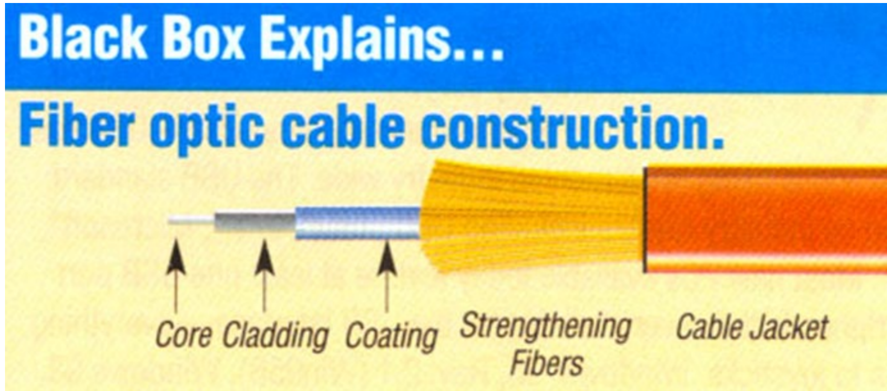
SRM INSTITUTE OF SCIENCE & TECHNOLOGY
(Deemed to be University u/s 3 of UGC Act, 1956)

# 15EC431E-PHOTONICS & OPTICAL NETWORKS

Greek word "phos" meaning light



# UNIT II- Optical Waveguides, Optical Sources and Detectors

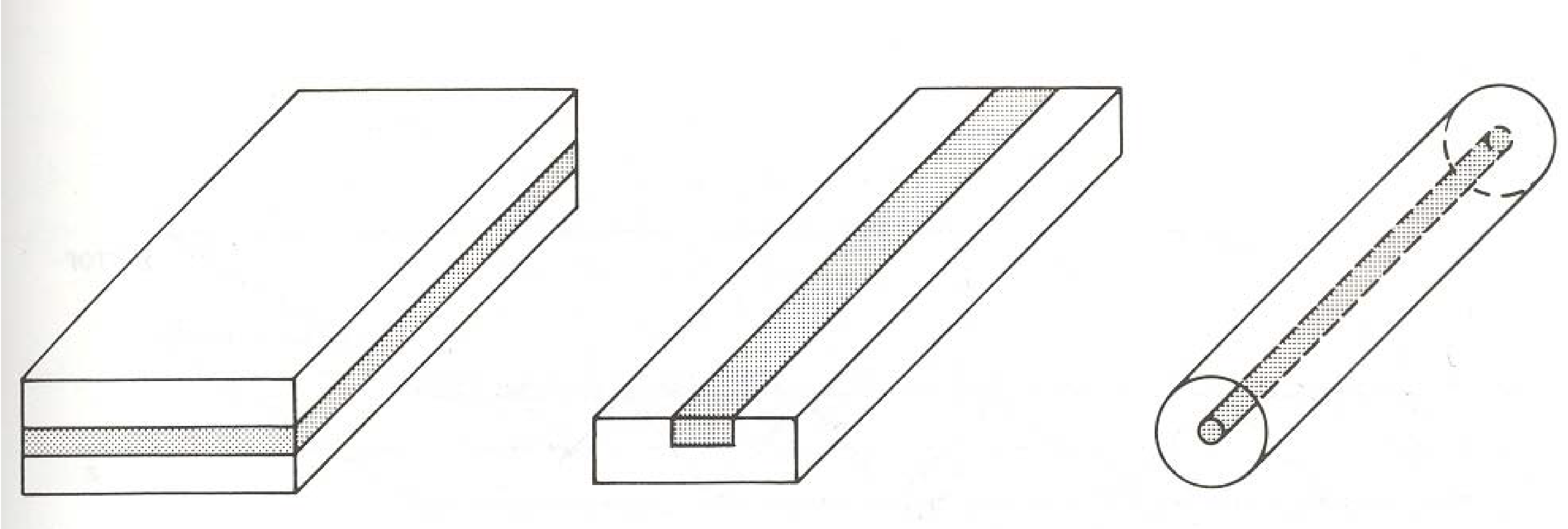
- Light Propagation in Optcial Waveguides
- Classification of Fibers , Single Mode Fiber
- Nonlinear Effects
- Laser Fundamentals
- Optical feedback , threshold condition
- Injection Laser Diode (ILD), Quantum well, DFB,
- Laser Modes
- Photo detection, PIN and Avalanche Photo diode (APD)
- Quantum Efficiency, Responsivity and Speed of Response
- Noise mechanism in photo detectors.

# Properties of Optical Fiber

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

# Propagation of Light in Optical Waveguides

- Light can be confined by an optical waveguide. The waveguide is formed by a medium which is embedded by an another medium of lower refractive index.
- The medium of higher refractive index acts as a “light trap”. Light is confined in the waveguide by multiple total internal reflections.
- By doing so light can be transported from one location to another location.
- Waveguides can be distinguished in terms of slabs, strips and fibers.
- The most widely applied waveguide structure is the optical fiber, which is made out of two concentrically cylinders of low-loss glass with slightly different refractive index.



Waveguides can be distinguished in terms of a slab, a strip or a fiber.

# Light Propagation in Optical Fibers

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

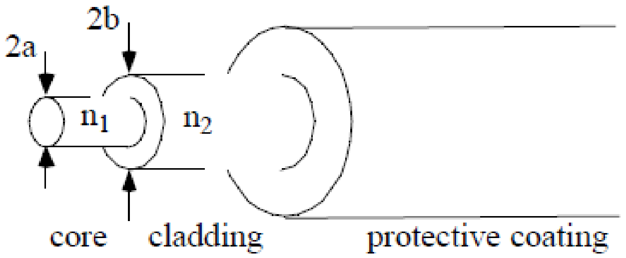
| Speed of light in free space / speed of light in the material = Refractive Index |
|---|

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

| lower refractive index = higher speed |
|---|

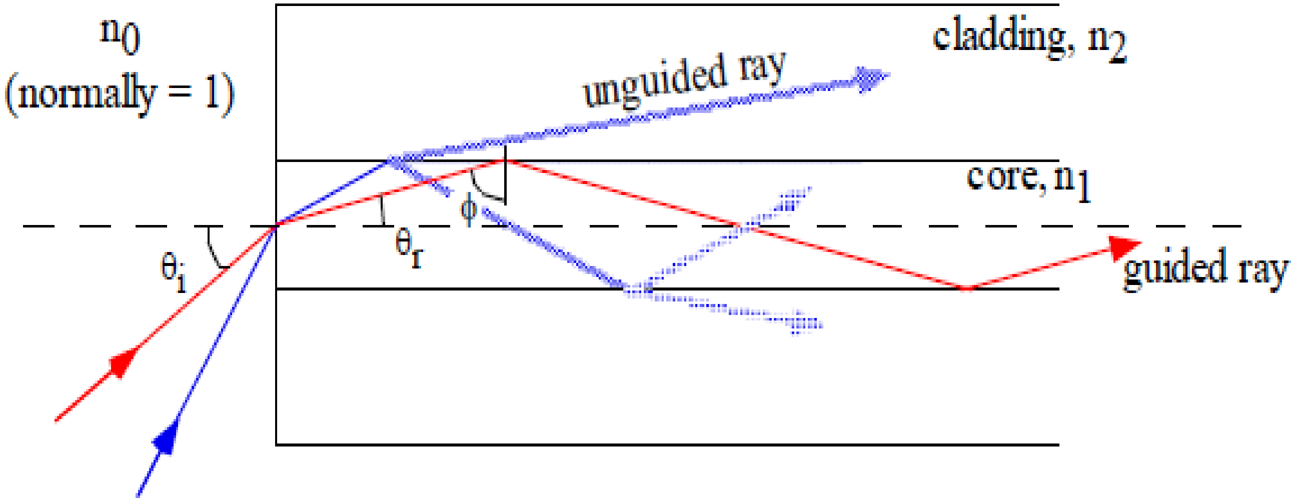
# Basics of Fiber Optic Waveguide

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

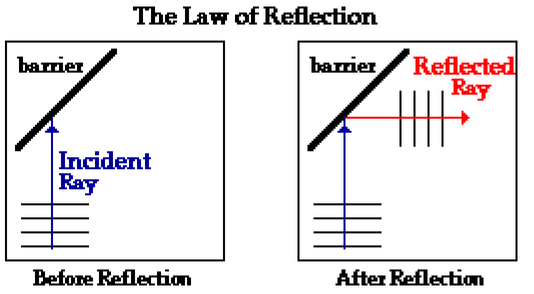


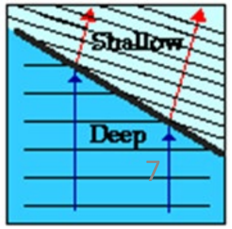
# Geometrical-Optics Description

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




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




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

# Total Internal Reflection

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

# Critical Angle & Numerical Aperture

Apply Snell's law at input

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

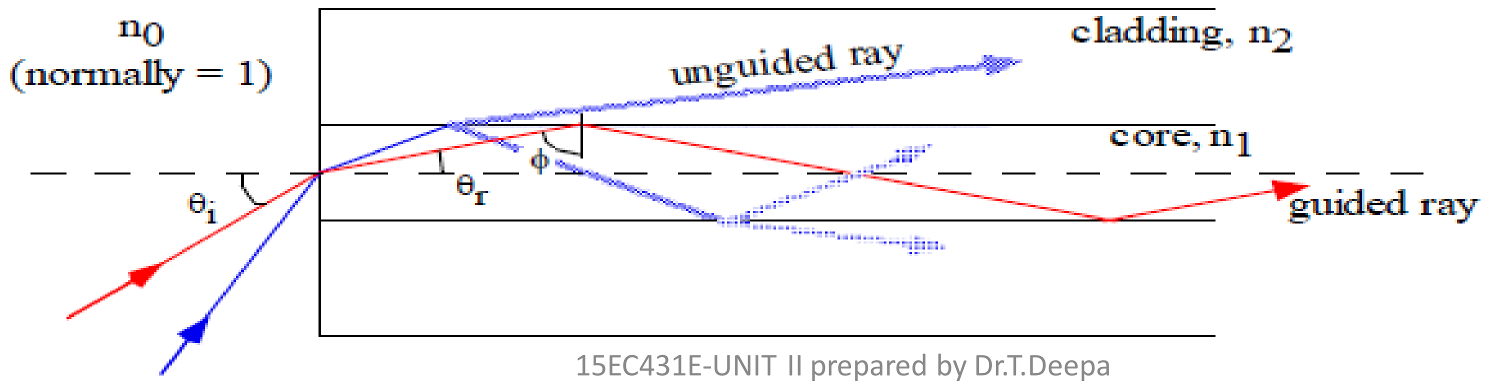
Minimum critical angle $\phi_c$ for total internal reflection

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

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

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

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



# Optical-Power Measurement

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

***Decibel*** (dB) expresses a power ratio according to

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

The photo current is proportional to the optical power

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

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

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

Examples:

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

# Classification of Optical Fibers

## Based on Refractive Index :

1. Step Index Fiber

2. Graded Index Fiber

## Based on Mode of Propagations :

1. Single Mode

2. Multimode

Multimode optical fiber with stepped index

Multimode optical fiber with graded index

# Index Profile of the Fiber

- The index profile of an optical fiber is a graphical representation of the magnitude of the refractive index across the fiber

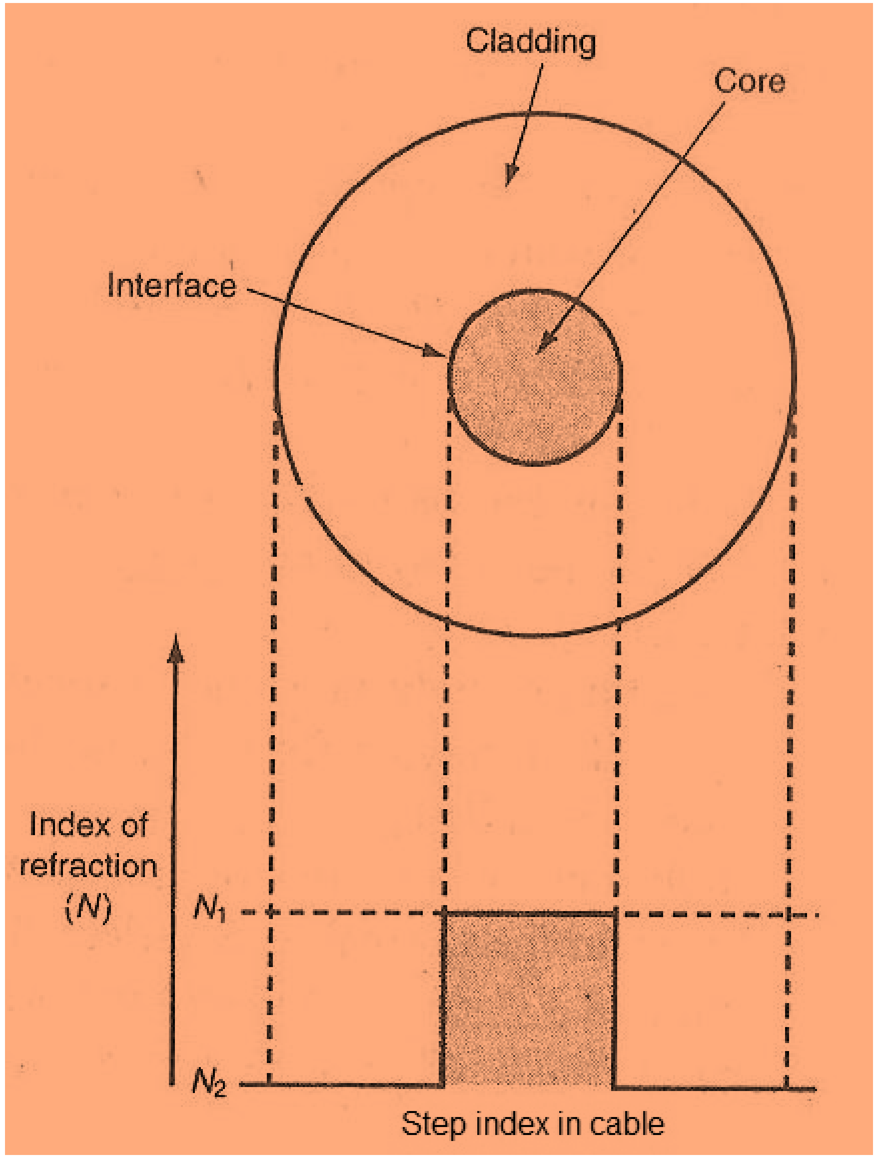
- There are two basic ways of defining the index of refraction variation across a cable

  1. Step Index Fiber
  2. Graded Index Fiber

## Step Index Fiber:

- The refractive index of the core is uniform throughout and undergoes an abrupt change (or step) at the cladding boundary.
- This is called a step-index fiber
- Step index is sharply defined as " a step in the index of refraction where the fiber core and cladding interface"

# Step Index Fiber




- The refractive index $n_1$ of the core is uniform (constant) and the refractive index $n_2$ of the cladding is slightly lower than $n_1$
- The refractive index profile for this type of fiber makes a step change at the core-cladding interface
- Refractive index profile n(r) may be defined as

$$n(r) = \begin{cases} n_1 & ; \quad r<a \ \ (\text{core}) \\ n_2 & ; \quad r \geq a \ \ (\text{cladding}) \end{cases}$$

r- radial distance from the fiber axis
a – core radius

- The propagation of light wave within the core of step index fiber takes the path of meridional ray. i.e. ray follows a zig-zag path of straight line segments
- The core typically has diameter of 50-80 µm and the cladding has a diameter of 125 µm.

# Graded-Index Fiber

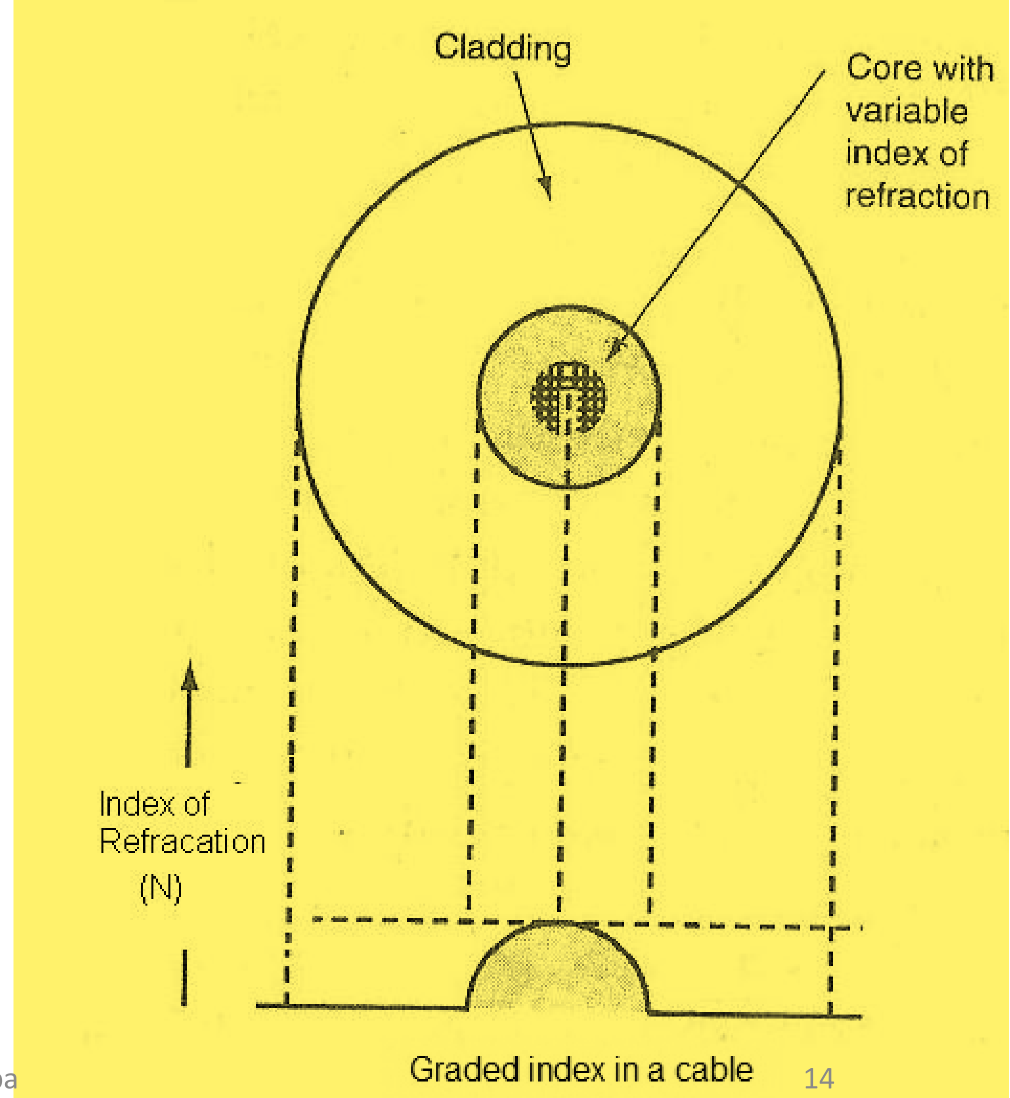
- The core refractive index is made to vary as a function of the radial distance from the center of the fiber. **This type is a graded-index fiber.**

- The index of refraction varies smoothly and continuously over the diameter of the core

- The graded index has a core made from many layers of glass

- In the graded index (GRIN) fiber **the refractive index is not uniform**

- Within the core, it is highest at the center and decreases smoothly and continuously with distance towards the cladding.



