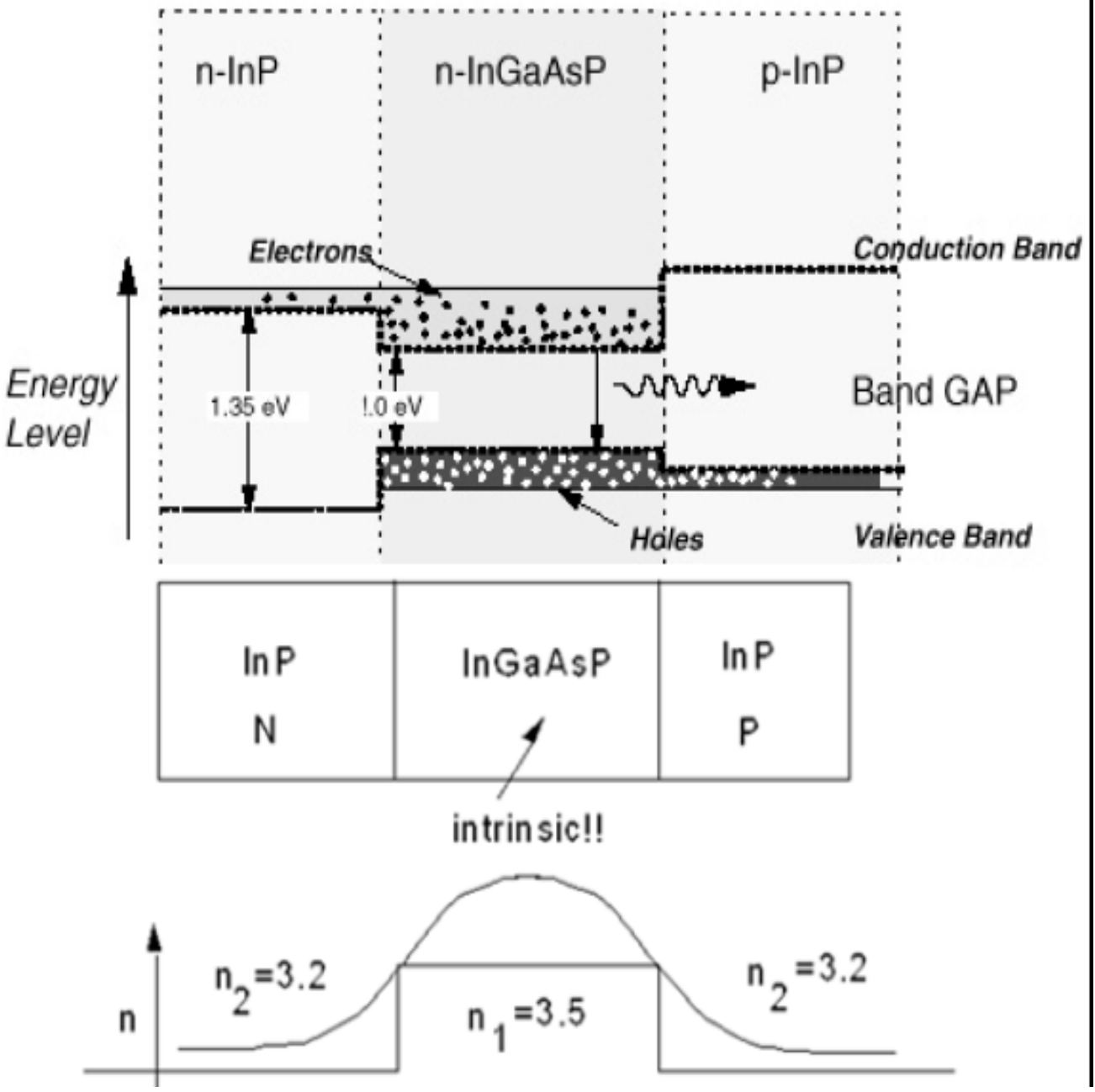
- The double heterojunction forms a barrier which restricts the region of electron-hole recombination to the lower bandgap material. This region is then called the "active" region

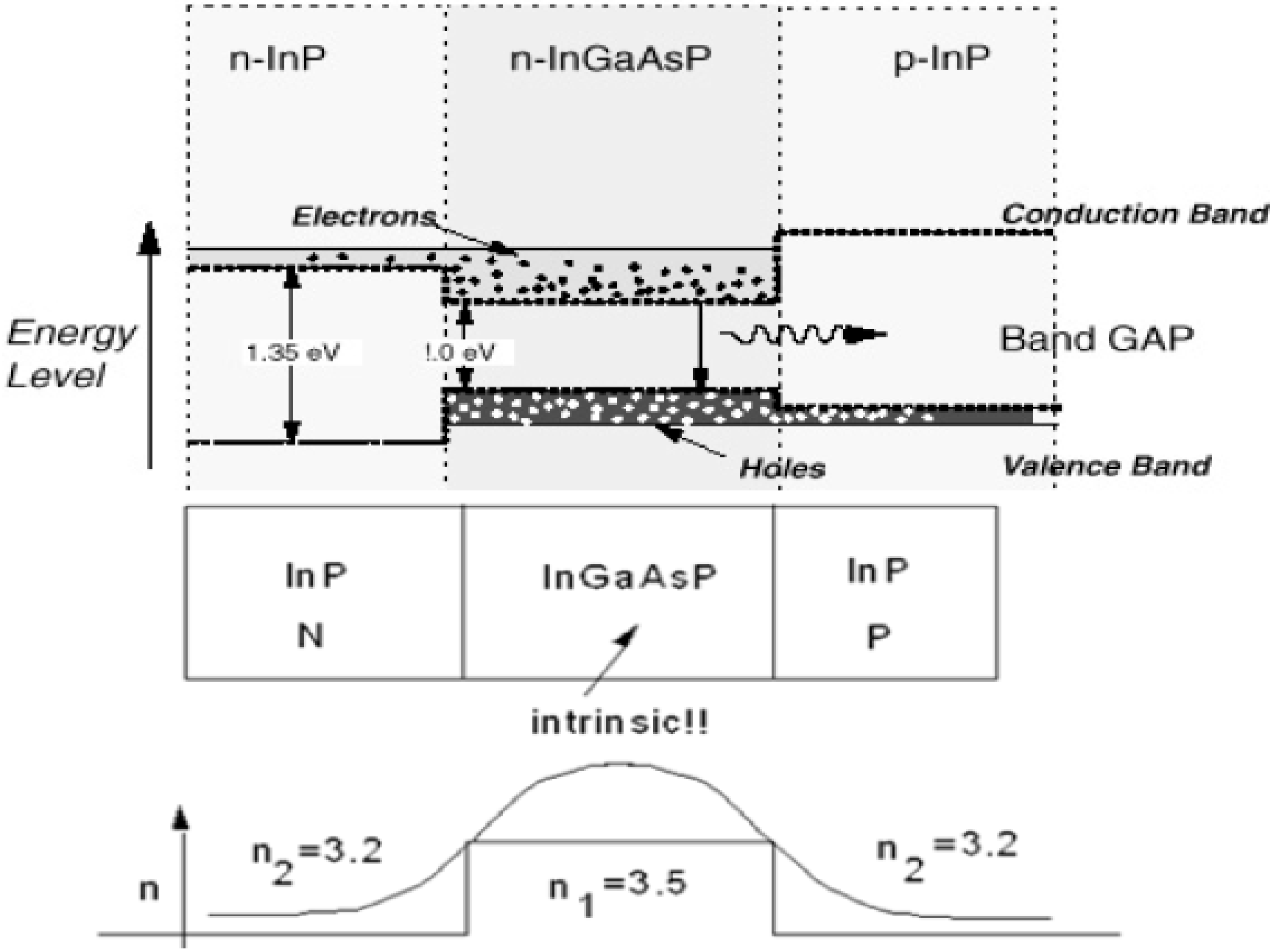



Electrical Contact
p-InP
P-InP
n-InGaAsP
Insulator
SiO2
Insulator
SiO2
N-InP
Active
region
Confinement
layers
n-InP
Substrate
Electrical Contact

Double Heterojunction

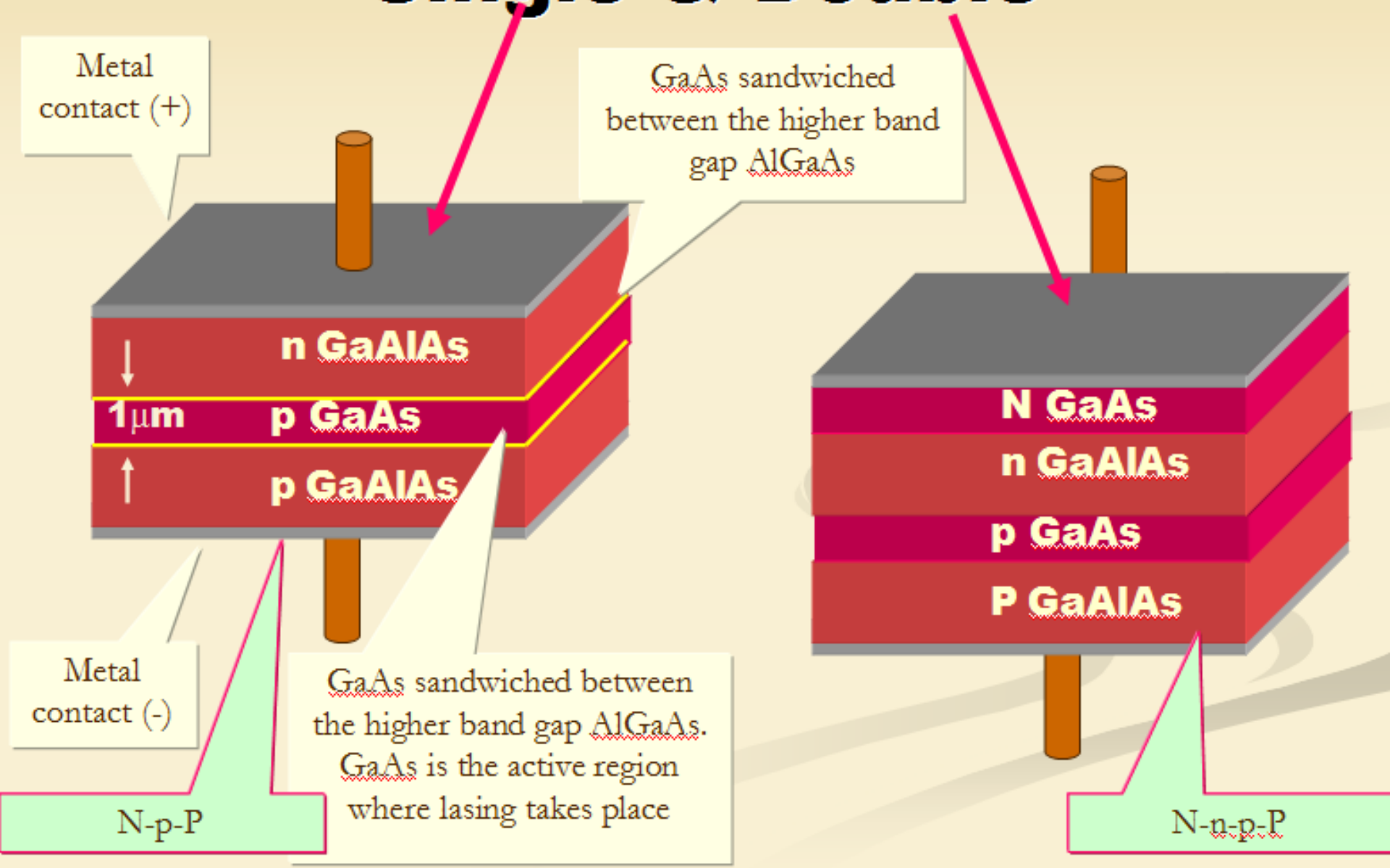
- The valence band of n-InGaAsP is at a higher energy than the valence band of the adjacent n-InP. The conduction band is at a lower energy level.
- p-InP has higher energy levels than n-InP but the bandgap is the same




n-InP
n-InGaAsP
p-InP
Electrons
Conduction Band
Energy Level
1.35 eV
!.0 eV
Band GAP
Holes
Valence Band
InP
N
InGaAsP
InP
P
intrinsic!!
n
n_2=3.2
n_1=3.5
n_2=3.2

- Electrons are attracted across the left-hand junction from the n-InP to n-InGaAsP.
- Holes are attracted across the right-hand junction from the p-InP into the n-InGaAsP.
- Recombination takes place in the n-InGaAsP and spontaneous emission occurs.
- The heterojunction allows to have a small active region where the light is produced.
- The material in the active region has a higher refractive index than that of the material surrounding it. This means that a mirror surface effect is created at the junction which helps to confine and direct the light emitted.

The Heterojunction Laser Single & Double



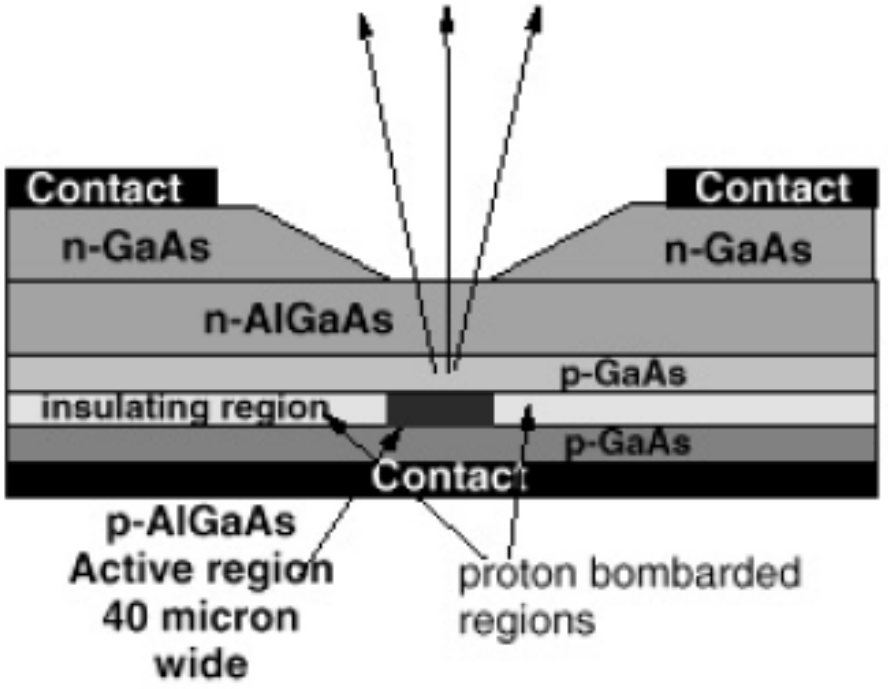
TYPES OF LED STRUCTURES

- Surface Emitting LED (S-LED) ;
- Edge Emitting LED (E-LED) .

Surface Emitting LED (SLED)

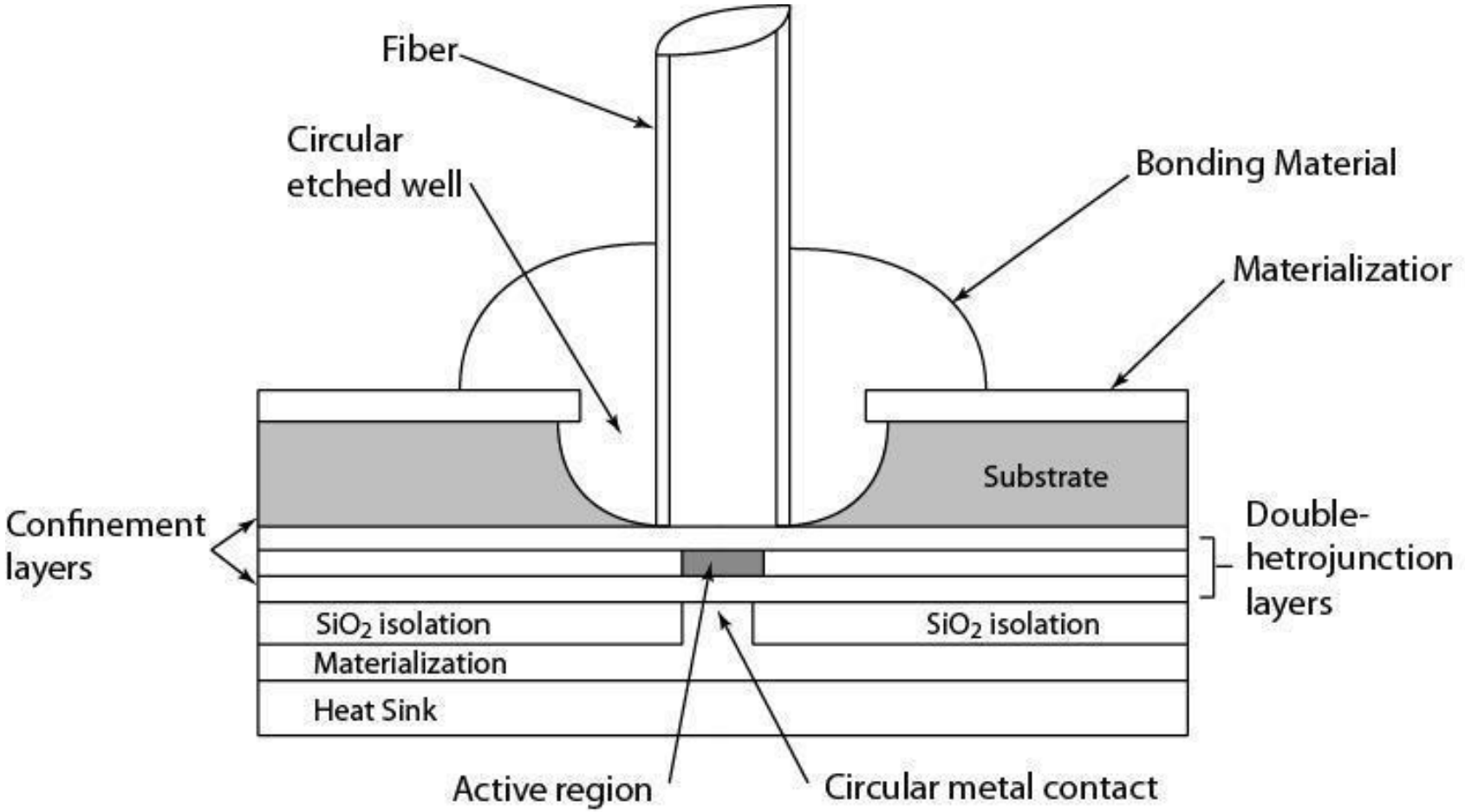
- Method for obtaining high radiance is to restrict the emission to a small active region within the device – Burrus & Dawson (1970)

- Power coupled into the fiber is dependent on many factors; *distance and alignment between emission area and fiber, emission pattern and interfacing medium*
  - More Power
  - Poor Radiance



- Coupling lens used to increase efficiency.
- Short optical Links with Large NA fibers.
- Data rates less than 20 Mbps.

S-LED Coupling with Fiber



The active region is limited to a circular section that has an area compatible with the fiber-core end face.

Surface Emitting LED

- The surface-emitting LED is also known as the Burrus LED in honor of C. A. Burrus, its developer.
- In SLEDs, the size of the primary active region is limited to a small circular area of 20micron to 50micron in diameter.
- The primary active region is below the surface of the semiconductor substrate perpendicular to the axis of the fiber.
- A well is etched into the substrate to allow direct coupling of the emitted light to the optical fiber. The etched well allows the optical fiber to come into close contact with the emitting surface.

Working of S-LED

- When the SLED is forward-biased, photons are generated in the p-GaAs layer.

- The emission from the top surface is ensured by the upper n+ AlGaAS and lower p+ AlGaAs layers of the hetero-structure.

- Therefore, radiance of the device in the forward direction is very high.

- Although the fiber is properly aligned to optimize the coupling of the emitted radiation with the fiber, there is some loss due to the Lambertian distribution of radiation intensity.

- Difference between refractive index of adjacent layers confines the optical power in the central GaAs.

Emission Pattern

- Emission pattern is isotropic with a 120^{o} half-power beam width.
- This isotropic pattern from the SLED is called a Lambertian pattern.
- Power distribution is described by $PD = P \cos \theta$
- Where θ is the angle between the direction of the observation and the line orthogonal to the radiating surface
- This implies that the source is equally bright when viewed from any direction but the power diminishes as $\cos \theta$.
- Thus the power is down to 50% of its peak when $\theta = 60^{o}$ so that half power beam width is 120^{o}

Edge Emitter LED (E-LED)

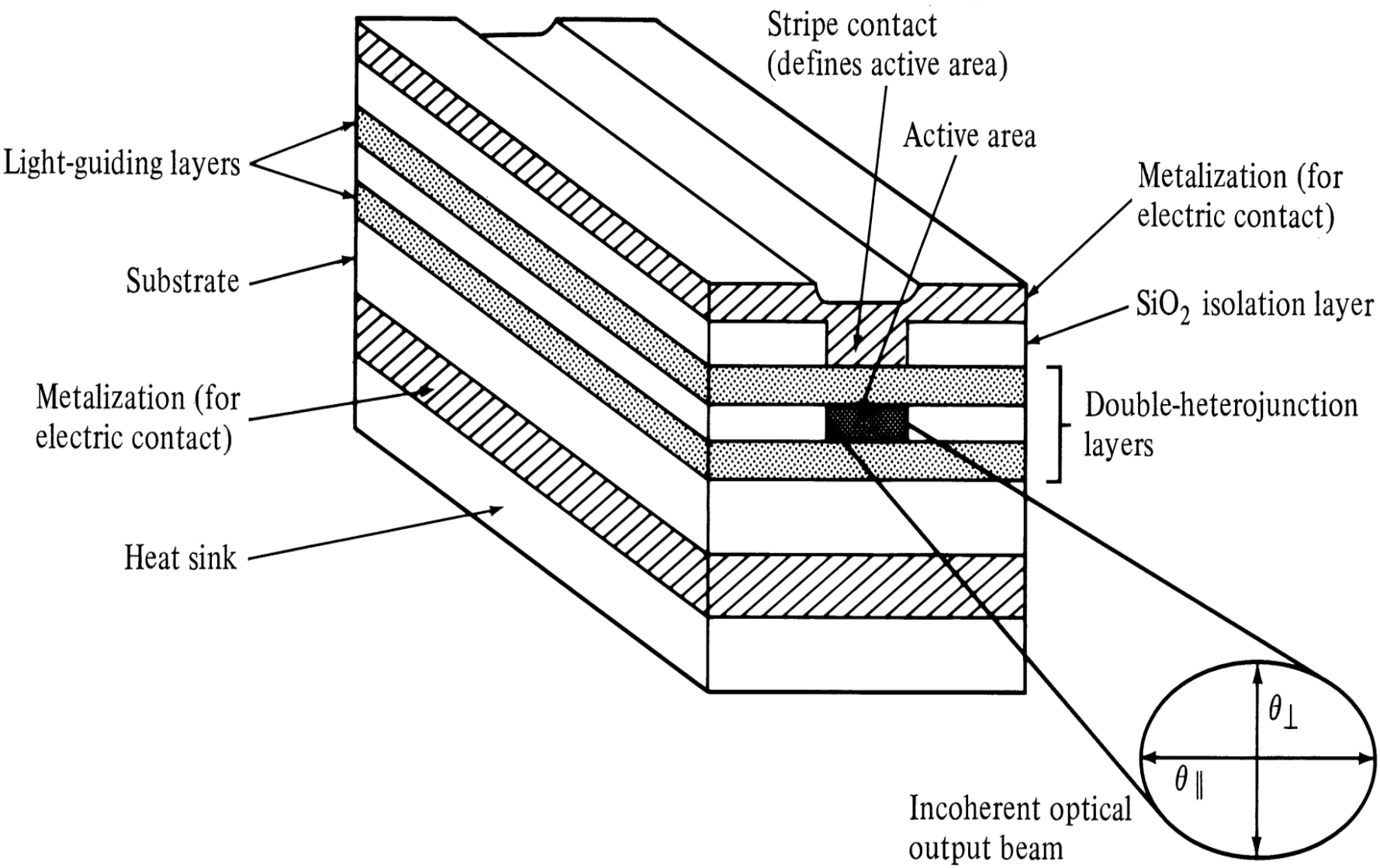
•The demand for optical sources for longer distance, & higher bandwidth system led to the development of edge-emitting LEDs.

• It shows the different layers of semiconductor material. The primary active region of the ELED is a narrow stripe, which lies below the surface of the semiconductor substrate.

•The semiconductor substrate is cut or polished so that the stripe runs between the front and back of the device.

•The polished or cut surfaces at each end of the stripe are called facets.

E-LED


Stripe contact
(defines active area)
Active area
Light-guiding layers
Metalization (for
electric contact)
Substrate
SiO_2 isolation layer
Metalization (for
electric contact)
Double-heterojunction
layers
Heat sink
$\theta_\perp$
$\theta_\parallel$
Incoherent optical
output beam

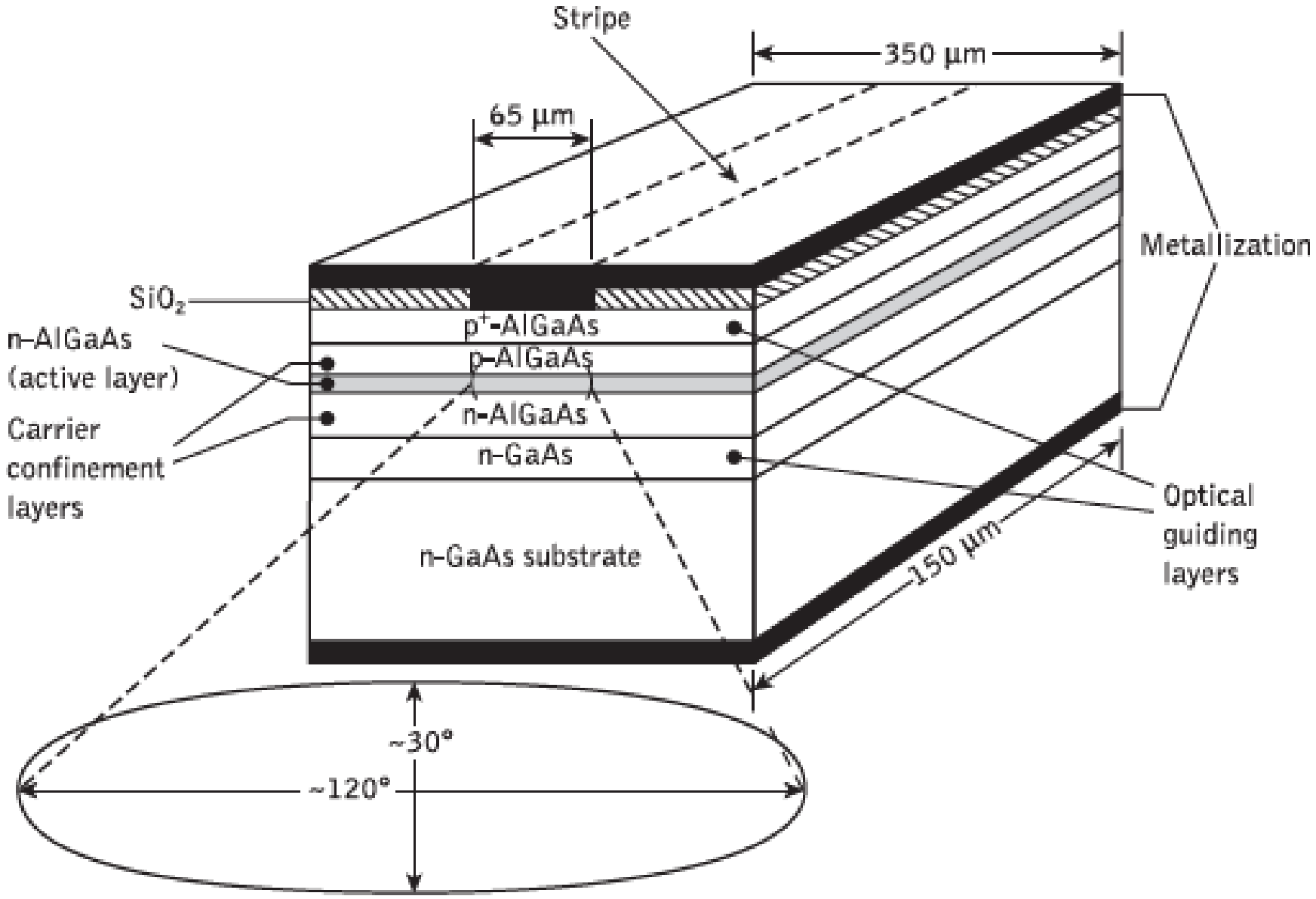


Figure 7.7 Schematic Illustration of the structure of a stripe geometry DH AlGaAs edge-emitting LED

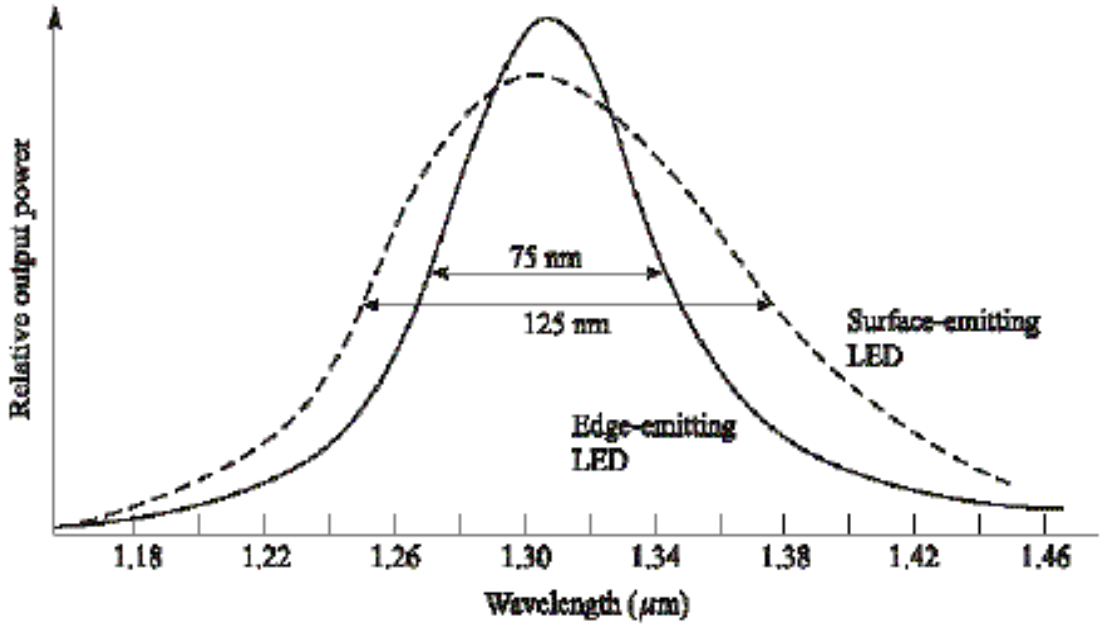
Working of E-LED

- In an ELED the rear facet is highly reflective and the front facet is antireflection-coated.
- The rear facet reflects the light propagating toward the rear end-face back toward the front facet.
- By coating the front facet with antireflection material, the front facet reduces optical feedback and allows light emission.
- ELEDs emit light only through the front facet & in a narrow emission angle allowing for better source-to-fiber coupling.
- Edge-emitting double-heterojunction LED. The output be a mislambertian in the plane of the pn-junction and highly directional perpendicular to the pn-junction.

Edge-emitting LED

- Have advantage of transparent guiding layers with a very thin active layer (50 to 100μm). This reduces self absorption and narrows the beam divergence.
- Light is emitted at one end face only.
- Couple more power to small NA fibers
- Higher data rates>100Mbps, better modulation
- Multimode and Single Mode fibers
- ELEDs provide narrower linewidth than SLED
- High radiance

Spectral Linewidth

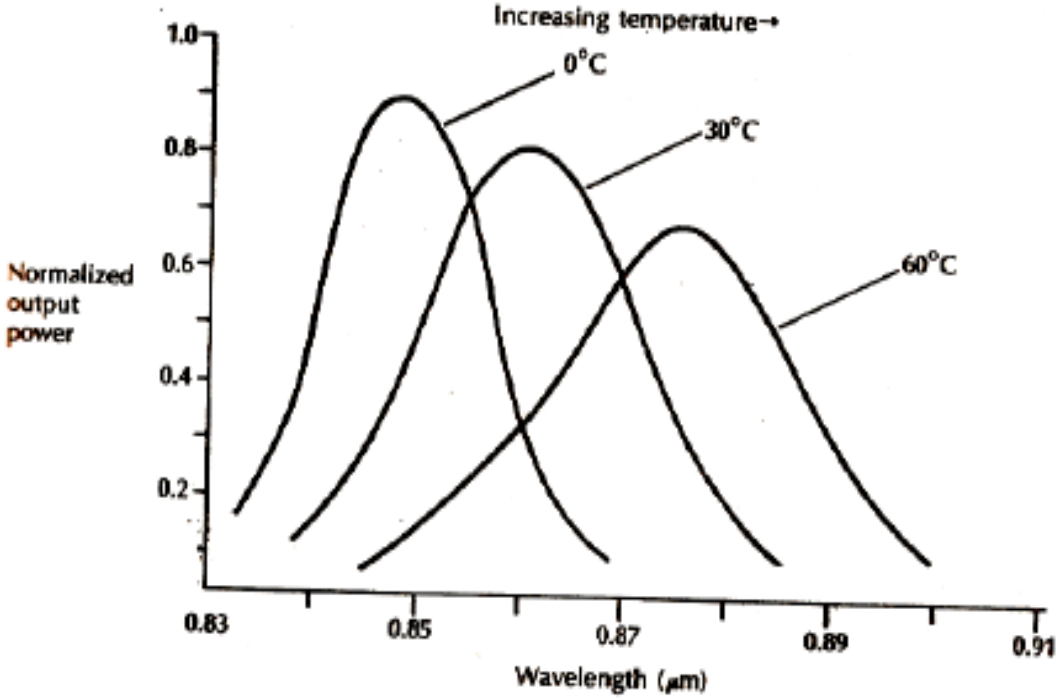


Typical spectral patterns for edge- and surface-emitting LEDs at 1310 nm.

- FWHM about 1.6 times smaller for ELED than SLED.
- Further narrowed by the Superluminescent operation; linewidth far smaller ≅ 30 nm
- The patterns broaden with increasing wavelength and are wider for surface emitters.

Temperature dependence

- Spectra tend to broaden with increase in temperature due to greater energy spread in carrier distributions at higher temperatures.
- Increase in temperature affect the peak emission wavelength as well.



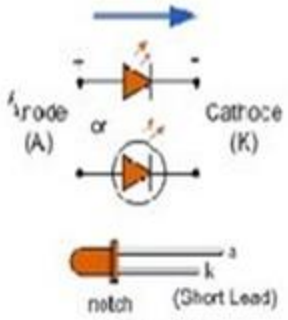
Spectral variation with temperature for AlGaAs SLED

SR. No.	SLED	ELED
1.	Easy to fabricate	Difficult to fabricate
2.	Easy to mount and handle	Difficult to mount and handle
3.	Require less critical tolerances	Need critical tolerance on fabrication
4.	Less Reliable	Highly reliable
5.	Low system performance	High system performance
6.	Less modulation Bandwidth	Better Modulation, Bandwidth of the order of hundreds of MHz
7.	Couple less optical power into low NA fiber	Couple more optical power into low NA fiber
8.	Light is emitted from the surface of active Layer	Light is emitted from edge of active Layer
9.	Wider spectral width	Narrow spectral width
10.	Maximum quantum efficiency is up to 60%	Internal quantum efficiency is in the range of 60% to 80%

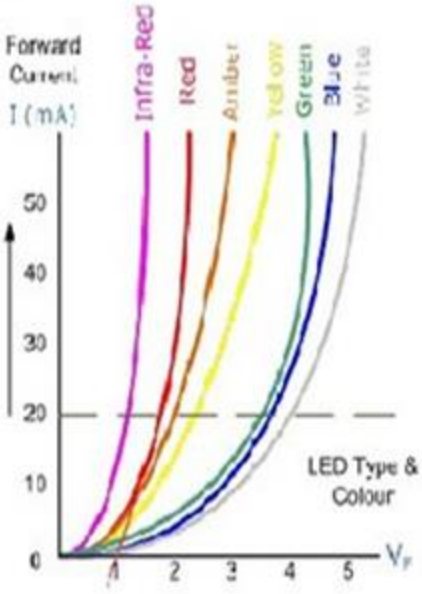
LED

- Inorganic semi-conductor junction
- AC rectifier character due to PN junction
- Excitons (e^--holes) are delocalised in the crystal: Energy bands
- Electrical mobility decreases with temperature
- Doping is necessary for getting free carriers
- Hetero-structures are limited due to crystal mesh mismatch
- Almost monochromatic emission linked to the energy gap





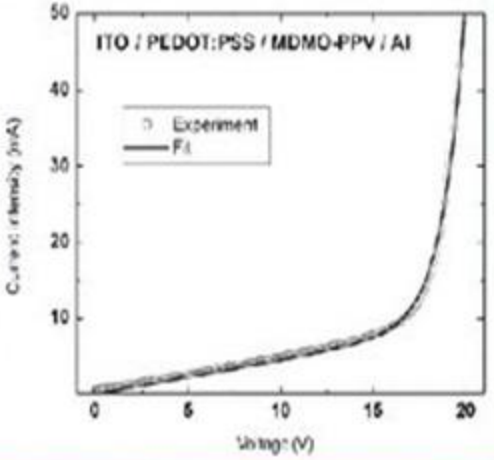
LED and its
I-V Characteristics



OLED

- Organic semi-conductor stack
- AC rectifier character due to work function difference between the two electrodes used for the carrier injection
- Excitons (e^--holes) are localized to single molecule
- Electrical mobility increases with temperature but stays very low
- Doping is not necessary for getting free carriers: they are injected from electrodes
- Structures choices are almost unlimited
- Large emission covering visible spectrum (molecular bands, mixing…)





UNIT II
OPTICAL SOURCE & DETECTORS

:Dr. Sanket B. Kasturiwala

Unit 2.2

Optical Source :

LASER

OPTICAL SOURCES

- The optical source is often considered to be the active component in an optical fiber communication system.

- Its fundamental function is to convert electrical energy in the form of current into optical energy(light) in an efficient manner.

- The light output should be effectively launched or coupled into the optical fiber.

The optical sources can be mainly divided into three categories:-

- Wideband ‘continuous spectra’ sources
  (Incandescent lamps)
- Monochromatic incoherent sources
  (LEDs)
- Monochromatic coherent sources
  (Lasers)

Monochromatic coherent sources

- Incoherent sources were not feasible for long distance communications
- Coherent sources include LASER which is widely used for long distance communication
- Generally used with single mode fibers as they provide low dispersion

Two energy bands :

- Conduction band (CB)
- Valence band (VB)

Fundamental processes

- Absorbed photon creates an electron-hole pair
-Recombination of an electron and hole can emit a photon.

