Part 02
Lecture 01

ECE 423

Optical Communications

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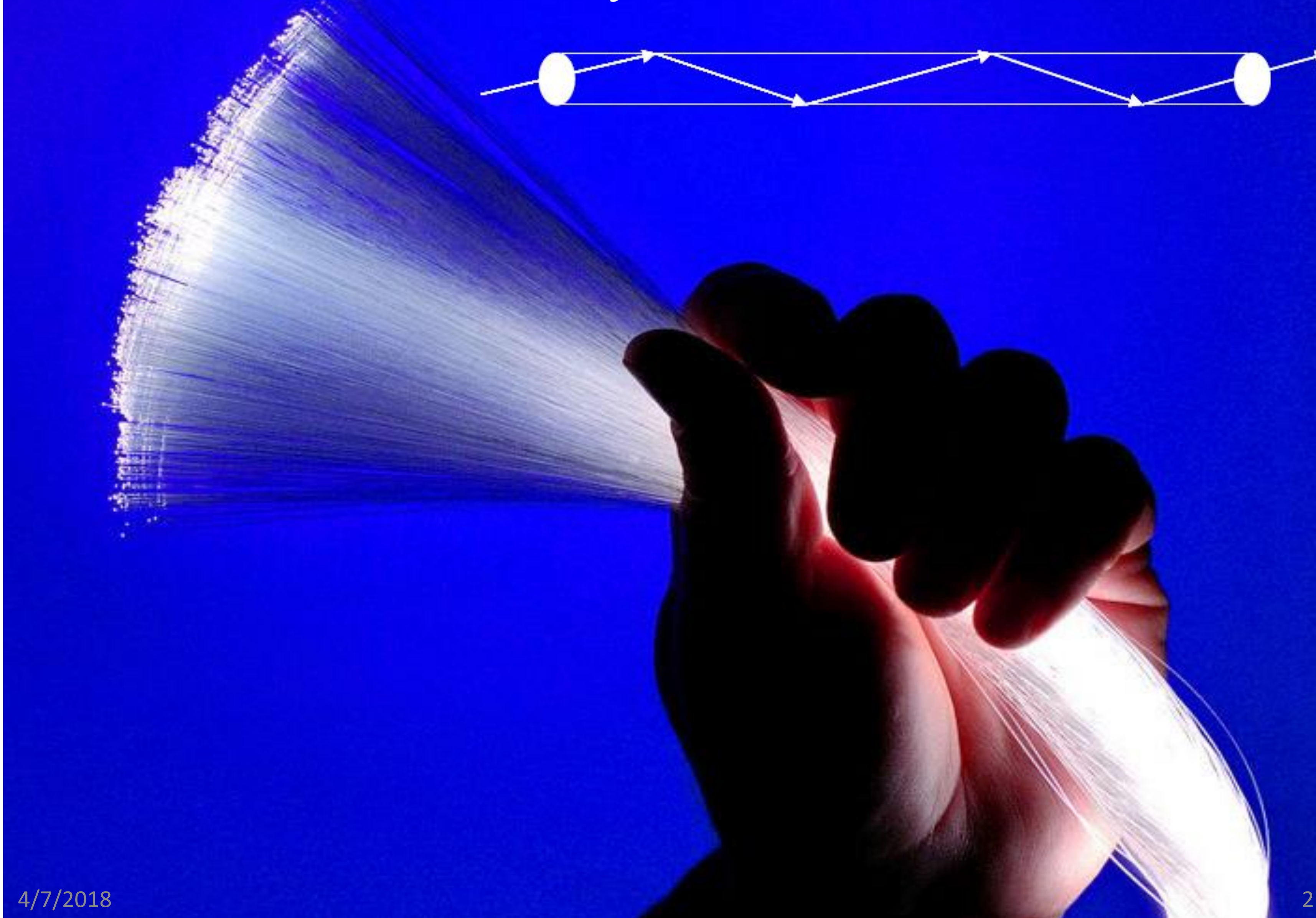
Optical fiber Is a dielectric channel used to guide light by total internal reflection



What is optical Fiber?