# Graded-Index Fiber (Contd)

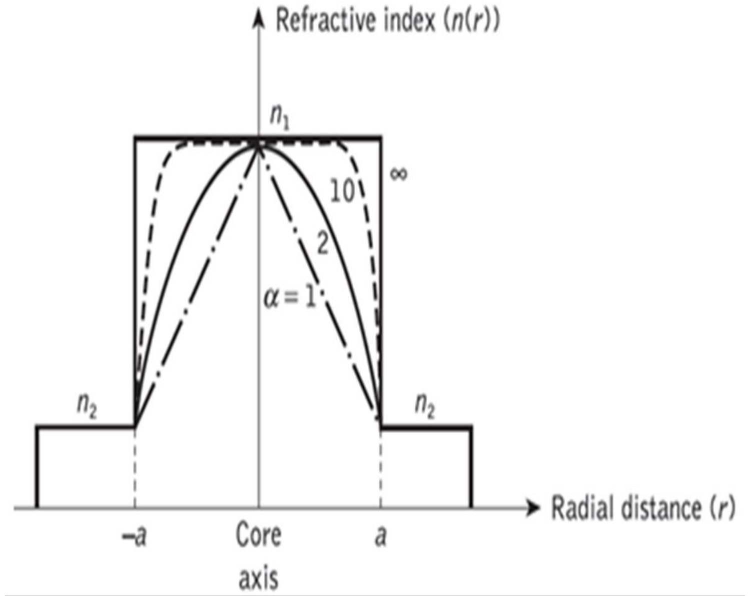
- The refractive index profile across the core takes the parabolic nature.

- In graded index fiber the light waves are bent by refraction towards the core axis and they follow the curved path down the fiber length. This results because of change in refractive index as they moved away from the center of the core

- A graded index fiber has lower coupling efficiency and higher bandwidth than the step index fiber. It is available in 50/125 µm and 62.5/125 µm sizes.

- The 50/125 µm fiber has been optimized for long haul applications and has a smaller numerical aperture and higher bandwidth.

- 62.5/125 µm fiber is optimized for LAN applications which is




$$n(r) = \begin{cases} n_1 \left(1 - 2\Delta \left(\frac{r}{a}\right)^{\alpha}\right)^{1/2} & r < a \ (core) \\ n_1 (1 - 2\Delta)^{1/2} & r \geq a \ (cladding) \end{cases}$$

# Graded-Index Fiber Parameters

- The parameters defined for SI fibers ( NA, Δ, V) may be applied to GI fibers and give comparison between two. However, in GI fibers situation is more complicated because of radial variation of RI of core from the axis, NA is also function of radial distance.

Local Numerical Aperture

$$\mathrm{NA}(r) = \begin{cases} [n^2(r) - n_2^2]^{1/2} \simeq \mathrm{NA}(0)\sqrt{1 - (r/a)^\alpha} & \text{for} \quad r \le a \\ 0 & \text{for} \quad r > a \end{cases}$$

Axial Numerical Aperture

$$\mathrm{NA}(0) = [n^2(0) - n_2^2]^{1/2} = (n_1^2 - n_2^2)^{1/2} \simeq n_1\sqrt{2\Delta}$$

Number of bounded modes in a Graded Index fiber

$$M_g = \left(\frac{\alpha}{\alpha+2}\right)(n_1 ka)^2 \Delta \cong \left(\frac{\alpha}{\alpha+2}\right)\left(\frac{V^2}{2}\right)$$

For parabolic profile core (α=2), $M_g = V^2/4$ → Half the number supported by Step Index Fiber with the same V value

# Comparison between Step Index and Graded-Index Fiber

| Sr.No | Parameter | Step Index Fiber | Graded Index Fiber |
|---|---|---|---|
| 1 | Data rate | Slow | Higher |
| 2 | Coupling Efficiency | Coupling efficiency with fiber is higher | Lower Coupling Efficiency |
| 3 | Ray Path | By total internal reflection | Light ray travels in oscillatory fashion |
| 4 | Index Variation | | |
| 5 | Numerical Aperture | NA remains same | Changes continuously with distance from fiber axis |
| 6 | Material Used | Normally plastic or glass is preferred | Only glass is preferred |
| 7 | Bandwidth Efficiency | 10-20 MHz/km | 1 GHz/km |
| 8 | Pulse Spreading | Pulse spreading by fiber is more | Pulse spreading is less |
| 9 | Attenuation of light | Less, typically 0.34 dB/km at 1.3 um | More, 0.6 to 1 dB/km at 1.3 um |
| 10 | Typical Light Source | LED | LED, Lasers |
| 11 | Applications | Subscriber local network communication | Local and wide area networks |

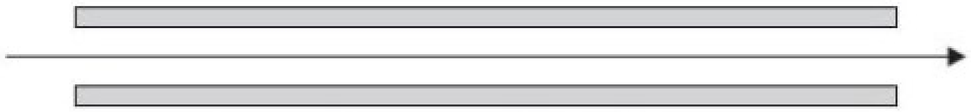
# Modes of Fiber

- Fiber cables can also be classified as per their mode
- Light rays propagate as an electromagnetic wave along the fiber. The two components, the electric field and the magnetic field form patterns across the fiber. These patterns are called modes of transmission.
- Need of Mode theory
  - To understand the behaviour of electromagnetic waves in waveguides.
  - The mode theory essentially classifies electromagnetic waves on the basis of wavelengths into different **modes**.
- The mode of a fiber refers to the number of paths for the light rays within the cable. According to modes optic fibers can be classified into two types

1. Single mode (or) mono mode fibers
2. Multimode fibers

# Single Mode Fiber

- Transmits only one mode of the light. It can carry only one wavelength of light across its length.
- This wavelength is usually 1310nm or 1550nm.
- Single mode optical fibers are much better than multimode optical fibers as they have more bandwidth and experience fewer losses. So the speed is unmatched.
- The diameter of the core is essentially of the same order as the wavelength of the light passing through it.
- Only lasers are used as a light source. To point out, the light used in single mode fibers are not in the visible spectrum.
- Since the light travels in a straight direction, there are fewer losses, and it can be used in applications requiring longer distance connections.
- An obvious disadvantage of single mode fiber is that they are hard to couple.



Singlemode Fiber

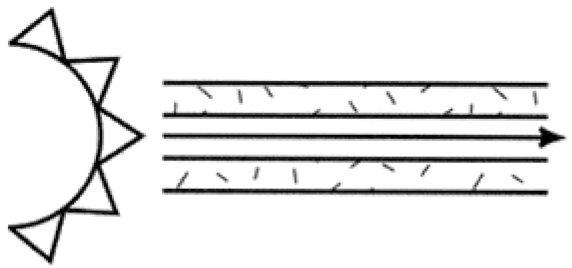
# Single Mode Fibers

- Single mode fibers are designed to allow only one mode of propagation. All other modes are attenuated either by leakage or absorption
- Single mode fibers are the best at retaining the fidelity of each light pulse over longer distance also they do not exhibit dispersion caused by multiple modes
- The core diameter of the single mode fiber ranges from 8-12 µm and it has very small index differences between the core and the cladding with a normalized frequency V = 2.405
- The core-cladding index difference varies between 0.2 and 1.0 %, and the core diameter should be chosen to be just below the cutoff of the first higher order mode.
- For the single mode fiber operation, only $LP_{01}$ mode can exist, also known as the fundamental mode of the fiber.
- Single mode propagation of the $LP_{01}$ mode step index fiber is possible over the range $0 \leq V \leq 2.405$

# Single mode fiber

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

"Single mode fiber"
single path through the fiber



# Single mode fibers

## Advantages:

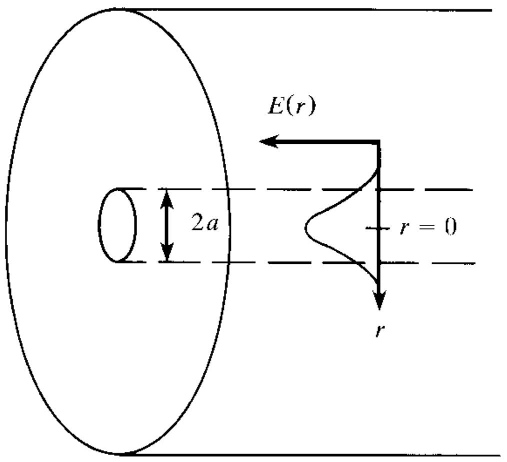
- No intermodal dispersion
- Information capacity of single mode fiber is large. – More information can be transmitted per unit of time.
- This gives single mode fiber have higher bandwidth compared to multimode fiber

## Disadvantages:

- Launching of light into single mode and joining of two fibers are very difficult
- Precision required for single mode connectors and splices are more demanding
- Fabrication is very difficult and hence the fiber so costly

# Mode-Field Diameter

- The mode field diameter (MFD) is an important parameter for characterizing single mode fiber properties which takes into account when the wavelength dependent electromagnetic field penetration into the fiber cladding.
- This parameter can be determined from the mode-field distribution of the fundamental $LP_{01}$ mode



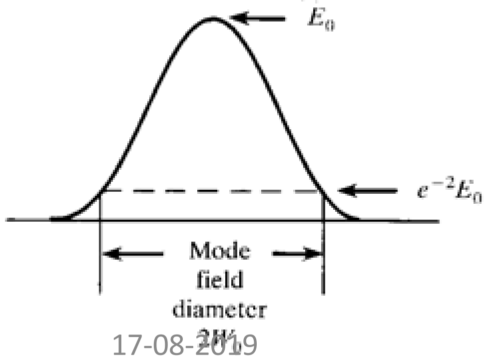

- A variety of models for characterizing and measuring the MFD have been proposed.
- The main consideration in all these methods is to approximate the electric field distribution
- Consider Gaussian approximation for the field amplitude distribution in the fiber as

$$E(r) = E_0 \exp\left(-\frac{r^2}{W_0^{\,2}}\right); \qquad \text{MFD} = 2W_0$$

Where r – is the radius of the field distribution

$E_0$ is the field at zero radius

$W_0$ is the width of the electric field distribution (or) spot size (or) mode field radius



# Mode-Field Diameter (Contd)

- In the fundamental mode of single mode fiber, MFD is generally taken the width $2W_0$ to be twice the $e^{-1}$ radius of the optical electric field (which is equivalent to the $e^{-2}$ radius of the optical power)

- The MFD width $2W_0$ of the $LP_{01}$ mode can be defined as

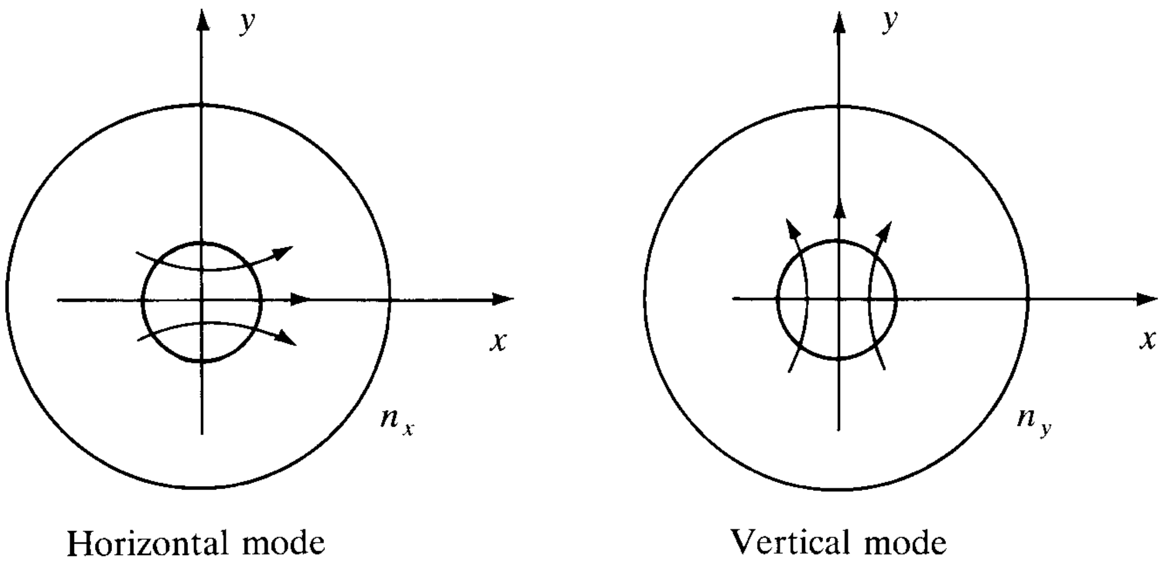
$$2W_0 = 2\left[\frac{2\int_0^{\infty} r^3\, E^2(r)dr}{\int_0^{\infty} rE^2(r)dr}\right]^{1/2}$$

Where E(r) denotes the field distribution of the $LP_{01}$ mode.

- In general, the mode field varies with the refractive index profile and thus deviates from a Gaussian distribution

# Propagation Modes in Single Mode Fibers

- The two independent degenerate modes propagate within the single mode fiber. The modes are very similar but their polarizations planes are orthogonal. These may be chosen arbitrarily as horizontal (H) and the vertical (V) polarizations




- Either one of the two polarization modes constitutes the fundamental $HE_{11}$ mode.

# Birefringence

- When the polarization modes propagate with different phase velocities and the difference between their effective refractive indices is called the birefringence

$$B_f = n_y - n_x$$

Where $n_x$ – Effective refractive index of horizontal mode, and
$n_y$ - Effective refractive index of vertical mode

- The birefringence may also be defined as

- $B_f = k_0(n_y - n_x)$ $k_0 = 2\pi/\lambda$ is the free space propagation constant.

# Fiber Beat Length

- If the light is injected into the fiber so that modes are excited, one mode is delayed in phase relative to the other as they propagate

- When the phase difference between two modes is an integral multiple of 2π,the two modes will beat at this point and the input polarization will be reproduced. The length over which the beating occurs is known as Fiber Beat Length

$$L_p = \frac{2\pi}{kB_f}$$

# Multimode fiber

- Multimode fiber was the first fiber type to be manufactured and commercialized
- Multimode means – numerous modes (light rays) are carried simultaneously though the waveguide
- In multimode, the light takes many paths through the core
- Multimode fiber has a much larger diameter, compared to single mode fiber, this allows large number of modes.
- The number of paths (modes) possible for a multimode fiber cable depends on the frequency (wavelength) of the light signal, the refractive indexes of the core and cladding, and the core diameter.

# Multimode fiber (Contd)

Mathematically, the number of propagation modes (N) in multimode fiber is expressed as

$$N \approx \left(\frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2}\right)^2$$

Where, d – core diameter (meters)

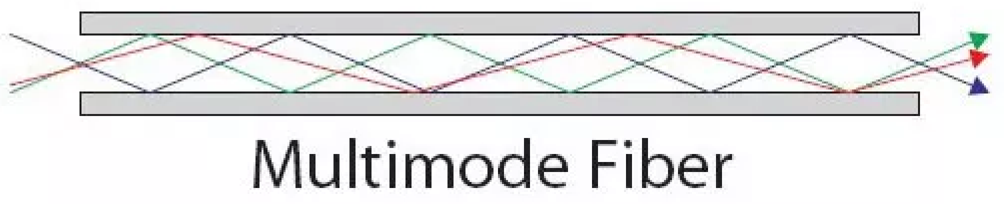
Wavelength (meters)

n1 – Refractive index of core and

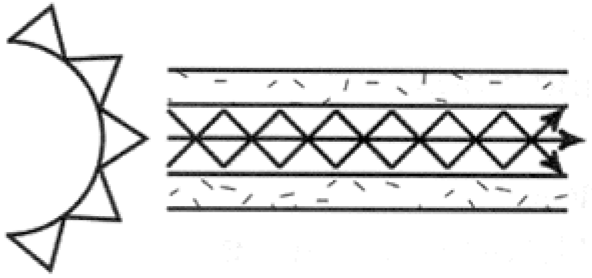
n2 – Refractive index of cladding

# Multimode optical fiber(Contd)

- Allows multiple modes of light to travel along their axis.
- a thicker core diameter.
- The wavelengths of light waves in multimode fibers are in the visible spectrum ranging from 850 to 1300 nm.
- The reflection of the waves inside the multimode fiber occurs at different angles for every mode. Consequently, based on these angles the *number* of reflections can vary.
- Since the basis of optical fiber communication is a total internal reflection, all modes with incident angles that do not cause total internal reflection get absorbed by the cladding. As a result, losses are created.
- We can have higher order modes, waves that are highly transverse to the axis of the waveguide can reflect many times. In fact, due to increased reflections at unusual angles, higher order modes can get completely lost inside the cable.
- Lower order modes are moderately transverse or even completely straight and hence fare better comparatively.
- There are two types of multimode optical fibers:
  - stepped index and graded index.

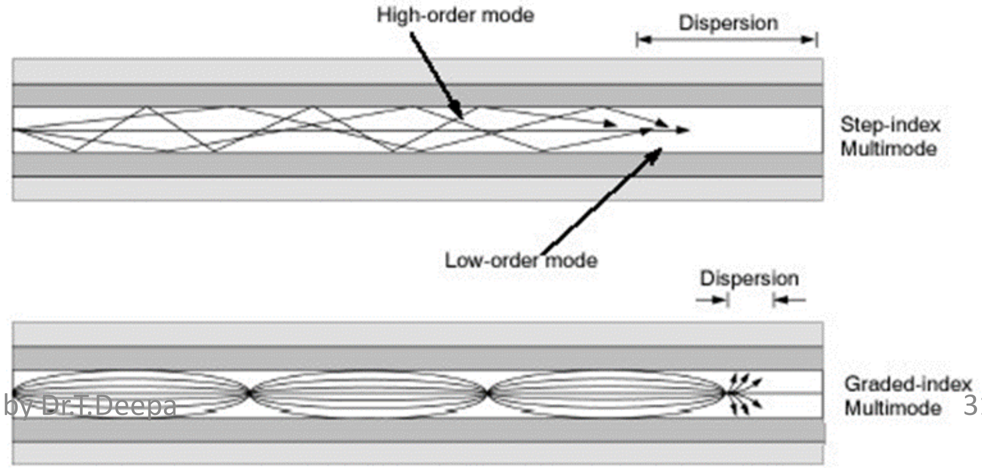



“Multimode fiber”
multiple paths through the fiber



# Types of Multimode fiber

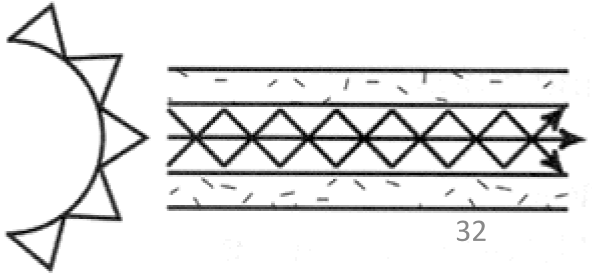
- When the index of refraction is constant within the core, the fibre is called
- a stepped-index (SI) fibre.
  - The refractive index of the core is uniform throughout the cable.
- Graded-index (GI) fibre reduces multimode dispersion by grading the refractive index of the core so that it smoothly tapers between the core centre and the cladding.
  - The refractive index of the core changes radially from the center of the core to its surface.