Types of photon emission :

- Spontaneous emission

- Random recombination of an electron-hole pair
- Dominant emission for light emitting diodes (LED)

- Stimulated emission

- A photon excites another electron and hole to recombine
- Emitted photon has similar wavelength, direction, and phase.
- Dominant emission for laser diodes

- Mathematically-

$$E_g = E_2 - E_1$$

$$\lambda = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)}(\mu m)$$

h = 6.636 x 10^{-34} *J s (Plank's constant)*

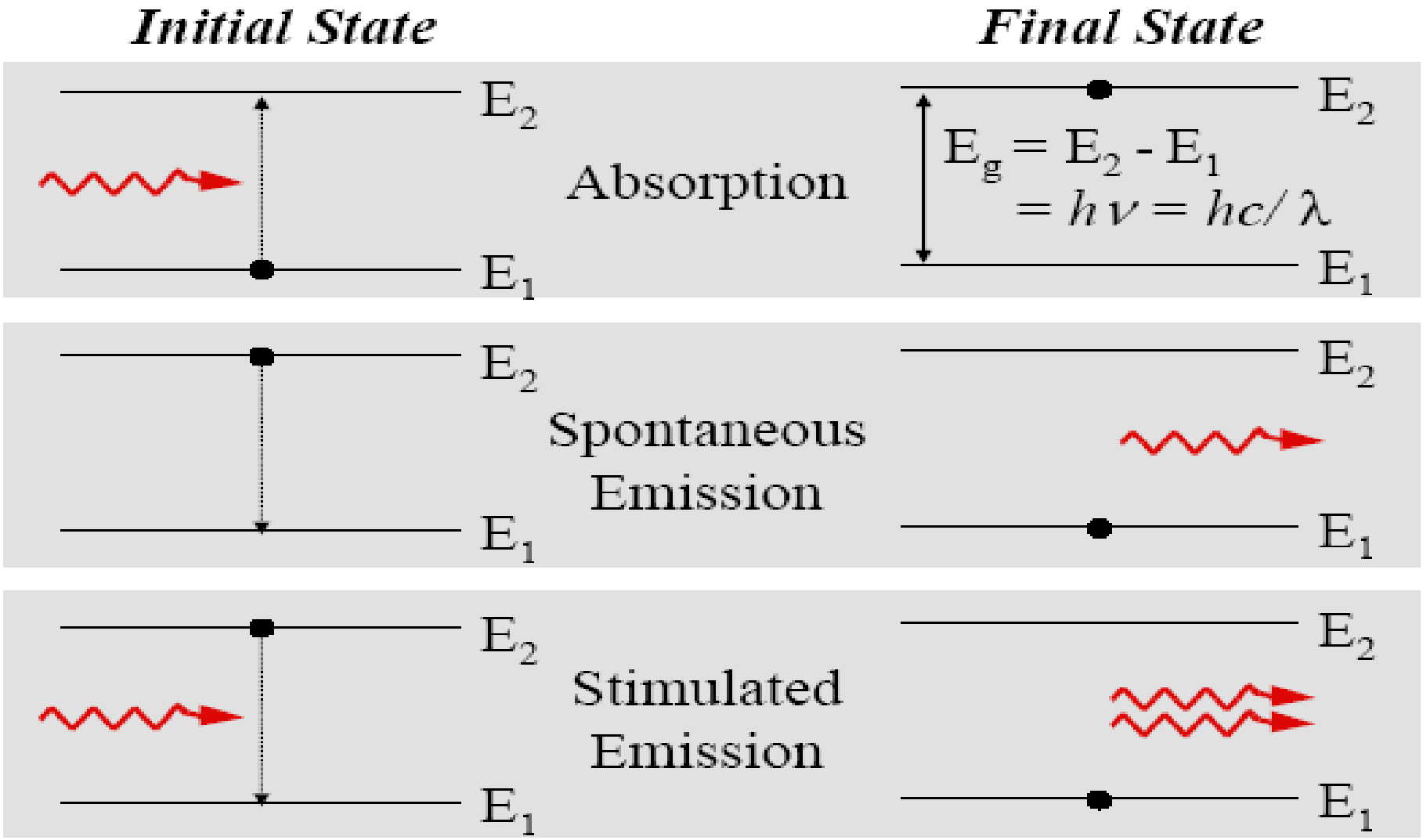
c = 3 x 10^{8} *m/s (velocity of light)*

Eg = Energy released by electron-hole recombination (approximately equal to the band gap energy)

E_2 = Higher Energy level (Excited State)

E_1 = Lower Energy Level (Ground State)

λ = *Optical Wavelength*



Energy state diagram showing: (a) absorption; (b) spontaneous emission; (c) stimulated emission. The black dot indicates the state of the atom before and after transition take place.

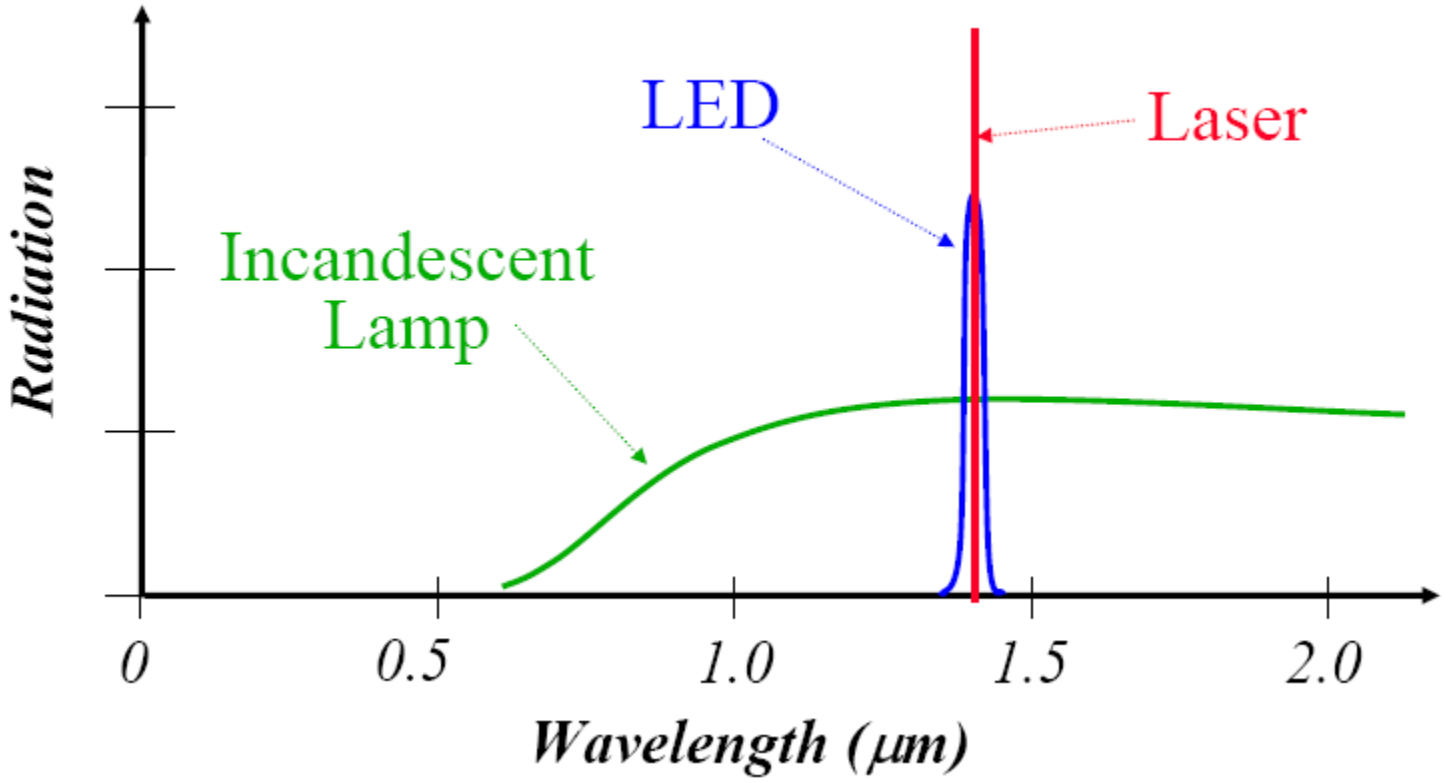
Monochromatic Coherent Sources

LASERS – Light Amplification by Stimulated Emission Radiation.

Principle : Stimulated Emission Radiation.

- Generate highly directional optical beams;
- Modulated by very high rate (beyond 10GHz);
- Produces coherent light source;

SPECTRAL WIDTH



Principles of LASER Action

- It is the stimulated emission process.
- The photon produced by stimulated emission is generally of an identical energy to the one and hence the light associated with them is the same frequency – Monochromatic.
- The light associated with the stimulating and stimulated photon is in phase and has a same polarization – Coherent.
- When an atom is stimulated to emit light energy by an incident wave, the liberated energy can add to the wave in constructive manner, providing amplification.
- Therefore, in contrast to spontaneous emission, coherent radiation is obtained.

In Stimulated Emission incident and stimulated photons will have

- Identical energy → Identical wavelength → Narrow linewidth
- Identical direction → Narrow beam width
- Identical phase → Coherence and
- Identical polarization

Stimulated Emission

The general concept of stimulated emission is via population inversion and optical feedback.

Carrier population inversion is achieved in an intrinsic semiconductor by the injection of electrons into the conduction band of the material.

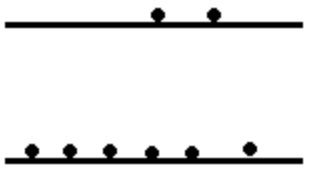
LASER requires:

* Population Inversion
* Optical feedback

Types: Gas laser, Semiconductor laser and Solid-state laser

Population Inversion

- Under the conditions of thermal equilibrium given by the Boltzmann distribution, the lower energy level E1 of the two-level atomic system contains more atoms than the upper energy level E2 (i.e. **N1>N2**)



- To achieve optical amplification, it is necessary to create a non-equilibrium distribution of atoms such that the population of the upper energy level is greater than that of the lower energy level (i.e. **N2 > N1**)
- This condition is known as **Population Inversion**

- Population inversion is achieved using '**Pumping**' technique which makes use of an external energy source.

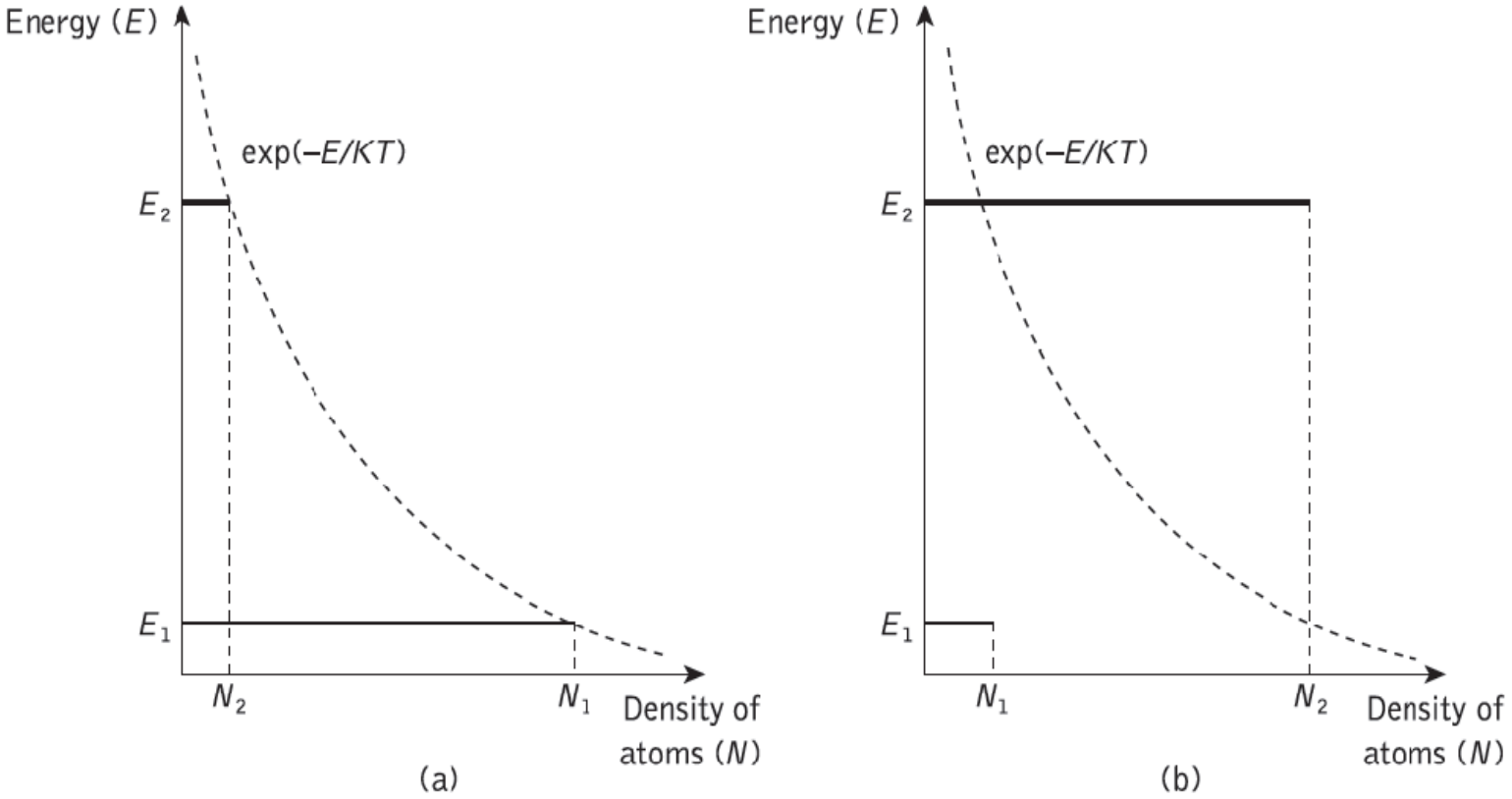


Figure 6.2 Populations in a two-energy-level system: (a) Boltzmann distribution for a system in thermal equilibrium; (b) a nonequilibrium distribution showing population inversion

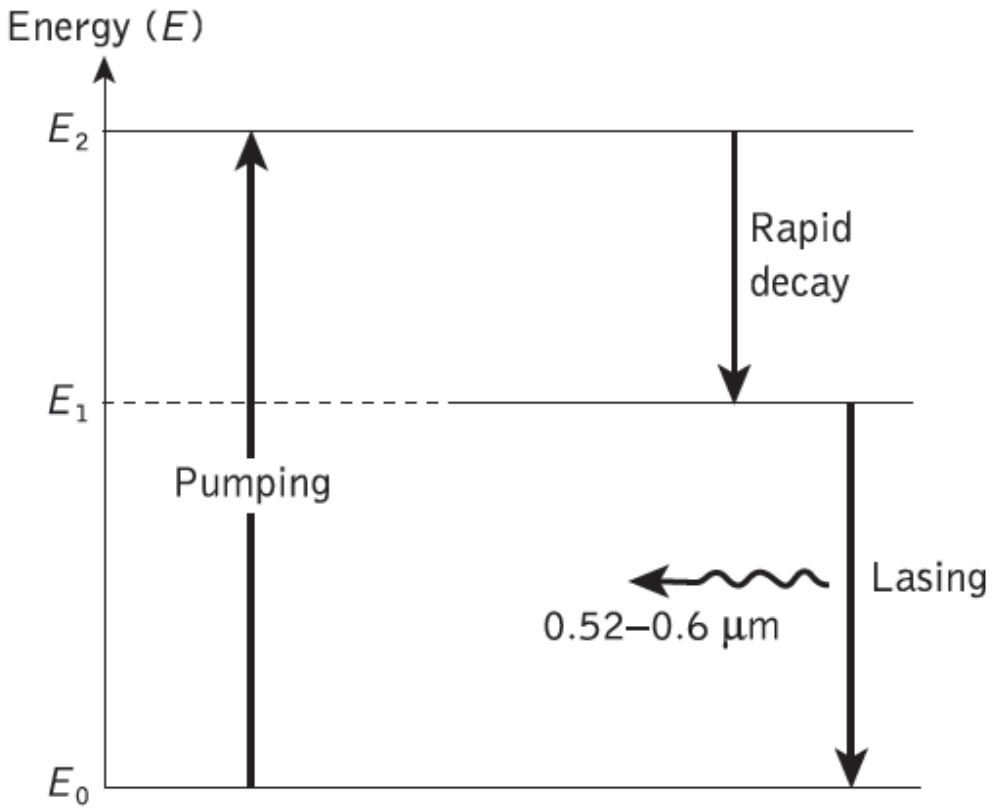


Fig a. Three-level system – ruby (crystal) laser

- Three levels
  - **E0** -ground level
  - **E1**-metastable level E1
  - **E2**- third level above the metastable level

- Initially, the atomic distribution follows Boltzmann's law

- Using pumping the electrons in some of the atoms may be excited from **E0--->E2**

- Since E2 is a normal level the electrons will rapidly decay by non-radiative processes to either E1 or directly to E0
  E2---> E1 E1---> E0.

- The metastable level **E1 exhibits a much longer lifetime than E2** which allows a large number of atoms to accumulate at E1
- Over a period the density of atoms in the metastable state N1 becomes greater than N0 **(N1>N0)**

- Stimulated emission causes and hence lasing can then occur, creating radioactive electron transitions between levels E1 and E0.

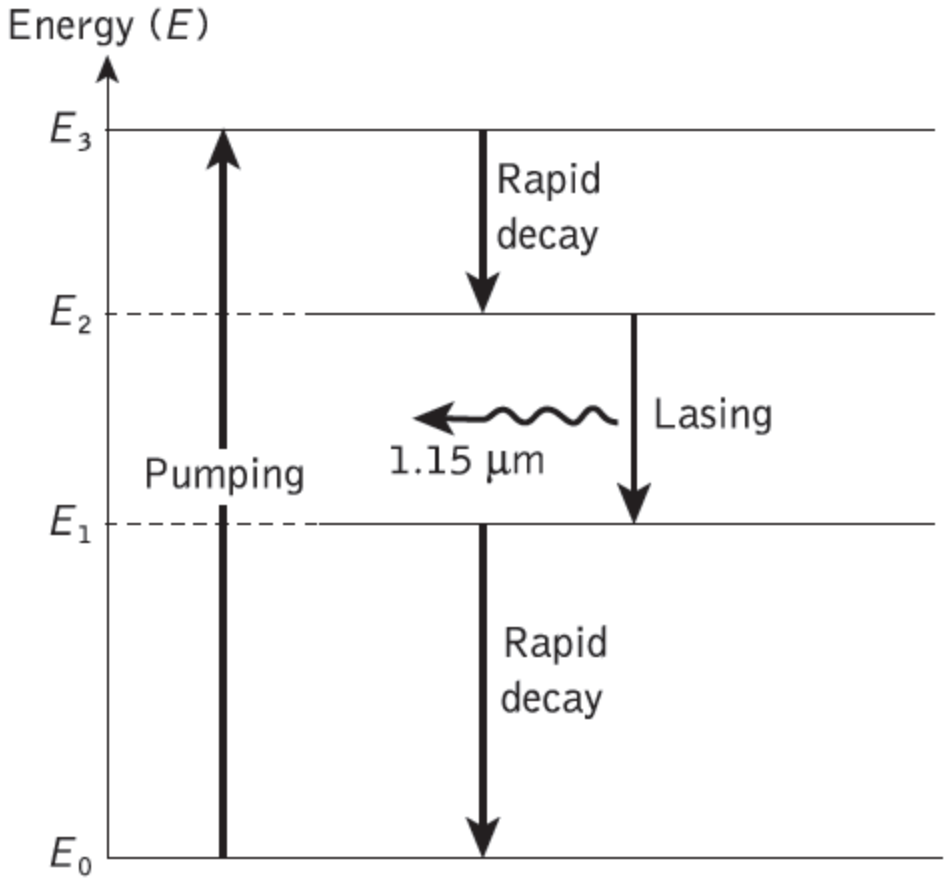


Fig (b) four-level system He–Ne (gas) laser

•**<u>Four level lasers</u>** is an improvement on a system based on three level systems

•The material is pumped to level E3, which is a fast decaying level

• The atoms decay rapidly to level E2, which is a metastable level

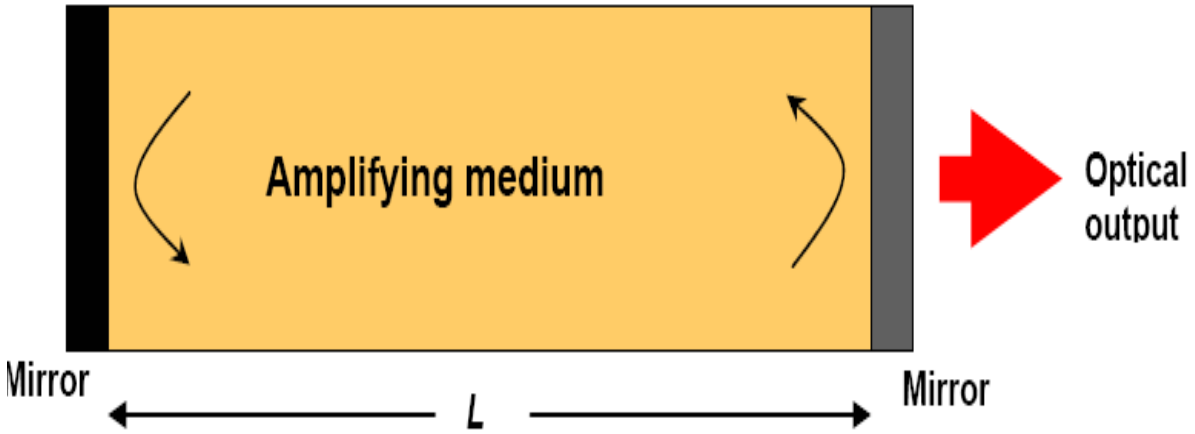
•The stimulated emission takes place from level E2 to level E1 from where the atoms decay back to level E0

•In this case, the laser transition takes place between the third and second excited states

•Since lower laser level E1 is a fast decaying level which ensures that it rapidly gets empty and as such always supports the population inversion condition

Optical Feedback

- Light amplification in laser occurs when a photon colliding with an atom in the excited energy state causes the stimulated emission of a second photon and then both these photons release two more.
- Continuation of this process effectively creates multiplication, and when the electromagnetic waves associated with these protons are in phase, amplified coherent emission is obtained.
- To achieve this laser action it is necessary to contain photons with the laser medium and maintain the conditions for coherence.
- This is accomplished by placing or forming mirrors at either end of the amplifying medium.
- Furthermore, if one mirror is made partially transmitting, useful radiation may escape from the cavity.



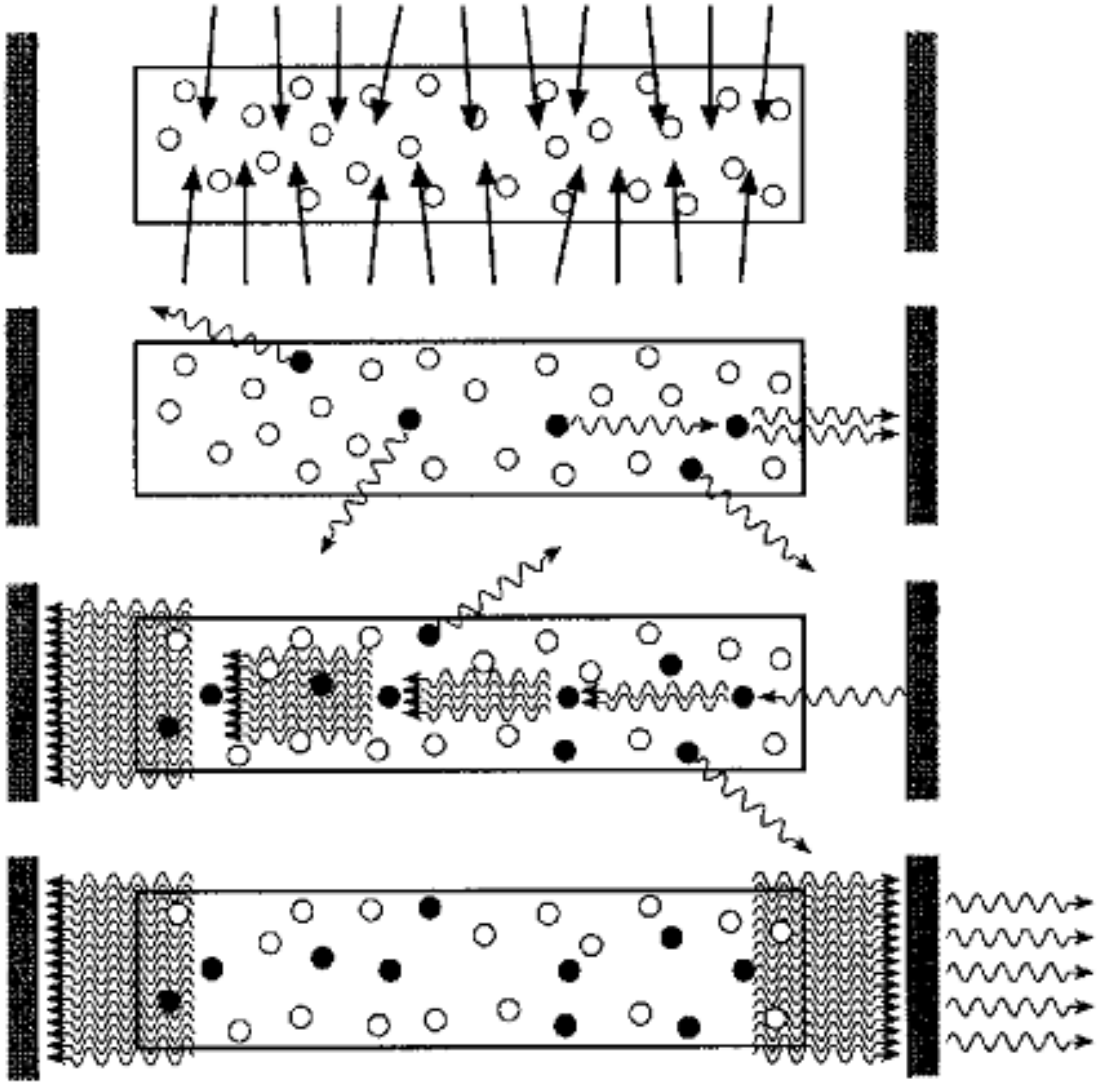
•The basic laser structure incorporating plane mirror.

•The optical signal is fed back many times whilst receiving amplification (stimulated emission) as it passes through the medium.

•One mirror is made partially transmitting to allow useful radiation escape from the cavity.

•The structure acts as a Fabry-Perot resonator, it is the combination of stimulated emission and feedback that gives a gain and a continuous output.

How a Laser Works

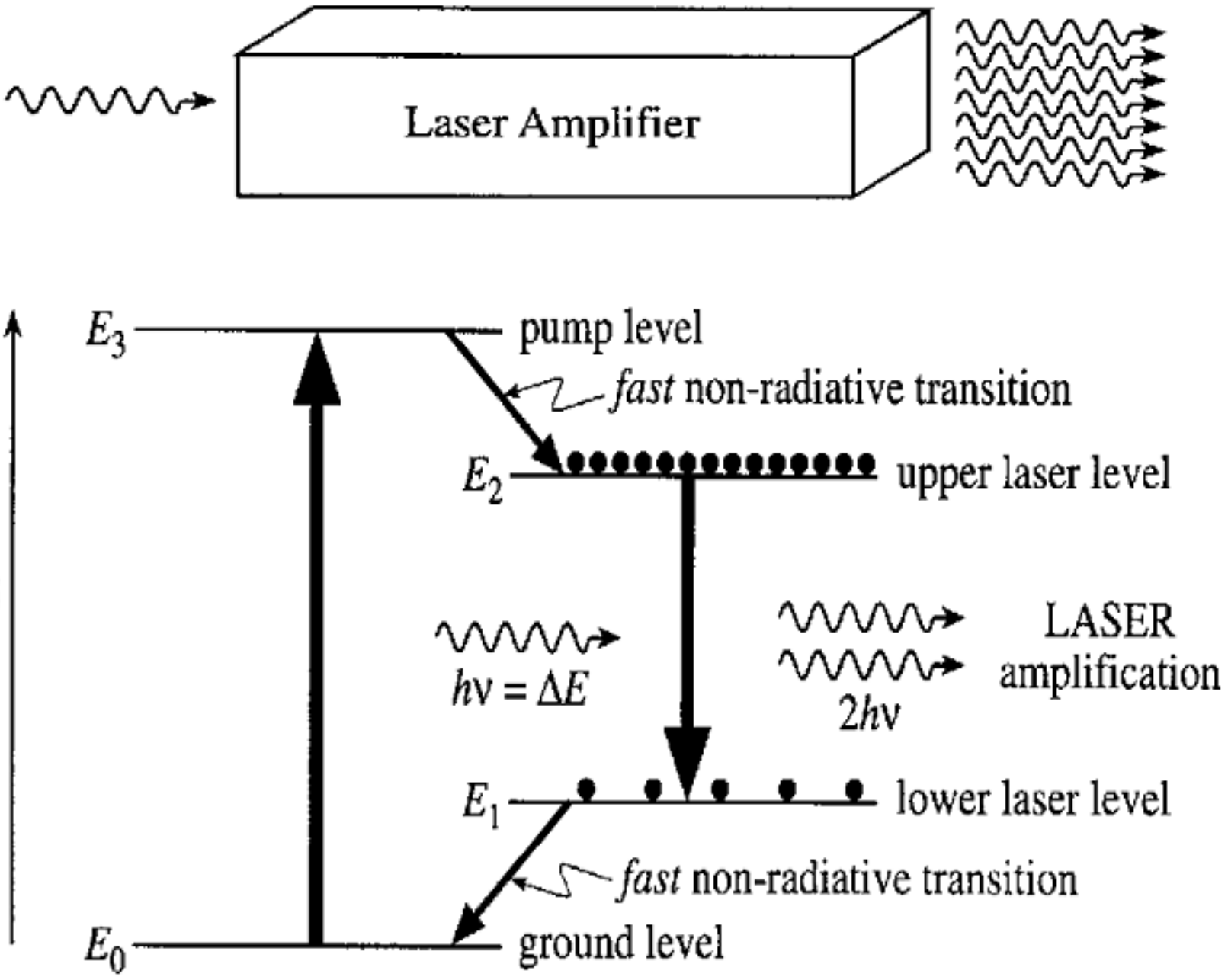


pump on
○ = atoms in excited state

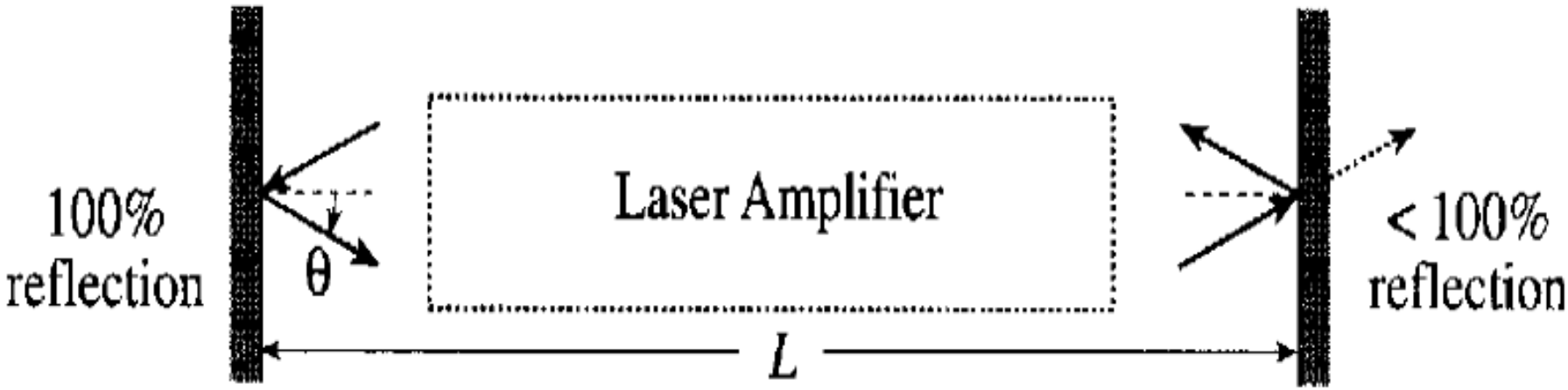
spontaneous emission &
rare stimulated emission

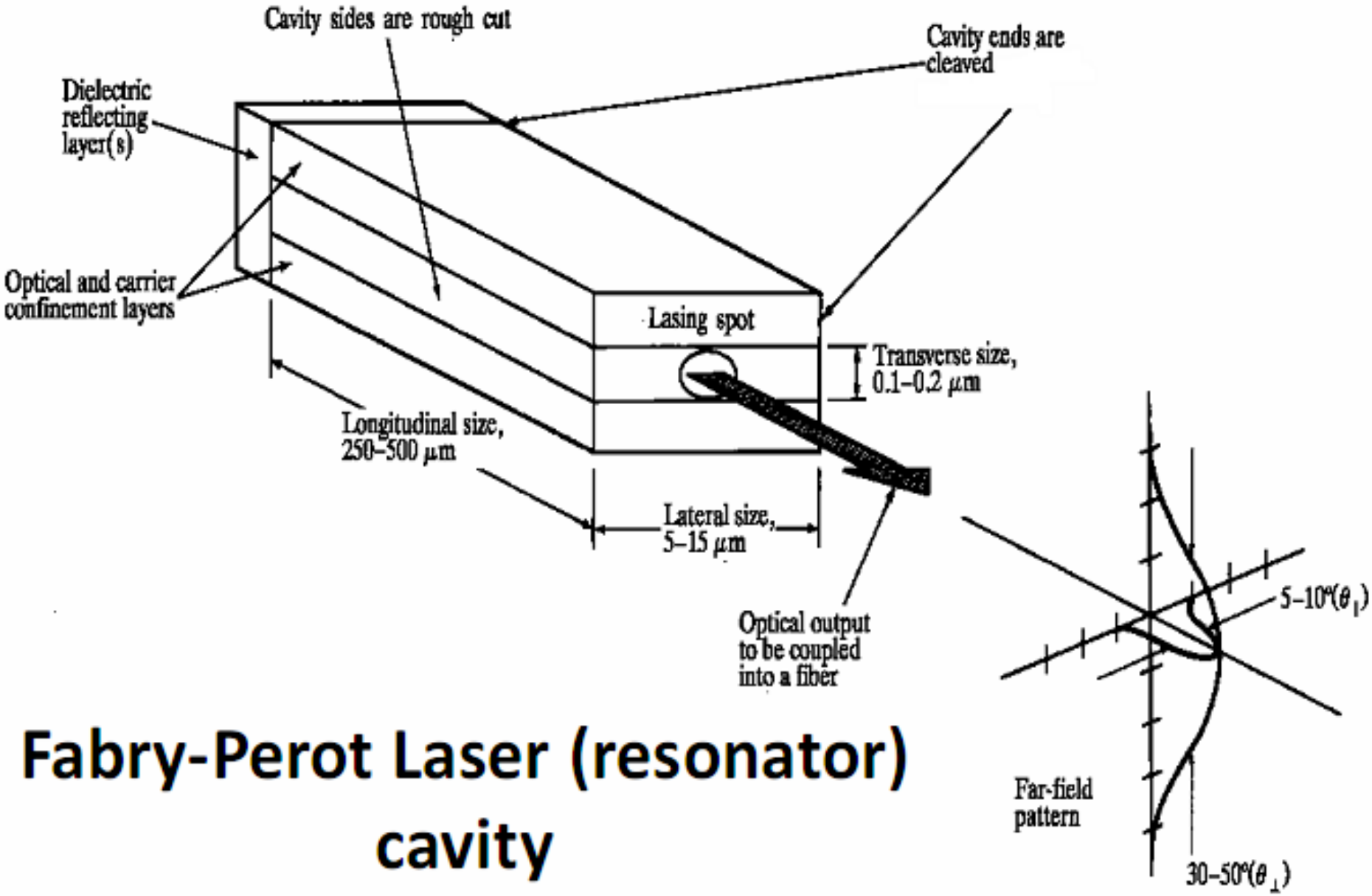
stimulated emission of
light along the laser axis

steady-state
laser operation


Laser Amplifier
energy
E_3
pump level
fast non-radiative transition
E_2
upper laser level
$h\nu = \Delta E$
LASER
amplification
$2h\nu$
E_1
lower laser level
fast non-radiative transition
E_0
ground level

Mirror Reflections





Fabry-Perot Laser (resonator) cavity

THRESHOLDING CONDITION

- Lasing is the condition at which light amplification becomes possible on laser diode.

- Requirement for lasing is that a population inversion to be achieved.

- In addition, a minimum or threshold gain within the amplifying medium should be attained.

- Steady state conditions for laser oscillations are achieved when gain in amplifying medium balances total losses.

- At the lasing threshold a steady state oscillation takes place

- The magnitude and phase of the returned wave must be equal to those of the original wave

- On each round trip the beam passes through the medium twice

- The fractional losses incurred by the light beam is

- **Fractional loss= r1*r2*exp(-2nL)**

  n – Signal loss coefficient per unit length

  L - Length of the amplifying medium between the mirrors

  r1 & r2 - reflectivities of the two mirrors

  (Frensel reflection coefficients)

- Lasing occurs when the gain of one or several guided modes is sufficient to exceed the round trip through the cavity

- Increase in beam intensity from the simulated emission is exponential

- **Fractional gain = exp(2gL)**

  g – Gain coefficient per unit length

• For oscillations to occur, the gain should balance the total losses

Gain*Losses =1

$$[\exp(2gL)] \cdot [r1*r2*\exp(-2nL)] = 1$$

$$r1*r2*\exp(2(g-n)L) = 1$$

- The threshold gain per unit length

$$gth = nth + \left(\frac{1}{2L}\right) ln\left(\frac{1}{r1.r2}\right)$$

• The second term of R.H.S. above eqn. represents transmission loss through the mirrors

Comparison between LED and LASER

LED	Laser Diode
• Low efficiency	• High efficiency
• Slow response time	• Fast response time
• Lower data transmission rate	• Higher data transmission rate
• Broad output spectrum	• Narrow output spectrum
• In-coherent beam	• Coherent output beam
• Low launch power	• Higher bit rate
• Higher distortion level at the output	• High launch power
• Suitable for shorter transmission distances.	• Less distortion
• Higher dispersion	• Suitable for longer transmission distances
• Less temperature dependent	• Lower dispersion
• Simple construction	• More temperature dependent
• Life time 10^7 hours	• Construction is complicated
	• Life time 10^7 hours

Efficiency

•Total efficiency (external quantum efficiency) η_T which is efficiency defined as:

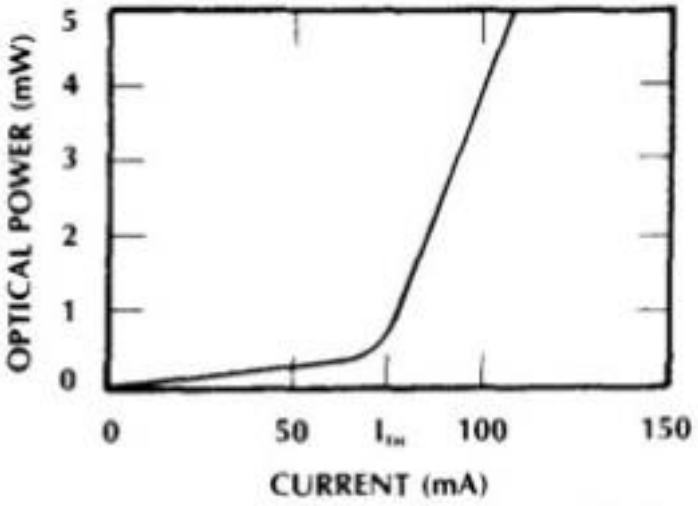
$$\eta_i = \frac{\text{number of photons produced in the laser cavity}}{\text{number of injected electrons}} = \frac{P_e/hf}{I/e} \simeq \frac{P_e}{IE_g}$$

• The external power efficiency of the device (or device efficiency) η_{ep} in converting electrical input to optical output is given by:

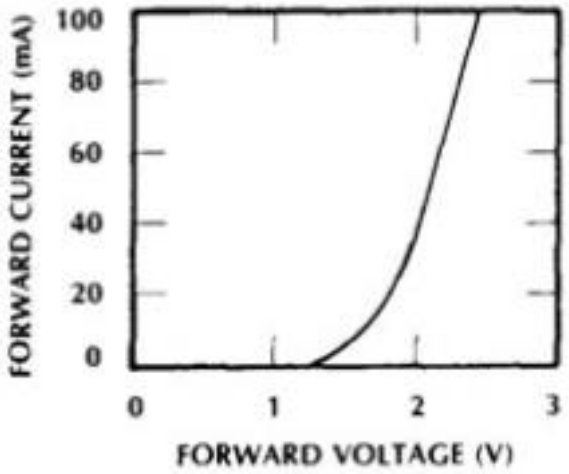
$$\eta_{ep} = \frac{P_e}{P} \times 100 = \frac{P_e}{IV} \times 100\%$$

$$\eta_{ep} = \eta_T \left(\frac{E_g}{V} \right) \times 100\%$$

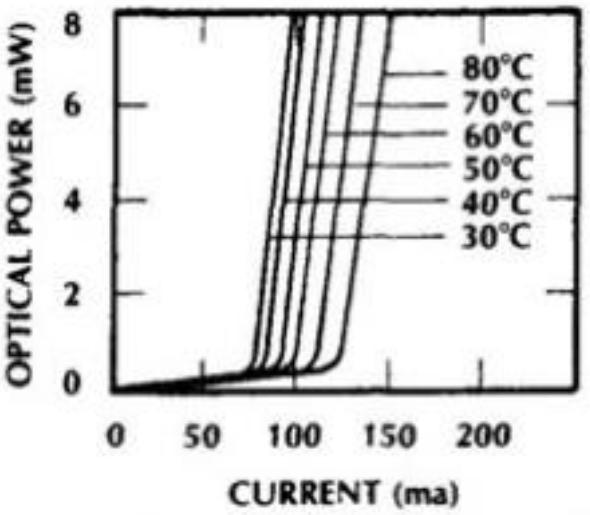
Characteristics of Laser Diode



Power-current relationship for a laser diode.

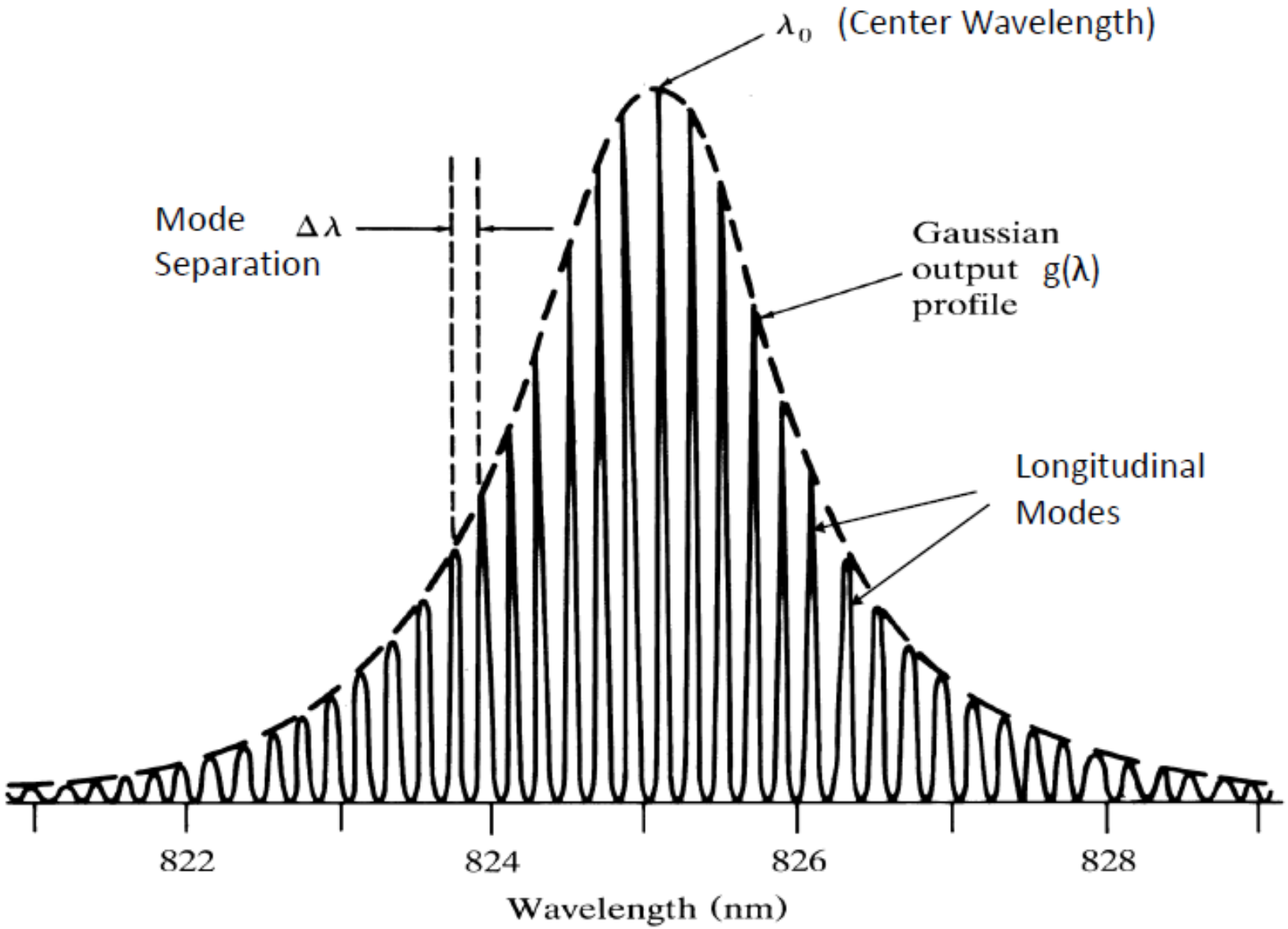


Typical voltage-current characteristic for a laser diode.

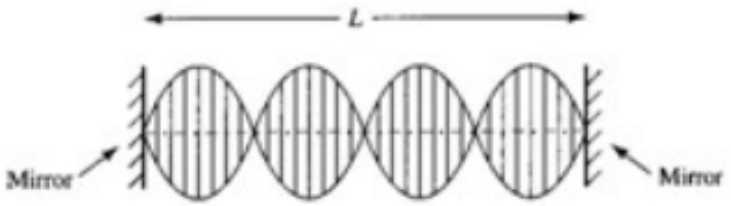


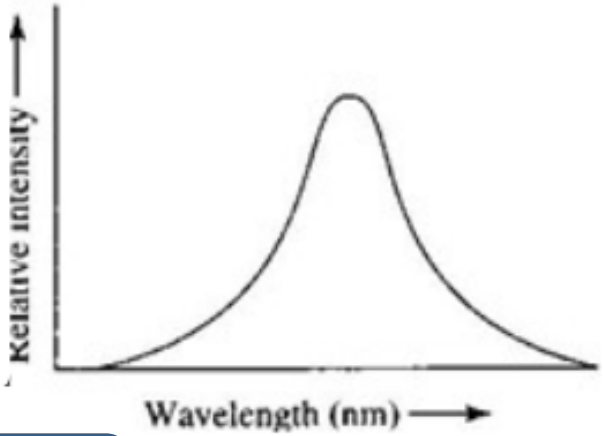
Temperature dependence of a laser diode.

Laser Output Spectrum



Laser Longitudinal Mode





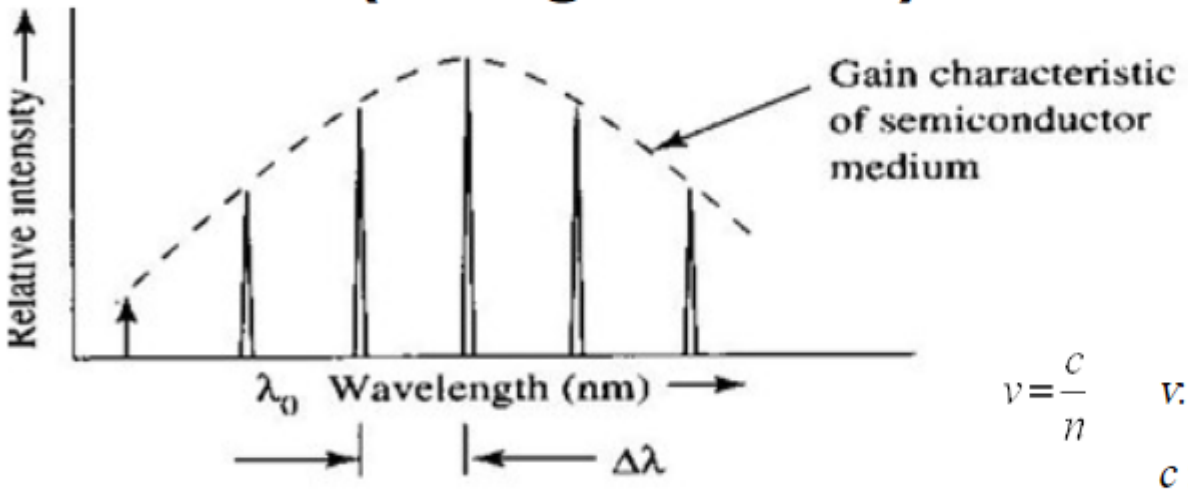
Optical resonance: $L = m\frac{\lambda}{2} \quad (m:\text{integer}) \Rightarrow \lambda = \frac{2L}{m}$

where λ: wavelength of the resonating frequency, *L*: length of the cavity, *m* : an integral

Eg. laser diode : cavity length = 300 μm; AlGaAs : gap wavelength ≈ 800nm
How many wavelength will fit into the cavity ?

$$m = \frac{2L}{\lambda} = \frac{2\times 300\times 10^{-6}}{800\times 10^{-9}} \approx 750 \text{ wavelengths}$$

Multi-(Longitudinal) Mode Laser



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

v: velocity of the wave in cavity

c : speed of light

n : refractive index of cavity material

Cavity resonance frequency

$$f = \frac{mc}{2nL}$$

Spacing between the adjacent frequency (frequency spacing)

$$\Delta f = \frac{c}{2nL}$$

Wavelength spacing

$$\Delta\lambda = \frac{\lambda_0^2 \Delta f}{c} \left(= \frac{\lambda_0^2}{2nL} \right)$$

λ_0 : free space value of the wavelength

Laser Resonant Frequencies

- Resonant Frequency generated by Fabry-Perot Resonator :

$$f = \frac{m.c}{2L.n} \qquad m = 1,2,3,\ldots$$

m = No. of longitudinal modes ; c = Velocity of light ;

n = Refractive Index ;

L = Length between the Fabry-Perot Resonator Mirrors

- Optical Wavelength is given by

$$2L.n = \frac{m.c}{f} = m.\lambda$$

$$\lambda = \frac{2L.n}{m}$$

Frequency Spacing

$$\Delta f = \frac{c}{2Ln}$$

Wavelength Spacing

$$\Delta\lambda = \frac{\lambda^2}{2Ln}$$

Eg. Laser diode : cavity length = 300 μm

refractive index = 3.6 ; line width of the cavity = 2 nm

peak radiating wavelength λ_0 = 800 nm

Find output spectrum from the laser

frequency spacing: $\Delta f = \frac{c}{2nL} = \frac{3\times10^8}{2\times3.6\times300\times10^{-6}} = 139\times10^9\,Hz$

wavelength spacing: $\Delta\lambda = \frac{\lambda_0^2\Delta f}{c} = \frac{(800\times10^{-9})^2\times139\times10^9}{3\times10^8} = 0.275nm$

mode number: $\Delta m = \frac{2}{0.275} \approx 5.51$ (at most 6 modes)

Example : A GaAs laser is operating at 850 nm wavelength and has a length of 500 µm. If its refractive index is 3.7,

find (a) the frequency spacing between longitudinal modes;

(b) the wavelength spacing.

$$(a)\Delta f = \frac{c}{2Ln}$$

$$(b)\Delta\lambda = \frac{\lambda^2}{2Ln}$$

UNIT III
OPTICAL DETECTORS

: By Dr. Sanket B. Kasturiwala

Optical Detectors

- Its function is to convert the received optical signal into an electrical signal, which is then amplified before further processing.
- The detector is an essential component of an optical fiber communication system and is one of the crucial elements which dictate the overall system performance by means of signal attenuation along the link.
- Improvement of detector characteristics and performance thus allows the installation of fewer repeater stations and lowers both the capital investment and maintenance costs.
- The role the detector plays demands that it must satisfy very stringent requirements for performance and compatibility.

The ideal requirements for photo detector :

1. High sensitivity at operating wavelength.
2. High fidelity to reproduce the original waveform effectively.
3. Produce maximum electrical signal for a given amount of optical power.
4. Short response time to obtain a suitable bandwidth.
5. Dark currents, leakage currents, shunt conductance- low.
6. Stability of Performance characteristics.
7. Small size for effective coupling.
8. Not require excessive bias voltages or currents.
9. Highly reliable & capable of continuous stable operation at room temperature.
10. Low cost

Performance Parameters of Photodetector

Spectral Response – It is the photodetector's response as a photon frequency function.

Quantum Efficiency – The number of charge carriers generated for each photon

Responsivity – It is the output current separated by the total power of light dropping on the detector.

Noise-equivalent Power – It is the required amount of light power to generate a signal that is equivalent in size to the noise of the device.

Detectivity – The square root of the area of the detector separated by the noise equivalent power.

Gain – It is the photo detector's output current which is divided by the directly produced current by the incident photons on the detectors.

Dark Current- The flow of current throughout a detector even in the deficiency of light.

Response Time – It is the required time for a detector to go from 10 – 90% of the final output.

Noise Spectrum – The intrinsic noise current or voltage is a function of frequency that can be signified in a noise spectral density form.

Nonlinearity – The photo detector's nonlinearity limits the RF output.

Photodetection Mechanisms

Photodetector converts light (power) into electrical signals (photocurrent)

There are two distinct photodetection mechanisms

1 External photoelectric effect :

- Photomultiplier Tubes (PMT)

2 Internal photoelectric effect :

- PN junction photodiodes
- PIN photodiodes
- Avalanche photodiodes

Photodetectors are classified into two types :

1) Photon detectors
2) Thermal detectors

Thermal detectors are not preferred in optical communication because it is inherently very slow.

Based on physical principle of their operation, photon detectors are further divided into :

a) Photoemissive effect
b) Photoconductive effect
c) Photovoltaic effect
d) Photoelectromagnetic effect



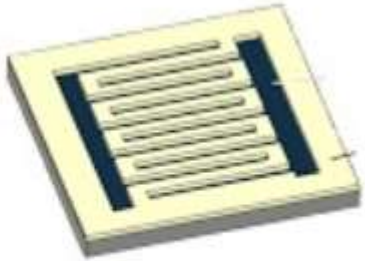
Photo Diode



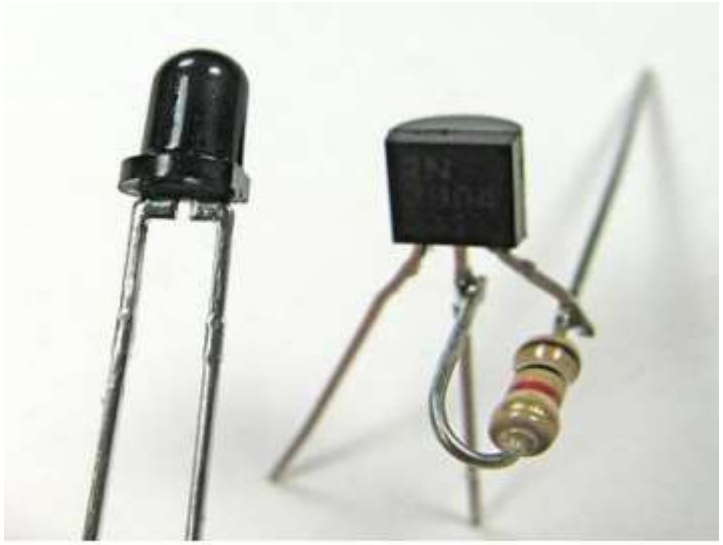
Photoconductive Detector



Phototube



MSM Photodetector





Photomultiplier

Optical Detection Principle

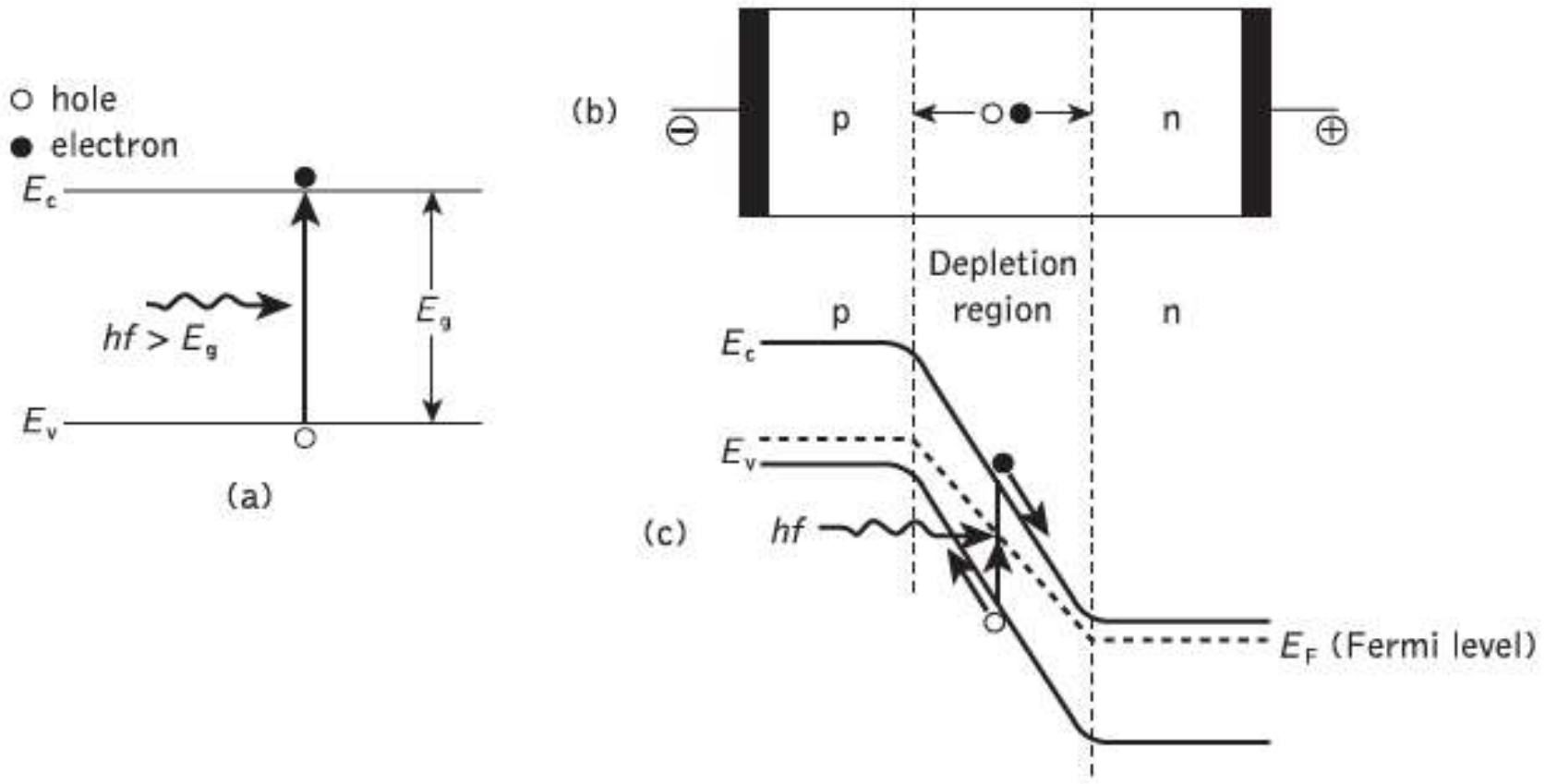


Figure 8.1 Operation of the *p–n* photodiode: (a) photogeneration of an electron–hole pair in an intrinsic semiconductor; (b) the structure of the reverse-biased *p–n* junction illustrating carrier drift in the depletion region; (c) the energy band diagram of the reverse-biased *p–n* junction showing photogeneration and the subsequent separation of an electron–hole pair

Optical Detection Principle . . .

Figure 8.1(a): A photon incident in or near the depletion region of this device which has an energy ***hf ≥ Eg*** *of the fabricating material* excite an electron from the valence band into the conduction band. This process leaves an empty hole in the valence band and is known as the photogeneration of an electron–hole (carrier) pair.

Figure 8.1(b) : Carrier pairs so generated near the junction are separated and swept (drift) under the influence of the electric field to produce a displacement by current in the external circuit in excess of any reverse leakage current.

Figure 8.1(c) : Photogeneration and the separation of a carrier pair in the depletion region forming the reverse leakage current *(photocurrent)* of the diode of this reverse-biased p–n junction.

❖ The depletion region must be sufficiently thick to allow a large fraction of the incident light to be absorbed in order to achieve maximum carrier pair generation for photocurrent flow.

Absorption Coefficient

• The absorption of photons in a photodiode to produce carrier pairs and thus a photocurrent is dependent on the absorption coefficient α_0 of the light in the semiconductor used to fabricate the device.

• At a specific wavelength and assuming only bandgap transitions (i.e. intrinsic absorber) the photocurrent *Ip produced by incident light of optical power Po is*

$$I_p = \frac{P_o e(1-r)}{hf}[1-\exp(-\alpha_0 d)]$$

where *e is the charge on an electron,*

r is the Fresnel reflection coefficient at the semiconductor–air interface and

d is the width of the absorption region.

• The absorption coefficients of semiconductor materials are strongly dependent on wavelength.

Quantum Efficiency

• The quantum efficiency η is defined as the fraction of incident photons which are absorbed by the photodetector and generate electrons which are collected at the detector terminals:

$$\eta = \frac{\text{number of electrons collected}}{\text{number of incident photons}} \qquad \eta = \frac{r_e}{r_p}$$

where *rp* is the incident photon rate (photons per second) and
re is the corresponding electron rate (electrons per second).

• The quantum efficiency is generally less than unity as not all of the incident photons are absorbed to create electron–hole pairs.

• Quantum efficiency always quoted as a percentage
(e.g. a quantum efficiency of 75% is equivalent to 75 electrons collected per 100 incident photons).

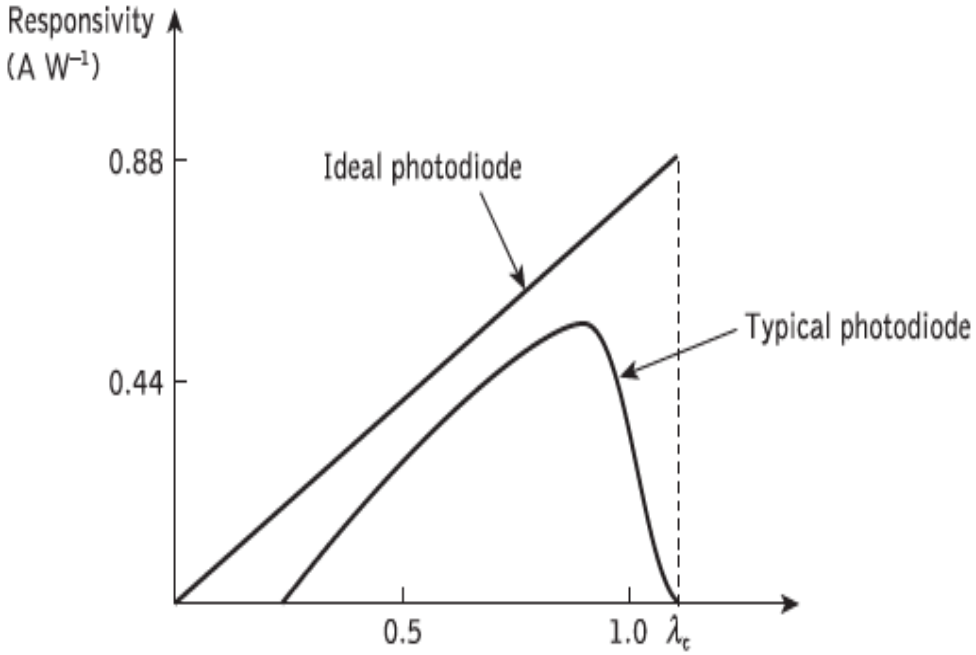
• Finally, in common with the absorption coefficient, the quantum efficiency is a function of the photon wavelength and must therefore only be quoted for a specific wavelength.

Responsivity

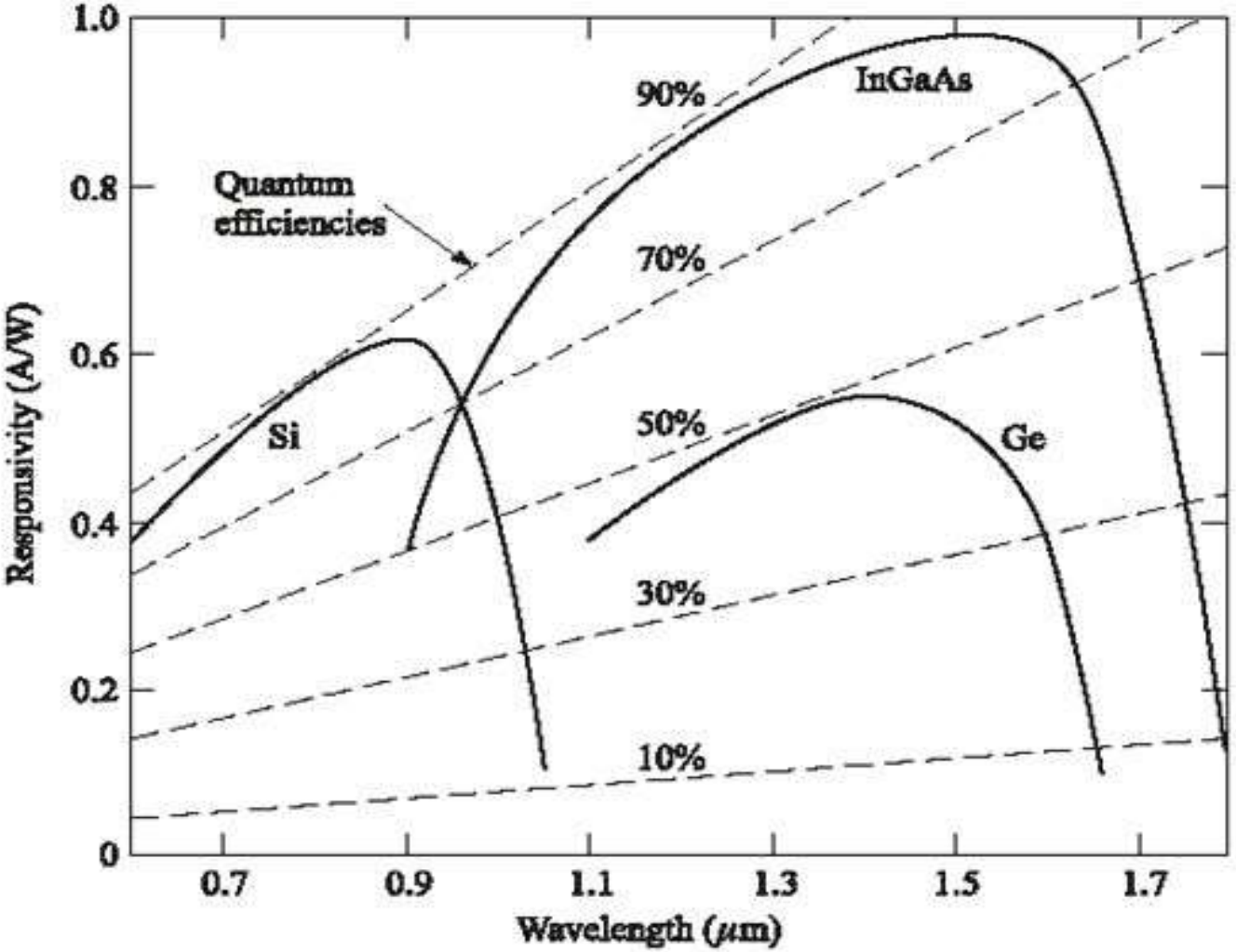
$$R = \frac{I_p}{P_o} (\text{A W}^{-1}) \qquad R = \frac{\eta e \lambda}{hc}$$

where *Ip is the output photocurrent in amperes and Po is the incident optical power in watts* (i.e. output optical power from the fiber).

- The responsivity is a useful parameter as it gives the transfer characteristic of the detector (i.e. photocurrent per unit incident optical power).
- Responsivity is directly proportional to the quantum efficiency at a particular wavelength.



Responsivity vs. wavelength



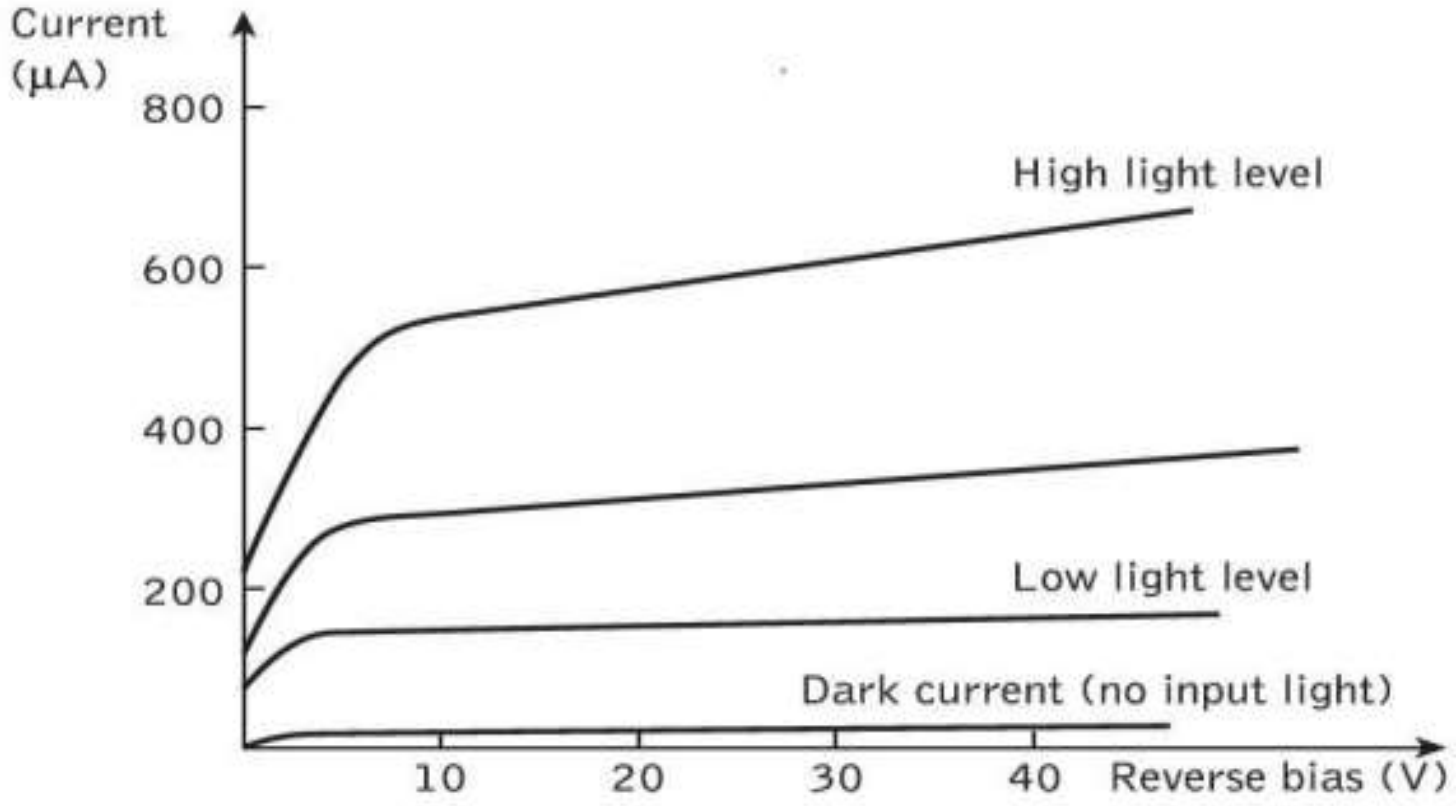


Figure Typical *p–n* photodiode output characteristics

The different operating conditions when moving from no light input to a high light level.

• It is desirable that photon be absorbed in the depletion layers that it can contribute maximum in generation of photocurrent.

•The existence of electric field across the junction facilitate the rise of photocurrent.

•The primary operating wavelength regions for FO communication systems are 650 nm, 850nm, 1310nm and 1550nm.

•The photodetectors which are used in these systems are:-

-PN junction photodiodes ;

-PIN photodiodes ;

-Avalanche photodiode

Three main factors limit the speed of response of a photodiode

1. *Drift time of carriers through the depletion region.*

2. *Diffusion time of carriers generated outside the depletion region.(Diffusing time is large)*

3. *Time constant (RC) incurred by the capacitance of the photodiode with its load.*

Various figure of merit parameters have been used to asses the noise performance of optical detectors. most commonly used are Noise equivalent power (NEP), Detectivity (D) and Specific detectivity (D^*).

Noise Equivalent Power (NEP): The minimum input optical power required to generate photocurrent, equal to the rms noise current in a 1Hz bandwidth. NEP is essentially the minimum detectable power.

Detectivity(D): The characteristic detectivity (D) is the inverse of NEP, 1/NEP.

Specific Detectivity (D*): It is detectivity multiplied by the square root of the area (A) of the photodetector, ($D^*=D\sqrt{A}$) for a 1Hz bandwidth.

Due to above requirements, only *photodiodes* are used as photo detectors in optical communication systems ::

- Positive-Intrinsic-Negative (*pin) photodiode*
  - No internal gain

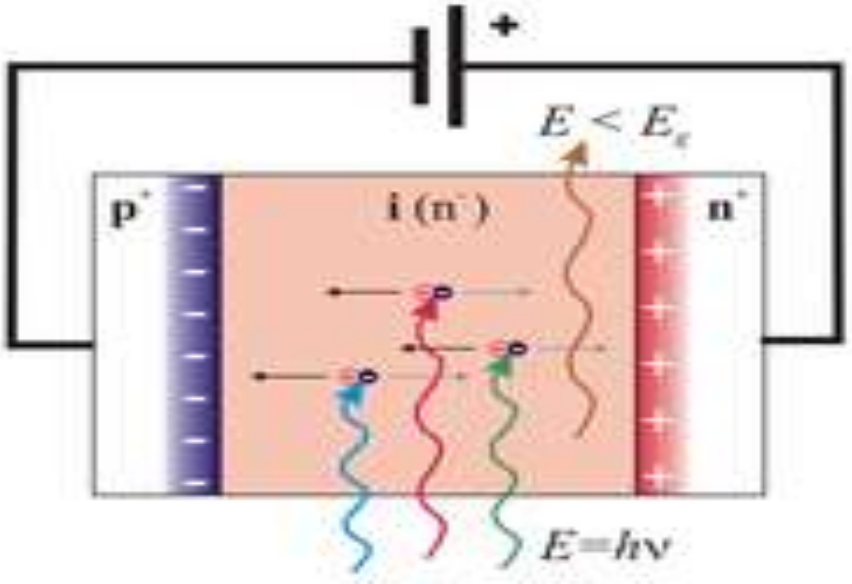
- Avalanche Photo Diode (*APD)*
  - An internal gain of *M due to self multiplication*

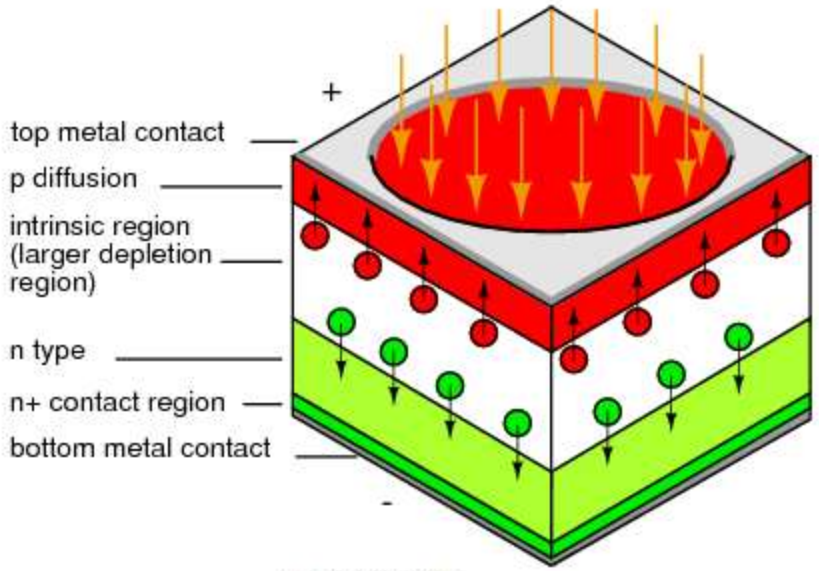
1. P-i-N Photodiode

•To allow operation at longer wavelengths where the light penetrates more deeply into the semiconductor material, a wider depletion region is necessary.

•To achieve this the *n-type material is doped so lightly that it can be considered intrinsic, and to make a low resistance* contact a highly doped *n-type (n+) layer is added.*

•*This creates a p–i–n (or PIN)* structure, where all the absorption takes place in the depletion region.





PIN photodiode.