# Introduction –Dispersion

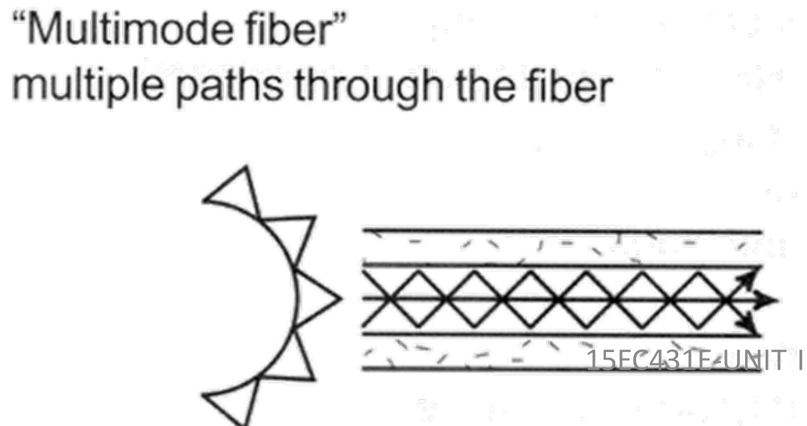
- **Multi-mode optical fiber** is a type of optical fiber mostly used for communication over short distances, such as within a building or on a campus.
- Typical multi-mode links have data rates of 10 Mbit/s to 10 Gbit/s over link lengths of up to 600 meters (2000 feet).
- Multi-mode fiber has a fairly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

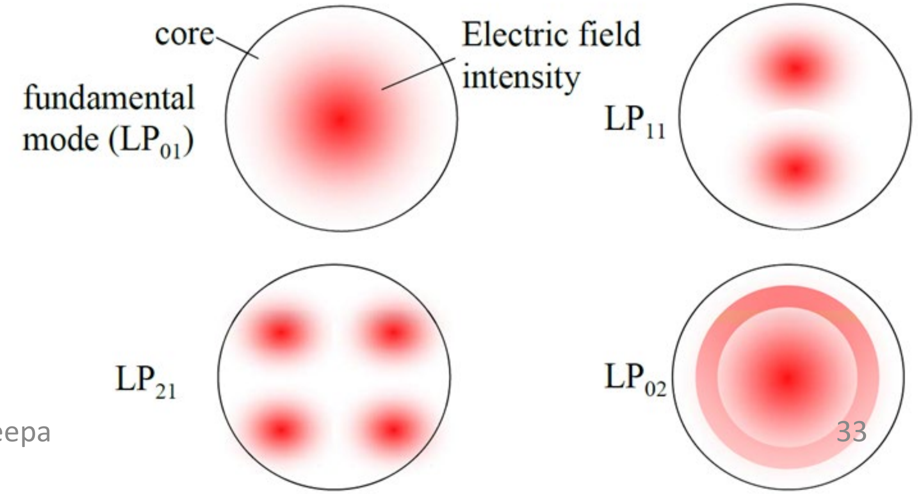
"Multimode fiber"
multiple paths through the fiber



# Multimode Dispersion

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



# Multimode Fiber Causes

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

# Advantages of Multimode Fiber

- The larger core radii as well as numerical apertures of multimode fibers make it easier to launch optical power into the fiber
- Connecting together of similar fibers are easy
- Light can be launched into a multimode fiber using LED. Although LED’s have less optical output power than laser diodes,
- LED’s are easier to make and less expensive and have longer life times.
- Fabrication is less difficult and so fiber is not costly.

# Comparison between single mode and multimode fiber

| Sl. No | Single Mode Fiber | Multi Mode Fiber |
|---|---|---|
| 1 | Core diameter 2 to 10 µm | Core diameter is greater than single mode<br>Step Index : 50 µm to 400 µm<br>Graded Index : 30 µm to 100 µm |
| 2 | Cladding diameter : 125 µm | Cladding diameter<br>Step Index : 125 to 500 µm<br>Graded Index : 100 to 150 µm |
| 3 | Propagation of only fundamental mode | Multiple modes propagate |
| 4 | No intermodal dispersion as only one mode is transmitted | Greater intermodal dispersion due to multiple modes |
| 5 | Superior transmission due to absence of modal noise | Modal noise is present |

# Introduction to Nonlinear Fiber Optics

## Linear Optics vs Non Linear Optics

Linear optics- 'Optics of weak light':

Light is deflected or delayed but its frequency is unchanged.

Non-Linear optics-'Optics of intense light':

We are concerned with the effects that light itself induces as it propagates through the medium.

# Nonlinear Optics: Study of interaction of light in matter

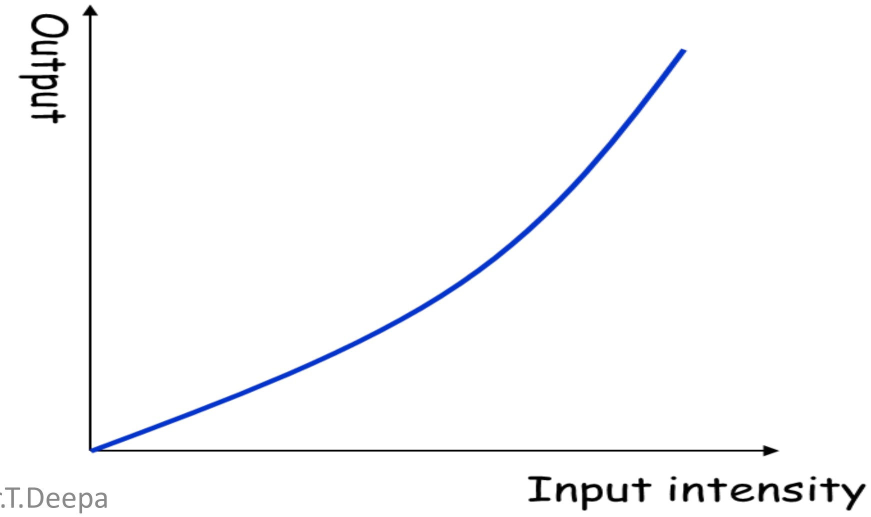
- We can control "n" by the light itself or manipulate one beam with the other.
- Leads to a Great variety of technical innovations.

Optical wave manipulation is one of the future technologies for optical processing.

- It has various applications in fiber-optic communications and optoelectronics which makes it an increasingly important topic among electrical engineers.

# Start of Nonlinear Optics

- Nonlinear optics started by the discovery of Second Harmonic generation shortly after demonstration of the first laser. (**Peter Franken** et al 1961)
- When the intensity of the incident light to a material system increases the response of medium is no longer linear

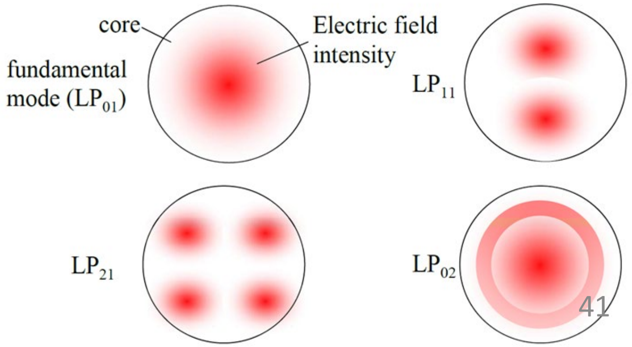


# Introduction – Nonlinearity of Fibers

- In an optical fiber, light is confined to a small transverse region, so that even moderate optical powers leads to high optical intensities.
- In addition, light often propagates over considerable distances in a fiber. For these reasons, nonlinear effects due to fiber nonlinearities often have substantial effects.
- This is particularly the case if fibers are used to transmit short pulses, and in fiber amplifiers for short pulses.

# Non Linear Fiber Optics

- When the optical intensity inside an optical fiber increases, the refractive index of the fiber gets modified.
- The wave propagation characteristics the become a function of optical power.
- Unlike linear fiber optics, where the propagation constant is a function of fiber and the wavelength only, the propagation constant becomes a function of optical power in addition to the other parameters.
- Inside a single mode optical fiber, an optical power of few tens of mW may drive the medium into non-linearity.



# The Kerr Nonlinearity

- Definition – Kerr Effect: a nonlinear interaction of light in a medium with an instantaneous response, related to the nonlinear electronic polarization.
- The simplest and most common nonlinear effect in fibers is the Kerr effect.
- The Kerr effect is a nonlinear optical effect occurring when intense light propagates in crystals and glasses, but also in other media such as gases. Its physical origin is a nonlinear polarization generated in the medium, which itself modifies the propagation properties of the light.
- The Kerr effect is the effect of an instantaneously occurring nonlinear response, which can be described as modifying the refractive index. In particular, the refractive index for the high intensity light beam itself is modified according to
- Essentially, this means that the phase delay in the fiber gets larger if the optical intensity increases. This can be described via an increase of refractive index in proportion to the intensity:

$$\Delta n = n_2 I$$

with the *nonlinear index* $n_2$ and the optical intensity $I$. The $n_2$ value of a medium can be measured

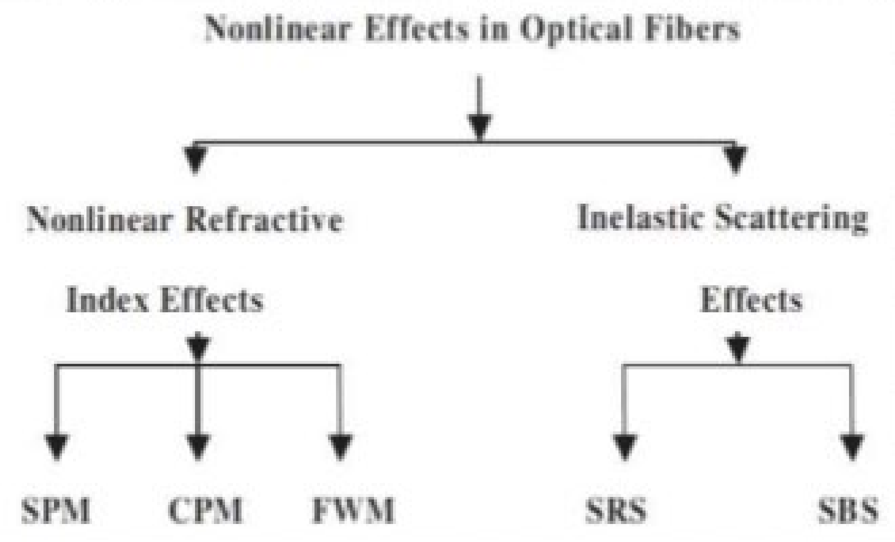
e.g. fluoride glasses or chalcogenide fibers, often have substantially stronger nonlinearities.

# Optical Fiber Losses

## Nonlinear Optical Effects

- Optical waveguides do not always behave as linear channels where optical output power is equal to optical input power.
- Several nonlinear effects occurs which causes scattering.
- **Nonlinear Scattering is the transfer of optical power from one mode to be transferred in either the forward or backward direction or other modes at different frequency.**
- The types of nonlinearities are:

1. **Stimulated Raman Scattering**
2. **Stimulated Brillouin Scattering**
3. **Self Phase Modulation**
4. **Cross Phase Modulation**
5. **Four Wave Mixing**



# Self Phase Modulation (SPM)

- One of the consequences (results) of the Kerr effect is self-phase modulation (SPM). This means that a light wave in the fiber experiences a nonlinear phase delay which results from its own intensity.
- For a fiber mode, the phase change per unit optical power and unit length is described by the proportionality constant

$$\gamma_{SPM} = \frac{2\pi n_2}{\lambda A_{eff}}$$

(in units of rad/(W · m))

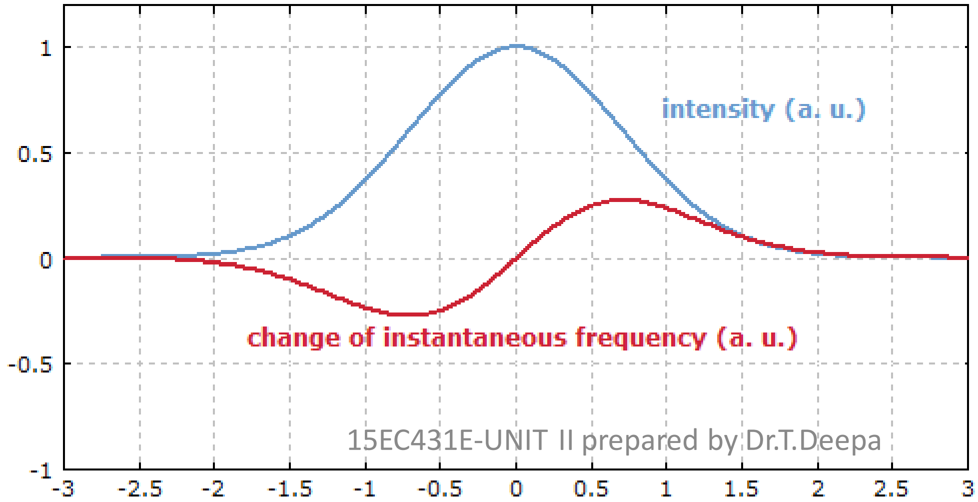
where $A_{eff}$ is the effective mode area. Interestingly, for a nearly Gaussian mode shape with beam radius $w$ this value is only half the value for a Gaussian beam in a homogeneous medium, where only the on-axis value is considered.

# SPM (Contd.)

- In the fiber, we have lower phase changes away from the fiber axis, and the overall nonlinear phase delay is only half the peak value.

# SPM (Contd.)

- If an optical pulse is transmitted through a fiber, the Kerr effect causes a time-dependent phase shift according to the time-dependent pulse intensity.
- In this way, an initial unchirped optical pulse acquires a so-called chirp, i.e., a temporally varying instantaneous frequency. This is shown in Figure 1:



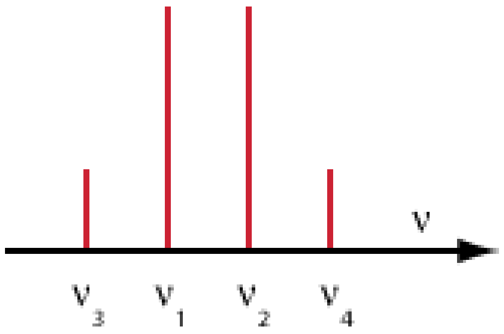
# Cross-phase Modulation

- If two different waves, e.g. at two different wavelengths, propagate together in a fiber, there can be a nonlinear phase change of each beam resulting from the intensity of the other beam. This phenomenon of cross-phase modulation (XPM).
- This is occurred in optical fiber communications with wavelength division multiplexing.
- for example,
- Curiously, the resulting phase changes are two times larger than one would expect from the equation for self-phase modulation as given above, if both beams have the same linear polarization. For XPM, we then have a phase change of beam 2 resulting from the intensity of beam 1 according to

$$\Delta n^{(2)} = 2 n_2 I^{(1)}$$

# Four-wave Mixing

- Another effect resulting from the Kerr effect is four-wave mixing.
- For example, if two wavelength components travel together through a fiber, four-wave mixing may lead to two new frequency components as shown in Figure




- the two input frequencies lead to a beat note, i.e., an oscillation of the total intensity with a frequency which is the difference of the two optical frequencies.
- Through the Kerr effect, this leads to a phase modulation, which creates sidebands. Note, however, that this process can be effective over long lengths of fiber only if it is phase-matched.
- Otherwise, the amplitudes added to the sidebands at some point in the fiber do not constructively add to those generated at other points.
- Therefore, four-wave mixing often occurs only near the zero dispersion wavelength of a fiber.

# Stimulated Brillouin scattering (SBS)

- SBS is an impairment seen in narrowband transmission over optical fiber at high laser power.
- Accurate modeling is necessary to predict the strength of this phenomenon.
- **Brillouin scattering**, refers to the interaction of light and material waves within a medium.
- For intense beams of light (e.g. laser) travelling in a medium, such as an optical fiber, the variations in the electric field of the **beam itself may induce acoustic vibrations in the medium via electrostriction or radiation pressure.**
- The beam may display Brillouin scattering as a result of those vibrations, usually in the direction opposite the incoming beam, a phenomenon known as **stimulated Brillouin scattering** (SBS).

# SBS (Cont’d)

- It is associated with acoustical phonons (in the gigahertz range). It turns out that this interaction can normally be intrinsically phase-matched only such that it couples two counter propagating optical waves.
- Energy conservation demands that the optical frequencies differ by the acoustic frequency. If we inject a single monochromatic wave into the fiber, there will be a nonlinear gain for counter propagating waves with optical frequencies which are lower by the *Brillouin frequency shift*

$$\nu_B = \frac{2 n \upsilon_a}{\lambda}$$

- which depends on the refractive index, the acoustic velocity and the vacuum wavelength.
- For silica fibers, the Brillouin frequency shift is of the order of 10–20 GHz, and the Brillouin gain occurs within a bandwidth of typically 50–100 MHz.
- For liquids and gases, the frequency shifts typically created are of the order of 1–10 GHz resulting in wavelength shifts of ~1–10 pm in the visible light.
- Stimulated Brillouin scattering is one effect by which optical phase conjugation can take place.

# Raman Scattering

- **Raman scattering** or the **Raman effect** is the inelastic scattering of a photon by molecules which are excited to higher vibrational or rotational energy levels.
- When photons are scattered from an atom or molecule, most of them are elastically scattered (Rayleigh scattering), such that the scattered photons have the same energy (frequency and wavelength) as the incident photons.
- A small fraction of the scattered photons (approximately 1 in 10 million) are scattered *inelastically* by an excitation, with the scattered photons having a frequency and energy different from, and usually lower than, those of the incident photons.
- In a gas, Raman scattering can occur with a change in energy of a molecule due to a transition to another (usually higher) energy level. Chemists are primarily concerned with this "transitional" Raman effect.