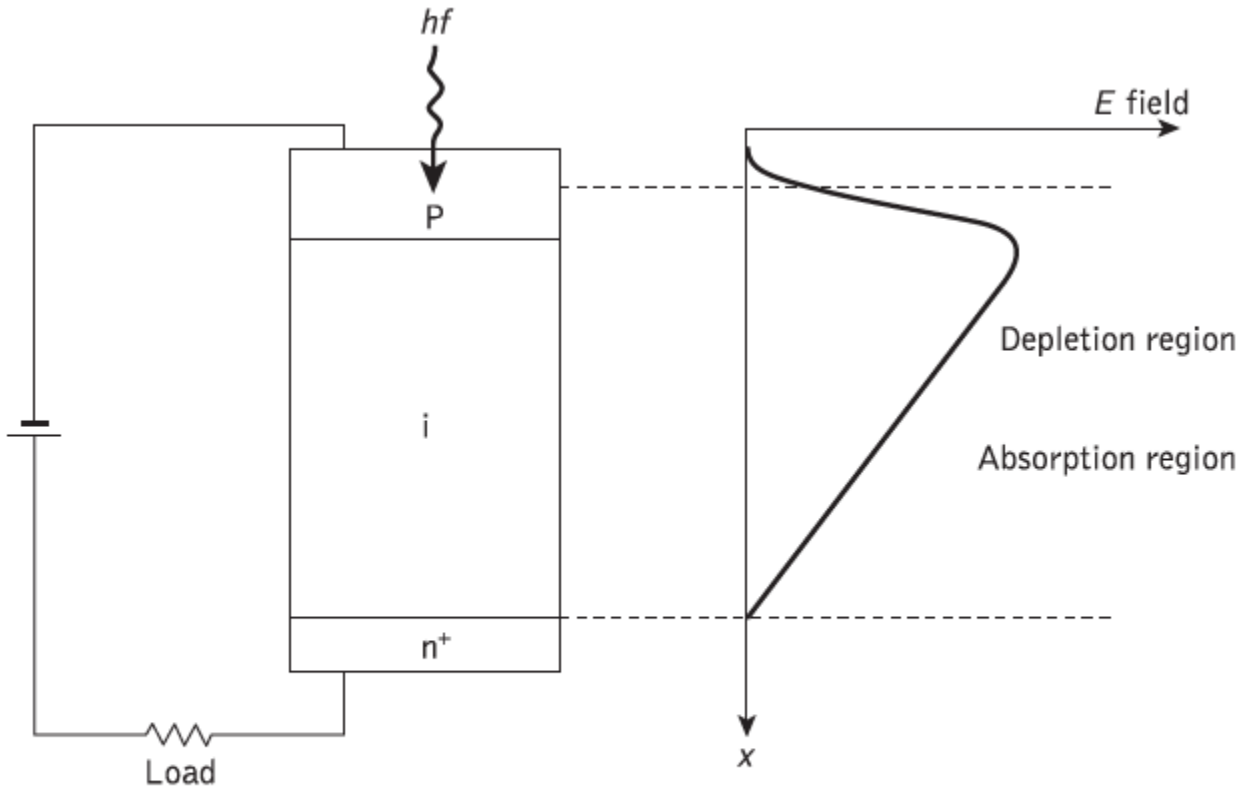
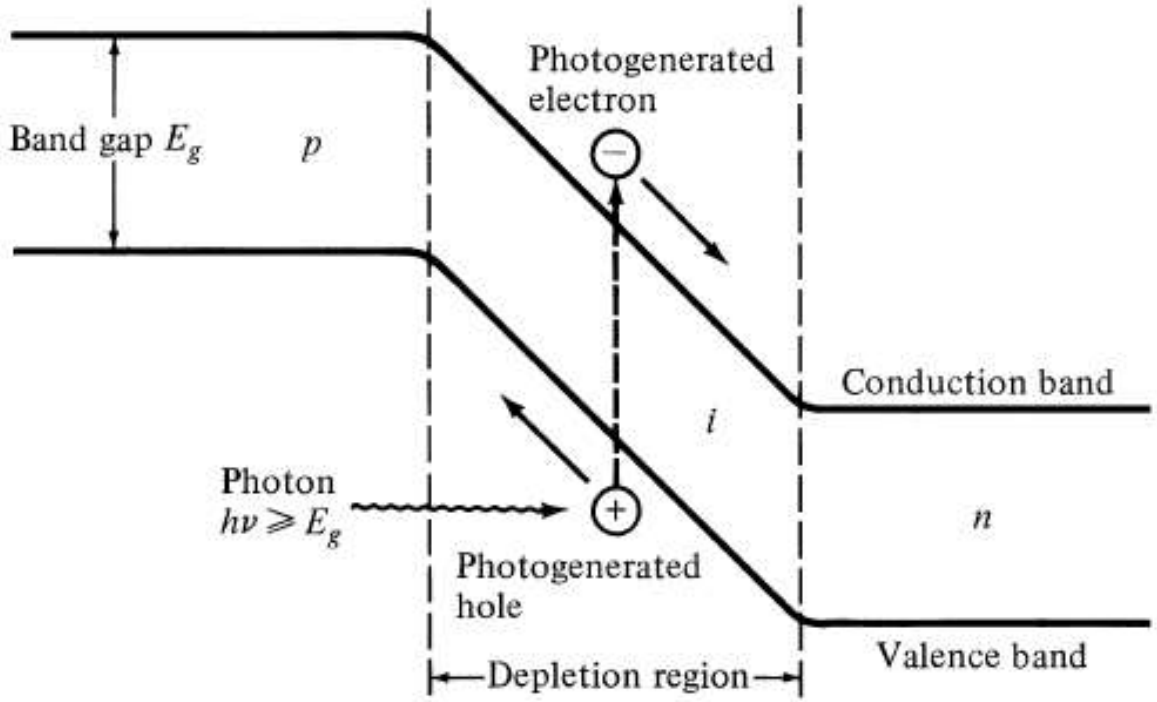


Figure 8.6 The *p–i–n* photodiode showing the combined absorption and depletion region

The diffusion contribution can be reduced by decreasing the widths of the *p- and n-regions and increasing the depletion-region width so that most of the incident optical* power is absorbed inside it. This is the main approach of *p–i–n photodiodes.*

PIN Energy-Band Biagram



$$\lambda_c = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)} \ \mu m$$

Cut off wavelength depends on the band gap energy

•The P-Intrinsic –N structure increases the distance between the P and N conductive layers, decreasing capacitance, increasing speed.

•The volume of the photo sensitive region also increases, enhancing conversion efficiency.

•The performance of p–i–n photodiodes can be improved considerably by using a double-heterostructure design. Similar to the case of semiconductor lasers, the middle i-type layer is sandwiched between the p-type and n-type layers of a different semiconductor whose bandgap is chosen such that light is absorbed only in the middle i-layer.

•The bandwidth can extend to 10's of GHz. PIN photodiodes are the preferred for high sensitivity, and high speed at moderate cost.

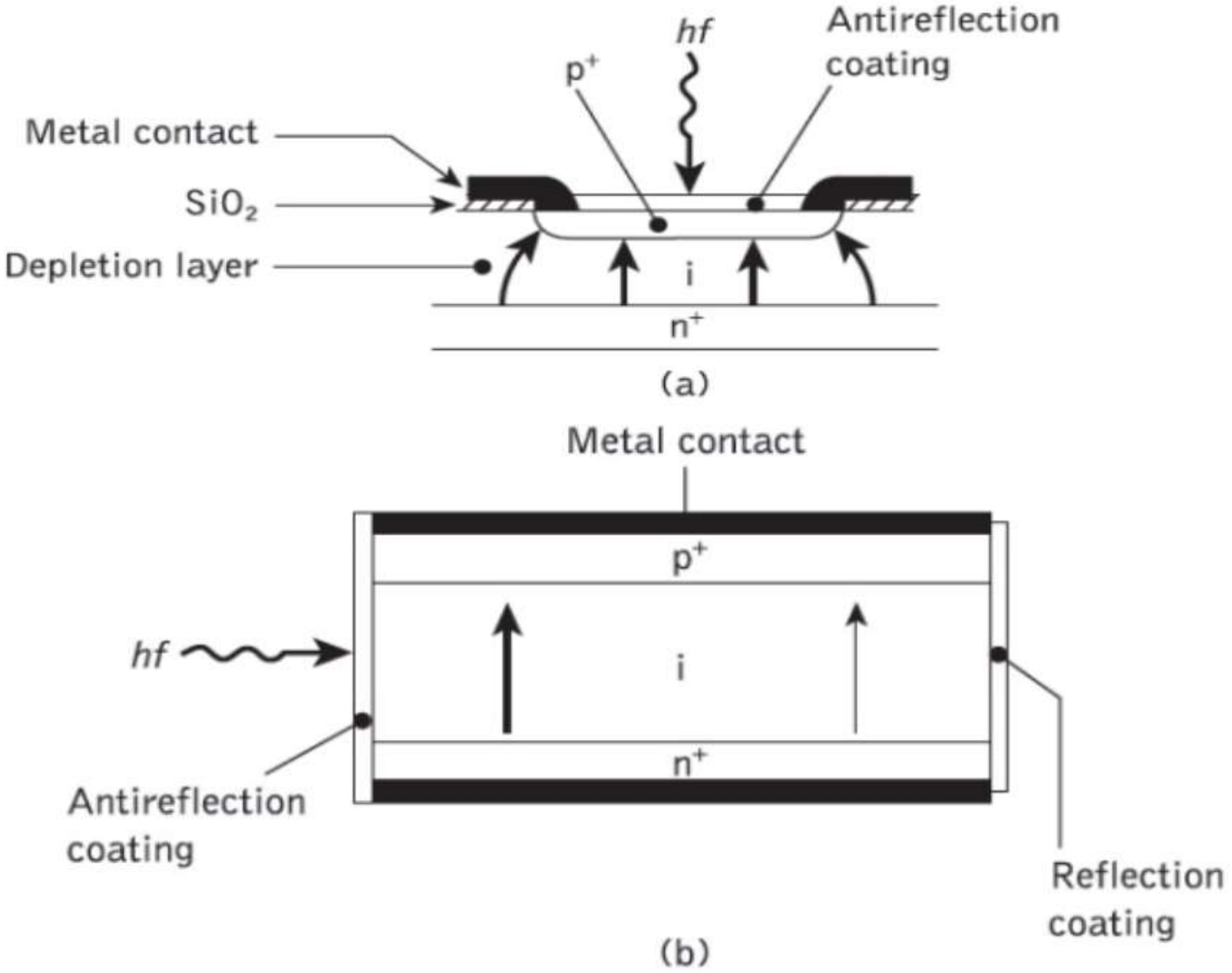


Figure (a) Structure of a front-illuminated silicon *p–i–n* photodiode.
(b) Structure of a side illuminated (parallel to junction) *p–i–n* photodiode

•Figure 4.5(a) shows the device structure together with the electric-field distribution inside it under reverse-bias operation. Because of its intrinsic nature, the middle *i-layer offers a high resistance, and most of the voltage drop occurs across it.*

•As a result, a large electric field exists in the *i-layer. In essence, the depletion region* extends throughout the *i-region, and its width W can be controlled by changing the* middle-layer thickness.

•The optimum value of W depends on a compromise between *speed* and *sensitivity.*

•The responsivity can be increased by increasing W so that the quantum efficiency η approaches 100%

Parameter	Symbol	Unit	Si	Ge	InGaAs
Wavelength	λ	μm	0.4–1.1	0.8–1.8	1.0–1.7
Responsivity	R	A/W	0.4–0.6	0.5–0.7	0.6–0.9
Quantum efficiency	η	%	75–90	50–55	60–70
Dark current	I_d	nA	1–10	50–500	1–20
Rise time	T_r	ns	0.5–1	0.1–0.5	0.02–0.5
Bandwidth	Δf	GHz	0.3–0.6	0.5–3	1–10
Bias voltage	V_b	V	50–100	6–10	5–6

Advantages and Disadvantages

The advantages of photodetector include the following.

- Photodetectors are small in size.
- Its detection speed is fast.
- Its detection efficiency is high.
- They generate less noise.
- These are not expensive, compact & lightweight.
- They have a long lifetime.
- They have high quantum efficiency.
- It doesn’t require high voltage.

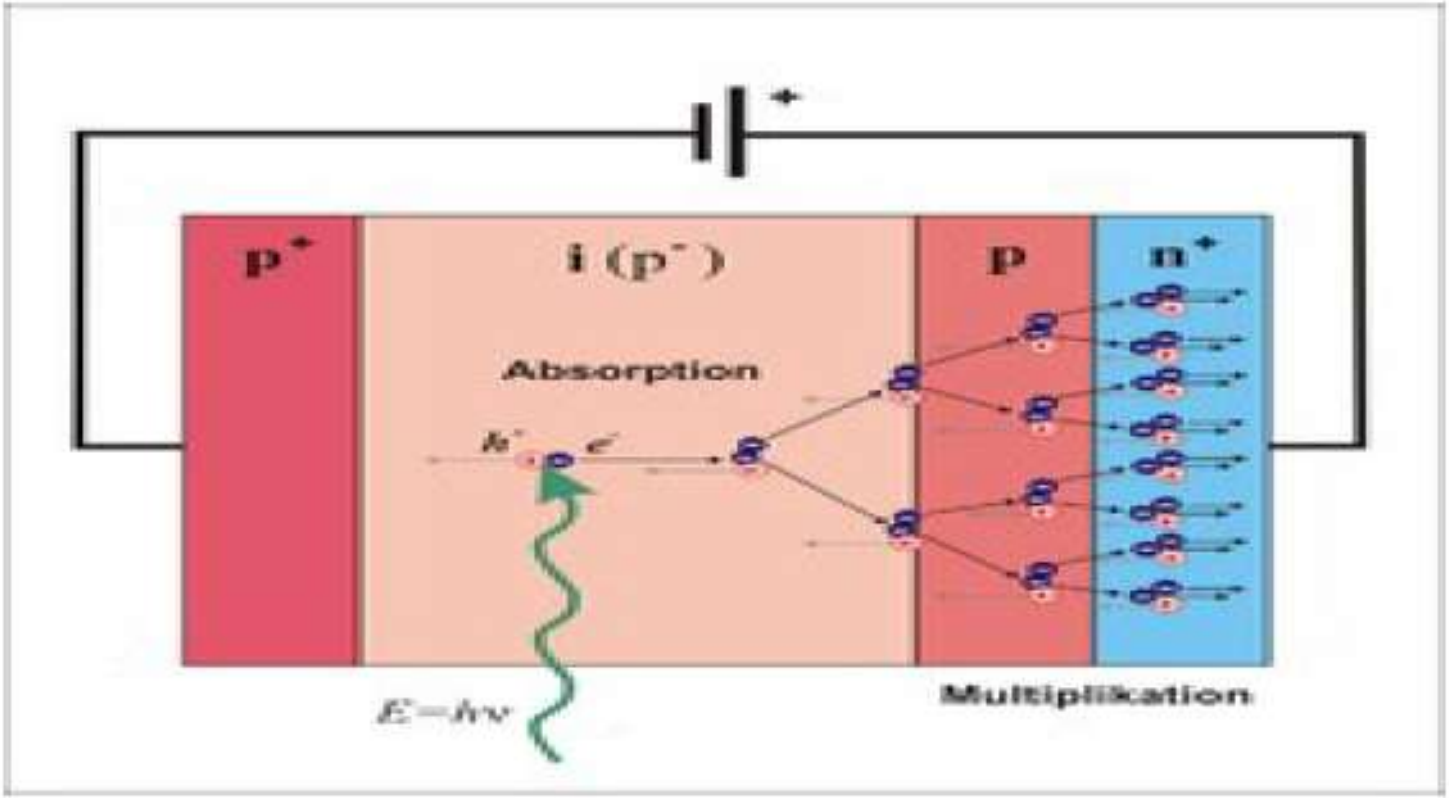
Disadvantages of photodetector :

- They have very low sensitivity.
- They have no internal gain.
- The response time is very slow.
- The active area of this detector is small.
- Change within current is extremely small, so may not be adequate to drive the circuit.
- It requires offset voltage.

2. Avalanche Photodiode

- APD has an internal gain obtained by having a *high electric field* that energizes photo-generated electrons and holes
- These electrons and holes ionize bound electrons in the valence band upon colliding with them
- This mechanism is known as *impact ionization*
- The newly generated electrons and holes are also accelerated by the high electric field and they gain enough energy to cause further impact ionization
- This phenomena is called the avalanche effect.

Structure
Avalanche Photodiode (APD)



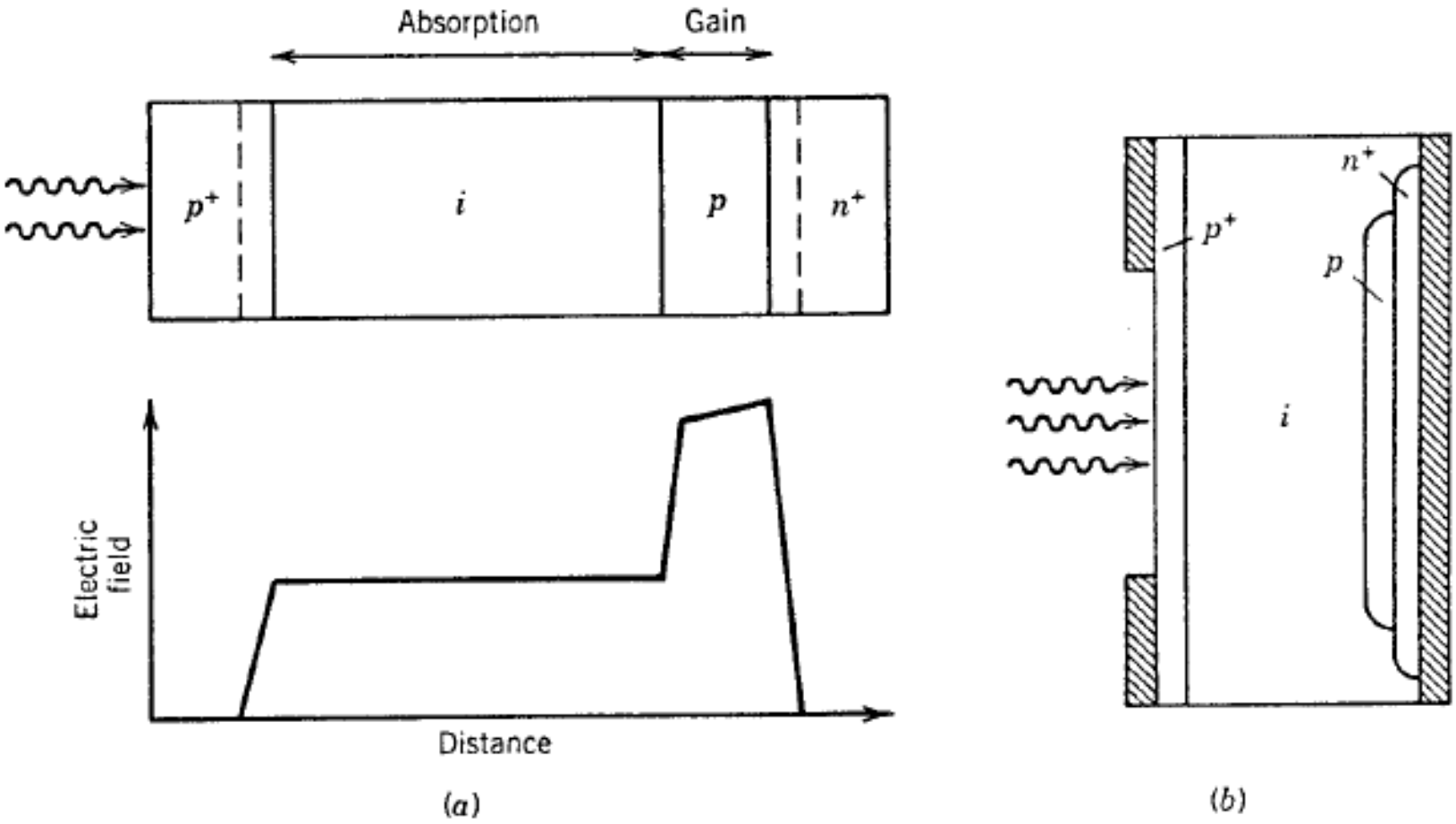
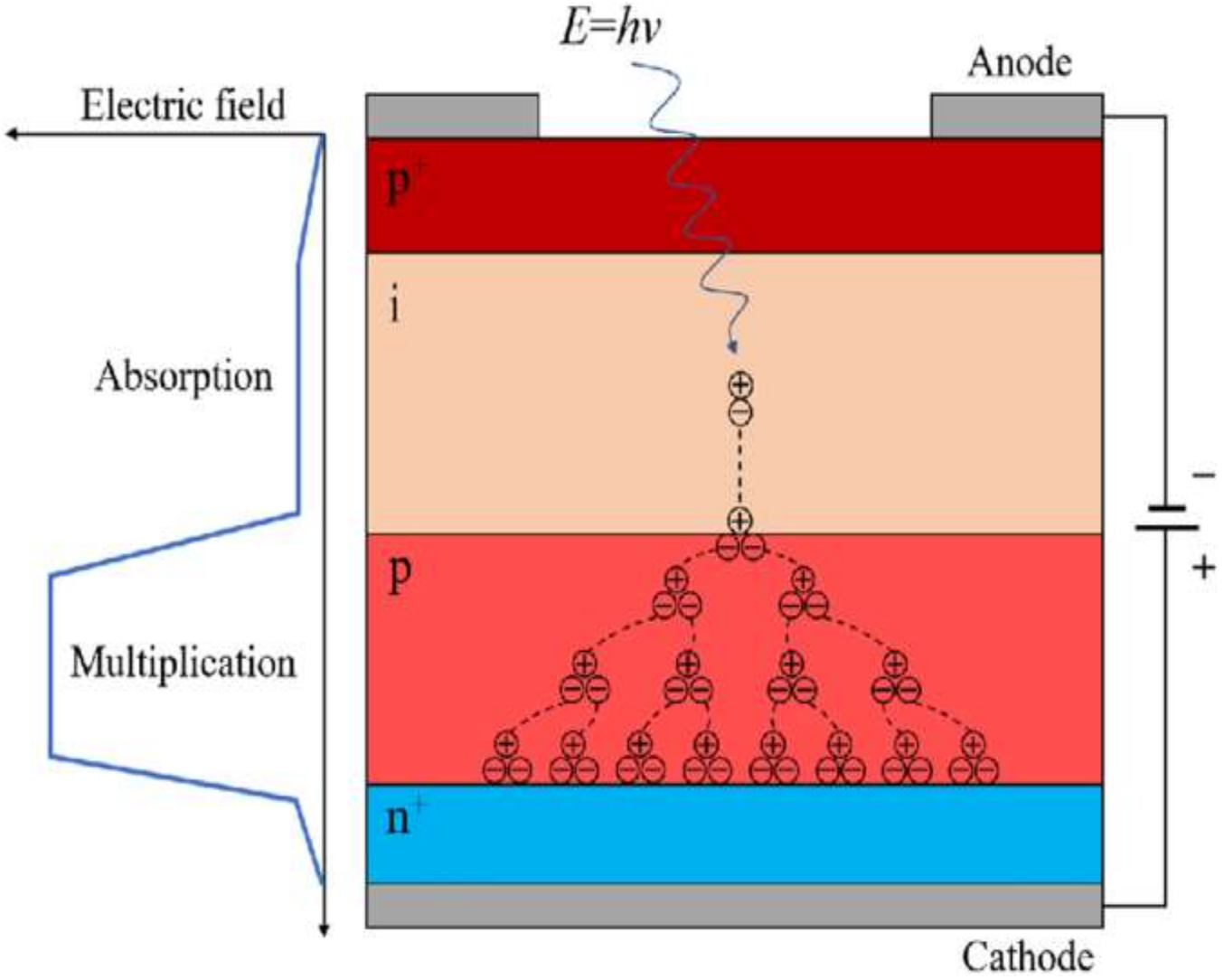


Figure 4.8: (a) An APD together with the electric-field distribution inside various layers under reverse bias; (b) design of a silicon reach-through APD.


E=hv
Anode
Electric field
p+
i
Absorption
p
Multiplication
n+
−
+
Cathode

•Figure 4.8(a) shows the APD structure together with the variation of electric field in various layers.

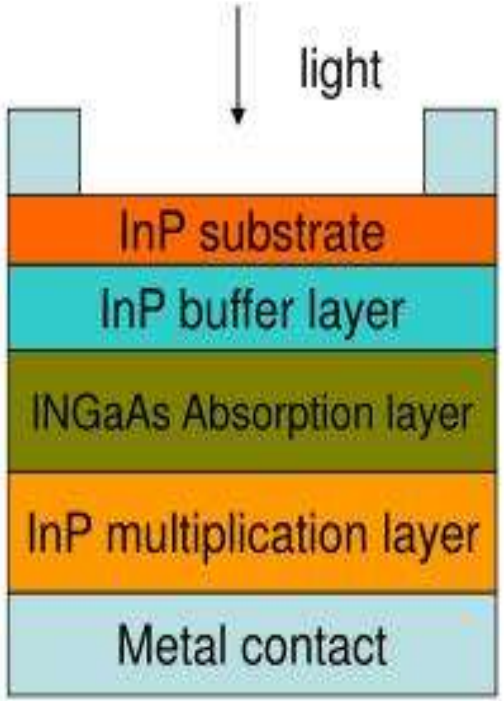
•Under reverse bias, a high electric field exists in the *p-type layer sandwiched between i-type and n+-type layers. This layer* is referred to as the *multiplication layer, since secondary electron–hole pairs are generated* here through impact ionization and is the phenomenon that leads to avalanche breakdown in ordinary reverse-biased diodes.

•The *i-layer still acts as the depletion region* in which most of the incident photons are absorbed and primary electron–hole pairs are generated.

•Electrons generated in the *i-region cross the gain region and generate* secondary electron–hole pairs responsible for the current gain.

Structures for InGaAs APDs

- Separate-absorption-and multiplication (SAM) APD



Multiplication Factor

The multiplication factor M is a measure of the internal gain provided by the APD. It is defined as:

$$M = \frac{I}{I_p} \tag{8.30}$$

where I is the total output current at the operating voltage (i.e. where carrier multiplication occurs) and I_p is the initial or primary photocurrent (i.e. before carrier multiplication occurs).

The quantum efficiency of a particular silicon RAPD is 80% for the detection of radiation at a wavelength of 0.9 μm. When the incident optical power is 0.5 μW, the output current from the device (after avalanche gain) is 11 μA. Determine the multiplication factor of the photodiode under these conditions.

Solution: From Eq. (8.11), the responsivity:

$$R = \frac{\eta e \lambda}{hc} = \frac{0.8 \times 1.602 \times 10^{-19} \times 0.9 \times 10^{-6}}{6.626 \times 10^{-34} \times 2.998 \times 10^{8}}$$

$$= 0.581 \text{ A W}^{-1}$$

Also, from Eq. (8.4), the photocurrent:

$$I_p = P_o R$$
$$= 0.5 \times 10^{-6} \times 0.581$$
$$= 0.291 \text{ μA}$$

Finally, using Eq. (8. 30):

$$M = \frac{I}{I_p} = \frac{11 \times 10^{-6}}{0.291 \times 10^{-6}}$$

$$= 37.8$$

The multiplication factor of the photodiode is approximately 38.

MERITS

PIN

• detect high energy charged or uncharged particles & also electromagnetic radiation
• no gain, so useful in some applications
• no high operating voltage required
• low noise & cost
• high efficiency
• long lifetime

APD

• large gain
• greater level of sensitivity
• high speed

DEMERITS

PIN:

- Less sensitivity
- No internal gain
- Small area
- Slow response time

APD:

- Much higher operating voltage required
- Much higher level of noise
- Output is not linear
- Requires high reverse bias for operation
- Not as widely used due to low reliability

APPLICATIONS

PIN photodiode most widely used
Audio CD players
DVD players
Computer CD drives
Optical communication systems
Nuclear radiation detectors

APD

level of gain is of importance for high voltage requirement.
Laser range finders
fast receiver modules for data communications
high speed laser scanner (2D bar code reader)
speed gun
PET Scanner
microscopy and particle detection.

Chapter 7
SYSTEM DESIGN CONSIDERATIONS

7.1 INTRODUCTION

Design of optical fiber communication system requires proper understanding of limitations imposed by losses, dispersion and non-linearity of fiber. These factors must be considered to ensure that enough light signal reaches the receiver. Entire system will not operate properly if the amount of light is not right. Since the properties of fiber depends on wavelength, choice of operating wavelength is major design issue.

7.1.1 Requirements of System Design:

Basic requirements of system design are:

1) Type of transmission (Analog or Digital)

It depends on the type of signals user want to transmit. If the television signal is to be transmitted, then analog transmission is more suitable since it requires less bandwidth and better linearity. If the data or sampled voice is to be transmitted, then the digital transmission is more suitable.

2) System Fidelity

System fidelity is defined as the correctness of the data received at the receiver. For digital transmission system, it is specified in terms of Bit error rate (BER). In optical communication system, BER should be less than 10^{-9}. BER is defined as:

$$\text{Bit Error Rate (BER)} = \frac{\text{Number of bits in error}}{\text{Total number of bits transmitted}}$$

For an analog transmission system, it is specified in terms of received signal to noise ratio (SNR). In addition to this, inter-modulation distortion is used which describes the linearity of the system.

3) Spacing between the terminal equipment or intermediate repeaters.

4) Bandwidth required for transmission.

5) Reliability

System should be able to adopt new technology as well as accommodate higher data rates with least possible changes.

6) Cost

There are three types of cost i.e. installation, components and maintenance costs. Installations and maintenance costs are the initial costs. Installation cost is more than component cost for longer links. Maintenance cost is more expensive to keep the optical link in working condition for at least 20 to 25 years.

7.2 DIGITAL LINKS

7.2.1 Point-to-Point Links

Point-to-point link consists of a transmitter and a receiver. It is a simplest communication link. It also sets the basis for examining more complex system architectures. Fig. 7.1 shows a simple point-to-point link.

System requirements needed in analyzing a optical fiber link are :

1) Transmission distance
2) Data rate or channel bandwidth
3) Bit error rate

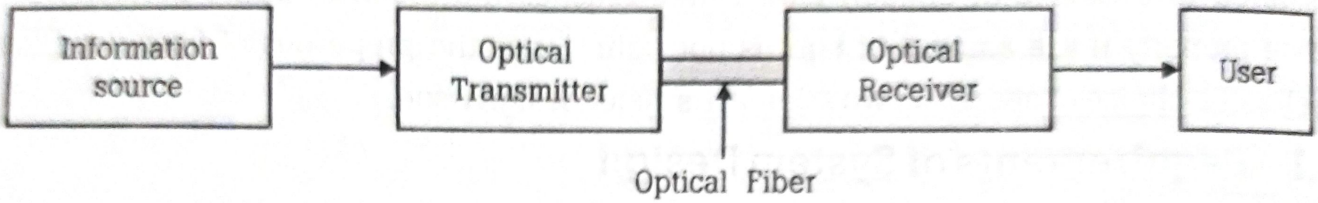


Fig.7.1 : Simple Point-to-Point Link

To fulfill these requirements, designer has a choice of following components along with their characteristics :

Table 7.1 : Components and their characteristics

Sr. No.	Components	Characteristics
1	Optical fiber (Single or Multiple fiber)	a) Core size b) Core refractive index c) Bandwidth or dispersion d) Attenuation e) Numerical aperture or MFD
2	Optical source (LED or LASER diode)	a) Emission wavelength b) Spectral width c) Output power d) Emission pattern e) Effective radiating area f) Number of emitting modes
3	Photodetector (PIN or APD)	a) Responsivity b) Speed c) Operating wavelength d) Sensitivity
4	Connectors (Single or Multichannel)	a) Losses b) Size c) Type of mounting

Desired system performance can be achieved by performing two analyses such as :

a) Link power budget analysis.

b) Rise time budget analysis.

Link power budget analysis determines the power margin between optical transmitter output and receiver sensitivity. Receiver power is the difference between transmitted power and link losses.

Rise time budget analysis determines the dispersion limitation of optical fiber link.

Note : As the data rate increases, power delivering capacity of optical source decreases and power requirement of the photodetector increases.

7.2.1.1 System Considerations

System considerations are as follows :

1) Operating wavelength
2) Photodetector
3) Optical source
4) Optical fiber

❖ **Operating Wavelength**

Selection of operating wavelength depends on transmission distance and attenuation. For short distance communication, 770 nm to 910 nm region is preferred. For long distance communication, O-band to U-band region is preferred due to lower attenuation and dispersion.

❖ **Photodetector**

To select a photodetector, following factors are taken into consideration :

a) Minimum optical power that must fall on photodetector to satisfy BER (Bit Error Rate) at specified data rate.
b) Design cost
c) Circuit complexity
d) Bias voltage

❖ **Optical Source**

To select a proper optical source, following factors are taken into consideration :

a) Signal dispersion
b) Data rate
c) Transmission distance
d) Cost

❖ **Optical Fiber**

Optical fiber selection depends on type of light source and amount of dispersion that can be tolerated. To select a fiber, following factors are taken into consideration :

a) Numerical aperture (NA)
b) Attenuation characteristics

7.2.1.2 Link Power Budget

Link power budget analysis is a simple method to determine the power margin between optical transmitter output and minimum receiver sensitivity required to establish a specified bit error rate (BER).

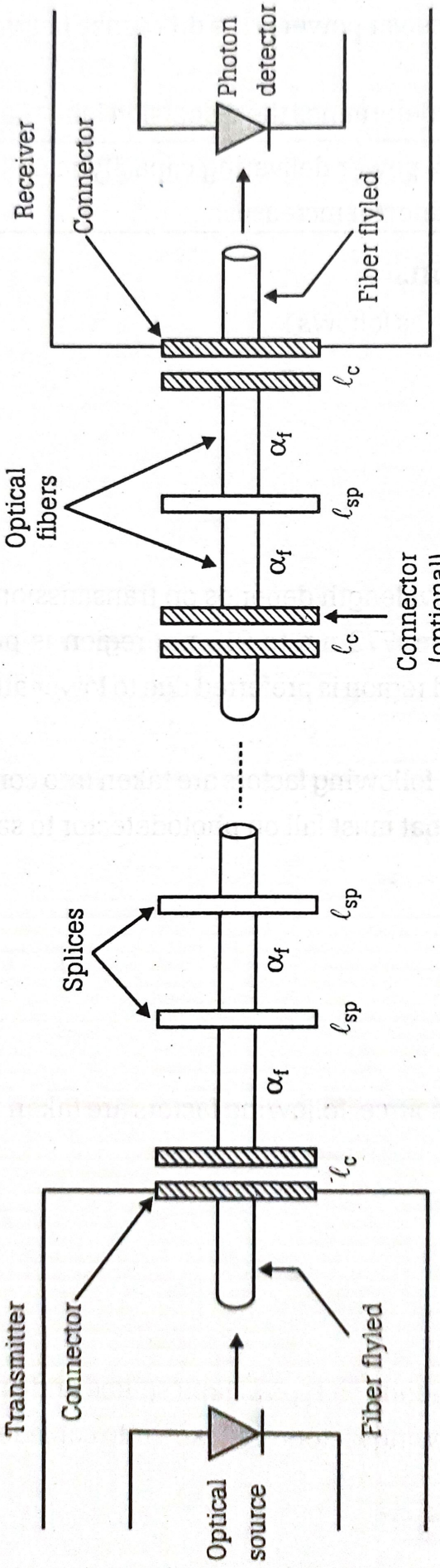


Fig.7.2 : Optical Power Loss Model for Point to Point Link

Fig. 7.2 shows an optical power loss model for a point-to-point link.

Optical power received at the photodetector depends on optical power coupled into the fiber and losses in fiber, connectors and splices. Each component in the optical link has a specific loss in dB (decibel).

If P_{in} and P_{out} are the optical powers entering and leaving the component respectively, then the loss of the component is given by :

$$\text{Loss} = 10\log\left(\frac{P_{out}}{P_{in}}\right) \quad \ldots (7.1)$$

Generally, link margin of 6 to 8 dB is used for systems without additional components.

Link loss budget determines the total optical power loss between light source and photodetector. Then, this loss is allocated to cable attenuation, connector, splice and system margin. If P_S is the transmitted optical power and P_R is the receiver sensitivity, then

$$P_T = P_S - P_R$$
$$= N_c \ell_c + N_{sp} \ell_{sp} + \alpha_f L + P_{SM} \quad \ldots (7.2)$$

where,

N_c = Number of connectors

ℓ_c = Connector loss

N_{sp} = Number of splices

ℓ_{sp} = Splice loss

α_f = Fiber attenuation in dB/km

L = Transmission distance

P_{SM} = System margin

For the Fig. 7.2, Eq (7.2) can be expressed as :

$$P_T = 2\ell_c + N_{sp} \ell_{sp} + \alpha_f L + P_{SM} \quad \ldots (7.3)$$

Ex. 7.1 : A 5 km fiber link is to be installed for following data :

a) Fiber attenuation of 1 dB/km.

b) 11 connectors with connector loss of 1.3 dB/connector.

c) Receiver sensitivity of – 50 dBm.

d) System margin of 6 dB.

Calculate the source power. (Assume no splices)

Solution : Given :

Length of fiber link, L = 5 km

Fiber attenuation, α_f = 1 dB/km

Number of connectors, $N_c = 11$

Connector loss, $\ell_c = 1.3$ dB/km

System margin, $P_{SM} = 6$ dB

Receiver sensitivity, $P_R = -50$ dBm

We know that total optical power loss is given by :

$$P_T = P_S - P_R$$

But,

$$P_T = N_c \ell_c + N_{sp} \ell_{sp} + \alpha_f L + P_{SM}$$

$$\therefore P_S - P_R = N_c \ell_c + N_{sp} \ell_{sp} + \alpha_f L + P_{SM}$$

$$P_S = N_c \ell_c + N_{sp} \ell_{sp} + \alpha_f L + P_{SM} + P_R$$

Since no splices are present.

$$\therefore P_S = N_c \ell_c + \alpha_f L + P_{SM} + P_R$$

$$\therefore P_S = (11 \times 1.3) + (1 \times 5) + 6 + (-50)$$

$$\therefore \mathbf{P_S = -24.7 \text{ dBm}}$$

Ex. 7.2 : In a fiber link, output power of optical source is 5 dBm, source to fiber coupling loss is 3 dB, connector loss of 2 dB, 50 splices with splice loss of 0.1 dB/splice and fiber attenuation for 100 km is 25 dB. Calculate the power margin for :

APD receiver sensitivity of – 40 dBm.

Solution :

Component/Loss parameter	Output/Sensitivity/Loss	Power margin (dB)
Source output	5 dBm	
Receiver sensitivity	– 40 dBm	
Allowed loss [5 – (– 40)]		45
Coupling loss	3 dB	42
Connector loss	2 dB	40
Splicing loss (50 x 0.1)	5 dB	35
Fiber attenuation	25 dB	10 (final margin)

∴ Final power margin is 10 dB which is sufficient margin for this link.