# Raman Scattering (Cont'd)

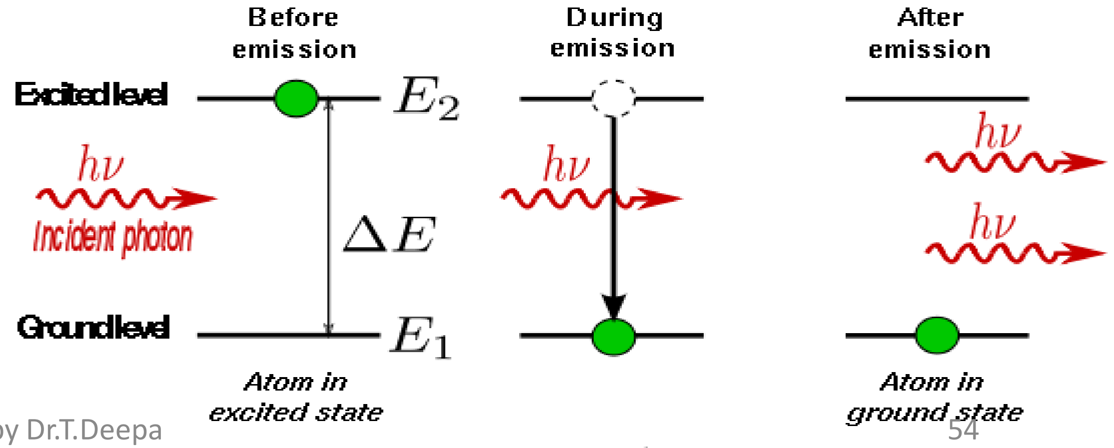
- Definition: a nonlinear scattering process.
- The nonlinear response of a transparent optical medium to the optical intensity of light propagating through the medium is very fast, but not instantaneous. In particular, a non-instantaneous response is caused by vibrations of the crystal (or glass) lattice. When these vibrations are associated with optical phonons, the effect is called *Raman scattering*.
- The Raman-scattering process takes place spontaneously; i.e., in random time intervals, one of the many incoming photons is scattered by the material. This process is thus called *spontaneous Raman scattering*.
- Stimulated Raman scattering is a nonlinear-optical effect. It can be described using a third-order nonlinear susceptibility.

# Definition of LASER

- A LASER is a quantum mechanical optical device that amplifies light by a process called STIMULATED EMISSION.
- LASER - Light Amplification by Stimulated Emission of Radiation
- Inspiration for LASERS: Albert Einstein - 1917

# Definition of LASER

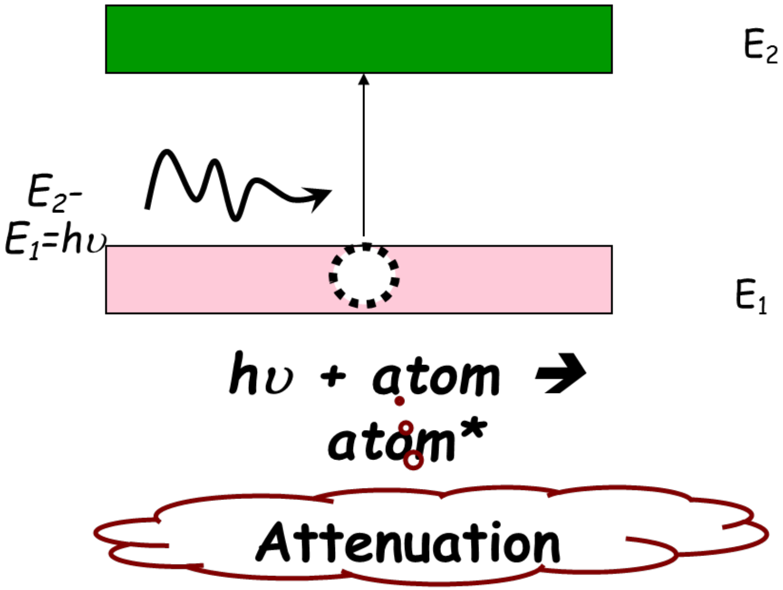
- **A LASER is a quantum mechanical optical device that amplifies light by a process called STIMULATED EMISSION.**
- **LASER - Light Amplification by Stimulated Emission of Radiation**
- A **laser** is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term "laser" originated as an acronym for "**light amplification by stimulated emission of radiation**".
- The first laser was built in 1960 by Theodore H. Maiman at Hughes Research Laboratories, based on theoretical work by Charles Hard Townes and Arthur Leonard Schawlow.
- **Inspiration for LASERS: Albert Einstein - 1917**



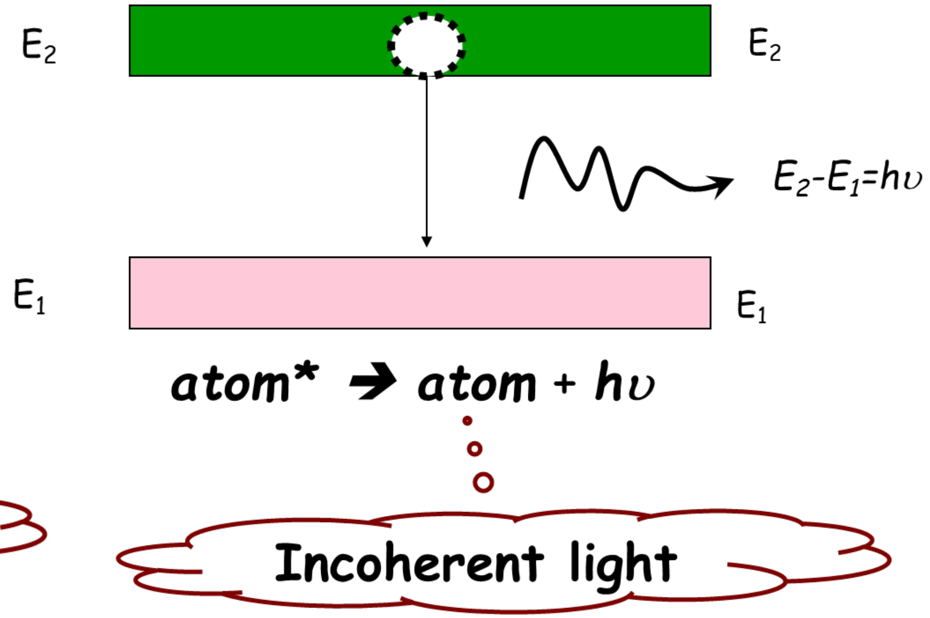

$$E_2 - E_1 = \Delta E = h\nu$$

# Interaction of Light with Matter

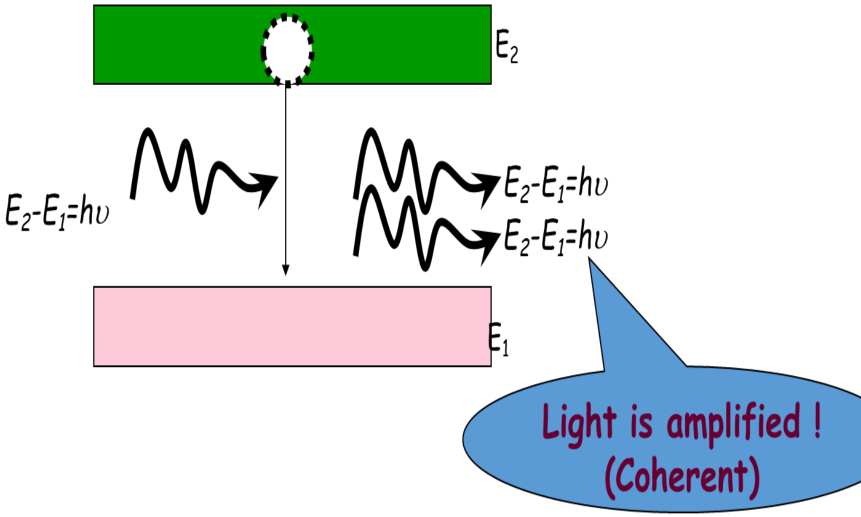
## 1. Absorption



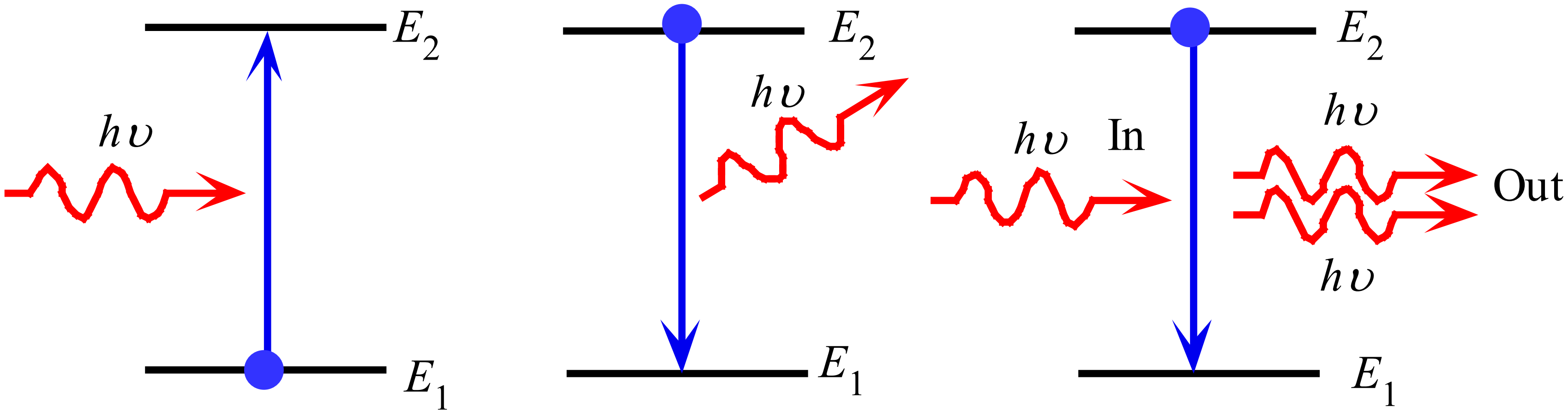

## 2. Spontaneous Emission




## 3. Stimulated Emission



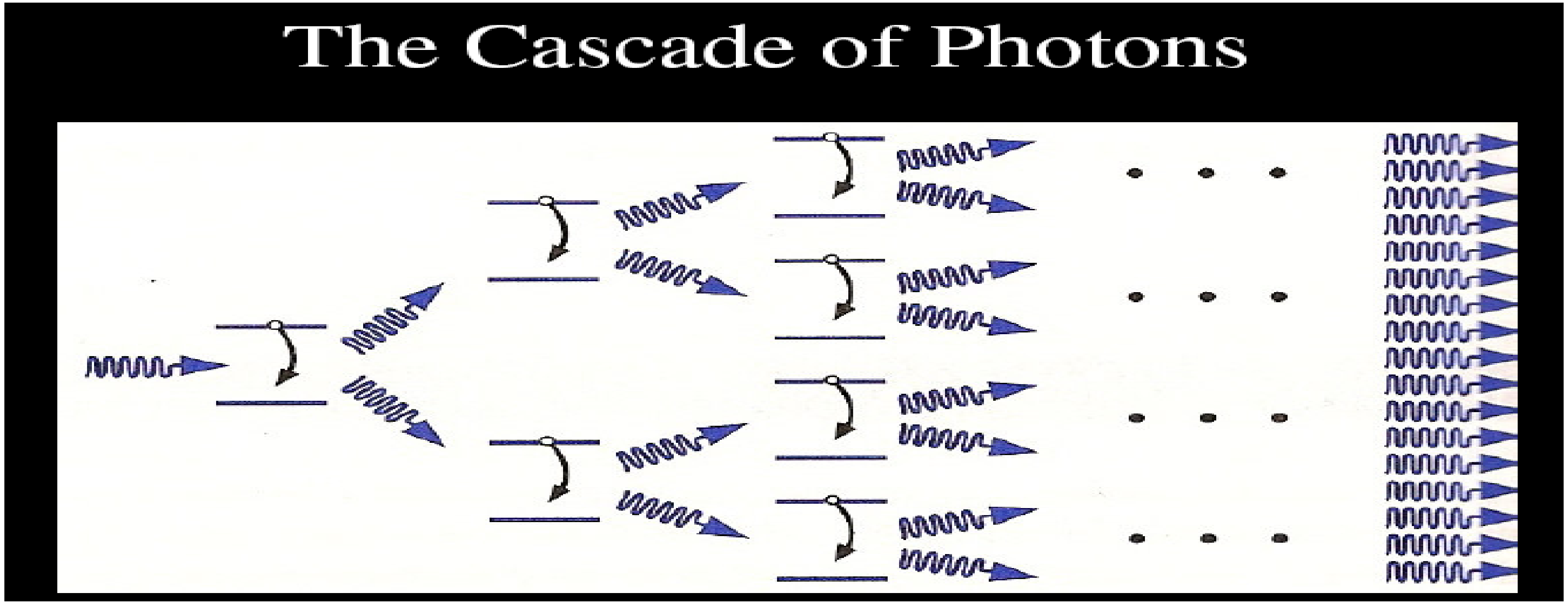
# A Recap of Three Processes




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

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

# Amplification by Stimulated Emission



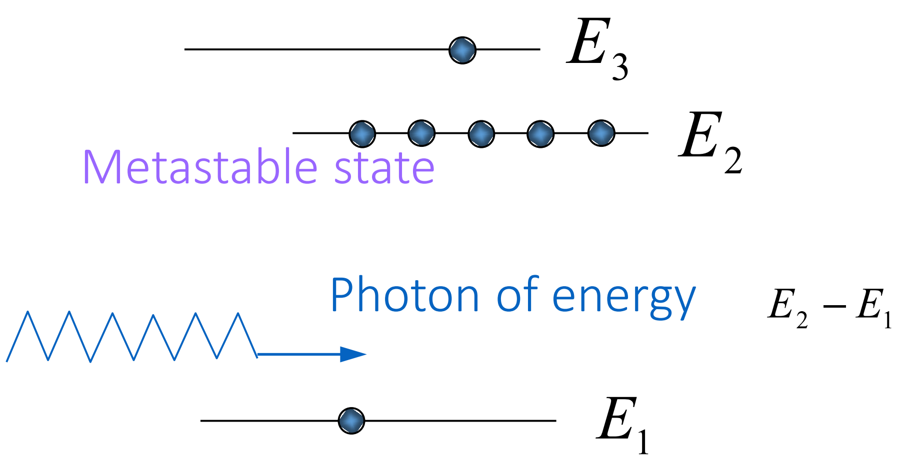
# Population Inversion

In order to obtain the coherent light from stimulated emission, two conditions must be satisfied:

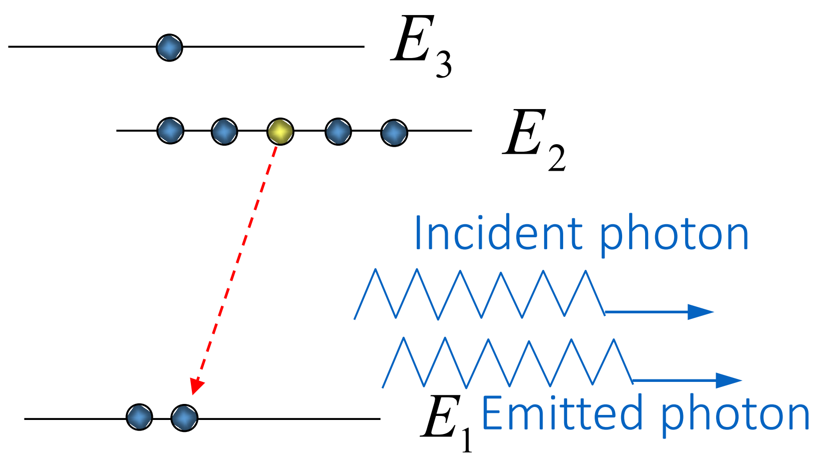
1. The atoms must be excited to the higher state. That is, an inverted population is needed, one in which more atoms are in the upper state than in the lower one, so that emission of photons will dominate over absorption.

# Metastable State

2. The higher state must be a metastable state – a state in which the electrons remain longer than usual so that the transition to the lower state occurs by stimulated emission rather than spontaneously.

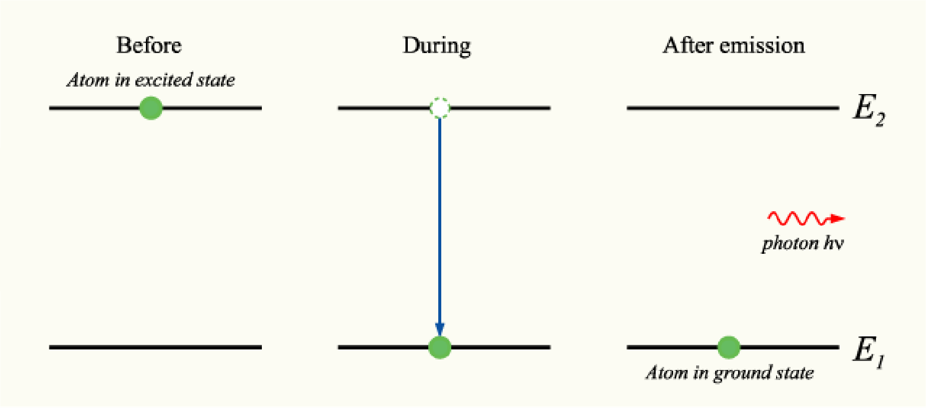


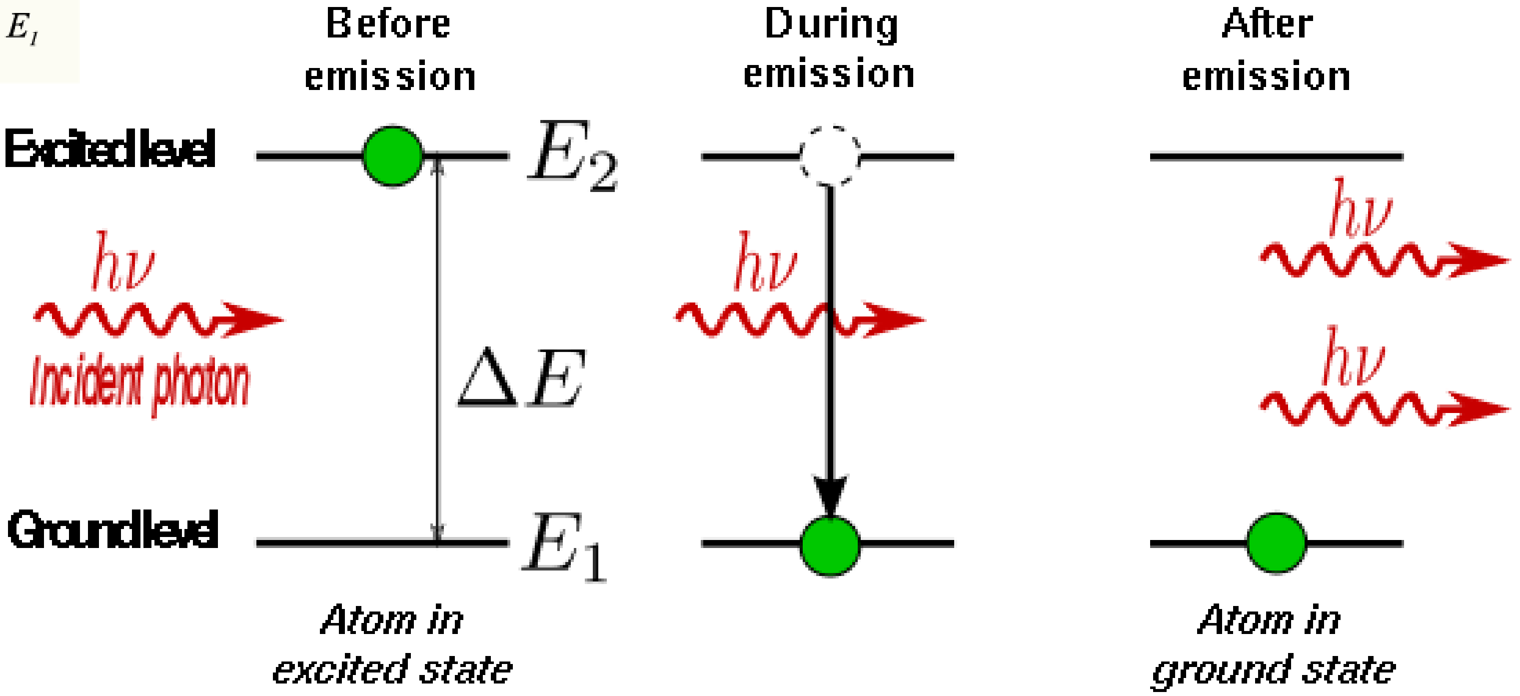

Metastable system




Stimulated emission

# The interaction of light with matter




$$E_2 - E_1 = \Delta E = h\nu$$

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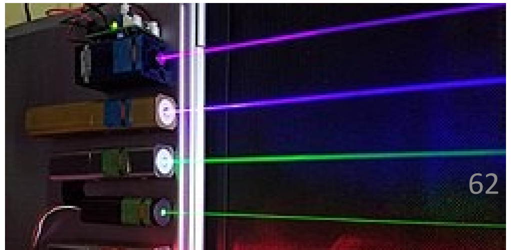
# Spontaneous Emission

- **Spontaneous emission** is the process in which a quantum mechanical system (such as an atom, molecule or subatomic particle) transitions from an excited energy state to a lower energy state (e.g., its ground state) and **emits a quantum in the form of a photon**.
- Spontaneous emission is ultimately responsible for most of the light we see all around us.
- If atoms (or molecules) are excited by some means other than heating, the spontaneous emission is called luminescence.
- **LASERS** start via spontaneous emission, then during continuous operation work by stimulated emission.