Ex. 7.3 : A 160 m fiber link operating at 850 nm has following data :

a) Fiber loss of 2.5 dB/km.

b) Four connectors with connector loss of 0.7 dB/connector.

c) Receiver sensitivity of – 32 dBm.

d) 5 m optical jumper cable is required at each end i.e. (Transmitter and receiver). Each jumper cable introduces a loss of 3 dB.

e) LASER diode output power - 20 dBm.

Calculate final power margin.

Solution :

Component/Loss parameter	Output/Sensitivity/Loss	Power margin (dB)
Source output	–20 dBm	
Receiver sensitivity	– 32 dBm	
Allowed loss [–20 – (– 32)]		12
Connector loss	2.8 dB	9.2
Jumper Cable loss	6 dB	3.2
Fiber loss (0.160 x 2.5)	0.4 dB	2.8 (final margin)

$\therefore$ Final power margin = **2.8 dB**

Ex. 7.4 : Calculate the power margin of a fiber link having transmitted power of 10 μW and receiver sensitivity of 1 μW.

Solution : Given :

Transmitted optical power, $P_S = 10\,\mu W$

$\therefore\ P_S(dB) = -20\ dBm$

Receiver sensitivity, $P_R = 1\,\mu W$

$P_R(dB) = -30\ dBm$

Power Margin is given by :

$P_T = P_S - P_R$

$\therefore P_T = -20\ dBm - (-30\ dBm) = 10\ dB$

$\therefore$ **Power margin = 10 dB**

Ex. 7.5 : Calculate the receiver sensitivity of an optical link having power margin of 10 dB and transmitted optical power of 25 μW.

Solution : Given :

Power margin, $P_T = 10$ dB

Transmitted optical power, $P_S = 25\ \mu W$

$$\therefore P_s(dBm) = 10\log\left(\frac{25\times10^{-6}}{1\times10^{-3}}\right)$$

$\therefore P_S(dBm) = -16.0206$ dBm

Power Margin is given by :

$P_T = P_S - P_R$

$P_R = P_S - P_T$

$\therefore P_R = -16.0206 - 10 = -26.0206$ dBm

$\therefore$ **Receiver sensitivity = – 26.0206 dBm**

Ex. 7.6 : An engineer has following components available :

a) LASER diode operating at 850 nm and capable of coupling a power of 1 mW into fiber.

b) 10 sections of cable each of which is 500 m long, has attenuation of 4 dB/km and has connectors on both ends.

c) Connector loss of 2 dB/connector

d) PIN photodiode receiver with – 45 dBm sensitivity

e) APD receiver with – 56 dBm sensitivity

Engineer wishes to construct 5 km link operating at 20 Mbps. State which receiver should be used if 6 dB system operating margin is required ?

Solution : Given :

Transmitted optical power, $P_S = 1$ mW

$\therefore\ P_S(dBm) = 0$ dBm

Fiber attenuation, $\alpha_f = 4$ dB/km

Transmission distance, $L = 5$ km

Connector loss, $\ell_c = 2$dB

PIN photodiode receiver sensitivity = – 45 dBm

APD receiver sensitivity = – 56 dBm

System margin, $P_{SM} = 6$ dB

A) PIN Photodiode Receiver

Since 10 sections of 500 m long cable is given :

Hence, 11 connectors are required.

Power margin is given by :

$P_T = P_S - P_R$

OR $P_T = N_c \ell_c + N_{sp} \ell_{sp} + \alpha_f L + P_{SM}$

And assuming no splices, we get,

$\therefore P_S - P_R = N_c \ell_c + \alpha_f L + P_{SM}$

$\therefore 0 - (-45) = (11 \times 2) + (4 \times L) + 6$

$\therefore 45 = 22 + 4L + 6$

$$\therefore L = \frac{45 - 22 - 6}{4}$$

$= 4.25$ km

$\therefore$ Transmission distance of 5 km cannot be met with these components.

b) APD Receiver

$P_S - P_R = N_c \ell_c + \alpha_f L + P_{SM}$

$\therefore 0 - (-56) = (11 \times 2) + (4 \times L) + 6$

$\therefore 56 = 22 + 4L + 6$

$$\therefore L = \frac{56 - 22 - 6}{4}$$

$= 7$ km

$\therefore$ Transmission distance of 5 km can be easily met with these components.

Ex. 7.7 : A 7 km optical fiber link operating at 20 Mbps has following components :

a) LED emitting at 850 nm and launching power of 100 μW including connector loss.

b) Fiber attenuation of 2.6 B/km

c) Connector loss at the receiver is 1.5 dB

d) Splices are used at every km and splice loss of 0.5 dB/splice

e) Receiver sensitivity of – 41 dBm

f) Safety margin is 6 dB

Perform optical power budget and determine the systems viability.

Solution : Given :

Transmitted power (including connector loss).

$P_S = 100\ \mu W$

$P_S(dBm) = -10$ dBm

Component/Loss parameter	Output/Sensitivity/Loss	Power margin (dB)
Source output	–10 dBm	
Receiver sensitivity	– 41 dBm	
Allowed loss [–10 – (– 41)]		31
Coupling loss (7 x 2.6)	18.2 dB	12.8
Splice loss (6 x 0.5)	3 dB	9.8
Connector loss at the receiver	1.5 dB	8.3
Safety Margin	6 dB	2.3

Since the system provides excess power margin of 2.3 dB, it is viable.

7.2.1.3 Rise Time Budget

Rise time budget analysis determines the dispersion limitation of an optical fiber link. In rise time budget analysis overall system rise time is the root mean square of rise times from each contributor to pulse rise time degradation i.e.

$$t_{sys} = \sqrt{\sum_{i=1}^{N} t_i^2} \quad \ldots (7.4)$$

where, t_i = Rise time from each contributor

Main contributors in system speed are :

a) Transmitter rise time t_{TX}

b) Modal dispersion rise time t_{MOD}

c) Group velocity dispersion rise time t_{GVD}

d) Receiver rise time t_{RX}

Now, the overall system rise time is given by :

$$t_{sys} = \sqrt{t_{TX}^2 + t_{MOD}^2 + t_{GVD}^2 + t_{RX}^2} \quad \ldots (7.5)$$

where, all the rise times are in nanoseconds.

For single mode fibers, modal dispersion rise time $t_{MOD} = 0$

Transmitter rise time is determined from light source and its driving circuitry.

Receiver rise time is the time taken by receiver output to increase from 10 % to 90 % of the maximum value of waveform. If B_{RX} is receiver bandwidth in MHz, then the receiver rise time in ns is given by :

$$t_{RX} = \frac{350}{B_{RX}} \quad \ldots (7.6)$$

Modal dispersion rise time for multimode fiber is given by :

$$t_{MOD}(ns) = \frac{440}{B_{MOD}} \quad \ldots (7.7)$$

$$\text{or} \quad t_{MOD}(ns) = \frac{440L^q}{B_0} \quad \ldots (7.8)$$

where, B_{MOD} = Modal dispersion bandwidth

L = Length of fiber

q = Parameter ranging between 0.5 and 1.0

B_0 = Bandwidth of fiber of 1 km

Group velocity dispersion rise time is given by :

$$t_{GVD} = D\,\sigma_\lambda\,L \quad \ldots (7.9)$$

where, D = Dispersion in ns/(nm.km)

σ_λ = Half power spectral width of source

Now, the overall system rise time is given by :

$$t_{sys} = \sqrt{t_{TX}^2 + \left(\frac{440L^q}{B_0}\right)^2 + D^2\sigma_\lambda^2 L^2 + \left(\frac{350}{B_{RX}}\right)^2} \quad \ldots (7.10)$$

❖ Maximum Bit Rate

For RZ format, maximum bit rate or bandwidth is given by :

$$B_{RZ} = \frac{0.35}{t_{sys}} \quad \ldots (7.11)$$

For NRZ format, maximum bit rate is given by :

$$B_{NRZ} = \frac{0.7}{t_{sys}} \quad \ldots (7.12)$$

Ex. 7.8 : A multimode fiber link has following data :

a) LED along with its drive circuit has rise time of 15 ns.

b) Material dispersion rise time of 21 ns

c) Receiver bandwidth of 25 MHz

d) Modal dispersion rise time of 3.8 ns.

Calculate overall system rise time

Solution : Given :

Transmitter rise time, $t_{TX} = 15$ ns

Material dispersion rise time, $t_{MAT} = 21$ ns

Receiver bandwidth, $B_{RX} = 25$ MHz

$$\therefore t_{RX} = \frac{350}{25} = 14 \text{ ns}$$

Modal dispersion rise time, $t_{MOD} = 3.8$ ns

Overall system rise time is given by :

$$t_{sys} = \sqrt{t_{TX}^2 + t_{MAT}^2 + t_{MOD}^2 + t_{RX}^2}$$

$$\therefore t_{sys} = \sqrt{(15\text{ns})^2 + (21\text{ns})^2 + (3.8\text{ns})^2 + (14\text{ns})^2}$$

$$\therefore t_{sys} = 29.6047 \text{ ns}$$

Ex. 7.9 : A 10 km optical fiber link is to be designed. Rise time for chosen components are :
LED source = 10 ns
Intermodal dispersion = 5 ns/km
Intramodal dispersion = 2 ns/km
PIN detector = 8 ns
Calculate the maximum bit rate for RZ and NRZ format.

Solution : Given :

Transmitter rise time, $t_{TX} = 10$ ns

Intermodal dispersion rise time/km = 5 ns/km

∴ Intermodal dispersion rise time for 10 km = 5 x 10

$$\therefore t_{Intermodal} = 50 \text{ ns}$$

Intramodal dispersion rise time per km = 2 ns/km

∴ Intramodal dispersion rise time for 10 km i.e.

$t_{Intermodal} = 2 \times 10 = 20$ ns

Detector rise time, $t_{Detector} = 8$ ns

Overall system rise time is given by :

$$t_{sys} = \sqrt{t_{TX}^2 + t_{Intermodal}^2 + t_{Intramodal}^2 + t_{Detector}^2}$$

$$\therefore t_{sys} = \sqrt{(10 \text{ ns})^2 + (50 \text{ ns})^2 + (20 \text{ ns})^2 + (8 \text{ ns})^2}$$

$$\therefore t_{sys} = 55.3534 \text{ ns}$$

a) Maximum bit rate for RZ format is given by :

$$B_{RZ} = \frac{0.35}{55.3534 \times 10^{-9}} = 6.323 \text{ MHz}$$

$\therefore$ Maximum bit rate = **6.323 Mbps**

b) Maximum bit rate for NRZ format is given by :

$$B_{NRZ} = \frac{0.7}{55.3534 \times 10^{-9}} = 12.646 \text{ MHz}$$

$\therefore$ Maximum bit rate for NRZ format = **12.646 Mbps**

Optical Fiber System Design:

System Design Factors: To achieve high-quality transmission, careful decisions based on operating parameters apply for each component of a fiber optic transmission system.

Factors for Evaluating Fiber Optic System Design are as follows:

System Factors	Considerations/ Choices
Type of Fiber	Single-mode or Multimode
Dispersion	Regenerators or Dispersion Compensation
Fiber Nonlinearities	Fiber Charact., Wavelengths, and Transmitter Power
Operating Wavelength	780, 850, 1310, 1550 nm, and 1625 nm typical.
Transmitter Power	Typically expressed in dBm.
Source Type	LED or Laser
Receiver Sensitivity/Overload Charact.	Typically expressed in dBm.
Detector Type	PIN Diode, APD
Modulation Code	AM, FM, PCM, or Digital
Bit Error Rate (BER) (Digital Systems Only)	10^{-9}, 10^{-12} Typical

System Factors	Considerations/ Choices
Signal-to-Noise Ratio	Specified in decibels (dB).
Number of Connectors	Loss increases with the number of connectors.
Number of Splices	Loss increases with the number of splices.
Environmental Requirements	Humidity, Temperature, Exposure to Sunlight
Mechanical Requirements	Flammability, Indoor/Outdoor Application

RGPVNOTES

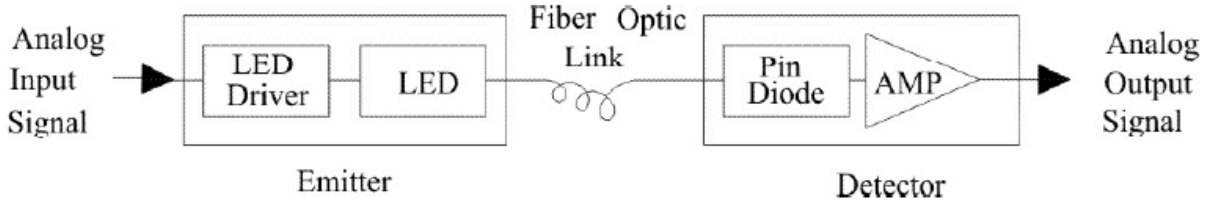
Modulation

In order to transmit information via an optical fiber communication system it is necessary to modulate a property of the light with the information signal. This property may be intensity, frequency, and phase with either digital or analog signals.

The choices are indicated by the characteristics of optical fiber, the available optical sources and detectors, and considerations of the overall system.

Intensity Modulation:

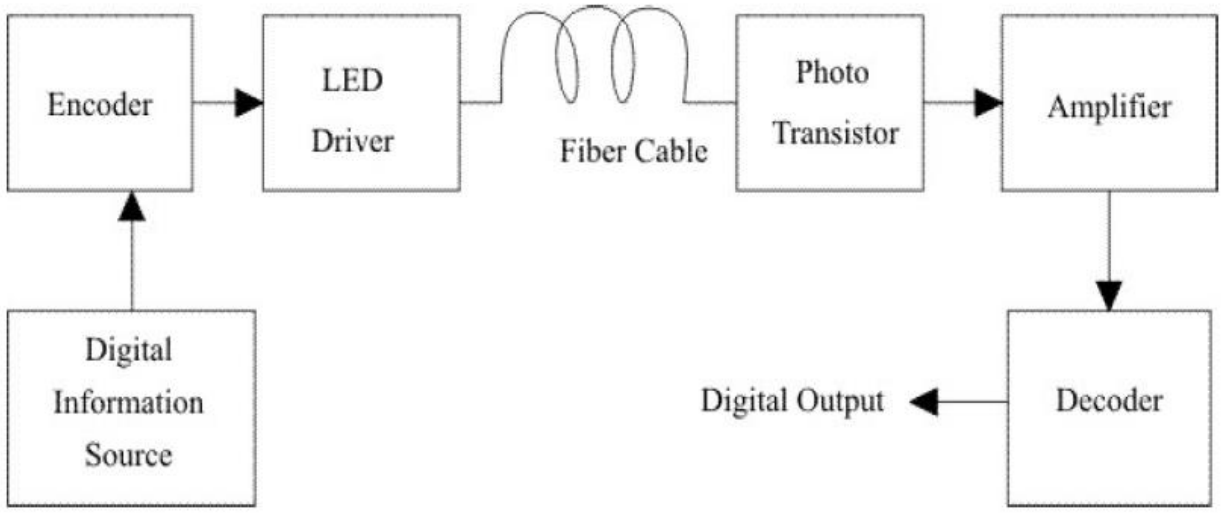
In this system the information signal is used to control the Intensity of the source. At the far end, the variation in the amplitude of the received signal is used to recover the original information signal.



The audio input signal is used to control the current through an LED which in turn controls the light output. The light is conveyed to the detector 1 circuit by optic fiber. The detector is a phototransistor that converts the incoming light to a small current which flows through a series resistor. This gives rise to a voltage whose amplitude is controlled by the received light intensity. The voltage is now amplified within the detector circuit and if necessary, amplified further by amplifier circuit.

Digital Modulation:

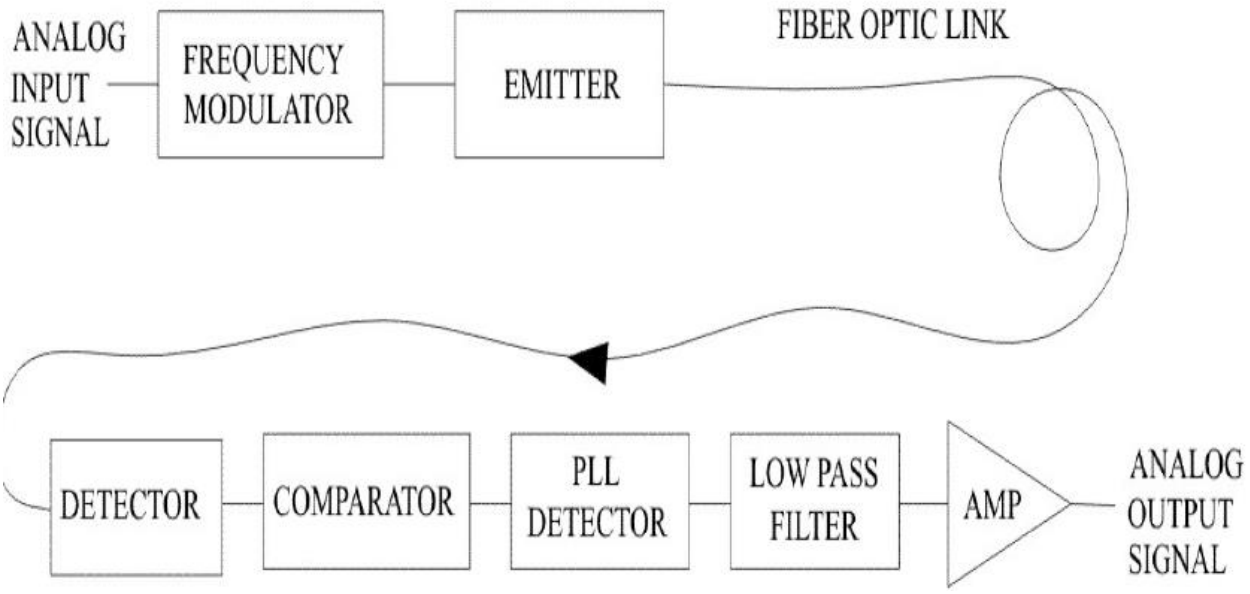
With digital modulation, discrete changes in light intensity are obtained (i.e. 'On-Off' pulses) figure 30 shows a block schematic of a typical digital optical fiber link.



Initially, input digital signal from the information source is suitably encoded for optical transmission. The LED drive circuit directly modulates the intensity of the light with encoded digital signal. Hence, a digital optical signal is launched into the optical fiber cable. An amplifier to provide gain follows the phototransistor used as detector. Finally, the signal obtained is decoded to give the original digital information.

Frequency Modulation:

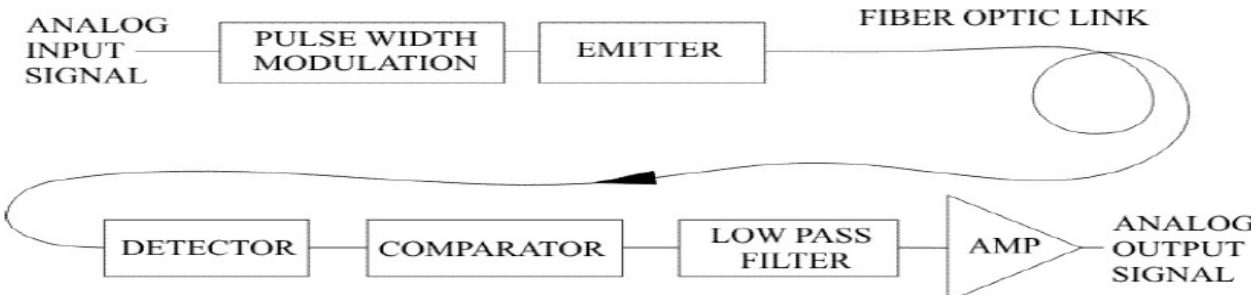
In the traditional form of FM the carrier frequency is changed or modulated by the amplitude of the analog signal. In a fiber optic system this is not feasible since both our light sources; the LED and the LASER are fixed frequency devices. In fiber optic systems FM is achieved by using the original analog input signal to vary the frequency of a train of digital pulses.



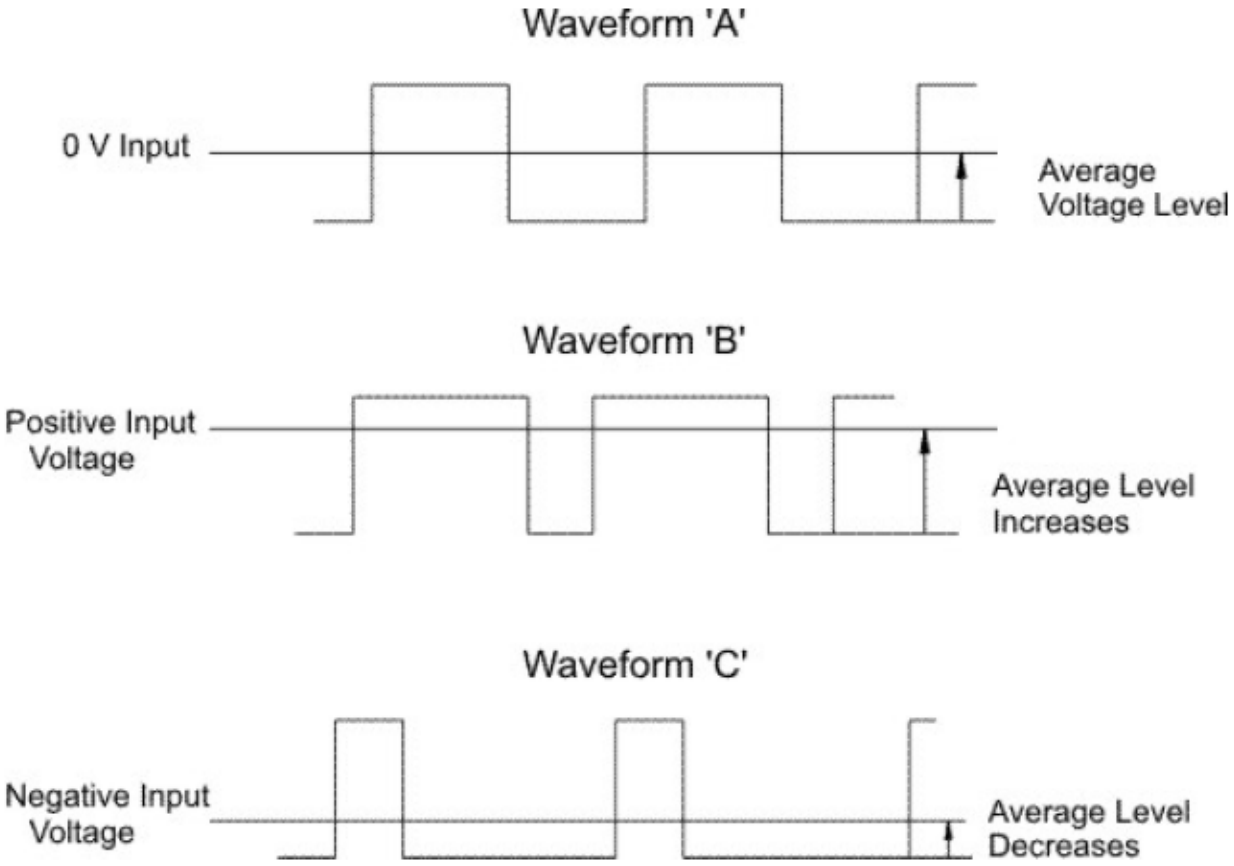
A circuit called Voltage Controlled Oscillator usually abbreviated as VCO achieves this. The digital pulses are communicated through the optic fiber and squared up at the receiver by a comparator in the same way as it was in amplitude modulation system. At this point, we convert the digital train back to the original analog signal by means of the Phase Locked Loop Detector (PLL). The PLL circuit performs a very simple function. It monitors an incoming signal and produces a DC Voltage output. If the input frequency increases, the DC voltage increases. If the frequency decreases, the DC voltage decreases in this way the original analog signal is recovered. The output of the PLL contains many unwanted frequency components. A Low Pass Filter removes these and then finally the signal is amplified to the desired level.

Pulse width modulation:

Pulse width modulation (PWM) is an alternative to frequency modulation. They are both digital transmission. In FM, you will remember, the incoming analog signal is used to change the frequency of the digital stream. In pulse width modulation the amplitude of the analog signal to be transmitted as the changes in the width of the pulse. It is an extremely simple system of modulation. Assume an input signal at zero volts.



The digital stream and the average voltage level would be as shown in figure below.



Pulse Width Modulation

If the input voltage moves to a positive value, the pulse width will increase and since the waveform is 'On' longer than it is 'Off' the average value increases. Similarly, if the input signal goes negative the width of the pulse will decrease. The average value of the digital voltage now decreases. You will now appreciate that the average voltage level is increasing and decreasing in accordance with the input voltage. At the far end of the transmission system the digital pulses are cleaned up by the comparator and then simply passed through a low pass filter. The filter removes the square waves but the average level remains to form the output signal. At this stage, the output signal is increasing and decreasing in step with the input, but you will remember that the 0V input signal produced a DC level at the output. This DC level must now be removed. We do this by means of blocking capacitors at the input to the final amplifier.

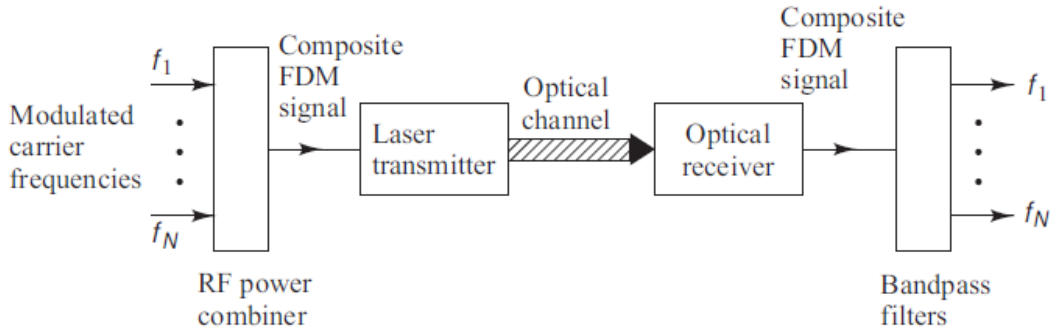
Multi-Channel Transmission

Need:

So far, we have examined only the case of a single signal being transmitted over a channel. In broadband analog applications, such as cable television (CATV) supertrunks, one needs to send multiple analog signals over the same fiber. To do this, one can employ a multiplexing technique where a number of baseband signals are superimposed electronically on a set of N subcarriers that have different frequencies f1, f2, ..., fN. These modulated subcarriers are then combined electrically through frequency-divison multiplexing (FDM) to form a composite signal that directly modulates a single optical source. Methods for achieving this include vestigial-sideband amplitude modulation (VSB-AM), frequency modulation (FM), and subcarrier multiplexing (SCM).

Multichannel Amplitude Modulation

AM is simple and cost-effective in that it is compatible with the equipment interfaces of a large number of CATV customers, but its signal is very sensitive to noise and nonlinear distortion. Although FM requires a larger bandwidth than AM, it provides a higher signal-to-noise ratio and is less sensitive to source nonlinearities. Microwave SCM operates at higher frequencies than AM or FM and is an interesting approach for broadband distribution of both analog and digital signals. To simplify the interface with existing coaxial cable systems, fiber links in CATV networks primarily use the AM-VSB scheme. The initial widespread application of analog fiber optic links, which started in the late 1980s, was to CATV networks. These coax-based television networks operate in a frequency range from 50 to 88 MHz and from 120 to 550 MHz. The band from 88 to 120 MHz is not used, since it is reserved for FM radio broadcast. The CATV networks can deliver over 80 amplitude-modulated vestigial-sideband (AM-VSB) video channels, each having a noise bandwidth of 4 MHz within a channel bandwidth of 6 MHz, with signal-to-noise ratios exceeding 47 dB. To remain compatible with existing coax-based networks, a multichannel AM-VSB format is chosen for the fiber optic system.



Standard technique for frequency-division multiplexing of N independent information-bearing signals

Above Figure depicts the technique for combining N independent messages. An information-bearing signal on channel i amplitude-modulates a carrier wave that has a frequency fi, where i = 1, 2..., N.

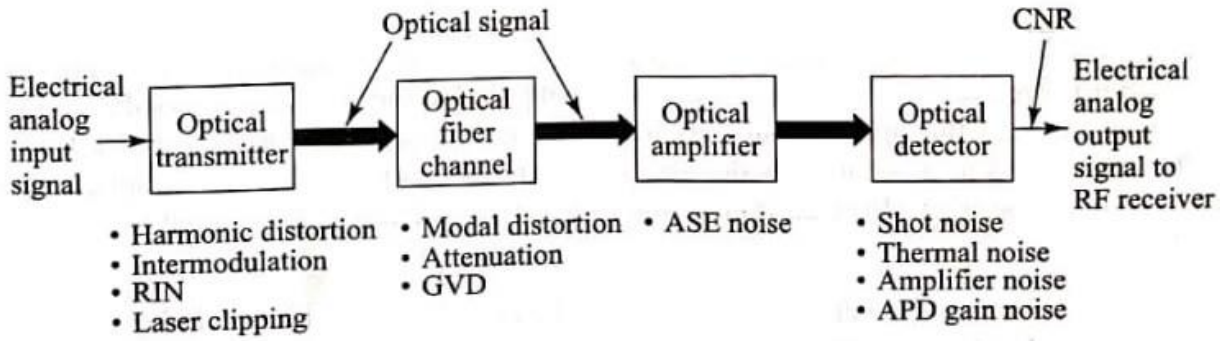
An RF power combiner then sums these N amplitude-modulated carriers to yield a composite frequency-division-multiplexed (FDM) signal that intensity-modulates a laser diode. Following the optical receiver, a bank of parallel bandpass filters separates the combined carriers back into individual channels. The individual message signals are recovered from the carriers by standard RF techniques.

For a large number of FDM carriers with random phases, the carriers add on a power basis. Thus, for N channels the optical modulation index m is related to the per-channel modulation index m_j by

$$m = \left(\sum_{i=1}^{N} m_i^2 \right)^{1/2}$$

When multiple carrier frequencies pass through a nonlinear device such as a laser diode, signal products other than the original frequencies can be produced, these undesirable signals are called Intermodulation Products, and they can cause serious interference in both in-band and out-of-band channels. The result is a degradation of the transmitted signal.

Analog Link in Optical Communication



- However, in many instances, it is more advantageous to transmit information in its original analog form instead of first converting it to a digital format.
- When implementing an analog fiber optic system, the main parameters one needs to consider are the carrier-to-noise ratio, bandwidth, spur free dynamic range, and signal distortion resulting from nonlinearities in the transmission system.
- ***Optical Transmitter*** Image shows the basic elements of an analog link. The transmitter contains either an LED or a laser diode optical source. The analog signal can then be sent using one of several modulation techniques. The simplest form for optical fiber links is direct intensity modulation, wherein the optical output from the source is modulated simply by varying the current around the bias point in proportion to the message signal level. Thus, the information signal is transmitted directly in the baseband. This is done using standard amplitude-modulation (AM), frequency-modulation (FM), or phase-modulation (PM) technique. No matter which method is implemented, one must pay careful attention to signal impairments in the optical source. These include harmonic distortions, intermodulation products, relative intensity noise (RIN) in the laser, and laser clipping.
- ***Fiber Channel*** In relation to the fiber-optic element shown in image, one must take into account the frequency dependence of the amplitude, phase, and group delay in the fiber. Thus, the fiber should have a flat amplitude and group-delay response within the passband required to send the signal free of linear distortion. In addition, since modal-distortion-limited bandwidth is difficult to equalize, it is best to choose a single-mode fiber. The fiber attenuation is also important, since the carrier-to- noise performance of the system will change as a function of the received optical power.
- ***Optical Detector*** The use of an optical amplifier in the link leads to additional noise, known as amplified spontaneous emission (ASE), as is described in this chapter. In the optical receiver, the principal impairments are quantum or shot noise, APD gain noise, and thermal noise.

Error Control

In any digital transmission system, errors are likely to occur even when there is a sufficient signal-to noise ratio to provide a low bit-error rate. The acceptance of a certain level of errors depends on the network user.

For example, digitized speech or video can tolerate occasional high error rates.

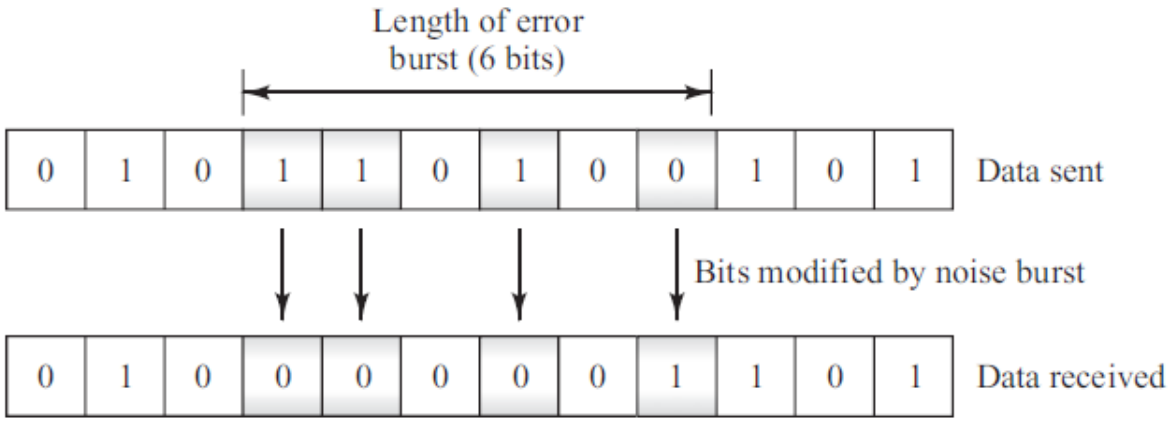
However, applications such as financial transactions require almost completely error-free transmission. In this case, the transport protocol of the network must compensate the difference between the desired and the actual bit-error rates.

To control errors and to improve the reliability of a communication line, first it is necessary to be able to detect the errors and then either to correct them or retransmit the information.

Error detection methods encode the information stream to have a specific pattern. If segments in the received data stream violate this pattern, then ERRORS have occurred.

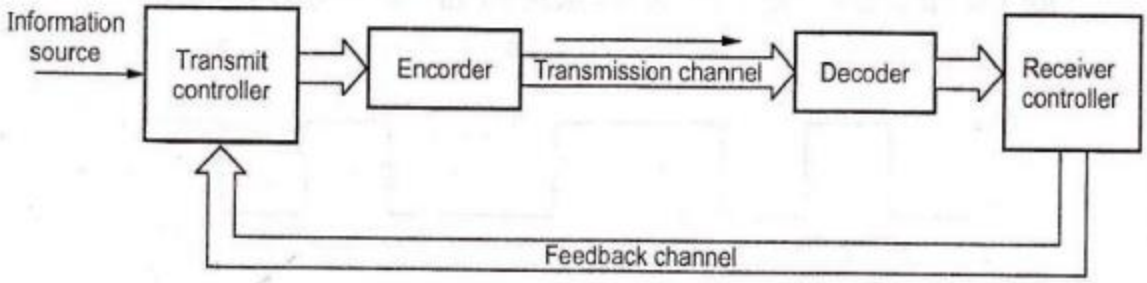
Error Detection

- **Single Bit Error:** An error in a data stream can be categorized as a single-bit error. As its name implies, a single-bit error means that only one bit of a data unit (e.g., a byte, code word, a packet, or a frame) is changed from a 1 to a 0, or vice versa.
- **Burst Error:** A burst error refers to the fact that more than a single bit in a data unit has changed. This type of error happens most often in a typical transmission system because the duration of a noise burst lasts over several bit periods.



Error Correction

- The data transmission reliability of a communication system can be improved by incorporating any of the two schemes Automatic Repeat Request (ARQ) and Forward Error Correction (FEC).
- In ARQ scheme, the information word is coded with adequate redundant bits so as to enable detection of errors at the receiving end. It an error is detected, the receiver asks the sender to retransmit the particular information word.
- Each retransmission adds one round trip time of latency. Therefore ARQ techniques are not used where low latency is desirable. Following figure shows the scheme of ARQ error correction scheme.



ARQ scheme

- Forward Error Correction (FEC) system adds redundant information with the original information to be transmitted. The error or lost data is used reconstructed by using redundant bit. Since the redundant bits to be added are small hence much additional BW is not required.
- Most common error correcting codes are cyclic codes. Whenever highest level of data integrity and confidentiality is needed FEC is considered.

UNIT 5

1. Fiber joints, splices and connectors and couplers.
2. Signal degradation in fibers – Attenuation, dispersion, bending losses, scattering losses, Absorption losses, propagation losses.

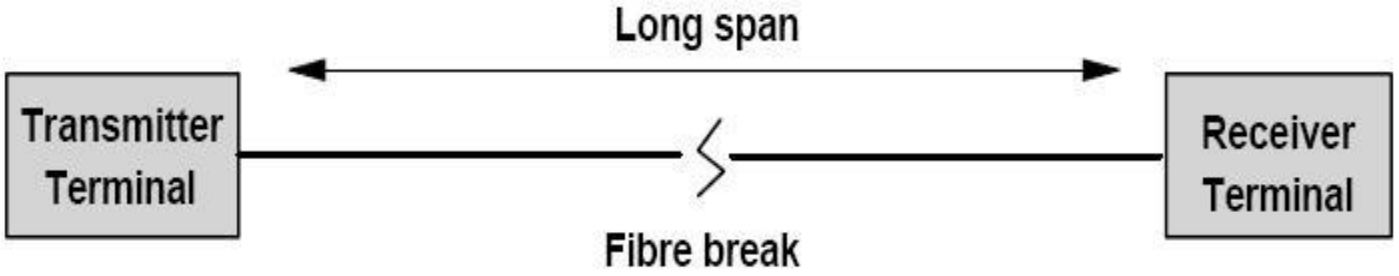
: By Dr. Sanket B. Kasturiwala

Fiber Joints

- Optical fiber links with any line communication system have a requirement for both jointing and termination.
- A single mode fiber has continuous performance length of around 200Km but such fiber spans cannot be installed.

Why we need joints

- Fiber can only be installed in lengths upto 2Km, for longer spans a joint is needed.
- For the repair of damaged fiber.
- For test purpose at terminal equipment.



- All of the fiber cable in a building cannot be installed as one continues cable run.
- Joints are needed to complete network cabling.
- Temporary access is needed for test purposes.

For fiber-fiber connection we need **joints** which are of two major types

– **Permanent Joints : Fiber splicing**

these are semi permanent or permanent joints (like electrical soldered joints)

– **Temporary Joints : Fiber connector / Couplers:**

these are removable joints, easy and fast coupling/uncoupling or mounting/demounting of fibers (like electrical plugs and sockets)

Purpose: fiber to fiber joints are designed to couple ideally all the light in one fiber to adjoining fiber

Fiber Splicing

➢A permanent or semi permanent joint formed between two individual optical fibers in the field or factory is known as a **FIBER SPLICE.**

➢**.** The process of joining is called as **Fiber Splicing**

➢Used to establish long haul optical fiber links.