# Stimulated Emission

- **Stimulated emission** is the process by which an **incoming photon of a specific frequency can interact with an excited atomic electron** , causing it to drop to a lower energy level.
- The liberated energy transfers to the electromagnetic field, creating a new photon with a phase, frequency, polarization, and direction of travel that are all identical to the photons of the incident wave.
- This is in contrast to spontaneous emission, which occurs at random intervals without regard to the ambient electromagnetic field.
- The process is identical in form to atomic absorption in which the energy of an absorbed photon causes an identical but opposite atomic transition: from the lower level to a higher energy level. In normal media at thermal equilibrium, absorption exceeds stimulated emission because there are more electrons in the lower energy states than in the higher energy states.

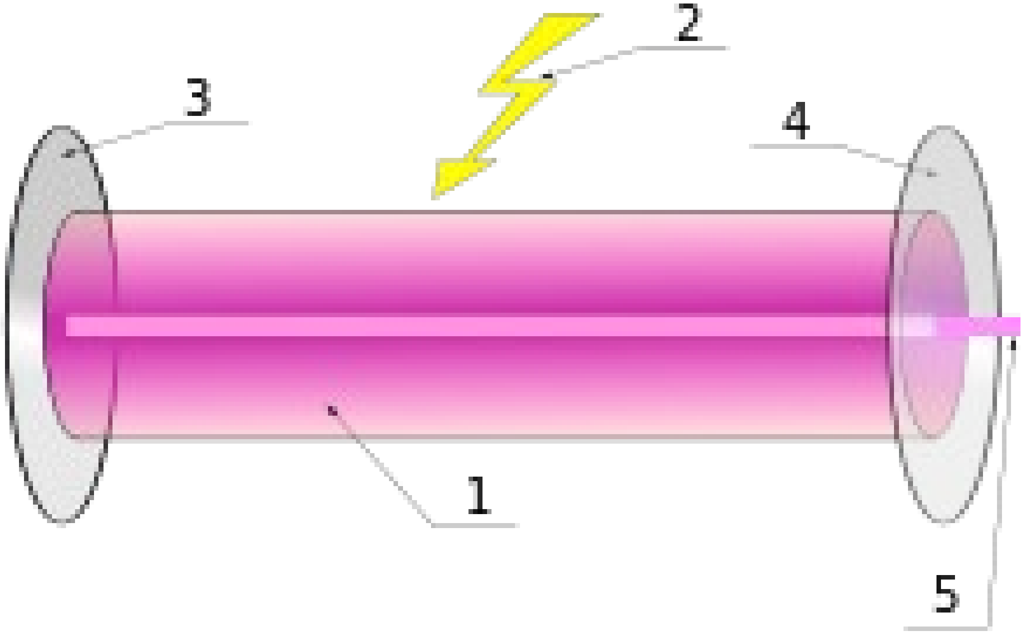


# Stimulated Emission (Cont’d)

- However, when a population inversion is present, the rate of stimulated emission exceeds that of absorption, and a net optical amplification can be achieved. Such a gain medium, along with an optical resonator, is at the heart of a laser or maser.
- Definition of Population inversion :
- In science, specifically statistical mechanics, a **population inversion** occurs while a system (such as a group of atoms or molecules) exists in a state in which more members of the system are in higher, excited states than in lower, unexcited energy states. It is called an "inversion" because in many familiar and commonly encountered physical systems, this is not possible. The concept is of fundamental importance in laser science because the production of a population inversion is a necessary step in the workings of a standard laser.

# Components of Typical Laser

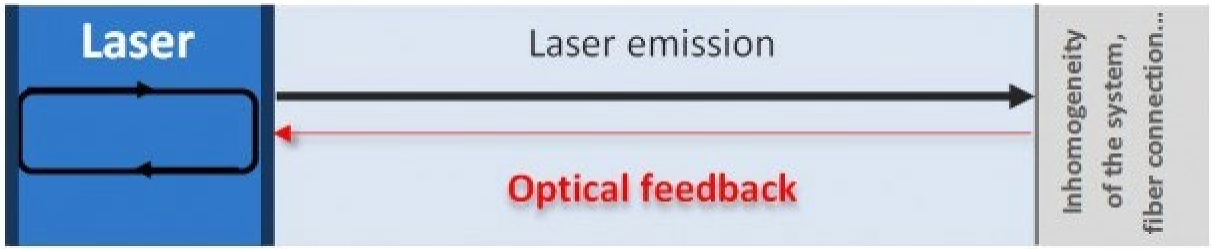
1.Gain medium/Cavity
2.Laser pumping energy
3.High reflector
4.Output coupler
5.Laser beam



# Optical Cavity

- An **optical cavity**, **resonating cavity** or **optical resonator** is an arrangement of mirrors that forms a standing wave cavity resonator for light waves.
- Optical cavities are a major component of lasers, surrounding the gain medium and **providing feedback of the laser light**.
- They are also used in **optical parametric oscillators and some interferometers**.
- Light confined in the cavity reflects multiple times producing standing waves for certain resonance frequencies.
- The standing wave patterns produced are called modes; longitudinal modes differ only in frequency while transverse modes differ for different frequencies and have different intensity patterns across the cross section of the beam.

# Optical Feedback in lasers



# Optical Feedback in lasers (Cont'd)

- The general function of lasers is based on optical feedback.
- Photons emitted from the active region are back-reflected by the mirrors into the gain medium.
- In this way, **optical feedback is realized and finally controls the process of stimulated emission**.
- Feedback is introduced into a laser when some portion of the optical output is back into the device.
- It comes from **optical elements like micro-lenses in fiber-coupled modules, fiber ends, fiber combiners, and also radiation from other sources.** Even very small portions of the light reflected can destabilize the laser and produce different kinds of **regular or irregular**, **reversible or irreversible effects**.
- Optical feedback has various effects on the operating characteristics of a laser.
- **Disadv:** It may cause unwanted instabilities in the laser output,
- **Adv**: Increasing the side mode suppression and narrowing the linewidth.

# Threshold Condition

- A small amount of gain is necessary for the operation of a laser. This amount can be realized only when the laser is pumped above a threshold level. The current which is required to reach the mentioned level threshold is called the **threshold current**

# Threshold condition (Contd)

- The **lasing threshold** is the lowest excitation level at which a laser's output is dominated by stimulated emission rather than by spontaneous emission.
- Below the threshold, the laser's output power rises slowly with increasing excitation. Above threshold, the slope of power vs. excitation is orders of magnitude greater.
- The line width of the laser's emission also becomes orders of magnitude smaller above the threshold than it is below. Above the threshold, the laser is said to be *lasing*.

# Threshold condition (Cont'd)

- The lasing threshold is reached when the optical gain of the laser medium is exactly balanced by the sum of all the losses experienced by light in one round trip of the laser's optical cavity. This can be expressed, assuming steady-state operation, as

$$R_1 R_2 \exp(2g_{\text{threshold}}\, l) \exp(-2\alpha l) = 1\ .$$

- R1 & R2 are the mirror (power) reflectivities,
- L is the length of the gain medium
- $\exp(2g_{\text{threshold}}\, l)$ is the round-trip threshold power gain
- $\exp(-2\alpha l)$ is the round trip power loss

- This equation separates the losses in a laser into localised losses due to the mirrors, over which the experimenter has control, and distributed losses such as absorption and scattering. The experimenter typically has little control over the distributed losses.

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# Threshold condition (Cont'd)

- The optical loss is nearly constant for any particular laser $(\alpha = \alpha_0)$, especially close to threshold. Under this assumption the threshold condition can be rearranged as

$$g_{\text{threshold}} = \alpha_0 - \frac{1}{2l}\ln(R_1 R_2).$$

Since $R_1 R_2 < 1$, both terms on the right side are positive, hence both terms increase the required threshold gain parameter. This means that minimising the gain parameter $g_{\text{threshold}}$ requires low distributed losses and high reflectivity mirrors. The appearance of $l$ in the denominator suggests that the required threshold gain would be decreased by lengthening the gain medium, but this is not generally the case. The dependence on $l$ is more complicated because $\alpha_0$ generally increases with $l$ due to diffraction losses.

# Injection Laser Diode

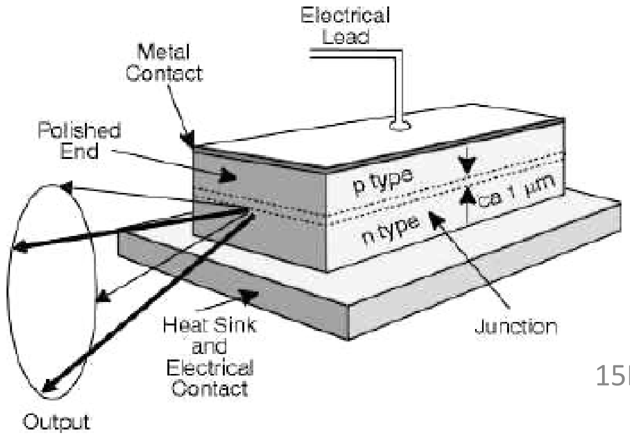
- A **laser diode**, (**LD**), **injection laser diode** (**ILD**), or **diode laser** is a semiconductor device similar to a light-emitting diode in which the laser beam is created at the diode's junction.
- Laser diodes are the most common type of lasers produced, with a wide range of uses that include fiber optic communications, barcode readers, laser pointers, CD/DVD/Blu-ray disc reading/recording, laser printing, laser scanning and light beam illumination.

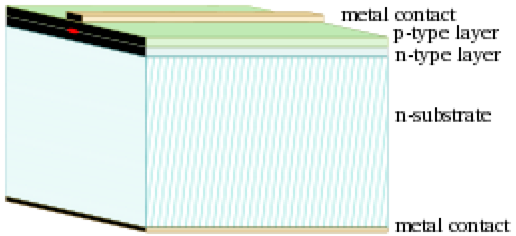
# Working Principle –ILD

- A laser diode is electrically a PIN diode. The active region of the laser diode is in the intrinsic (I) region, and the carriers (electrons and holes) are pumped into that region from the N and P regions respectively.
- all modern lasers use the double-hetero-structure implementation, where the carriers and the photons are confined in order to maximize their chances for recombination and light generation. Unlike a regular diode, the goal for a laser diode is to recombine all carriers in the I region, and produce light.
- Thus, laser diodes are fabricated using direct band-gap semiconductors.

# Working Principle –ILD (Cont’d)

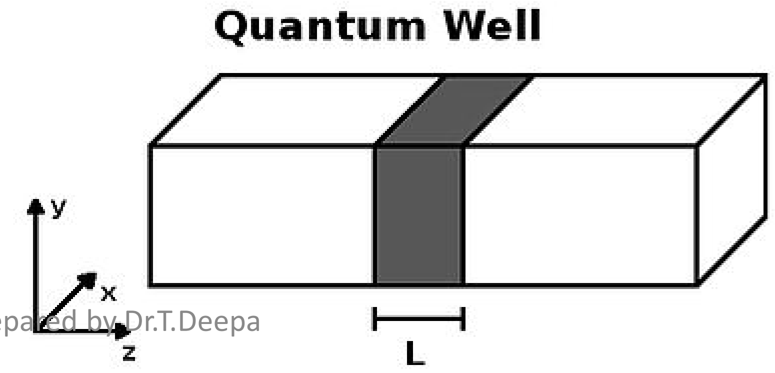
- The active layer most often consists of quantum wells, which provide lower threshold current and higher efficiency.
- Laser diodes form a subset of the larger classification of semiconductor *p-n* junction diodes. Forward electrical bias across the laser diode causes the two species of charge carrier – holes and electrons – to be "injected" from opposite sides of the *p-n* junction into the depletion region.
- Holes are injected from the *p*-doped, and electrons from the *n*-doped, semiconductor.
- Due to the use of charge injection in powering most diode lasers, this class of lasers is sometimes termed "injection lasers," or "injection laser diode" (ILD).




# What is Quantum well ?

- A **quantum well** is a potential well with only discrete energy values.
- The classic model used to demonstrate a quantum well is to confine particles, which were originally free to move in three dimensions, to two dimensions, by forcing them to occupy a planar region.
- The effects of quantum confinement take place when the quantum well thickness becomes comparable to the de Broglie wavelength of the carriers (generally electrons and holes), leading to energy levels called "energy subbands", i.e., the carriers can only have discrete energy values.



# Fabrication –Quantum well

- Quantum wells are formed in semiconductors by having a material, like gallium arsenide, sandwiched between two layers of a material with a wider bandgap, like aluminium arsenide. (Other example: layer of indium gallium nitride sandwiched between two layers of gallium nitride.)

# Quantum Well Laser

- If the middle layer is made thin enough, it starts acting like a quantum well.
- This means that in the vertical direction, electron energy is quantised.
- The difference between quantum well energy levels can be used for the laser action instead of the bandgap. This is very useful since the wavelength of light emitted can be tuned simply by altering the thickness of the layer.
- The efficiency of a quantum well laser is greater than that of a bulk laser due to a tailoring of the distrubution of electrons and holes that are involved in the stimulated emission (light producing) process.
- The problem with these devices is that the thin layer is simply too small to effectively confine the light. To compensate, another two layers are added on, outside the first three. These layers have a lower refractive index than the centre layers, and hence confine the light effectively. Such a design is called a separate confinement heterostructure (**SCH**) laser diode.

# Distributed Feedback laser (DFB)

- A **distributed feedback laser** (**DFB**) is a type of laser diode, quantum cascade laser or optical fiber laser where the active region of the device is periodically structured as a diffraction grating.
- This grating provides optical feedback for the laser. The reflection of the coating can be varied to make the laser oscillate near the Wavelength.
- DFB laser diodes do not use two discrete mirrors to form the optical cavity (as they are used in conventional laser designs).
- The grating acts as the wavelength selective element for at least one of the mirrors and provides the feedback, reflecting light back into the cavity to form the resonator.

# DFB (Distributed Feed Back) Lasers

- In DFB lasers, the lasing action is obtained by means of **periodic variations** of the refractive index which are incorporated into the multiple layer structure along the length of the diode. Here the cleaved facets are not required for **optical feedback**.

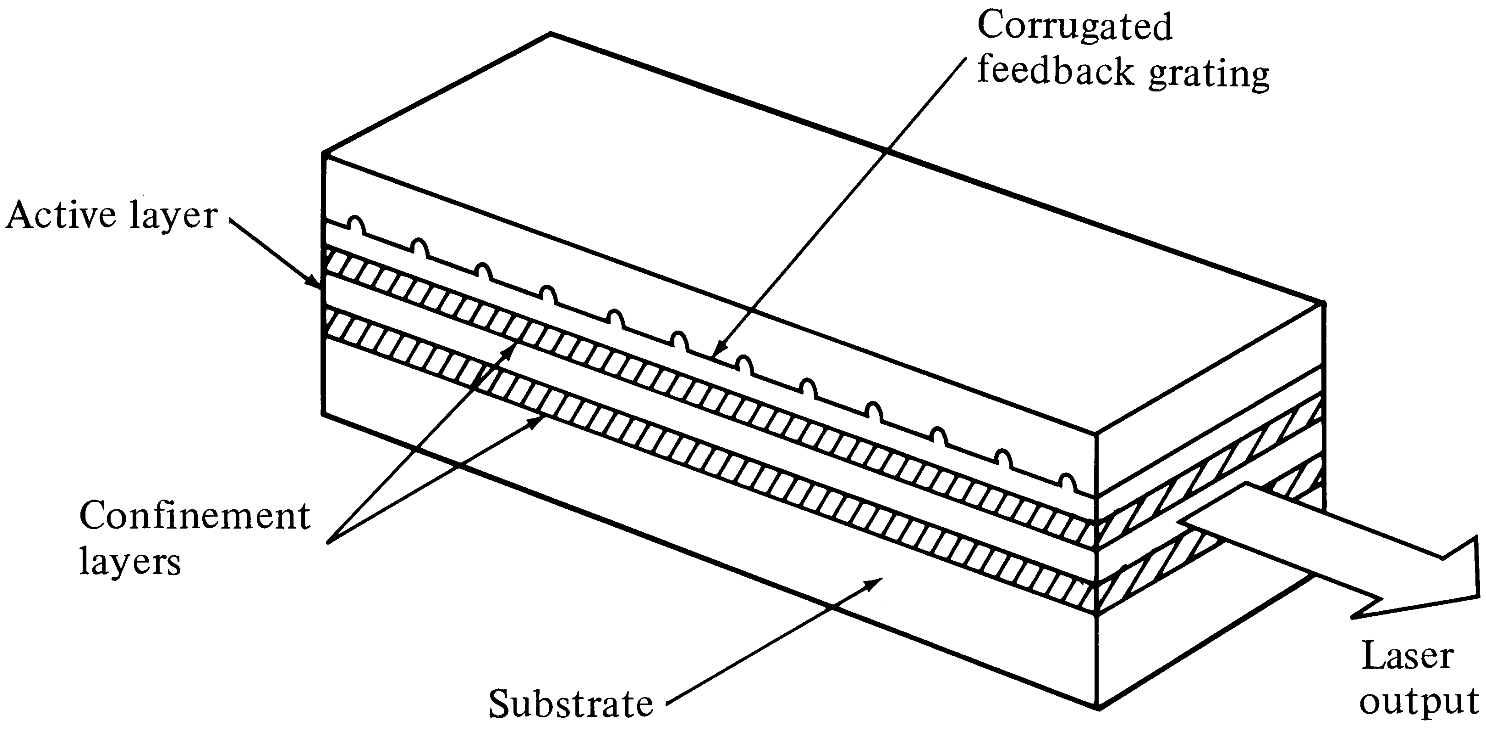



Fig. Structure of a distributed Feed Back (DFB) laser diode

# Modes and Threshold Conditions

## Modes of the cavity:

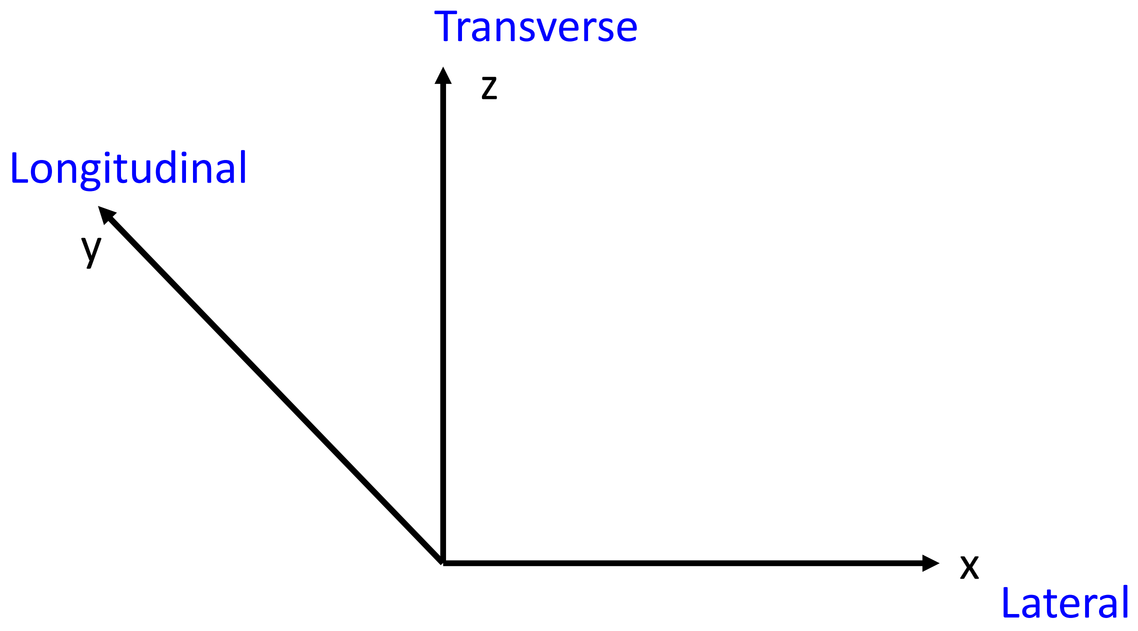
The optical radiation within the resonance cavity of a laser diode sets up a pattern of both electric and magnetic field lines is called the **“modes of the cavity”**

Two modes are available in the optical cavity. They are

**1. Transverse Electric (TE) modes**, and
**2. Transverse Magnetic (TM) modes**.

Each set of modes can be described in terms of longitudinal, lateral and transverse half-sinusoidal variations of the electro magnetic fields along the major axes of the cavity

# Modes and Threshold Conditions (Contd)




## Longitudinal Modes:

The longitudinal modes are related to the length L of the cavity and it determines the principal structure of the Frequency spectrum of the optical radiation.

Since L is much larger than the lasing wavelength of approximately 1 µm, many longitudinal modes can exist.

# Modes and Threshold Conditions (Contd)

## Lateral Modes:

- Lateral modes lie in the plane of the p-n junction. These modes depend on the side wall preparation and width of the cavity, and it determines the shape of the lateral profile of the laser beam.

## Transverse Modes :

- Transverse modes are associated with the electromagnetic field and beam profile in the direction perpendicular to the plane of the p-n junction.

- These modes determines the laser characteristics such as the radiation pattern and the threshold current density. i.e., the point at which the lasing starts

# Modes and Threshold Conditions (Contd)

- To determine the lasing conditions and the resonant frequencies, the EM wave propagating in the longitudinal direction in terms of the electric field phasor

$$E(z,t) = I(z) \cdot \exp[j(\omega t - \beta k)]$$

where

$I(z)$ is the optical field intensity,

$\omega$ is the optical radian frequency, and

$\beta$ is the propagation constant.

# Lasing Modes and Threshold Conditions (Contd)

- Lasing is the condition at which light amplification becomes possible in the laser diode. The condition for lasing is that a popular inversion can be achieved

- The stimulated emission rate into a given mode is proportional to the intensity of the radiation in that mode.

- The radiation intensity at a photon energy $h\nu$ varies exponentially with the distance $z$ that it traverses along the lasing cavity according to the relationship

$$I(z) = I(0).\exp\{[\Gamma g(h\nu) - \tilde{\alpha}(h\nu)]z\}$$

where

$g$ is the gain coefficient in the Fabry-Perot cavity,

$\tilde{\alpha}$ is the effective absorption coefficient of the material in the optical path, and

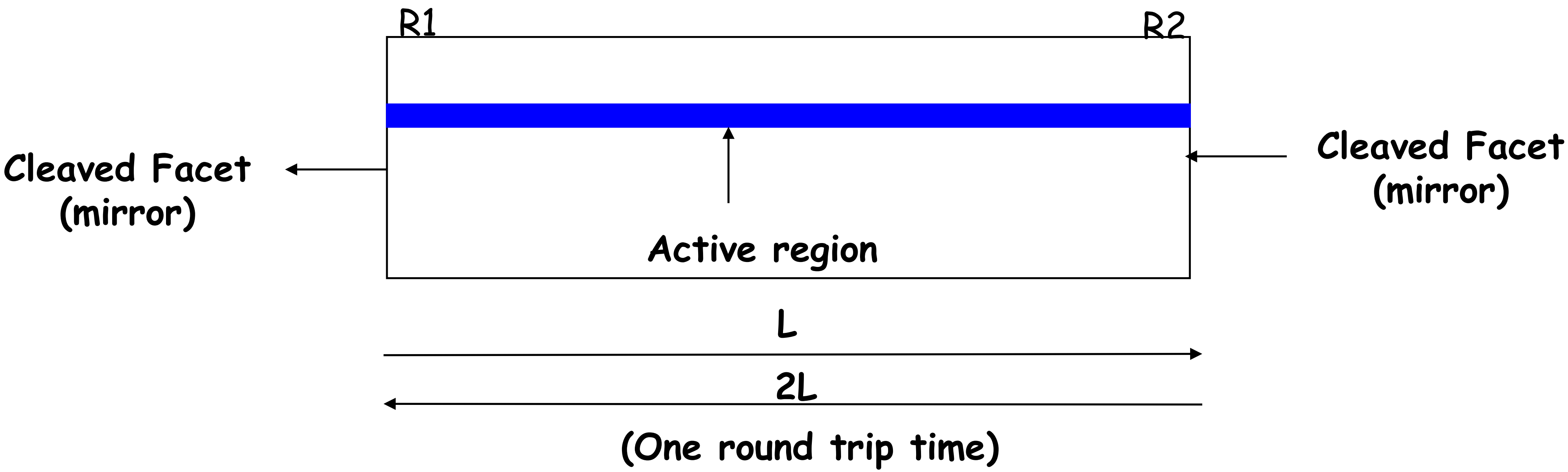
$\Gamma$ is the *optical-field confinement factor* -- the fraction of optical power in the active layer.

z is distance travelled in the cavity

$h\nu$ is Photon energy

# Modes and Threshold Conditions (Contd)

- Lasing occurs when the gain of guided modes exceed the optical loss during one roundtrip through the cavity. i.e. z=2L




- During the roundtrip $z = 2L$, only the fractions $R_1$ and $R_2$ of the optical radiation are reflected from the laser ends 1 and 2, respectively.

- Where $R_1$ and $R_2$ are the mirror reflectivities or Fresnel reflection coefficients, which are given by

$$R = [(n_1 - n_2)/(n_1 + n_2)]^2$$

# Modes and Threshold Conditions (Contd)

For the optical reflection at an interface between materials having refractive indices $n_1$ and $n_2$.
From this lasing condition, becomes

$$I(2L) = I(0)R_1R_2 \cdot \exp\{2L[\Gamma g(h\nu) - \tilde{\alpha}(h\nu)]\}$$

## Lasing Condition

At the lasing threshold, a steady-state oscillation takes place, and the magnitude and phase of the returned wave must be equal to those of the original wave:

***The condition of lasing threshold is given as***

*i) For Amplitude:* $I(2L) = I(0)$

**ii) For Phase:** $\exp[-j2\beta L] = 1$

The above equation gives information concerning the resonant frequencies of the Fabry-Perot cavity.

# Modes and Threshold Conditions (Contd)

- The condition to just reach the lasing threshold is the point at which the optical gain is equal to the total loss $\alpha_t$ in the cavity.

**Optical gain at threshold = Total loss in the cavity ($\alpha_t$)**

- The condition is

$$\Gamma g_{th} = \alpha_t$$
$$= \tilde{\alpha} + (1/2L).\ln(1/R_1R_2)$$
$$= \tilde{\alpha} + \alpha_{end}$$

**where $\alpha_{end}$ is the mirror loss in the lasing cavity.**

- *An important condition for lasing to occur is that, we must have the gain $g \geq g_{th}$.* This means that the pumping source that maintains the population inversion must be sufficiently strong to support or exceed all the energy-consuming mechanisms within the lasing cavity.

# Modes and Threshold Conditions (Contd)

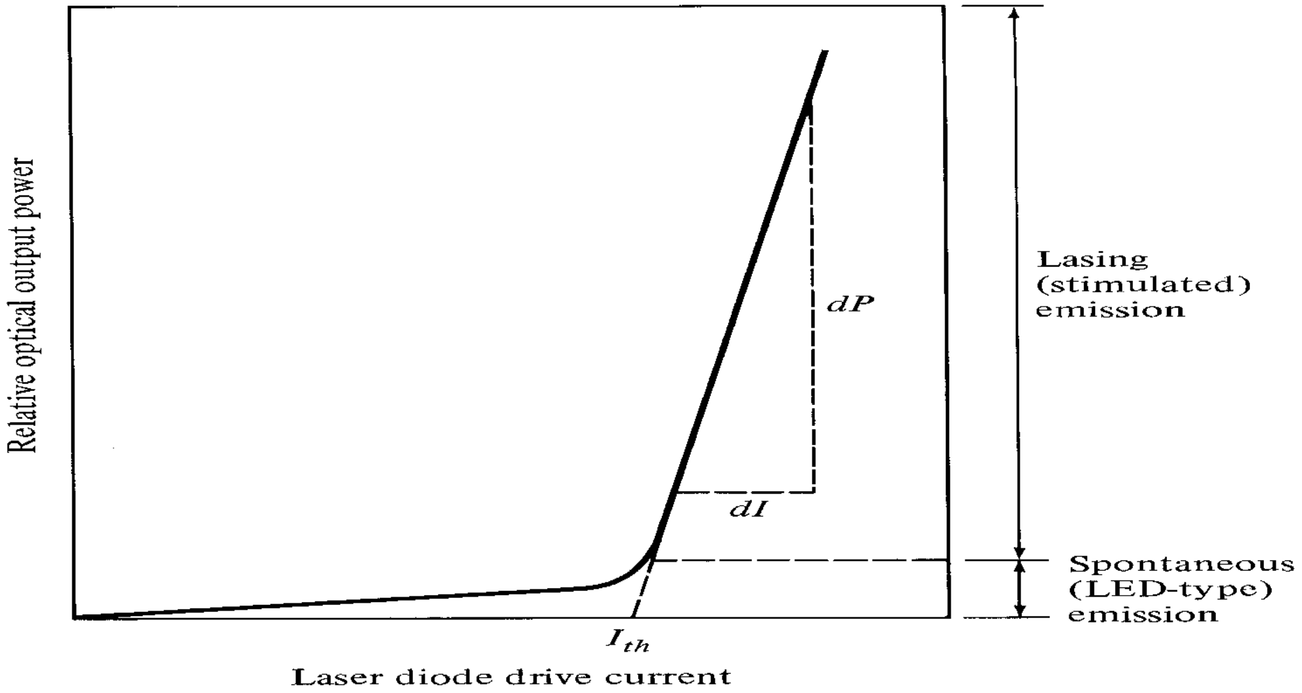



Fig. Relationship between optical output power and laser diode drive current. Below the lasing threshold, the optical output is a spontaneous LED-type emission.

- The *threshold current* $I_{th}$ is defined by extrapolation of the lasing region of the L-I curve, as shown in Fig.

- At high power outputs, the slope of the curve decreases because of junction heating.

- For laser structures that have strong carrier confinement, the *threshold current density* for stimulated emission $J_{th}$ can to a good approximation be related to the lasing-threshold optical gain by

$$g_{th} = \beta J_{th}$$

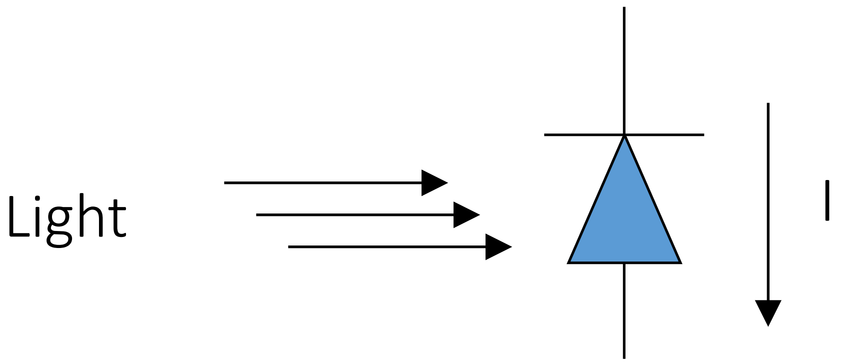
where b is a constant that depends on the specific device construction.

- The threshold current density ($J_{th}$) is given by

$$J_{th} = \frac{1}{\beta}\left(\bar{\alpha} + \frac{1}{2L}\ln\frac{1}{R_1 R_2}\right)$$

# Photo detection Principle

- A detector’s function is to convert the received optical signal into an electrical signal, which is then amplified before further processing.



# Optical Detectors

- Optical detectors are used to convert variation in optical power into corresponding variation in electric current.

- The photodetector works on the principle of optical absorption. The main requirement of light detector is its fast response.

- For fiber optic communication purpose most suited photodetectors are PIN (p – type – intrinsic – n- type) diode and Avalanche Photodiode (APD)

- The performance parameters of a photodetector are responsivity, quantum efficiency, response time and dark current

# Photo detection- PIN

- A **PIN diode** is a diode with a wide, undoped intrinsic semiconductor region between a p-type semiconductor and an n-type semiconductor region.
- The p-type and n-type regions are typically heavily doped .
- The wide intrinsic region is in contrast to an ordinary p–n diode. The wide intrinsic region makes the PIN diode an inferior rectifier (one typical function of a diode), but it makes it suitable for attenuators, fast switches, photodetectors, and high voltage power electronics applications.

# Applications – PIN

- PIN diodes are useful as RF switches, attenuators, photodetectors, and phase shifters.

# Photodetector - Requirements

a) High sensitivity (responsivity) at the desired wavelength. and low responsivity elsewhere

a) High fidelity. To reproduce the received signal waveform with fidelity (Example: for analog transmission the response of the photodetector must be linear with regard to the optical signal over a wide range).

b) Large electrical response to the received optical signal. The photodetector should produce a maximum electrical signal for a given amount of optical power.

d) Short response time. (pn-µsec, PIN/APD-nsec)

# Photodetector - Requirements

d) Minimum noise and reasonable cost
e) Insensitive to temperature variations
f) Stability.
g) Small size
h) Low bias voltage.
i) High reliability
j) Low cost
k) Long operating life

# Photodiodes

- 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

- Photodiodes are *reverse biased* for normal operation

# Photodetector - Characteristics

## 1. Responsivity

- Responsivity – The ratio of current output (Amp) to the incident optical power (light input) [watts].
  - varies with wavelength
  - theoretical maximum responsivity: 1.05A/W at 1300nm
  - typical responsivity: 0.8 - 0.9 A/W at 1300nm
  - formula for theoretical maximum responsivity (quantum efficiency = 100%)

$$R = \frac{I_p}{P_{in}} AW^{-1}$$

# Responsivity (Contd)

$$\eta = \frac{I_p/q}{P_{in}/h\gamma} = \frac{I_P}{q}\frac{h\gamma}{P_{in}}$$

$$\frac{I_P}{P_{in}} = \frac{\eta q}{h\gamma}$$

$$R = \frac{\eta q}{h\gamma} = \frac{\eta q \lambda}{hc}$$

$$R = \frac{\eta \cdot \lambda}{1240}$$

where:
R = theoretical maximum responitivity in Amps/Watt
η = quantum efficiency
λ = wavelength in nanometers

$q=1.6\times10^{-19}$, $h=6.63\times10^{-34}$, $c=3\times10^{8}$

# Responsivity (Contd)

Responsivity gives transfer characteristics of detector i.e. photo current per unit incident optical power.