➢Two types of splicing:

1. **Fusion splicing** *(permanent)*
2. **Mechanical splicing** *(semi permanent)*

(1) Fusion splicing is accomplished by applying localized heat (by flame or electric arc) at the interface between two butted, prealigned fiber end causing them to soften and fuse.

Fibers are positioned and clamped with the help of inspection microscope.

- splice loss: 0.1 dB-0.2dB
- weak in the vicinity of splice, tensile strength reduces

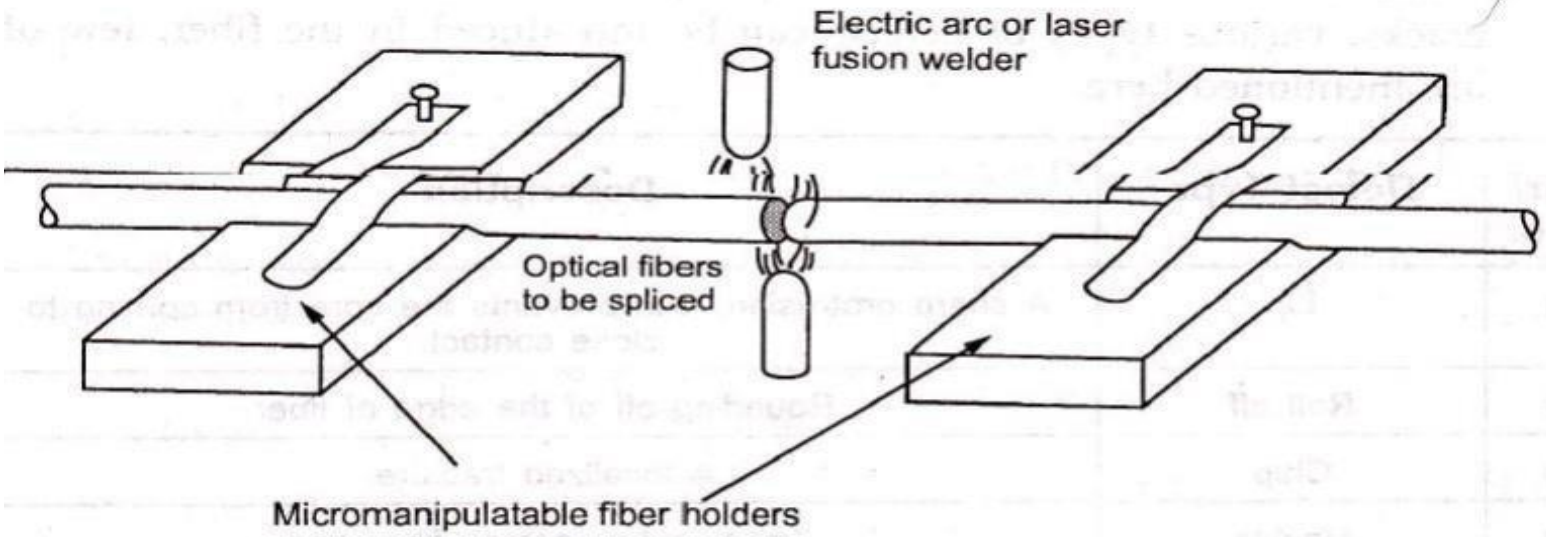
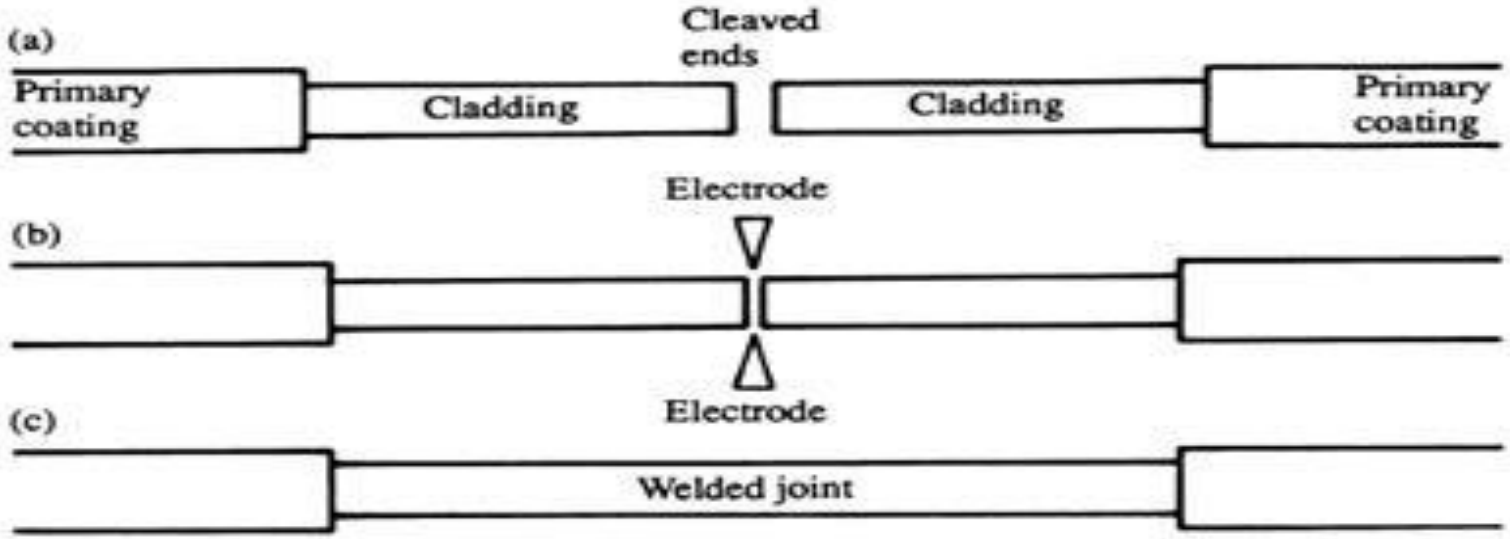


Fig. 4.2.1 Fusion splicing of optical fibers



When to use Fusion splicing technique?

Fusion splicers are used to join the ends of two fibre optics. It is usually done by using an electric arc tip. Modern technologies employ laser welding techniques too for a more clear fusion splicing amalgamation. The fusion splicing method is used in following conditions:

o When a certain part of the fibre cable breaks or cracks

o When the fibre cable portion creates undue resistance to the flow of data or electricity

o When the length of the layout is supposed to be enhanced to connect more points



Why use fusion splicing?

Fusion splicing is the most cost-effective technique used to join two or more fibre optic cables without damaging their physical attributes. Fusion splicing is done due to the following advantages:

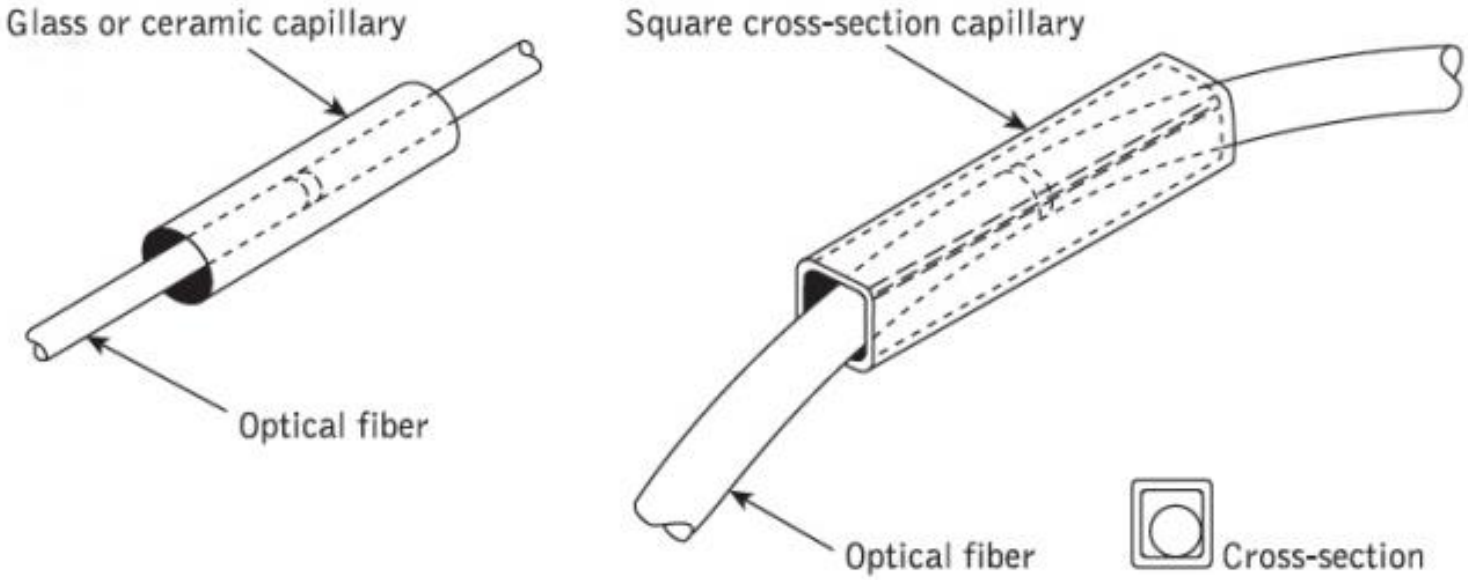
–It has 100 per cent reliability
– It prevents loss of data due to joining barriers
–It offers least order of reflectance
–The Fusion splicing ensures highest order of strength and durability
– It is applicable for both single mode fibre optic cables as well as the multimode ones.

2) In mechanical splicing

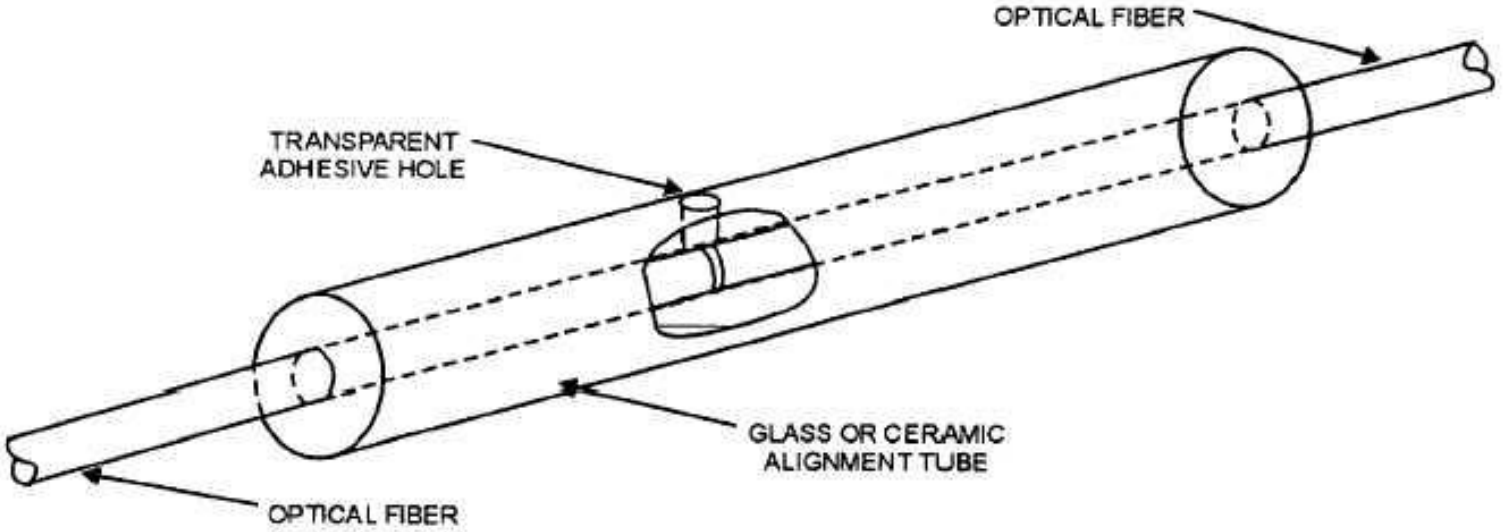
- Mechanical splices are used to create permanent joints between two fibers by holding the fibers in an alignment fixture and reducing loss and reflectance.
- It uses a transparent gel or optical adhesive between the fibers that matches the optical properties of the glass.
- Mechanical splices generally have higher loss and greater reflectance than fusion splices
- Fibers are held aligned by some mechanical means, like, using tubes around fiber ends or V-grooves into which butted fibers are placed.

(A) Glass or Ceramic Alignment Tube Splices Mechanical Splicing

- The inner diameter of this glass or ceramic tube is slightly larger than the outer diameter of the fiber.
- A transparent adhesive is injected into tube and bonds the two fibers together.
- The adhesive also provides index matching between the optical fibers. This technique relies on the inner diameter of the fiber.
- If the inner diameter is too large, splice loss will increase because of fiber misalignment.
- If the inner diameter is too small, it is impossible to insert the fiber into the tube.
- Insertion loss: 0.1 dB – 0.5 dB

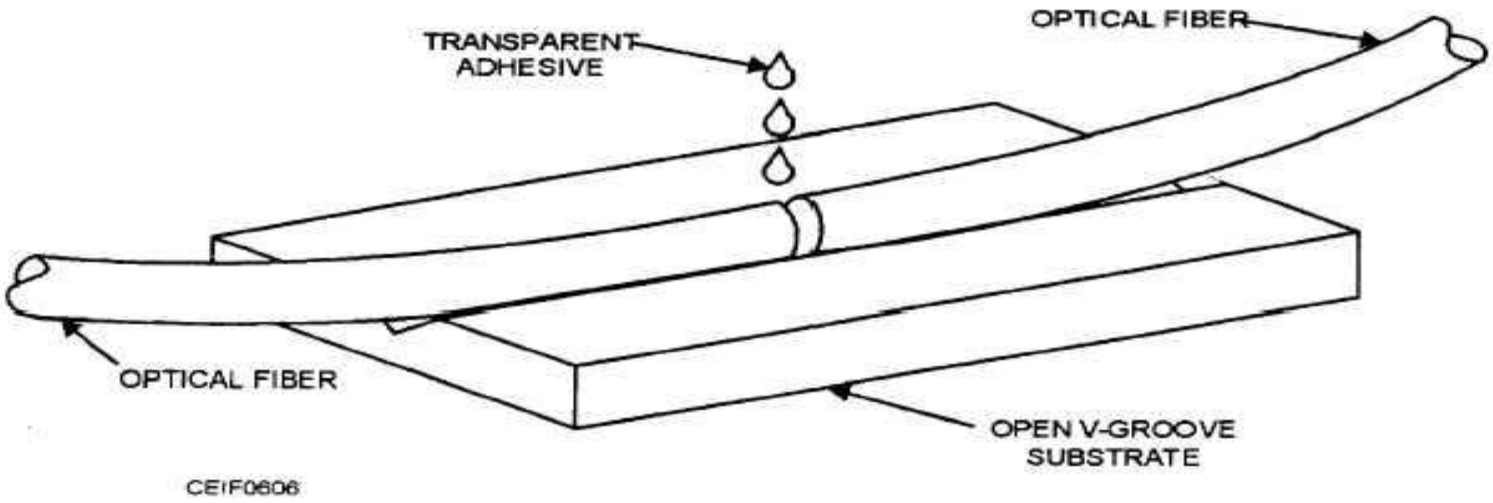


Techniques for tube splicing of optical fibers: (a) snug tube splice; (b) loose tube splice utilizing square cross-section capillary

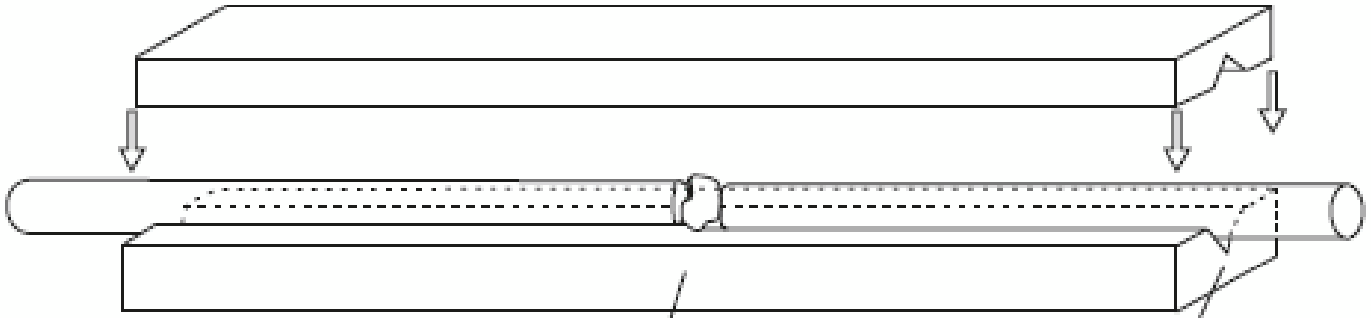


(B) V- groove Mechanical Splicing

- V-Grooved Splicing may involve sandwiching the butted ends of two prepared fibers between a V-Grooved substrate.
- When inserting the fibers into the grooved substrate, the V-Groove aligns the cladding surface of each fiber end.
- A transparent adhesive makes the splice permanent by securing the fiber ends to the grooved substrate.
- Insertion loss: 0.1 dB
- Splice loss depends on fiber size and eccentricity.



A lid is put on top and clipped or glued into place



Typical size: 4 mm × 4 mm × 40 mm

A blob of index matching gel
(or index matching epoxy)

Vee-groove in plastic,
glass or metal

Fiber Connectors

•The optical connectors are generally used to join/remove sources as well as detectors to optical fiber temporarily.

•Some of the principal requirements of a good connector design are as follows:

- Low losses
- Interchangeability
- Ease of assembly
- Low environmental sensitivity
- Low-cost and reliable construction
- Ease of connection
- Very fast installation in comparison with splices.
- Installation procedure should be coomon in all connector types

Fiber Connectors

- Every connector is defined by its **ferrule diameter.**
- Ferrules (made of ceramic) hold the end of the fibers and keeps them aligned.
- There are different connectors for **single mode** and **multi-mode fibers.**
- There are **screw and push pull** connectors.
- Fiber optic connectors are basically classified into :

➢ Butt Joint Connectors ;

➢ Expanded Beam Connectors

Fiber Connector Evaluation

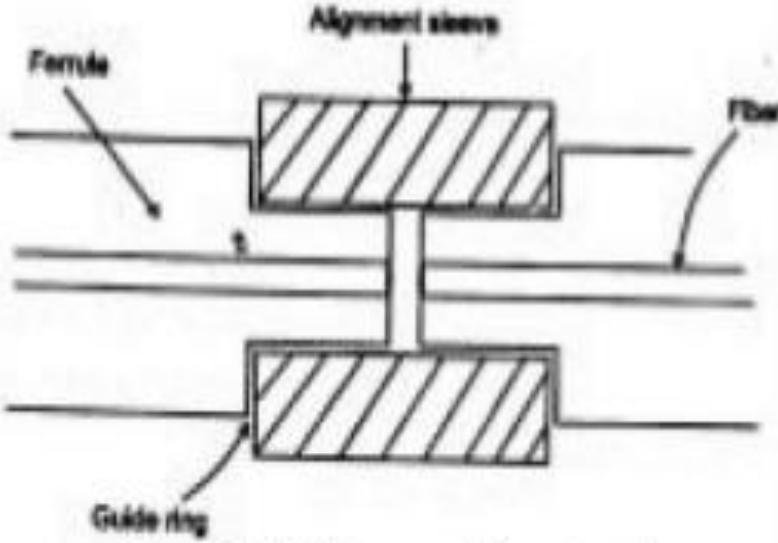
•TWO parameters define the quality of the connector:

- **Insertion loss: The power difference between the source** and the destination fibers (around 0.5dB).
- **Return loss: The amount of reflected power (around 40 –70dB).**

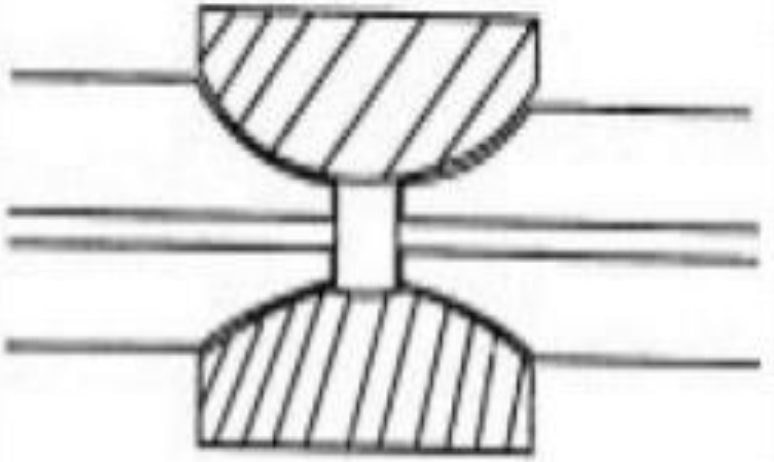
•A high quality connector has low insertion loss and high **absolute return loss value.**

Butt-Joint Alignment Mechanism

- Butt-Joint Alignment type connectors are:
- Straight Sleeve
- Tapered Sleeve
- In the straight sleeve connector, there is a metal, ceramic or molded plastic ferrule for each fiber and the ferrule fits into the sleeve.
- The fiber is epoxied into the drilled hole of the ferrule.
- In the straight sleeve connector or tapered sleeve connector the length of the sleeve and a guide ring on the ferrules determine the end separation of the fibers.
- In the tapered sleeve connector, the ferrules and sleeves are tapered.



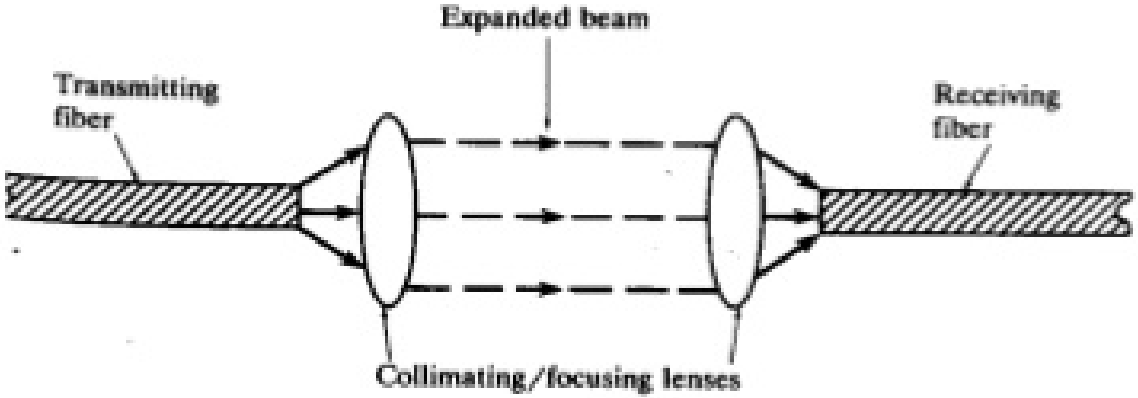
Straight Sleeve Mechanism



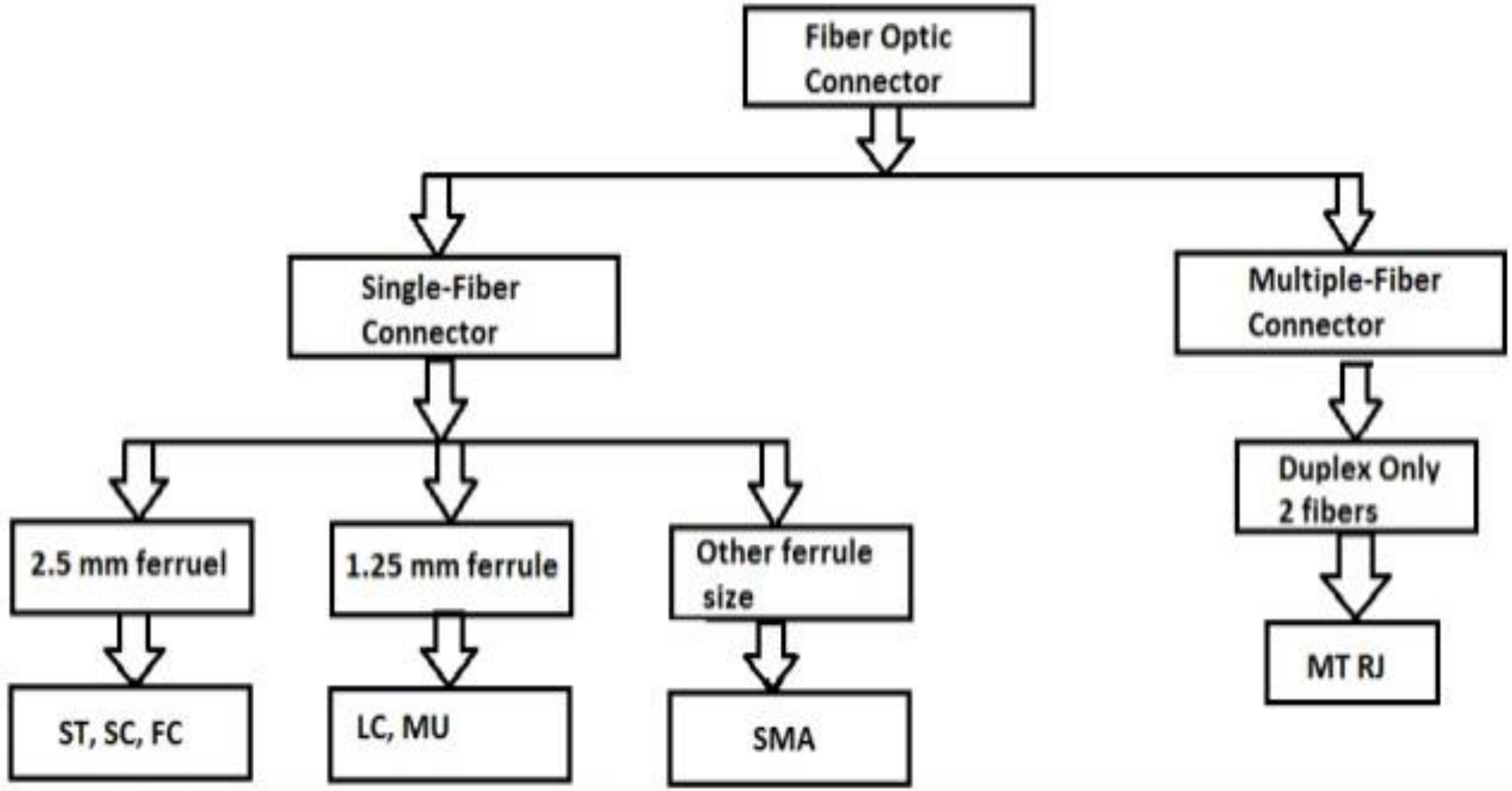
Tapered Sleeve Mechanism

Expanded Beam Fiber Optic connector

- Expanded beam connector employs lenses on the end of the fibers.
- The lenses collimate the light emerging from the transmitting fiber and focuses the beam on the receiving fiber
- The fiber to lens distance is equal to the focal length
- As the beam is collimated so even a separation between the fibers will not make a difference
- Connector is less dependent on the lateral alignment
- Beam splitters or switches can be inserted between the fibers



Classification of Optical Connector:



Types of Optical Connectors

- SC (Subscriber or Square or Standard connector)
- ST (Straight Tip)
- FC (Ferrule Connector or Fiber Channel)

- LC (Lucent Connector)
- MU (Miniature Unit)

- SMA (Subminiature Version A)

- MT-RJ (Mechanical Transfer Registered Jack or Media Termination - Recommended Jack);





Connector Types



ST



SC



FC



LC



MU



ESCON



MTRJ



VF45

Type of Connectors

Most common types:

SC connectors (Square Connector or Subscriber Connector or Standard Connector).



- A push-pull connector
- 2.5mm ferrule diameter
- Extremely common in datacom and telecom.

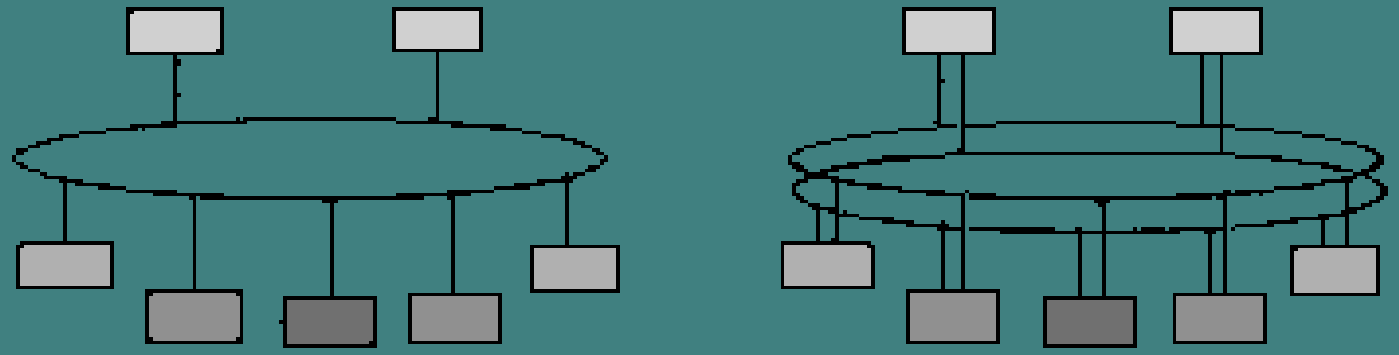
LC connectors (lucent connector, little connector).



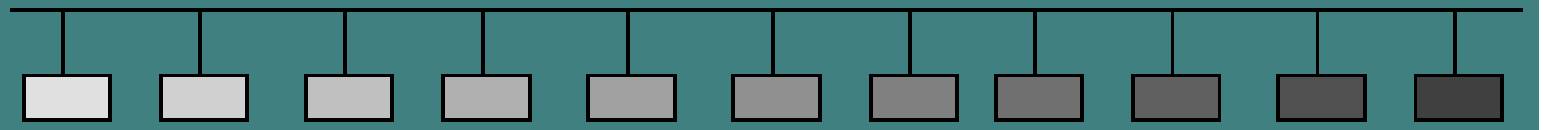
- Half the size of SC.
- 1.25 mm ferrule diameter

Optical Couplers

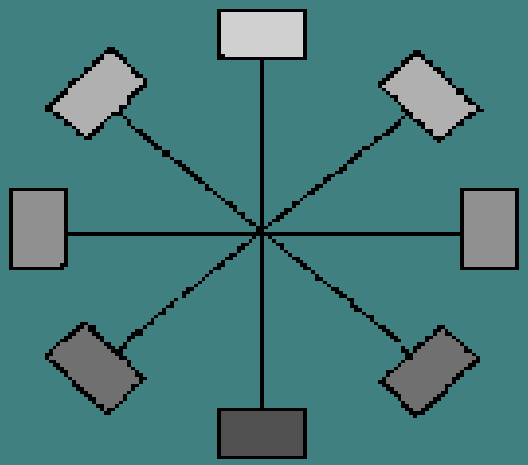
- Some fiber optic links require more than simple point-to-point connections. Such connections are more complex.
- These configurations require devices that can distribute an optical signal from one fiber among two or more fibers.
- These devices are called **Optical couplers.**
- In many cases requires fiber optic components that can redistribute (combine or split) optical signals throughout the system.
- Fiber optic couplers either **split** optical signals into multiple paths or **combine** multiple signals on one path. The number of input and output ports, expressed as an (N x M) configuration, characterizes a coupler .
- Fiber optic couplers attenuate the signal much more than a connector or splice because the input signal is divided among the output ports.
- For example, with a 1 X 2 fiber optic coupler, each output is less than one-half the power of the input signal (over a 3 dB loss).



(A) SINGLE AND DUAL RING ARCHITECTURES



(B) BUS ARCHITECTURE

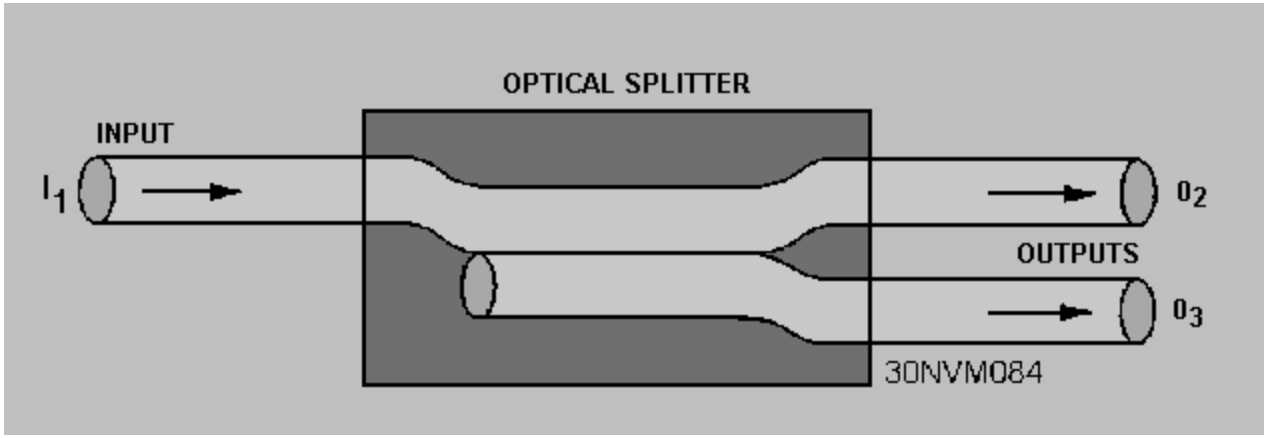


(C) STAR ARCHITECTURE

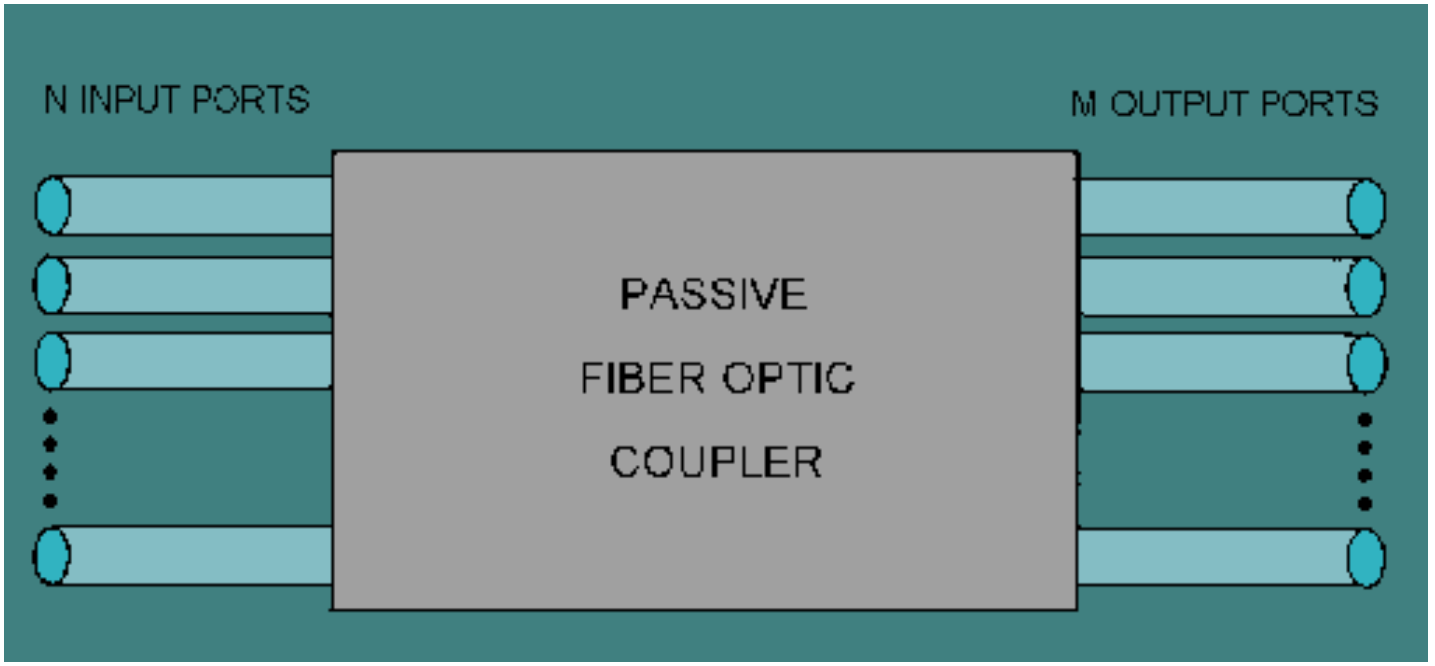
Types of couplers

Optical Splitters:

- The input optical power is normally split evenly between the two output fibers. This type of optical splitter is known as a **Y-coupler**.
- However, an optical splitter may distribute the optical power carried by input power in an uneven manner.
- An optical splitter may split most of the power from the input fiber to one of the output fibers. Only a small amount of the power is coupled into the secondary output fiber. This type of optical splitter is known as a **T-coupler**, or an optical tap.



- An **optical splitter** is a passive device that splits the optical power carried by a single input fiber into two output fibers.



2 x 2 Fiber Coupler

- A device with two inputs and tow outputs is called as 2 x 2 coupler. Fig. shows 2 x2 fiber coupler.

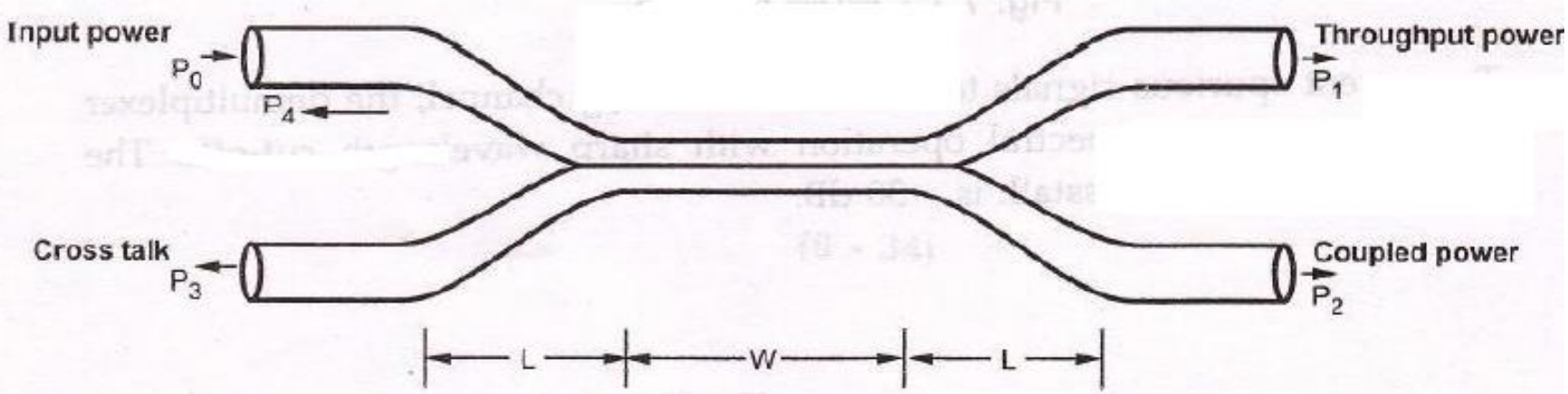


Fig 2×2 fiber coupler

- Fused biconically tapered technique is used to fabricate multiport couplers (directional coupler)
- The input and output port has long tapered section of length 'L'.
- The tapered section gradually reduced and fused together to form coupling region of length 'W'.
- Input optical power : P_0. Throughput power : P_1.
- Coupled power : P_2. Cross talk : P_3.
- Power due to reflection : P4.