Typical responsivities of PIN photodiodes are

- Silicon PIN photodiode at 900 nm → 0.65 A/W
- Germanium PIN photodiode at 1300 nm → 0.45 A/W
- InGaAs PIN photodiode at 1300 nm → 0.9 A/W

# Photodetector - Characteristics

## 2. Quantum Efficiency

- Quantum Efficiency - ratio of primary electron-hole pairs created by incident photons to the photons incident on the diode material

$$\eta = \frac{\text{number of electrons-hole pairs generated}}{\text{number of incident photons}}$$

$$\eta = \frac{r_e}{r_p} \qquad \eta = \frac{I_p / q}{P_{in} / h\nu}$$

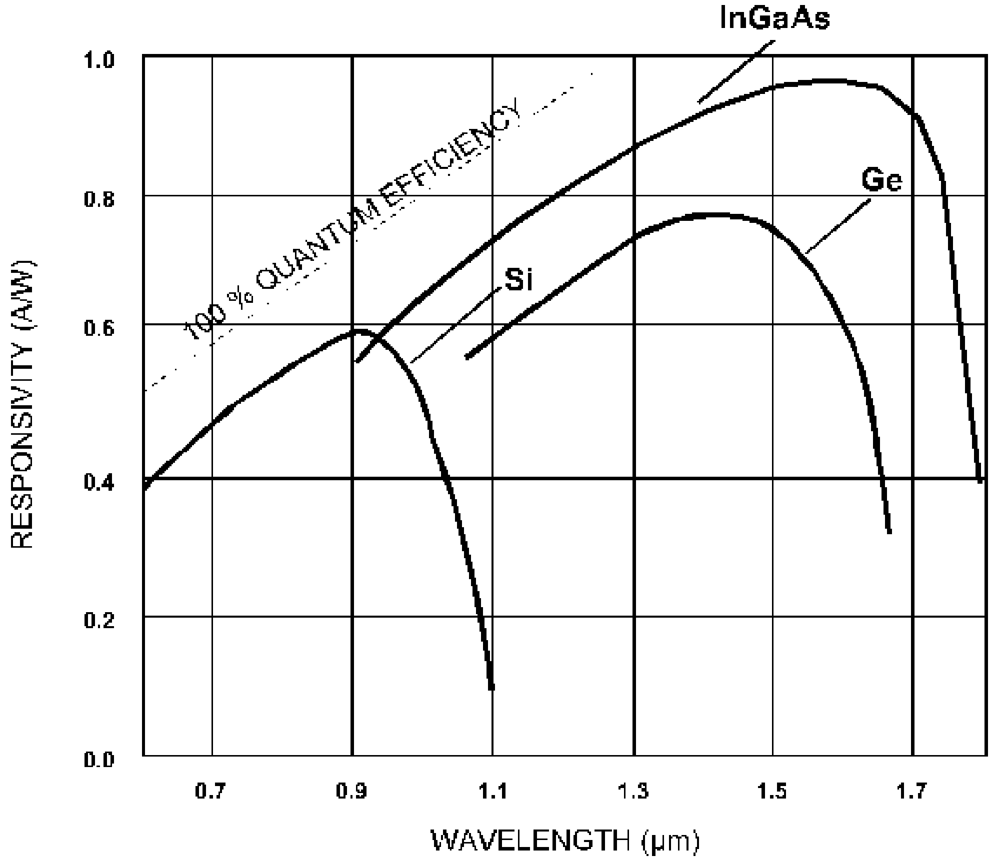



Figure 5.2 Typical Spectral Response of Various Detector Materials

*(Illustration courtesy of Force, Inc.)*

where $r_p$ is the incident photon rate (photon per second) and $r_e$ is the corresponding electron rate (electrons per second)

$I_p$ is average photo current ; $P_{in}$ is average optical power incident on photodetector

# Photodetector - Characteristics

Absorption coefficient of material determines the quantum efficiency.

Quantum efficiency $\eta < 1$ as all the photons incident will not generate e-h pairs. It is normally expressed in percentage.

**Quantum Limit** : For an ideal photodetector having quantum efficiency $\eta = 1$ and has zero dark current (i.e no output when light is absent), then the minimum received power for a specific bit-error rate is known as Quantum Limit

# Photodetector - Characteristics

## 3. Cut-off wavelength ($\lambda_c$)

- Any particular semiconductor can absorb photon over a limited wavelength region. The highest wavelength is known as cut off wavelength ($\lambda_c$). The cut-off wavelength is determined by bandgap energy $E_g$ of the material.

$$\lambda_c = \frac{hc}{E_g} = \frac{1.24}{E_g}$$

where,

Eg in electron volts (eV) and

$\lambda_c$ cut off wavelength (micrometers)

- Typical value of $\lambda_c$ for silicon is 1.06 µm and for germanium it is 1.6 µm
- The photodiode of long cut off wavelength can emit optical power in wide range that is used for fiber optic transmission.

# Photodetector - Characteristics

## 4. Capacitance of a detector

- dependent upon the active area of the device and the reverse voltage across the device.
- A smaller active diameter makes it harder to align the fiber to the detector.
- Also, only the center should be illuminated
  - photodiode response is slow at the edges.

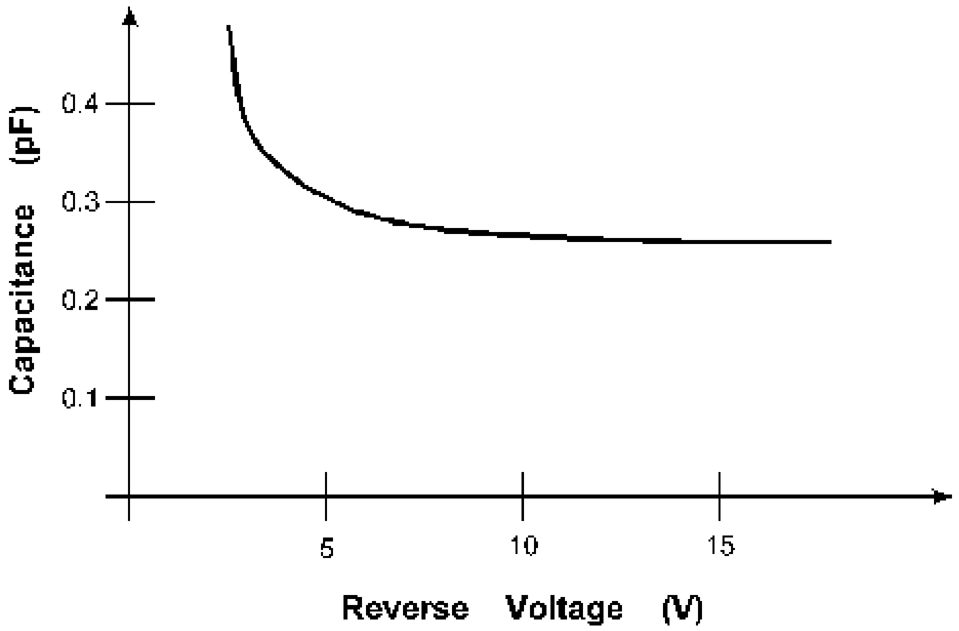
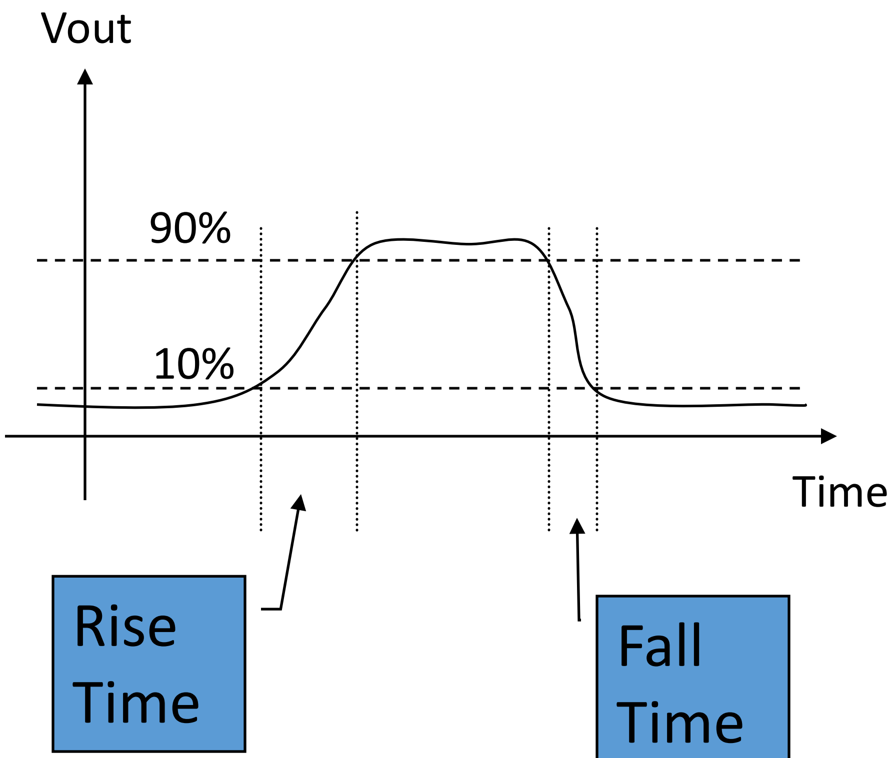



Figure 6.2 Capacitance versus Reverse Voltage

*(Illustration courtesy of Force, Inc.)*

## 5. Response Time




- Time needed for the photodiode to respond to optical input and produce an external current
- Dependent on
  - photodiode capacitance
  - load resistance
  - design of photodiode
- Measured between 10% and 90% of amplitude

# Problems

- Calculate the theoretical maximum responsivity of a detector at 1550nm.
- Calculate the theoretical maximum responsivity of a detector at 820nm.
- Calculate the -3dB frequency and rise time of a detector with a capacitance of 0.5pF operating into an impedance of 50W.

Answers: 1.25 Amps/Watt, 0.661 Amps/Watt, 6.4 GHz

- Calculate the responsively of a detector with quantum efficiency of 10% at 800 nm.

  Ans: 6.45 A/W

- A detector operating at 800 nm produces an output current of 80 A for an incident light beam of power 800 W. Calculate the quantum efficiency and responsivity of the detector.

  Ans: 0.1 A/W , 15.5%

# The PIN Photo-Detector

- The PIN photodiode is structured with *p* and *n* regions separated by a lightly *n*-doped intrinsic (*i*) region.
- Incident photon with energy ≥ band-gap energy of the photodiode will generate free electron-hole pairs, known as *photo-carriers*.
- The high electric field present in the depletion region causes the carriers to separate and be collected across the reverse-biased junction.
- This gives rise to a *photo-current* flow in an external circuit, with one electron flowing for every carrier pair generated.
- In the absence of light, PIN photodiodes behave electrically just like an ordinary rectifier diode. If forward biased, they conduct large amount of current.

# The PIN Photo-Detector (Contd)

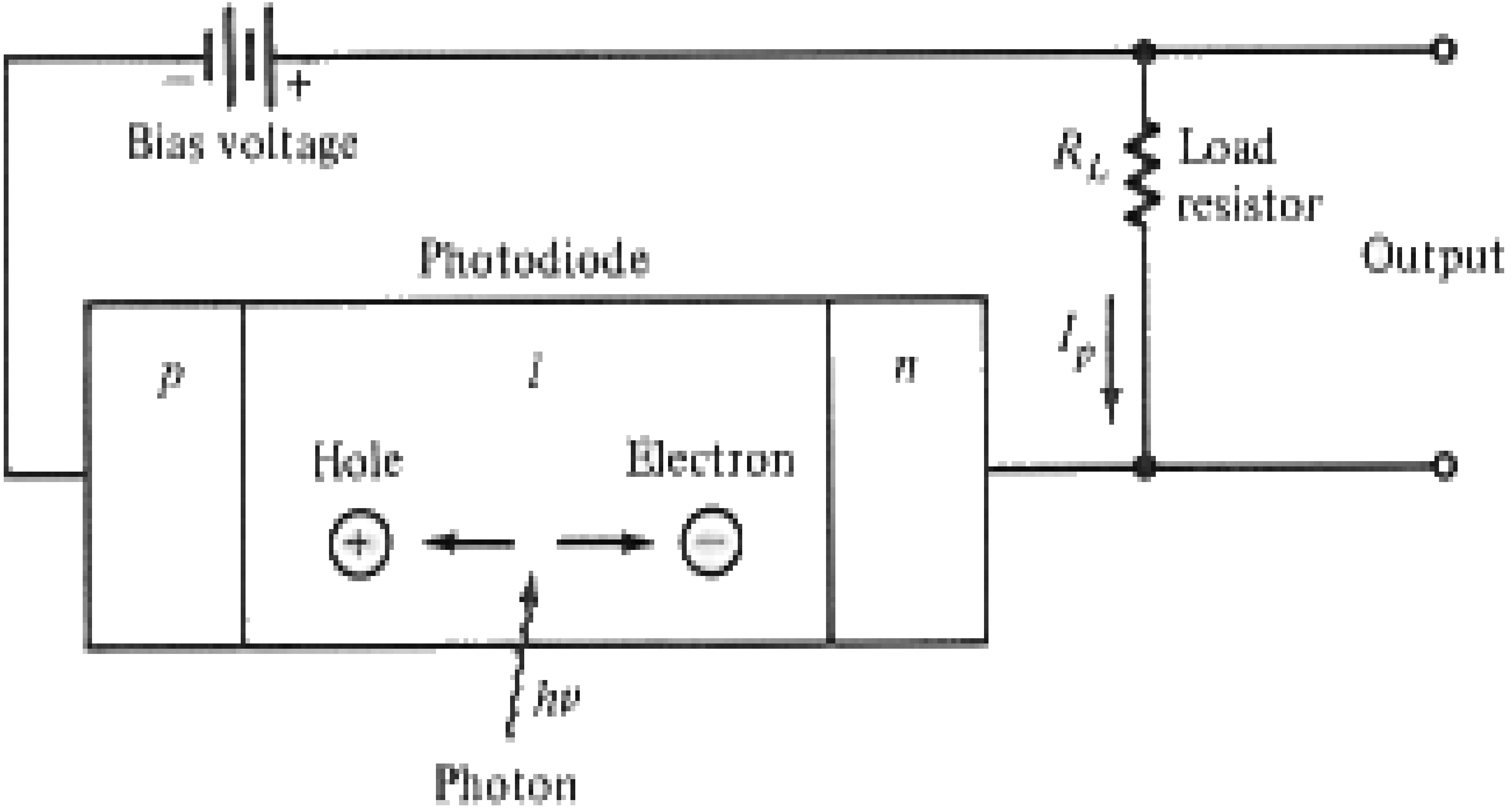



Fig. Schematic representation of a PIN photodiode circuit with an applied reverse bias.

# The PIN Photo-Detector(Contd)

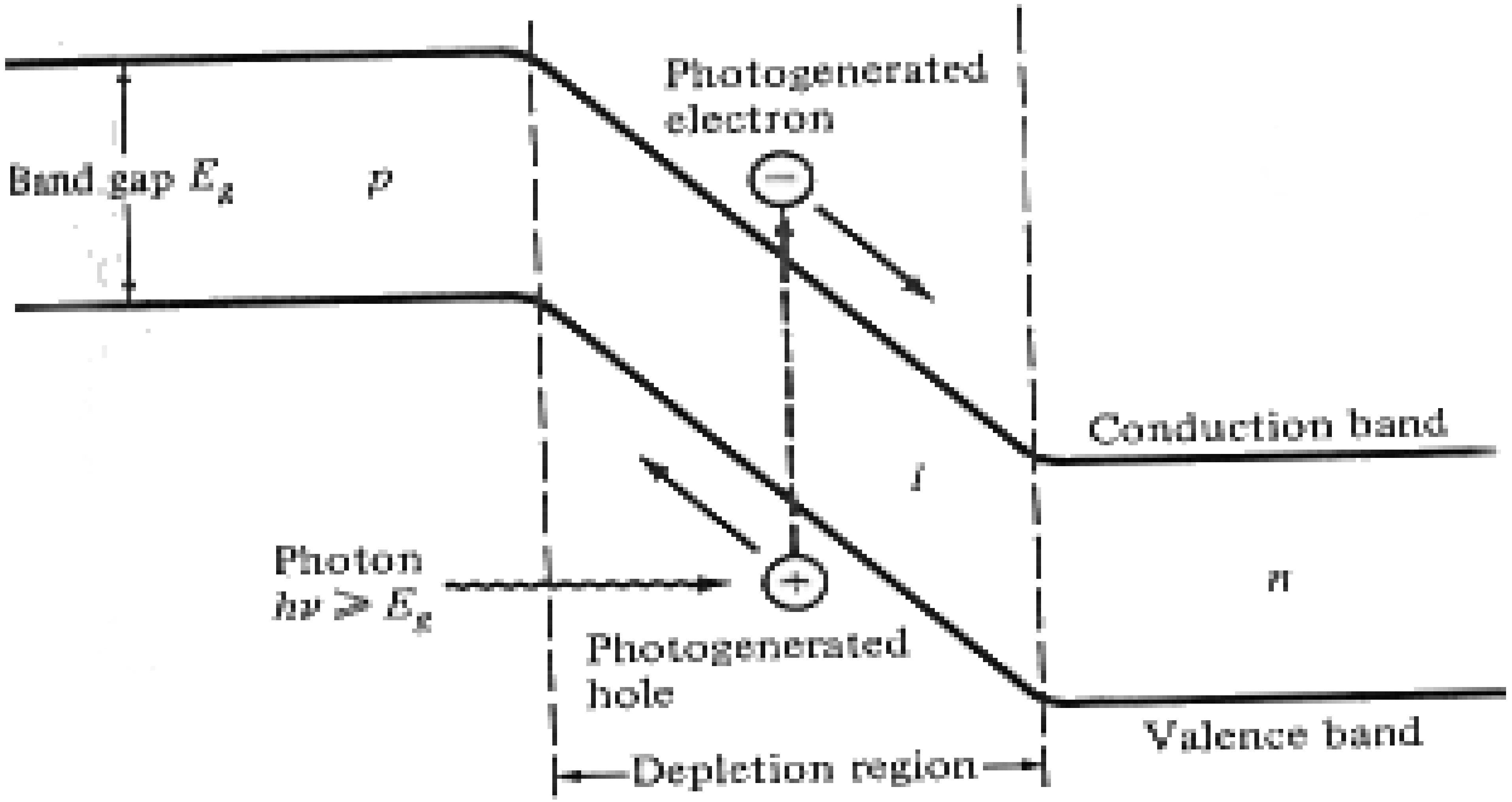



Fig. Simple energy-band diagram for a PIN photodiode. Photons with energy ≥ band-gap energy can generate free electron-hole pairs.

# The PIN Photo-Detector (Contd)

## Operating Modes:

PIN detectors can be operated in two modes

1. **Photovoltaic Mode**
2. **Photoconductive Mode**

## 1. Photovoltaic Mode:

- No bias is applied to the detector.
- In this case, the detector works very slow and output is approximately logarithmic to the input light level.
- Real world fiber optic receivers never use the photovoltaic mode.

## 2. Photoconductive Mode:

- The detector is reversed biased.
- The output in this case is a current that is very linear with the input light power.
- The intrinsic region somewhat improves the sensitivity of the device. It does not provide internal gain. The combination of different semiconductors operating at different wavelengths allow the selection of material capable of responding to the desired operating wavelength.

# The PIN Photo-Detector (Contd)

## Diffusion Length:

- As the charge carriers flow through the material, some electron-hole pairs will recombine and disappear.
- On the average, the charge carriers move a *diffusion length* $L_n$ or $L_p$ for electrons and holes, respectively.

## Carrier Life time:

- The time it takes for an electron or hole to recombine is known as the *carrier lifetime* and is represented by $\tau_n$ and $\tau_p$, respectively.
- The lifetimes and the diffusion lengths are related by

$$L_n = (D_n\tau_n)^{1/2} \quad \text{and} \quad L_p = (D_p\tau_p)^{1/2}$$

where $D_n$ and $D_p$ are the electron and hole diffusion coefficients, expressed in units of $cm^2/sec$.

# The PIN Photo-Detector

**Optical power absorbed**

- Optical radiation is absorbed in the semiconductor material according to the exponential law

$$P(x) = P_o[1 - \exp(-\alpha_s(\lambda)x)]$$

- Here, $\alpha_s(\lambda)$ is the *absorption coefficient* at wavelength $\lambda$,

  $P_o$ is the incident optical power level, and

  $P(x)$ is the optical power absorbed in a distance $x$.

# Absorption coefficient

a measure of the rate of decrease in the intensity of electromagnetic radiation (as light) as it passes through a given substance; the fraction of incident radiant energy **absorbed** per unit mass or thickness of an absorber; "absorptance equals 1 minus transmittance"

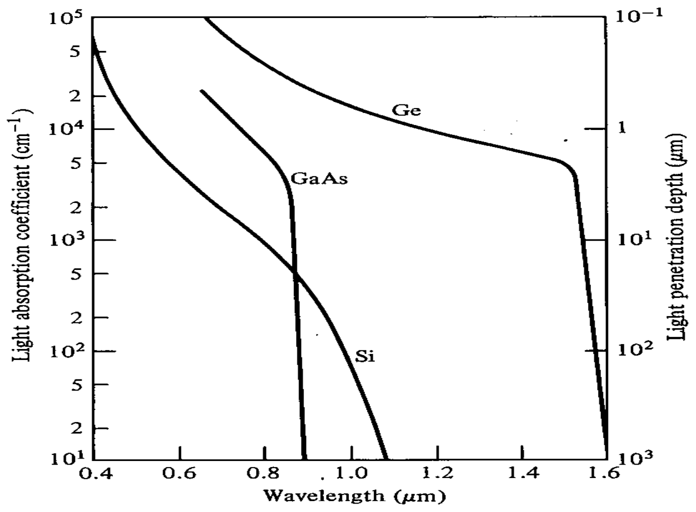



Fig. Optical absorption coefficient as a function of wavelength for Si, Ge, and GaAs.

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# The PIN Photo-Detector (Contd)

- The optical absorption coefficient versus wavelength is shown in Fig. or several photodiode materials.
- The cutoff $\lambda_c$ is determined by the band-gap energy $E_g$ of the material:

$$\lambda_c(\text{mm}) = hc/E_g = 12.4 / E_g(\text{eV})$$

- The cutoff wavelength is about 1.06-µm for Si and 1.6-µm for Ge.
- For longer wavelengths, the photon energy is not sufficient to excite an electron from the valence to the conduction band.

# Avalanche Photodiodes

- When a p-n junction diode is applied with high reverse bias, breakdown can occur by two separate mechanisms.

1. Direct ionization of the lattice atoms → Zener breakdown
2. **High voltage carriers causing Impact Ionization of the lattice atoms → Avalanche breakdown.**

APDs uses the avalanche breakdown phenomenon for its operation. The APD has its internal gain which increases its responsivity.

# Avalanche Photo Diode (APD)

- An **avalanche photodiode** (**APD**) is a highly sensitive semiconductor electronic device that exploits the photoelectric effect to convert light to electricity.
- APDs can be thought of as photodetectors that provide a built-in first stage of gain through avalanche multiplication. From a functional standpoint, they can be regarded as the semiconductor analog photomultipliers.
- By applying a high reverse bias voltage (typically 100–200 V in silicon), APDs show an internal current gain effect (around 100) due to impact ionization (avalanche effect).

# Application –APDs

- Typical applications for APDs are laser range finders, long-range fiber-optic telecommunication, and quantum sensing for azid-based control algorithms. New applications include positron emission tomography and particle physics.
- APD arrays are becoming commercially available, also lightning detection and optical SETI may be a future application.

# Avalanche Photodiodes (Contd)

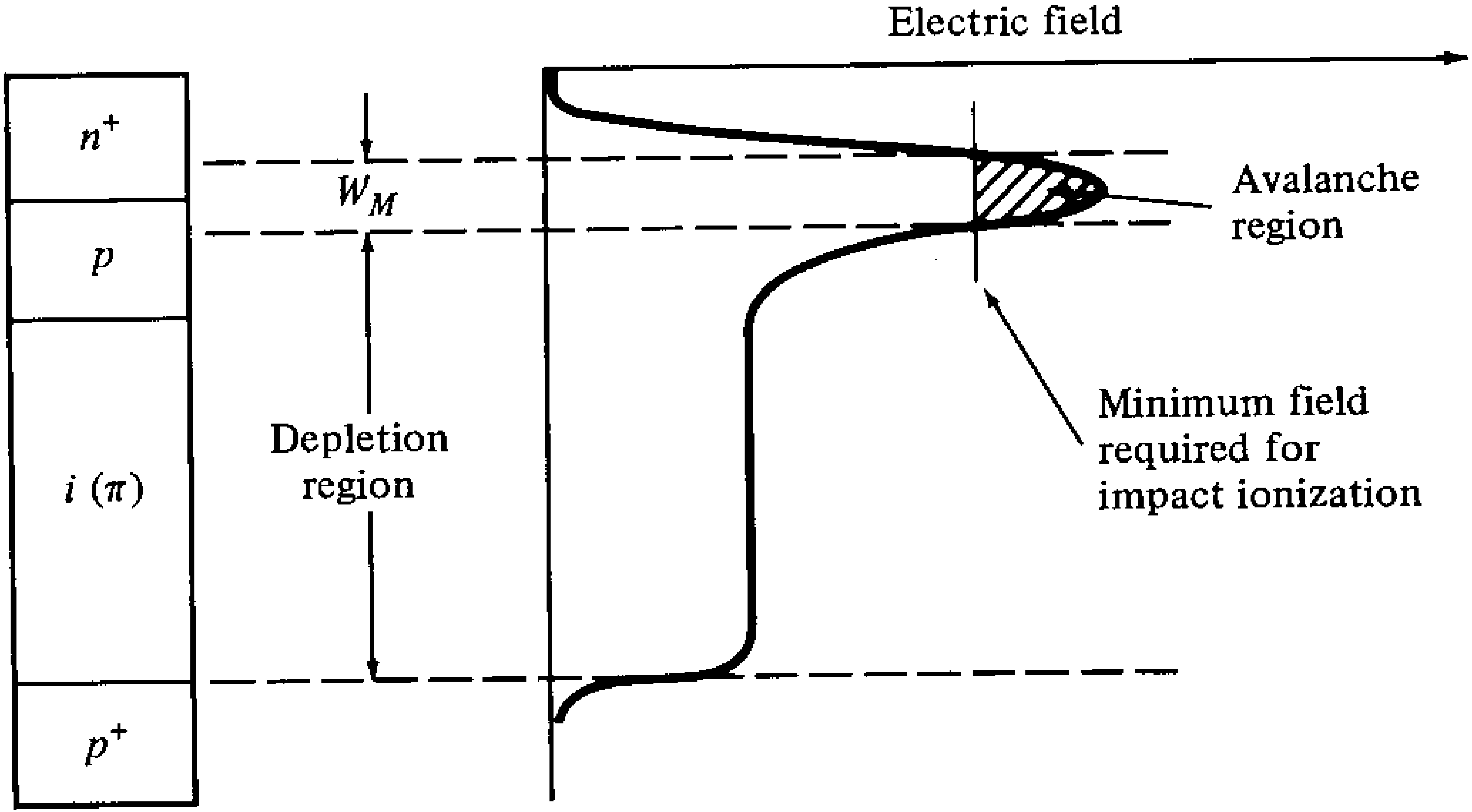



Fig. Reach-through avalanche photodiode structure and the electric fields in the depletion and multiplication regions.

# Impact Ionization

- **Impact ionization** is the process in a material by which one energetic charge carrier can lose energy by the creation of other charge carriers.

# Avalanche Photodiodes (Contd)

- The fig. shows the schematic structure of an APD. By virtue of the doping concentration and physical construction of the $n^+$ p junction, the electric field is high enough to cause impact ionization.

- Under normal operating bias, the I-layer is completely depleted.

- This is known as reach through condition, hence APDs are also known as Reach through APDs or RAPDs.

# Avalanche Photodiodes (Contd)

## Impact Ionization:

The photo generated carriers traverse a region where a very high electric field is present. These carriers can gain enough energy under high electric field and excite new electron-hole pairs. This phenomenon is called Impact Ionization

## Avalanche Effect:

During Ionization new generated carriers also accelerated by high electric field and gain enough energy to cause further impact ionization. This phenomenon is called avalanche effect.

# Avalanche Photodiodes (Contd)

- In normal usage, the RAPD is operated in the fully depleted mode. Light enters the device through the $p^+$ region and is absorbed in the p material, which acts as the collection region for the photo-generated carriers.
- The photo-generated electrons drift through the p region in the $pn^+$ junction, where a high electric field exists.
- It is in this high-field region that carrier multiplication takes place.

# Avalanche Photodiodes(Contd)

- The average number of electron-hole pairs created by a carrier per unit distance traveled is called the *ionization rate*.
- Most materials exhibit different *electron ionization rates* $\alpha$ and *hole ionization rates* $\beta$.
- The ratio $k = \beta/\alpha$ of the electron and hole ionization rates is a measure of the photo-detector performance.
- APDs constructed of materials in which one type of carrier largely dominates impact ionization exhibit low noise and large gain-bandwidth products.

# Avalanche Photodiodes(Contd)

- Similar to PIN photodiode, light absorption in APDs is most efficient in I-layer. In this region, E-field separates the carriers and the electrons drift into the avalanche region where carrier multiplication occurs.

- If the APD is biased close to breakdown, it will result in reverse leakage current. Thus APDs are usually biased just below breakdown, with the bias voltage being tightly controlled

# Avalanche Photodiodes (Contd)

## Avalanche Multiplication:

- The multiplication *M* for all carriers generated in the photodiode is defined by

$$M = I_M / I_p$$

where $I_M$ is the average value of the total multiplied output current and $I_p$ is the primary unmultiplied photocurrent.

## Responsivity:

- The performance of an APD is characterized by the responsivity given by

$$R_{APD} = (hq/hn)M = R_o M$$

where $R_o$ is the unity gain responsivity.

# Advantages and Disadvantages of APD

## Advantages:

- Excellent linearity over optical power range from nano watts to several microwatts.
- Better sensitivity (5 to 15 dB)
- Wide range of gain variation
- APD offers internal gain
- Better Signal to Noise ratio

## Disadvantages:

- Due to complex structure, fabrication is difficult
- APD and supporting circuitry is more expensive
- Random nature of gain mechanism contributes additional noise
- High voltage (50 to 400 V) and temperature compensation is needed for stabilization
- Internal gain of APD is temperature dependent.

# Comparison of PIN and APD

| S. No | Parameters | PIN | APD |
|---|---|---|---|
| 1 | Sensitivity | Less sensitive (0-12 dB) | More sensitive ( 5-15 dB) |
| 2 | Biasing | Low reverse biased voltage (5 to 10 V) | High reverse biased voltage (20 – 400 volts) |
| 3 | Wavelength region | 300 -1100 nm | 400 – 1000 nm |
| 4 | Gain | No Internal gain | Internal gain |
| 5 | S/N Ratio | Poor | Better |
| 6 | Detector Circuit | Simple | More complex |
| 7 | Conversion efficiency | 0.5 to 1.0 A/W | 0.5 to 100 A/W |
| 8 | Cost | Cheaper | More Expensive |
| 9 | Support circuitry required | None | High voltage and temperature compensation |

# Photodetector Noise

- The power SNR at the output of an optical receiver is

$$\frac{S}{N} = \frac{\text{singal power from photocurre nt}}{\text{photodecte ctor noise power} + \text{amlifier noise power}}$$

- To achieve a high SNR,

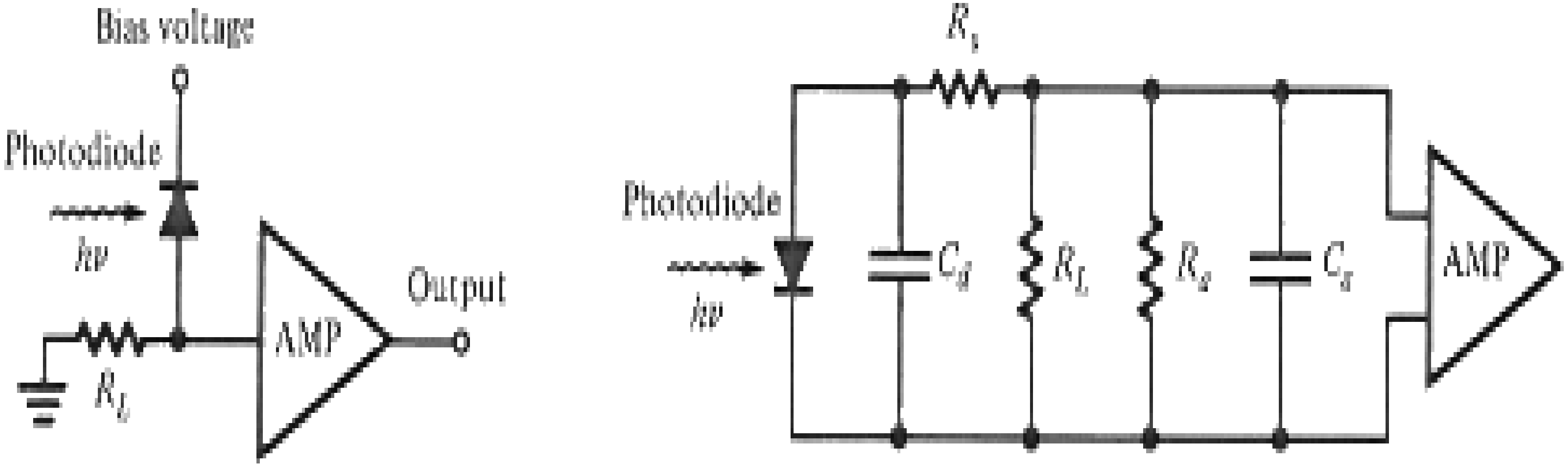
  1. PD must have a high h to generate a large signal power.

  2. PD and amplifier noises should be kept as low as possible.

- The sensitivity of a photodiode is describable in terms of the *minimum detectable optical power*. This is the optical power necessary to produce a photo-current of the same magnitude as the total rms noise current, or equivalently, a SNR of 1.

**SNR Can NOT be improved by amplification**

# Noise Sources




Simple model of a photo-detector receiver, and its equivalent circuit.

- In the receiver model of Fig, the photodiode has a small series resistance $R_s$, a total capacitance $C_d$ consisting of junction and packaging capacitances, and a bias (or load) resistor $R_L$.
- The amplifier following the photodiode has an input capacitance $C_a$ and a resistance $R_a$.

# Noise Sources (Contd)

- If a modulated signal of optical power $P(t)$ falls on the detector, the primary photo-current $i_{ph}(t)$ generated is

$$i_{ph}(t) = (hq/hn)P(t)$$

- The primary current consists of a dc value $I_p$ -- the average photo-current due to the signal power, and a signal component $i_p(t)$.
- For PINs, the mean-square signal current $\langle i_s^2 \rangle$ for a sinusoidally varying input signal of modulation index $m$ is

$$\langle i_s^2 \rangle = s^2_{s,PIN} = \langle i_p^2(t) \rangle = s_p^2 = m^2 I_p^2/2$$

where $s^2$ is the variance.

- For APDs, the mean-square signal current $\langle i_s^2 \rangle$ is

$$\langle i_s^2 \rangle = s^2_{s,APD} = \langle i_p^2(t) \rangle M^2$$

where M is the average avalanche gain.

# Noise Sources (Contd)

## Quantum Noise or Shot Noise

- The quantum or shot noise follow a Poisson process. The quantum noise current has a mean-square value
- Arises due optical power fluctuation because light is made up of discrete number of photons

$$\langle i_Q^2 \rangle = s_Q^2 = 2qI_p B M^2 F(M)$$

where $F(M) = M^x$, $0 \le x \le 1.0$, is a noise figure associated with the random nature of the avalanche process. For PIN photodiodes, M and F(M) are unity.

*F(M)*: APD Noise Figure    $F(M) \sim= M^x$ $(0 \le x \le 1)$

$I_p$: Mean Detected Current    *B* = Bandwidth

# Noise Sources (Contd)

## Dark or Leakage current Noise

There will be some (dark and leakage ) current without any incident light. This current generates two types of noise

- The mean-square value of the bulk dark current $i_{DB}$ arisen from thermally generated electrons and/or holes is given by

$$\langle i_{DB}^2 \rangle = s_{DB}^2 = 2qI_D BM^2 F(M)$$

where $I_D$ is the primary (unmultiplied) detector bulk dark current.

**Surface Leakage Current Noise:** **(not multiplied by M)**

- The surface dark current is simply referred to as leakage current. The mean-square value of this current is given by

$$\langle i_{DS}^2 \rangle = s_{DS}^2 = 2qI_L B$$

where $I_L$ is the surface leakage current. The surface dark current is not affected by the avalanche gain.

# Noise Sources (Contd)

The dark currents and the signal current are uncorrelated, the mean-square PD noise current $\langle i_N^2 \rangle$ can be written as

$$\langle i_N^2 \rangle = s_N^2 = \langle i_Q^2 \rangle + \langle i_{DB}^2 \rangle + \langle i_{DS}^2 \rangle$$

$$= s_Q^2 + s_{DB}^2 + s_{DS}^2$$

$$= 2q(I_p + I_D)M^2F(M)B + 2qI_LB$$

# Noise Sources (Contd)

The PD load resistor contributes a mean-square thermal (Johnson) noise current

$$<i_T^2> = s_T^2 = 4k_B TB/R_L,$$

where $k_B$ is Boltzmann's constant = 1.38054 X $10^{(-23)}$ J/K
and $T$ is the absolute temperature.

This Johnson noise can be reduced by using a load resistor which is large but still consistent with the receiver bandwidth requirements.

# Noise Sources (Contd)

The SNR at the input of the amplifier

$$SNR = \frac{\langle i_p^2 \rangle M^2}{2q(I_p + I_D)M^2 F(M)B + 2qI_L B + 4k_B TB / R_L}$$

- For PINs, the dominating noise currents are those of the detector load resistor (the thermal current $i_T$) and the active elements of the amplifier circuitry ($i_{amp}$).

- For APDs, the thermal noise is of lesser importance and the photo-detector noises usually dominate.

- The signal power is multiplied by $M^2$ and the quantum noise plus bulk dark current is multiplied by $M^2F(M)$.

# Signal to Noise Ratio (SNR)

Dark current and surface leakage current noise are typically negligible, If thermal noise is also negligible

$$SNR = \frac{\langle i_p^2 \rangle}{2q(I_p)F(M)B}$$

For analog links, (*RIN= Relative Intensity Noise)*

$$SNR = \frac{\langle i_p^2 \rangle M^2}{\left[2q(I_p + I_D)M^2F(M) + 4k_BT/R_L + (RIN)I_p^2\right]B}$$

# SNR (Contd)

- For a sinusoidally modulated signal, with $m = 1$ and $F(M)$ approximated by $M^x$, will yield

- The optimum gain at the maximum SNR can be found by differentiating the SNR equation with respect to $M$, setting the result equal to zero, and solving for $M$.

$$M_{opt}^{x+2} = \frac{2qI_L + 4k_B T / R_L}{xq(I_P + I_D)}$$

# Noise Equivalent Power (NEP)

- Source of noise in a detector is thermal fluctuation.
- Charged particles are always in a state of motion. Even when no radiation is incident on a device, a background current, whose magnitude could be in nano-amperes or pico-amperes, is generated. This is known as **dark current** .
- In order that a detector may be able to differentiate between such random noise and an incoming signal, the power of the signal must be greater than the noise signal.

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