Performance Parameters of Optical Coupler

1. Splitting ratio / coupling ratio

- Splitting ratio is defined as –

$$\text{Splitting ratio} = \left(\frac{P_2}{P_1 + P_2}\right) \text{x } 100\%$$

2. Excess loss:

- Excess loss is defined as ratio of input power to the total output power. Excess is expressed in decibels.

$$\text{Excess loss} = 10 \log\left(\frac{P_0}{P_1 + P_2}\right)$$

Performance Parameters of Optical Coupler

3. Insertion loss:

- Insertion loss refers to the loss for a particular port to port path. For path from input port I to output port j.

$$\text{Insertion loss} = 10 \log \frac{P_1}{P_2}$$

4. Cross talk :

- Cross talk is a measure of degree of isolation between input port and power scattered or reflected back to other input port.

$$\text{Cross talk} = 10 \log \left(\frac{P_3}{P_0} \right)$$

For a 2 x 2 fiber coupler, input power is 200 μW, throughput power is 90 μW, coupled power is 85 μW and cross talk power is 6.3 μW. Compute the performance parameters of the fiber coupler.

Solution : P0 = 200 μW

P1 = 90 μW

P2 = 85 μW

P3 = 6.3 μW

i) $$\text{Coupling ratio} = \left(\frac{P_2}{P_1 + P_2}\right) \times 100\%$$

$$\text{Coupling ratio} = \frac{85}{(95+85)} \times 100\%$$

Coupling ratio = **48.75 %**

ii) $$\text{Excess ratio} = 10 \log\left(\frac{P_0}{P_1 + P_2}\right) \text{dB}$$

$$\text{Excess ratio} = \mathbf{0.5799\ dB}$$

iii)iii) $$\text{Insertion loss} = 10 \log\left(\frac{P_0}{P_1}\right) \text{dB}$$

(For port 0 to port 1)

$$= 10 \log \frac{200}{90}$$

$$= \mathbf{3.46\ dB}$$

iv) $$\text{Cross talk} = 10 \log\left(\frac{P_3}{P_0}\right)$$

$$= 10\ log\left(\frac{6.3 \times 10^{-6}}{200}\right)$$

$$= \mathbf{-45\ dB}$$

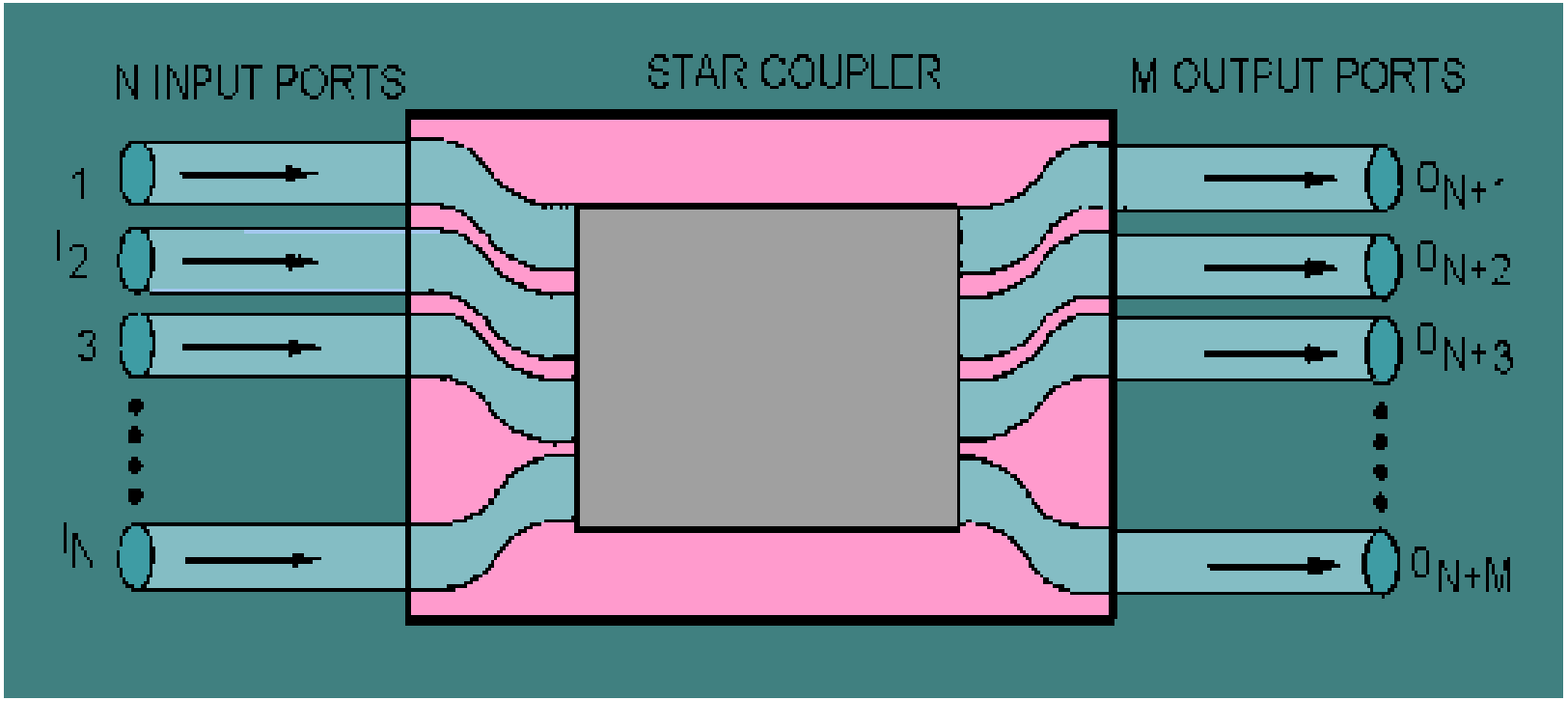
$$\text{Insertion loss} = 10 \log\left(\frac{P_0}{P_2}\right) \text{dB}$$

(For port 0 to port 2)

$$= 10 \log\left(\frac{P_0}{P_2}\right) \text{dB}$$

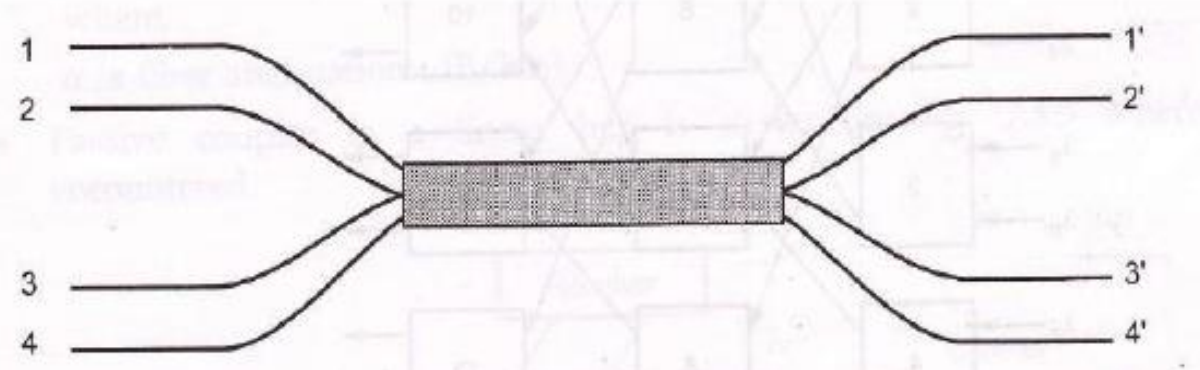
$$= \mathbf{3.71\ dB}$$

Star Coupler



Star Coupler

- Star coupler is mainly used for combining optical powers from N-inputs and divide them equally at M-output ports.
- The fiber fusion technique is popularly used for producing N x N star coupler. Fig. shows a 4 x 4 fused star coupler.



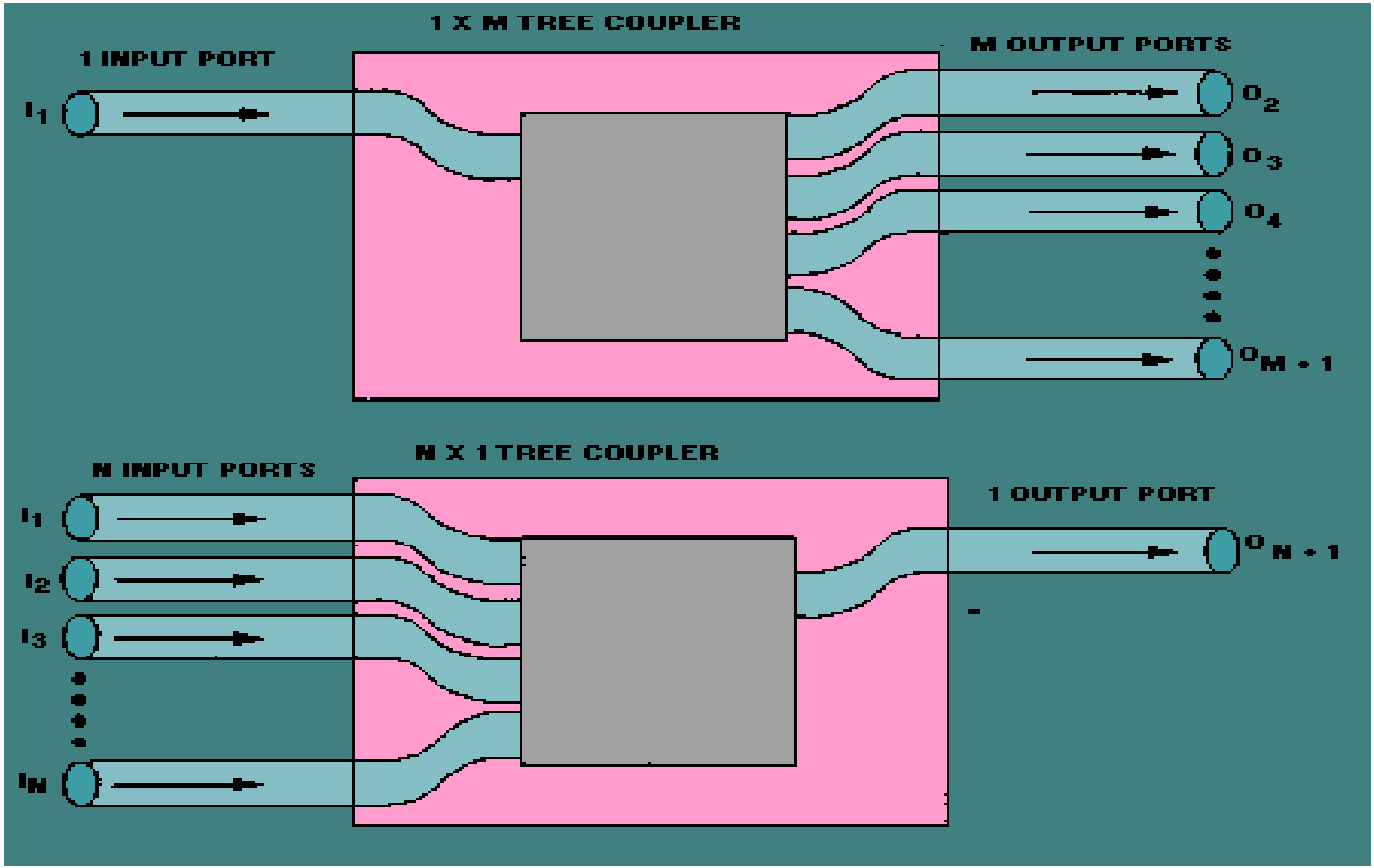
4×4 fused fiber star coupler

- The optical power put into any port on one side of coupler is equally divided among the output ports. Ports on same side of coupler are isolated from each other.
- Total loss in star coupler is constituted by splitting loss and excess loss.

$$\text{Solitting loss} = -10\log\left(\frac{1}{N}\right) = 10\log N$$

$$\text{Excess loss} = 10\log\left(\frac{P_{in}}{\sum_{i=1}^{N} P_{out,i}}\right)$$

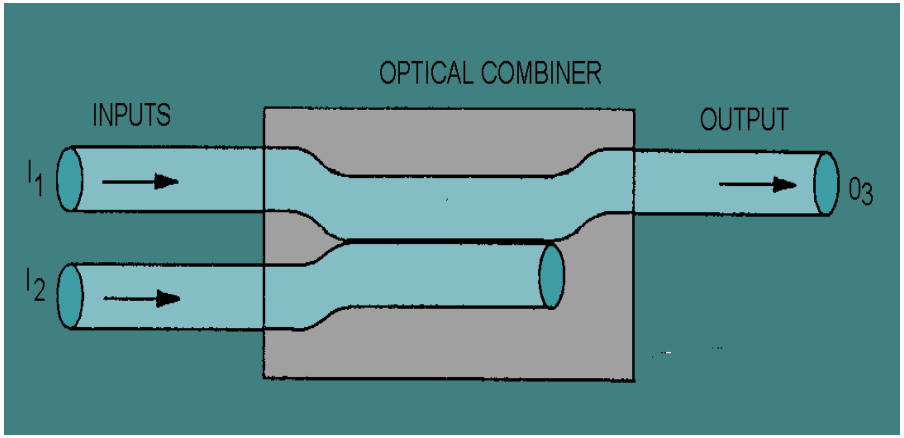
Tree Coupler



(1 X M) and (N X 1) tree coupler designs.

Optical Combiners:

An **optical combiner** is a passive device that combines the optical power carried by two input fibers into a single output fiber.



An **X coupler** combines the functions of the optical splitter and combiner.

The X coupler combines and divides the optical power from the two input fibers between the two output fibers.

Another name for the X coupler is the ***2 X 2 coupler.***

Fiber joint loss

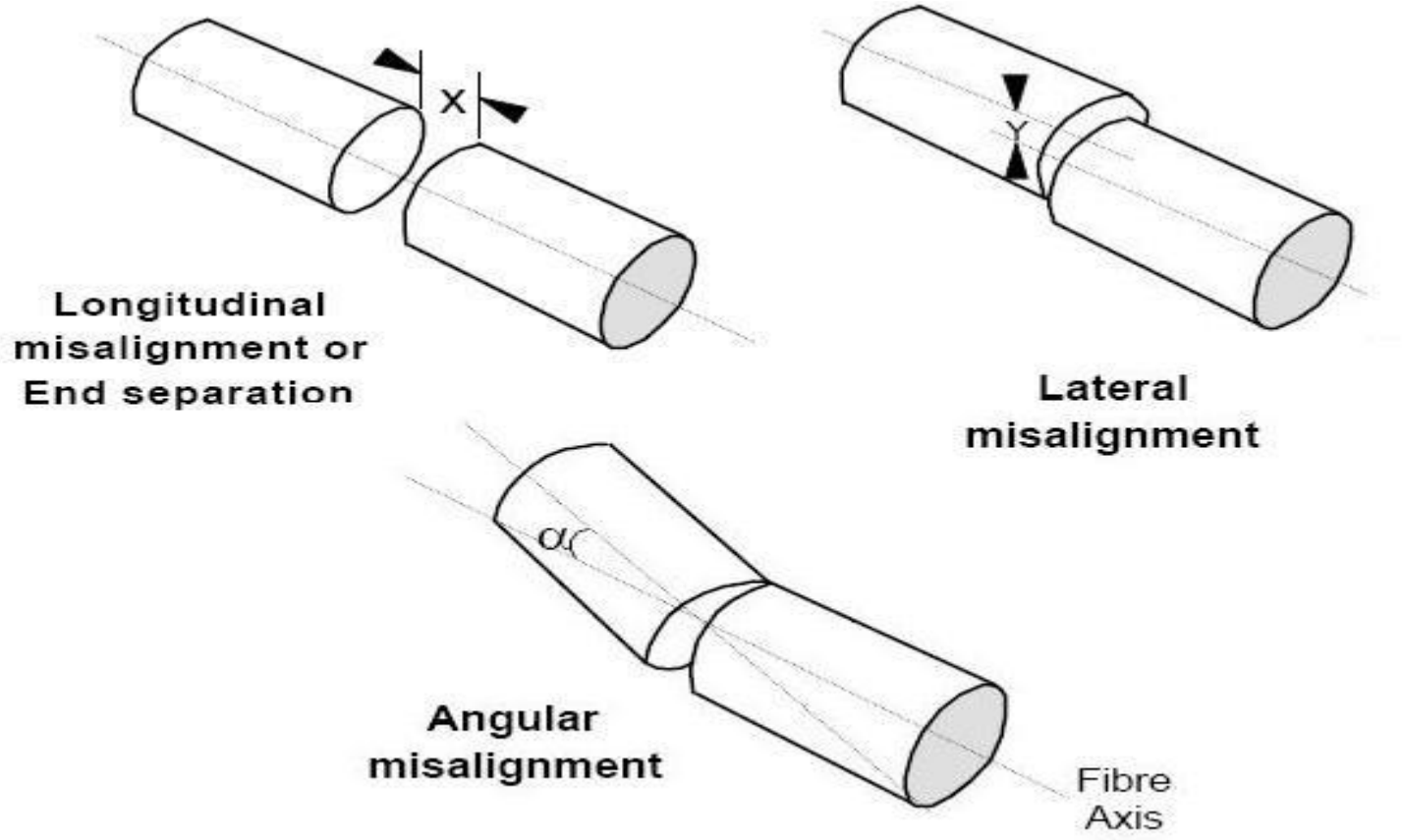
- In fiber-fiber connection, the optical loss encountered at interface.
- The loss in optical power through a connection is defined as

$$\text{loss} = 10 \log_{10} \frac{P_i}{P_o}$$

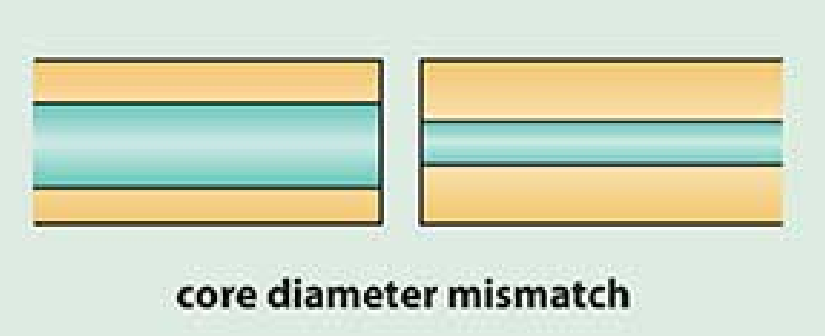
Po is the power emitted from the source fiber

Pi is the power accepted by the connected fiber

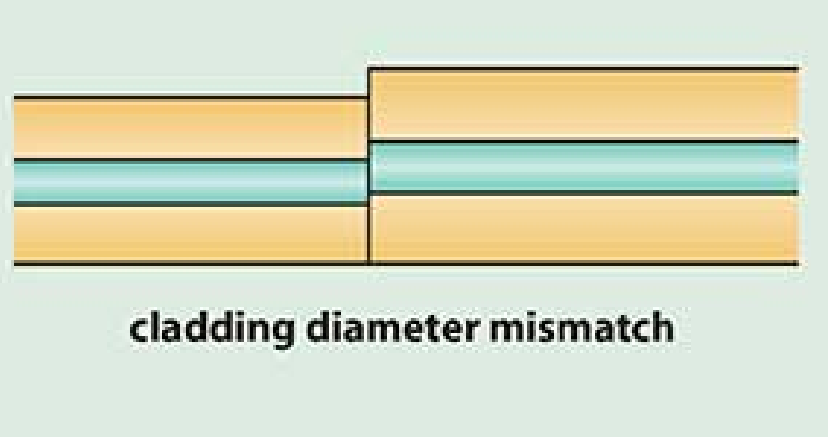
Types of Fiber core (Mechanical) Misalignment Loss



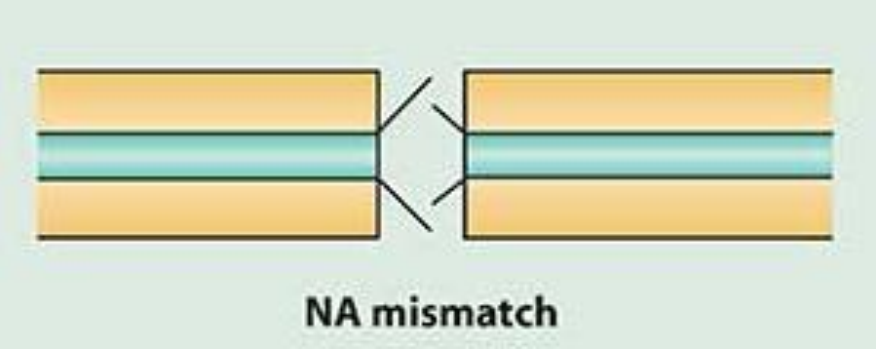
Fiber Parameter Mismatch Loss (Fiber – to – Fiber Loss)



core diameter mismatch



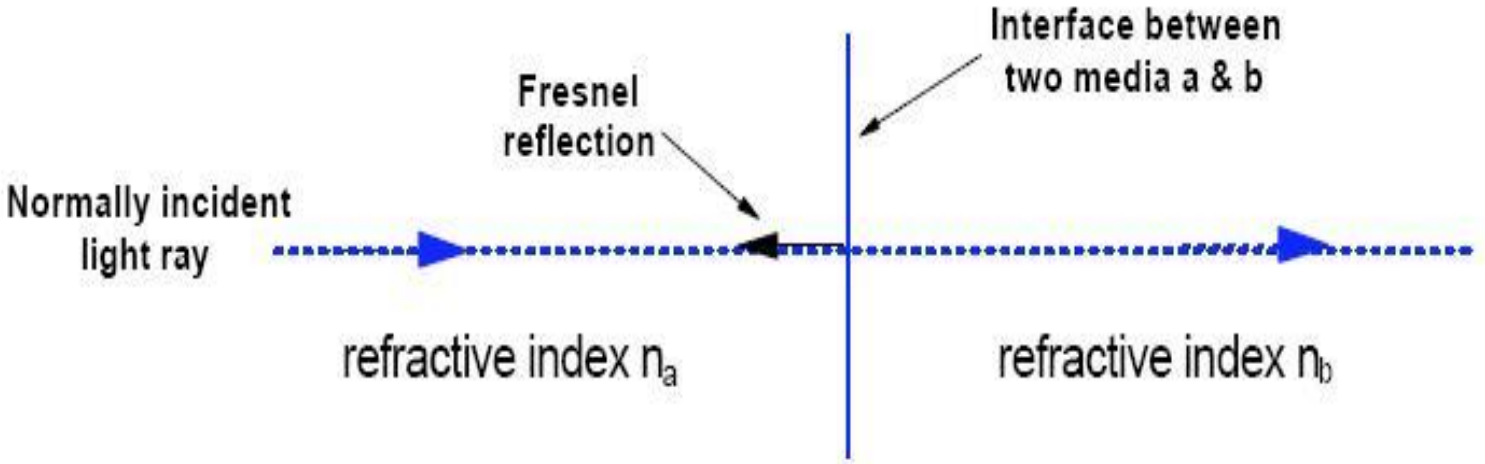
cladding diameter mismatch



NA mismatch

Fresnel Loss (Return Loss)

•When optical fibers are connected, optical power may be reflected back into the source fiber.
•Light that is reflected back into the source fiber is lost.
•This reflection loss, called **Fresnel reflection**, occurs at every fiber interface.



Fraction of light reflected at the interface

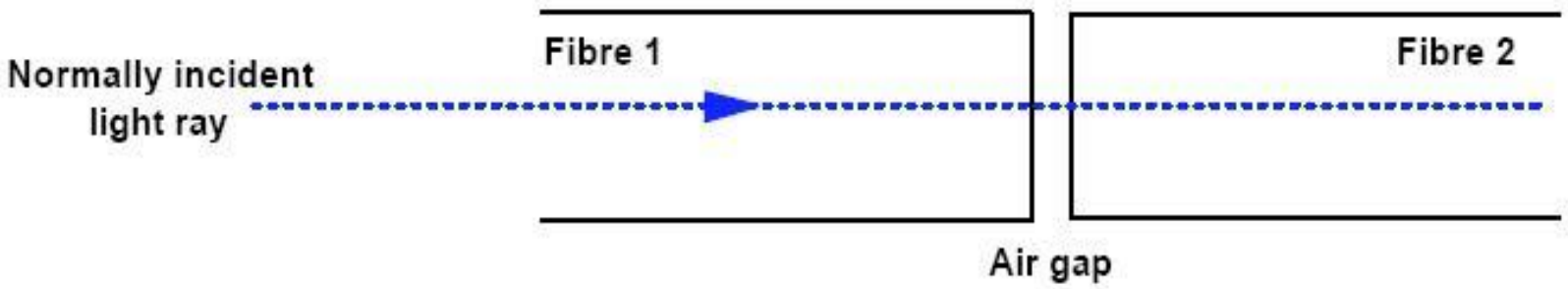
$$r = \frac{(n_a - n_b)^2}{(n_a + n_b)^2}$$

Fresnel loss in dB at the interface =

$$-10 \log_{10}\left[1 - r\right] = -10 \log_{10}\left[1 - \frac{(n_a - n_b)^2}{(n_a + n_b)^2}\right]$$

Fresnel Loss

- Typically Fresnel loss or reflection occurs at joints with an air gap
- For a fibre joint loss occurs twice, once at each fibre-air interface.
- This is accounted by doubling single interface loss (20 not 10 in the dB formula)



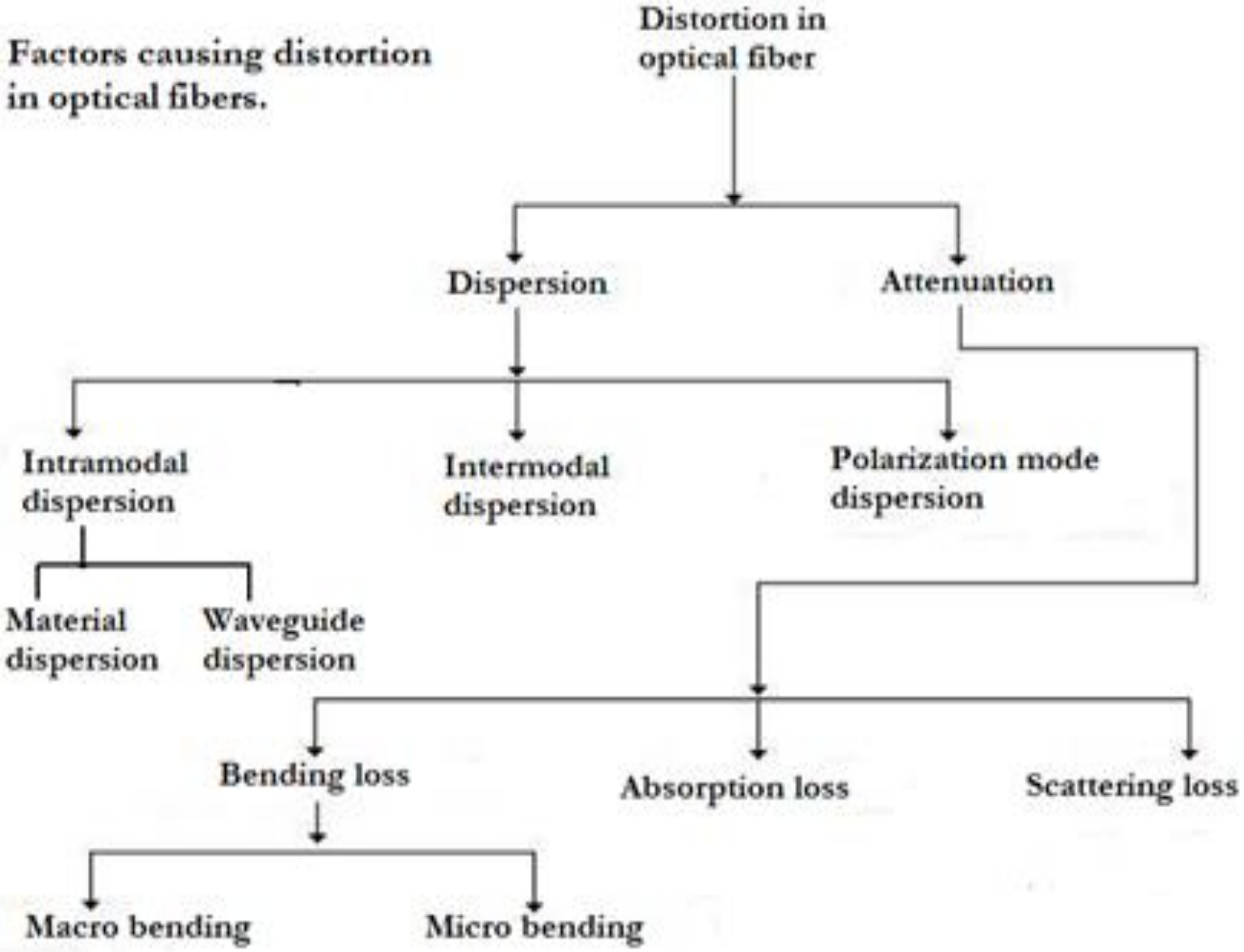
n_1 core refractive index n_0 refractive index of air

$$\text{Total Fresnel loss in dB} = -20 \log_{10}\left[1 - \frac{(n_1 - n_0)^2}{(n_1 + n_0)^2}\right]$$

➢**To reduce the amount of loss from Fresnel reflection, the air gap can be filled with an index matching gel.**

➢**The refractive index of the index matching gel should match the refractive index of the fiber core.**

Factors causing distortion in optical fibers.



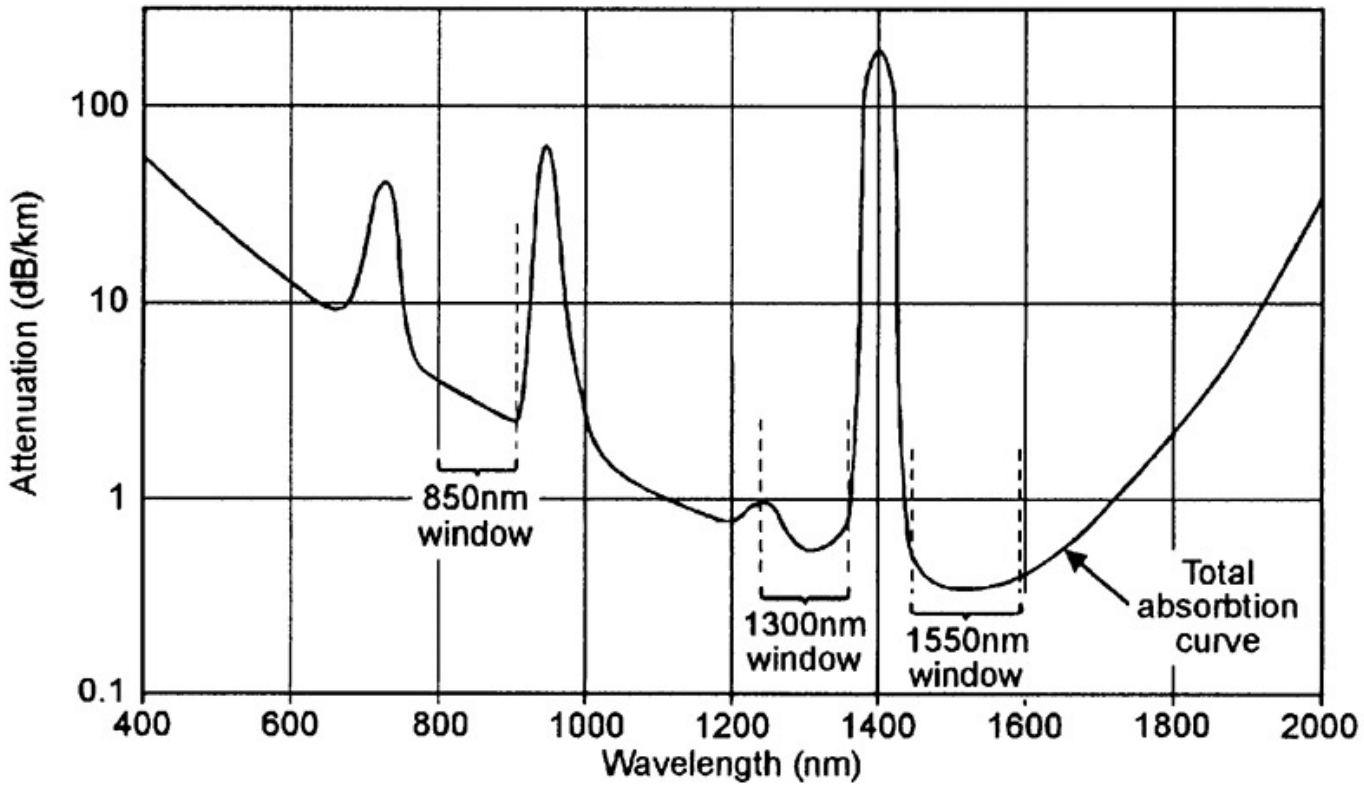
Attenuation

- Attenuation is the loss of power as the light travels inside the fiber.
- Attenuation limits the optical power which can reach the receiver, limiting the operating span of a system.
- Once the power of an optical pulse is reduced to a point where the receiver is unable to detect the pulse, an error occurs.
- **Attenuation is defined as the ratio of optical input power (Pi) to the optical output power (Po).**

$$\alpha = \frac{10}{L} \log_{10} \frac{P_i}{P_0}$$

- This relation defines the signal attenuation coefficients **α** in terms of length of fiber **L,** with units **dB/Km.**
- **example:** Signal's input power is 400W and the power at the receiver is 100W. The length of the fiber is 1Km.

attenuation = 10/1 * log(400/100) = 6 dB / Km



850 nm- 2.5 to 3.0 dB/km

1310 nm- 0.4 to 0.5 dB/km

1550 nm- 0.25 to 0.3 dB/km

Types of Attenuation

- **Absorption Loss:**

  Caused by the fiber itself or by impurities in the fiber, such as water and metals *(Dispersion)*

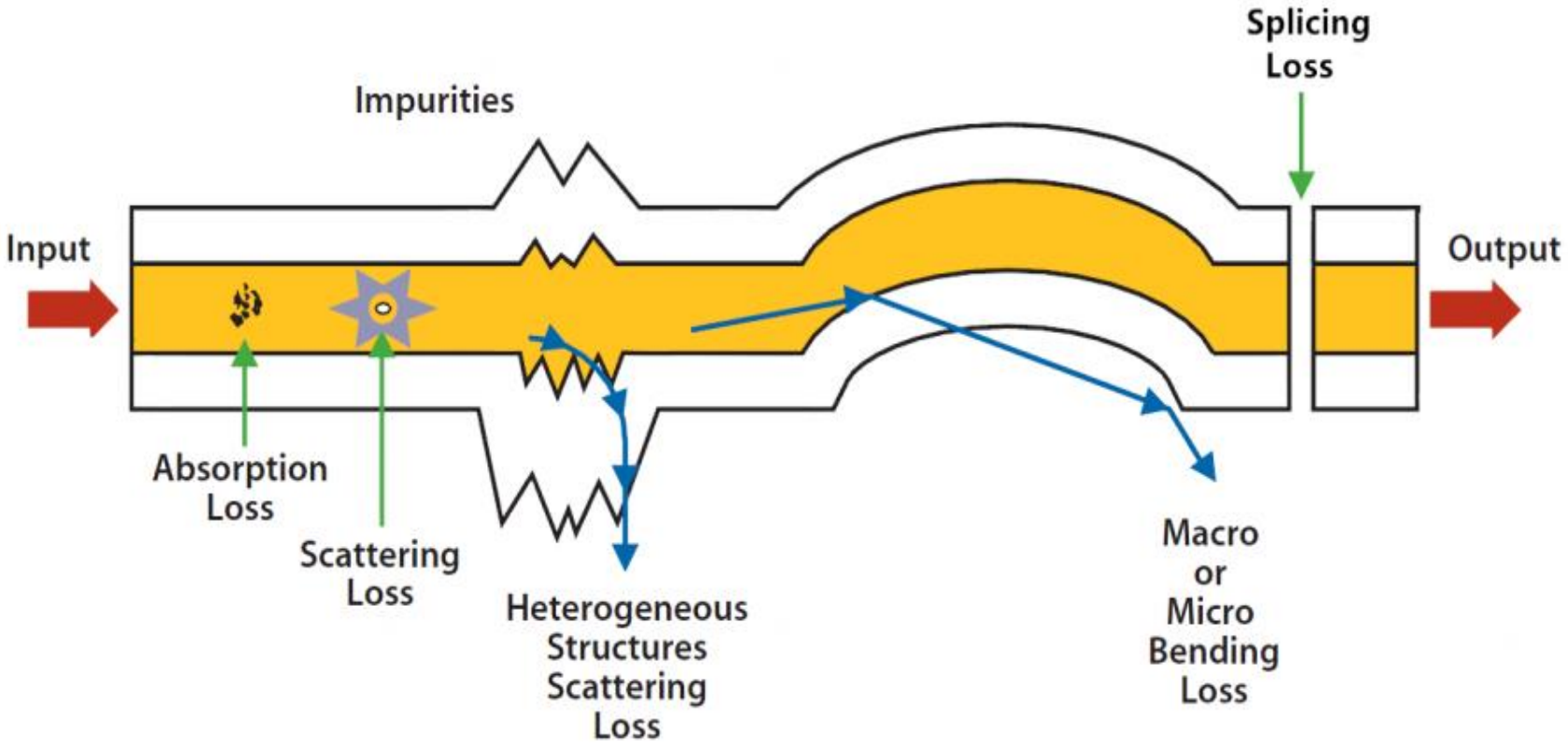
- **Radiation/Bending loss:**

  Loss induced by physical stress on the fiber*(micro bending or macro bending loss).*

- **Scattering Loss:**

  Intrinsic loss mechanism caused by the interaction of photons with the glass itself.

- **Splicing/Coupling Loss:**


Splicing
Loss
Impurities
Input
Output
Absorption
Loss
Scattering
Loss
Heterogeneous
Structures
Scattering
Loss
Macro
or
Micro
Bending
Loss

Signal Degradation Due to absorption Loss

Material Absorption Losses

- Material absorption is caused by absorption of photons within the fiber.
  - – When a material is illuminated, photons can make the valence electrons of an atom transition to higher energy levels
  - – Photon is destroyed, and the radiant energy is transformed into electric potential energy. This energy can then
    - Be re-emitted (scattering)
    - Frees the electron (photoelectric effects) (not in fibers)
    - Dissipated to the rest of the material (transformed into heat)
- In an optical fiber Material Absorption is the optical power that is effectively converted to heat dissipation within the fiber.
- **Two types of absorption exist:**
  - – **Intrinsic Absorption, caused by interaction with one or more of the** components of the glass.
  - – **Extrinsic Absorption, caused by impurities within the glass.**

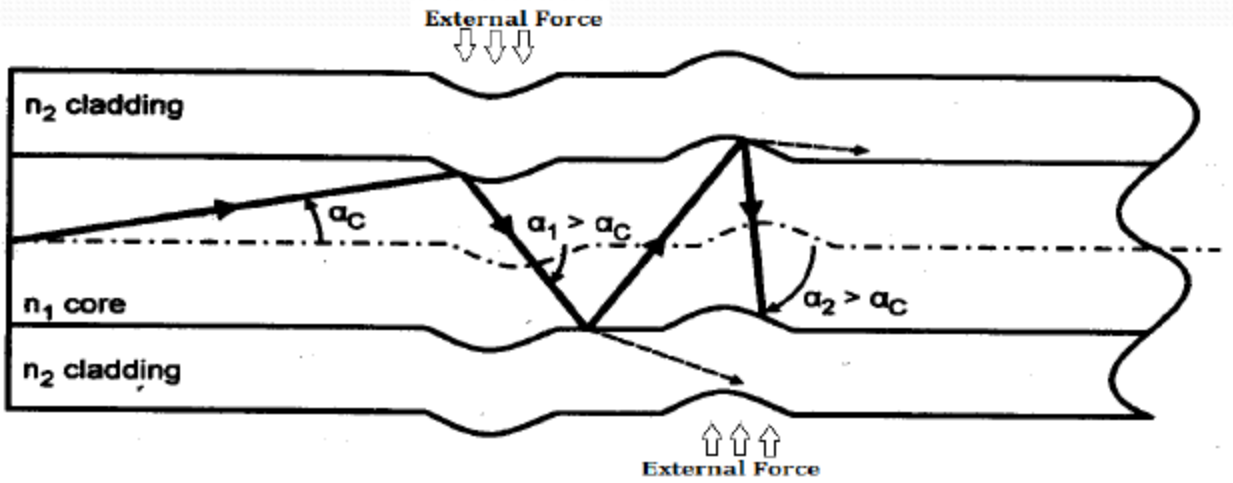
Signal Degradation Due to Bending Loss

Radiation/Bending Loss

Bending loss is classified according to the bend radius of curvature :

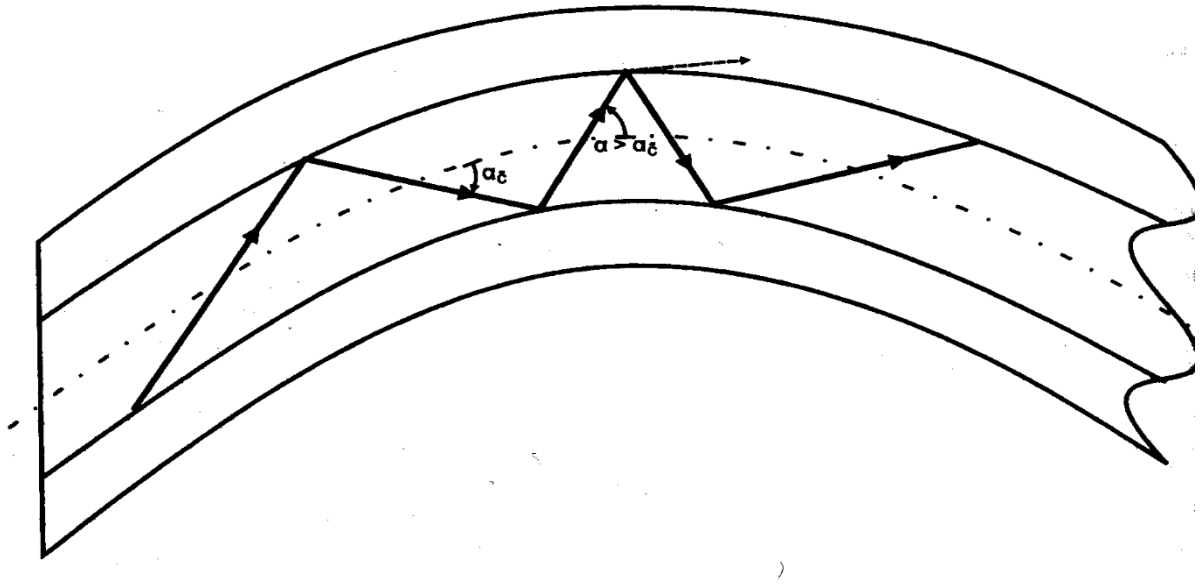
1. **Microbend Loss and**
2. **Macrobend Loss**

- **Microbend Loss** are caused by small discontinuities or imperfections in the fiber. Uneven coating applications and improper cabling procedure, external temp. factor increases micro bend loss. External forces are also a source of micro bends. This effect loss can be minimized during installation and testing.



Bending Loss

➢**Macrobend Losses** are observed when a fiber bend's radius of curvature is large compared to the fiber diameter. These bends are a great source of loss when the radius of curvature is less than several centimeters.



All both types of losses can be minimized by strengthening and flattening the fiber cable.

Signal Degradation due to Scattering Loss

Scattering of Light



Molecules and small particles in the atmosphere change the direction of light rays, causing them to scatter and resulting in colorful sunsets.

Scattering Loss

➢**Light scattering is a form of scattering in which light in the form of propagating** energy is scattered.

➢Light scattering can be thought of as the deflection of a ray from a straight path, for example by irregularities in the propagation medium, particles, or in the interface between two media.

➢Deviations from the law of reflection due to irregularities on a surface are also usually considered to be a form of scattering.

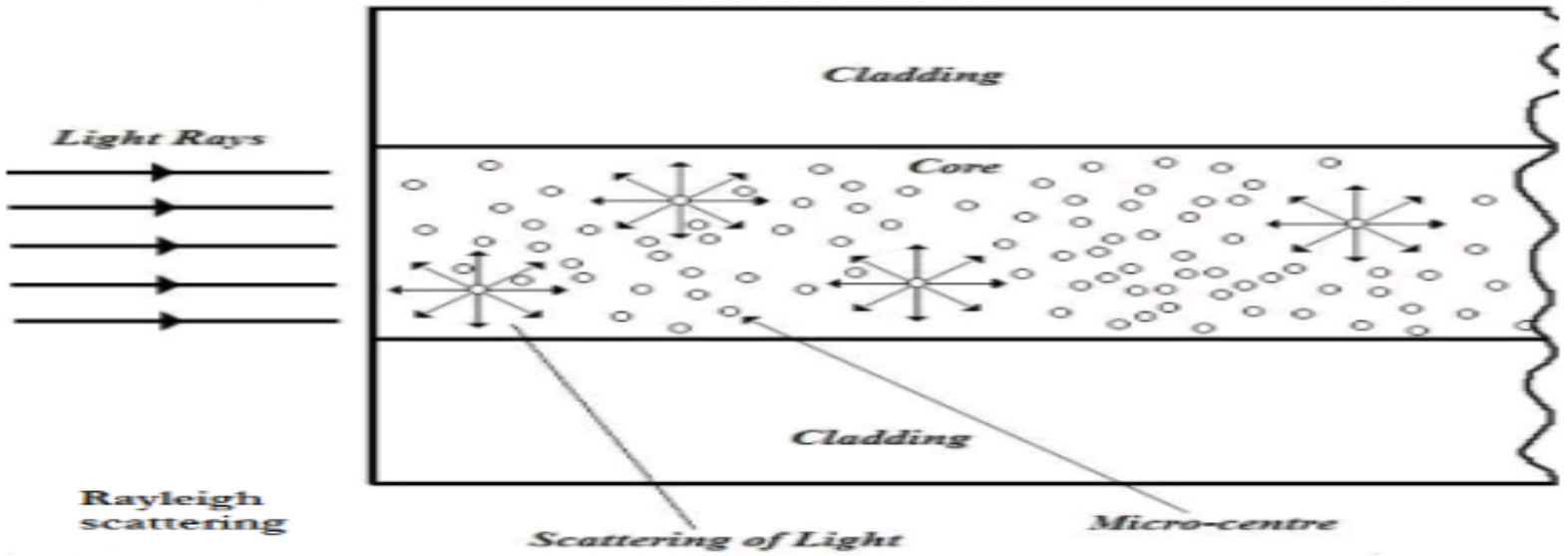


Figure 2.6

WDM

- WDM (Wavelength-division Multiplexing) is the technology of combing a number of wavelengths onto the same fiber simultaneously.
- A powerful aspect of WDM is that each optical channel can carry any transmission format. WDW increases the capacity of a fiber network dramatically.
- WDM is equivalent to the prism in the operating principle.

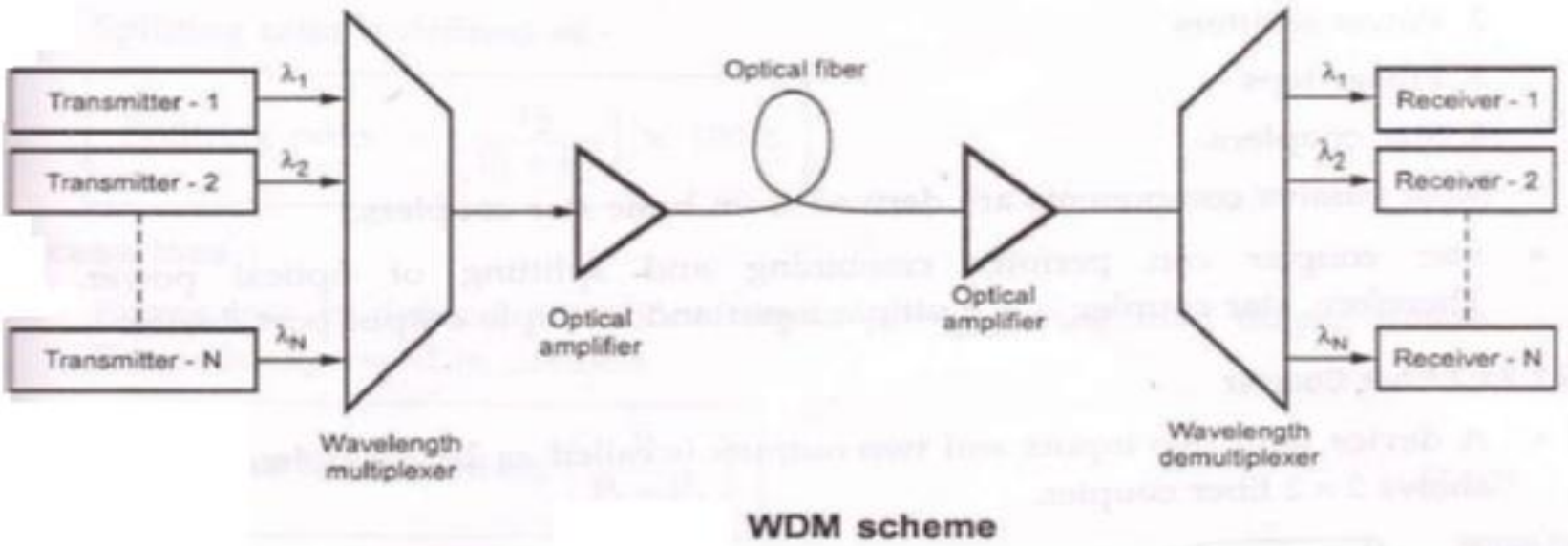
NEED OF WDM

Due to the rapid growth in telecommunication links, high capacity and faster data transmission rates over farther distances are required. To meet these demands, network managers are relying more and more on fiber optics.

Typically, there are three methods for expanding capacity:

- installing more cables,
- increasing system bitrate to multiplex more signals and
- wavelength division multiplexing.

Wavelength Division Multiplexing (WDM)



WDM scheme

- Optical signals of different wavelength (1300-1600 nm) can propagate without interfering with each other. The scheme of combining a number of wavelengths over a single fiber is called **wavelength division multiplexing (WDM).**
- Each input is generated by a separate optical source with a unique wavelength. An optical multiplexer couples light. At the receiving station, an optical demultiplexer is required to separate the different carriers.
- To prevent spurious (noise) signals to enter into receiving channel, the demultiplexer must have narrow spectral operation with sharp wavelength cut-offs.

Features of WDM

Important advantages or features of WDM are as mentioned below –

1. **Capacity upgrade:** Since each wavelength supports independent data rate in Gbps.
2. **Transparency:** WDM can carry fast asynchronous, slow synchronous, synchronous analog and digital data.
3. **Wavelength routing:** Link capacity and flexibility can be increased by using multiple wavelength.
4. **Wavelength switching:** WDM can add or drop multiplexers, cross connects and wavelength converters.

The implementation of WDM networks requires a variety of **passive and/or active devices** to combine, distribute, isolate, add, drop, attenuate, and amplify optical power at different wavelengths.

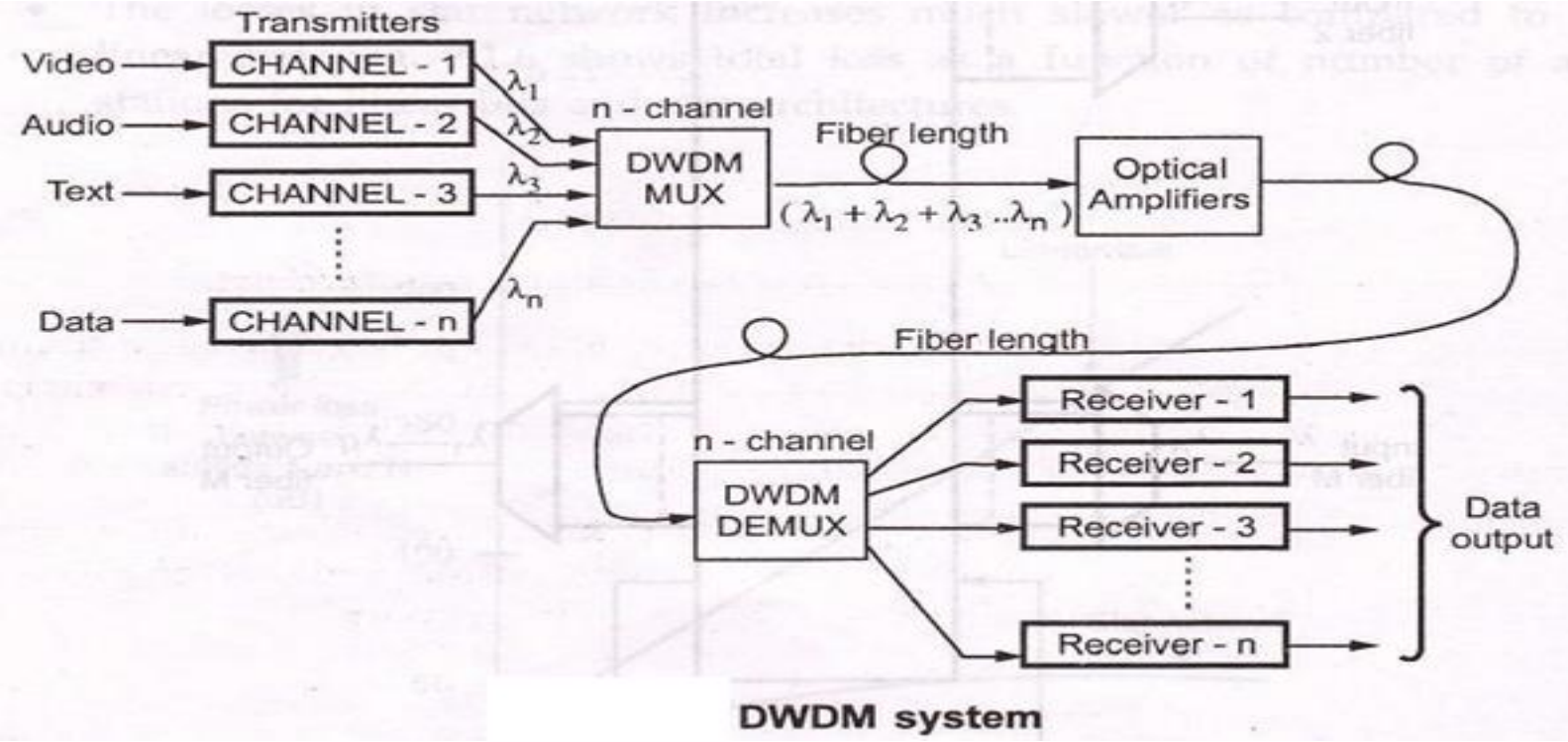
Passive devices

- require no external electric power or control for their operation, so they have a fixed application in WDM networks.
- used to separate and combine wavelength channels,
- to divide optical power onto a number of fiber lines, or to tap off part of an optical signal for monitoring purposes.
- Passive components are fabricated by using optical fibers by planar optical waveguides.
- Commonly required passive components are –
    1. N x N couplers
    2. Power splitters
    3. Power taps
    4. Star couplers.
- Star coupler can be used for combining and splitting of optical power. Therefore, star coupler is a multiple input and multiple output port device.

Active devices

- The performance of **active devices** can be controlled electronically, thereby providing a large degree of network flexibility.
- Active WDM components include tunable optical filters, tunable light sources, configurable add/drop multiplexers, dynamic gain equalizers, and optical amplifiers.

Dense Wavelength Division Multiplexing (DWDM) :



DWDM system

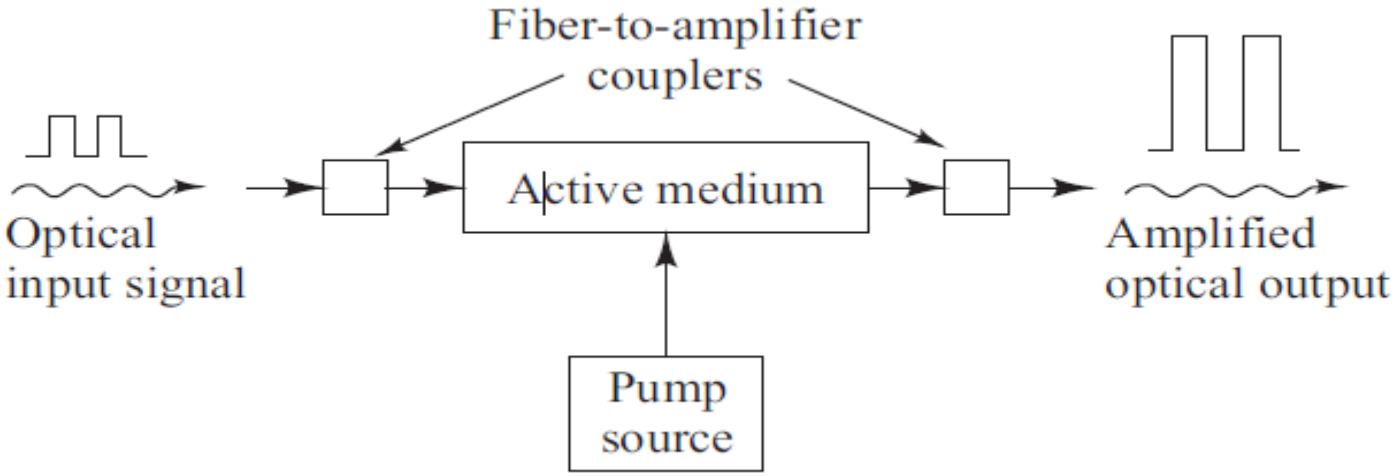
1) Data transmission technology having very large capacity and efficiency.
2) Multiple data channels of optical signals are assigned different wavelengths, and are multiplexed onto one fiber.
3) DWDM used single mode fiber to carry multiple light waves of different frequencies.
4) DWDM system uses Erbium – Doped Fiber Amplifers (EDFA) for its long haul applications, to overcome attenuation 10GHz signal is used.

Optical Amplifiers

- Most optical amplifiers amplify incident light through stimulated emission.
- An optical amplifier is nothing but a laser without feedback.
- Optical gain is achieved when the amplifier is pumped optically or electrically to achieve population inversion.
- Optical amplification depends on-

    - Frequency (or wavelength) of incident signal.

    - Local beam intensity.



- The external pump source energy is absorbed by the electrons in the active medium.
- The electrons shifts to the higher energy level producing population inversion.
- Photons of incoming signal triggers these excited electrons to lower level through a stimulated emission process, producing amplified optical signal.

Amplifier Types

- The optical amplifiers can be classified into two main types.
- Both the types are of *stimulated emission* process.

1. **S**emiconductor **O**ptical **A**mplifier **(SOA).**
2. **E**rbuim **D**oped **F**iber **A**mplifier **(EDFA).**

Semiconductor Optical Amplifier (SOA)

- SOA is a Laser diode without end mirrors and with antireflection coating coupled to both fiber ends.
- Light coming in either fiber is amplified by a single pass through the laser diode.
- In SOA, amplification takes place without many reflections.
- By Changing chemical composition (P, Ga, In, As), ampl. Gain can be increased. SOA has rapid gain response 1 ps to 0.1 ns.
- SOA works in both low attenuation windows i.e. 1300nm and 1550nm.
- SOA consumes less power and has fewer components.
- Two major types of SOA are –

    a. Fabry - Perot Amplifier (FPA)

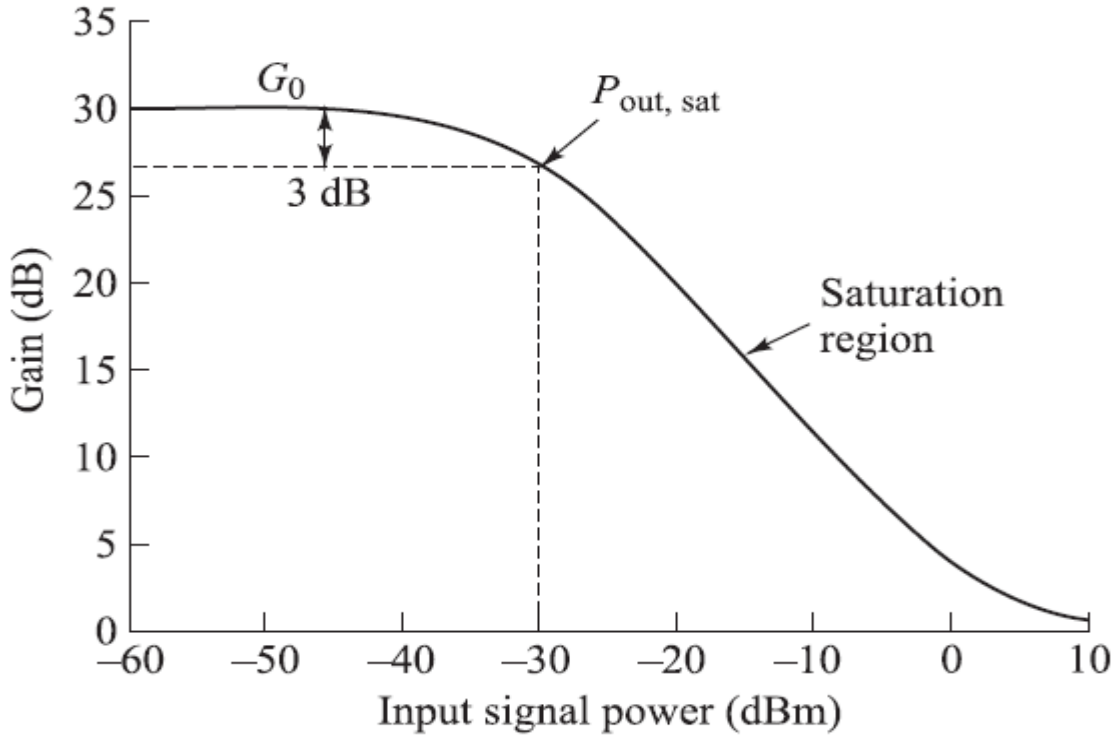
    b. Travelling Wave Amplifier (TWA)

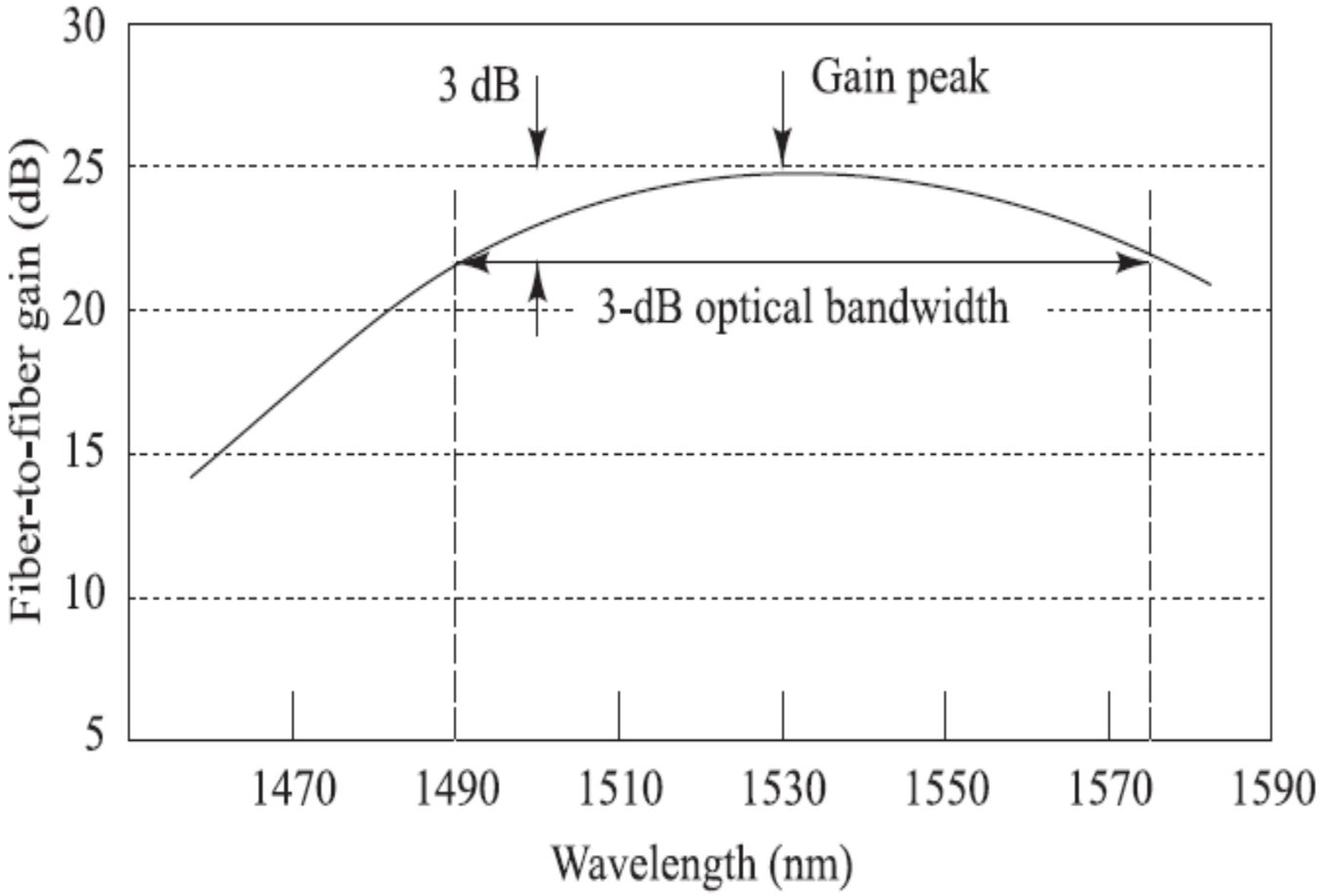
Amplifier Gain

One of the most important parameters of an optical amplifier is the signal gain or amplifier gain G, which is defined as

$$G = \frac{P_{s,out}}{P_{s,in}}$$

where $P_{s,in}$ and $P_{s,out}$ are the input and output powers, respectively, of the optical signal being amplified.





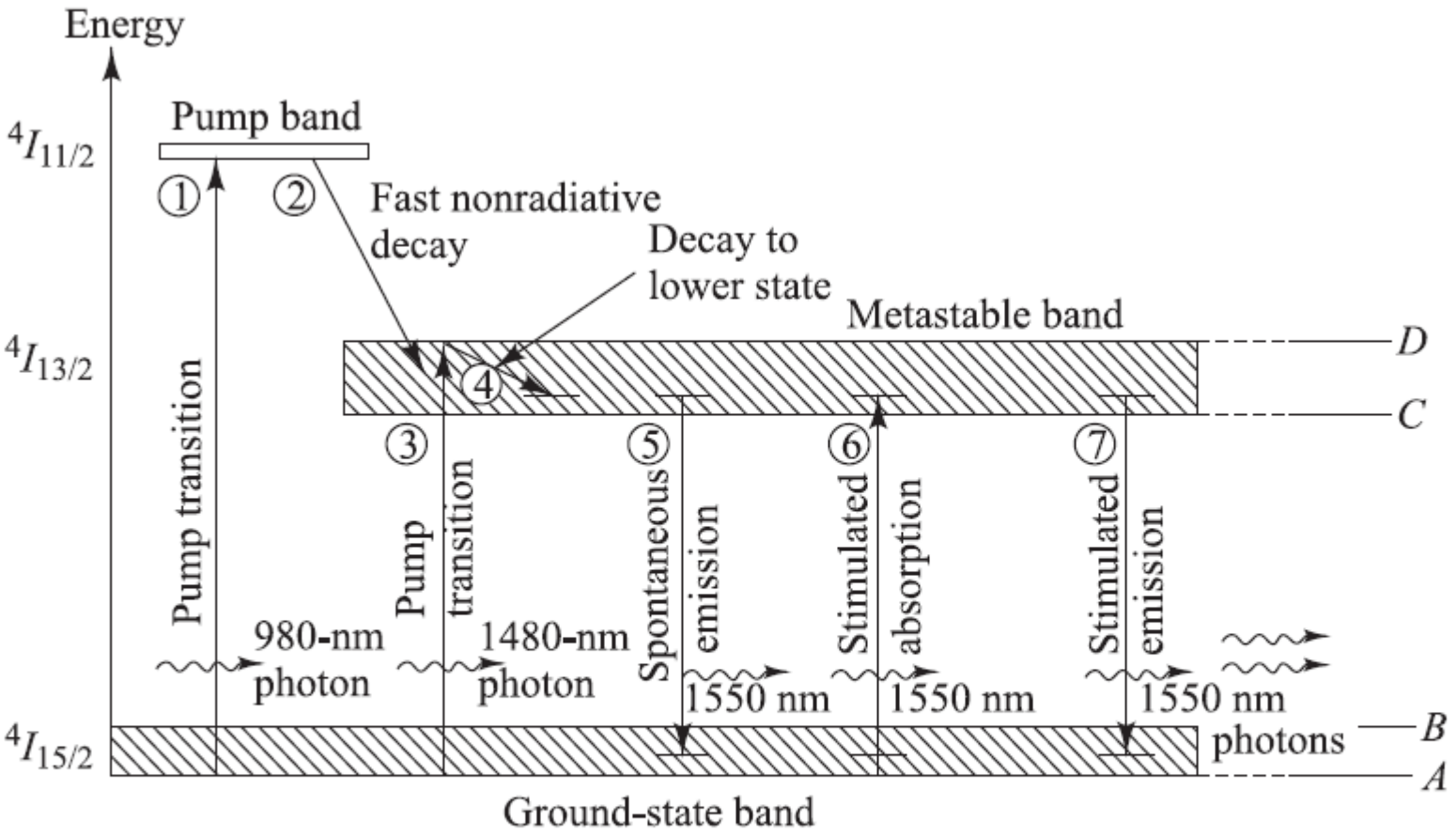
Typical gain-versus-wavelength characteristic for an SOA with a peak gain of 25 dB at 1530 nm. The definition of the 3-dB optical bandwidth is illustrated

Erbium Doped Fiber Amplifier (EDFA)

- The ions constitute the active medium through which optical gain is obtained.
- When optically pumped, these ions are excited to an higher energy state.
- In accordance with the type of ion used, DFAs can be used in a broad spectral range: from the visible part to the infrared region of the spectrum.
- A popular material for long-haul telecommunication applications is a silica fiber doped with erbium, which is known as an Erbium-Doped Fiber Amplifier or **EDFA.**
- The operation of a standard EDFA normally is limited to the 1530 to 1565 nm region.

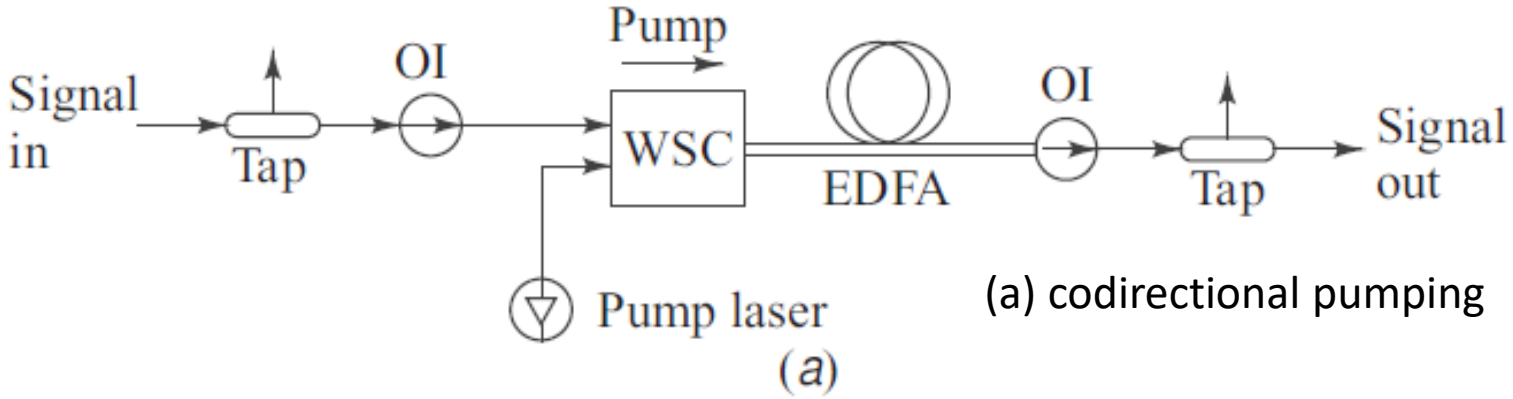
Amplification Mechanism

Whereas semiconductor optical amplifiers use external current injection to excite electrons to higher energy levels, optical fiber amplifiers use optical pumping.



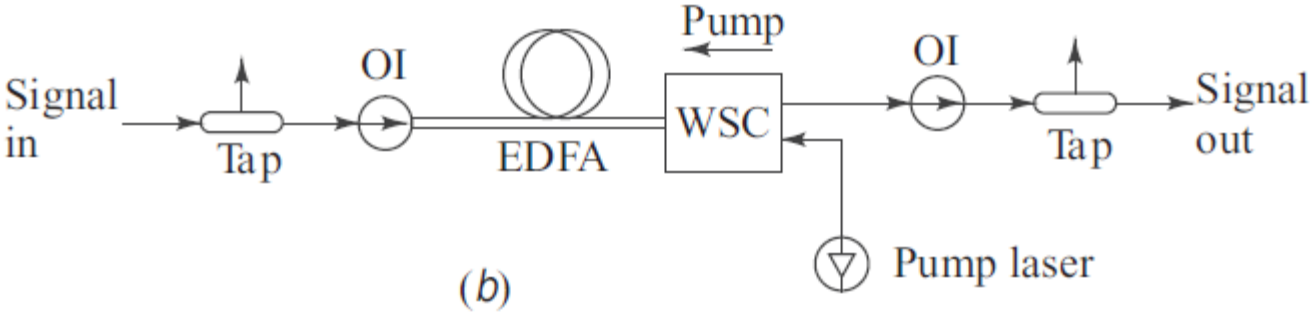
Simplified energy-level diagrams and various transition processes of Er^{3+} ions in silica

EDFA Architecture



(a) codirectional pumping

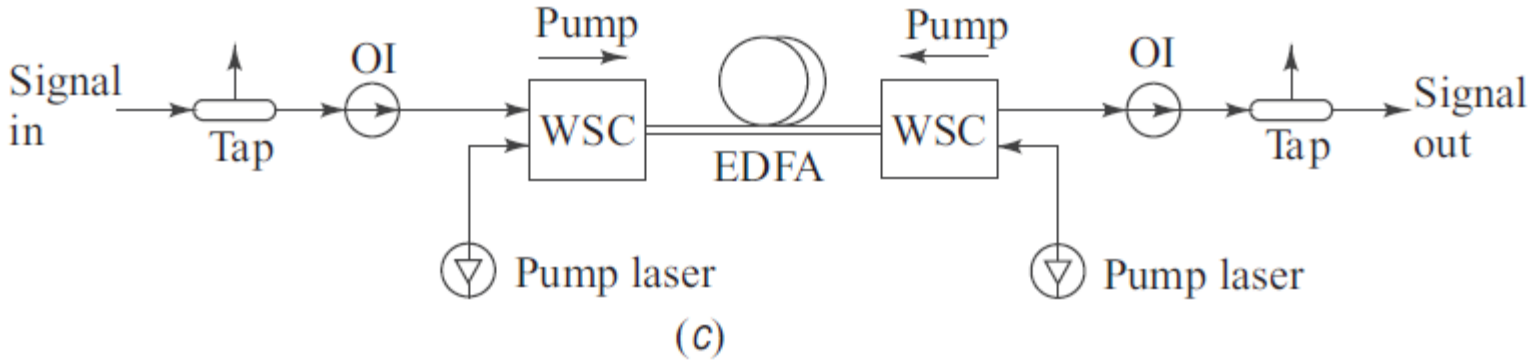
The pump light is usually injected from the same direction as the signal flow. This is known as **codirectional pumping.**



(b) counterdirectional pumping

It is also possible to inject the pump power in the opposite direction to the signal flow, which is known as **counterdirectional pumping.**

OI: Optical isolator
WSC: Wavelength-selective coupler



(c) dual pumping

OI: Optical isolator
WSC: Wavelength-selective coupler

one can employ either a single pump source or use **dual-pump schemes**, with the resultant gains typically being +17 dB and +35 dB, respectively.

EDFA : Power-Conversion Efficiency

The input and output signal powers of an EDFA can be expressed in terms of the principle of energy conservation

$$\mathrm{PCE} = \frac{P_{s,\mathrm{out}} - P_{s,\mathrm{in}}}{P_{p,\mathrm{in}}} \approx \frac{P_{s,\mathrm{out}}}{P_{p,\mathrm{in}}} \leq \frac{\lambda_p}{\lambda_s} \leq 1$$

we see that the maximum output signal power depends on the ratio λ_p/λ_s. For the pumping scheme to work, we need to have $\lambda_p < \lambda_s$, and, to have an appropriate gain, it is necessary that $P_{s,\mathrm{in}} \leq P_{p,\mathrm{in}}$.

Amplifier Gain

$$G = \frac{P_{s,\mathrm{out}}}{P_{s,\mathrm{in}}} \leq 1 + \frac{\lambda_p P_{p,\mathrm{in}}}{\lambda_s P_{s,\mathrm{in}}}$$