- An optical fiber is a flexible, transparent fiber made by drawing glass (silica) or plastic to a diameter slightly thicker than that of a human hair.
- Optical fibers are used most often as a means to transmit light between the two ends of the fiber and find wide usage in fiber-optic communications

Optical communication system

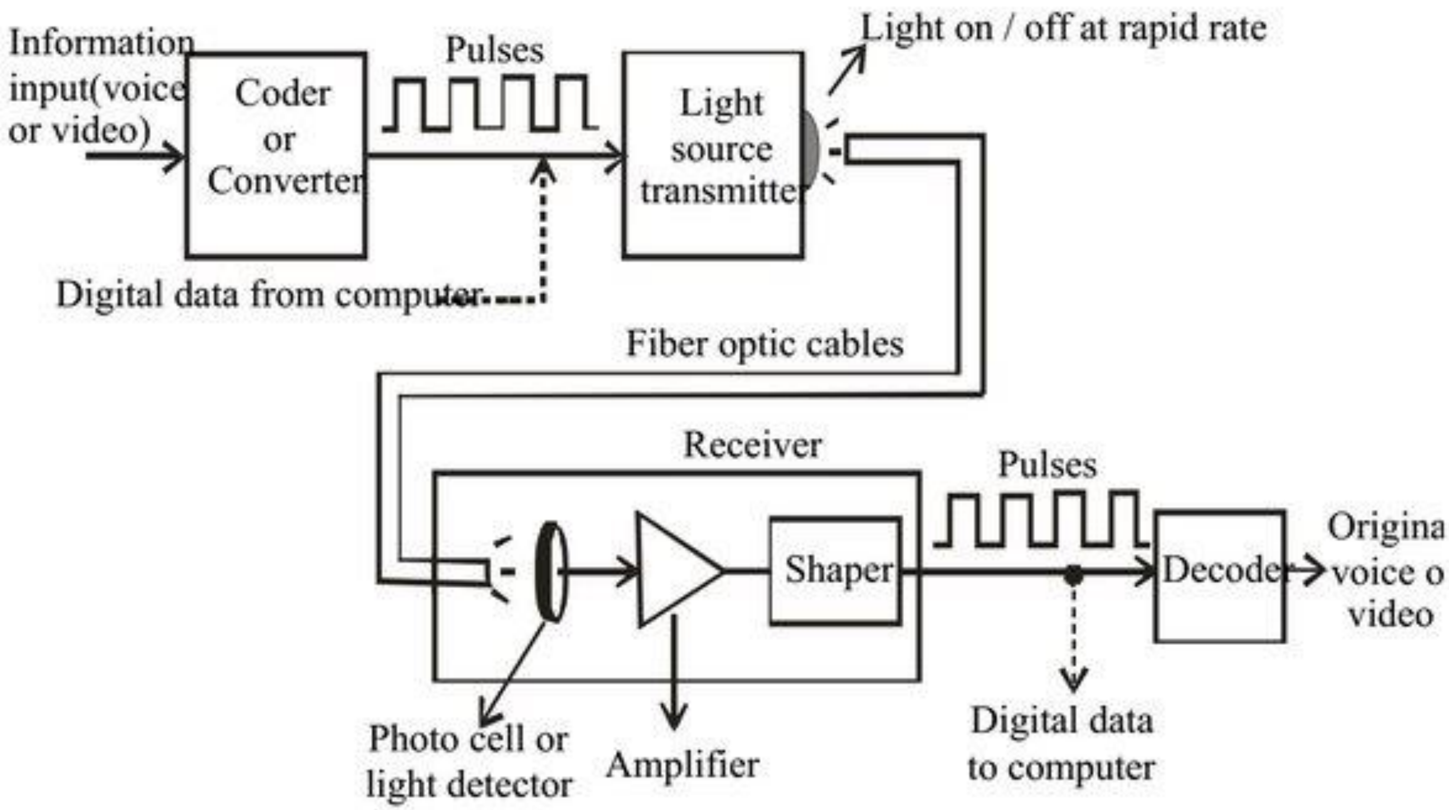
Advantages of optical fibers:

- ❑ Smaller and lighter than other types of cables
- ❑ Very high tensile strength
- ❑ Optical fiber has a bandwidth capability of 400MHz/km or greater.
- ❑ OF can provide data transmission performance up to 10Gbps, 40Gbps and even 100Gbps with new hardware that is now available.
- ❑ Lower losses.
- ❑ Greater repeater spacing.
- ❑ OF cables are immune to electromagnetic interference.
- ❑ Secure Transmissions.

Disadvantages of optical fibers:

- High cost
- Needs more expensive TX & RX
- More difficult and expensive to splice than wire

Optical communication system



Photodetectors

- A photoconductor is a semiconductor which exhibits a change in conductance (resistance) when radiant energy is incident on it.

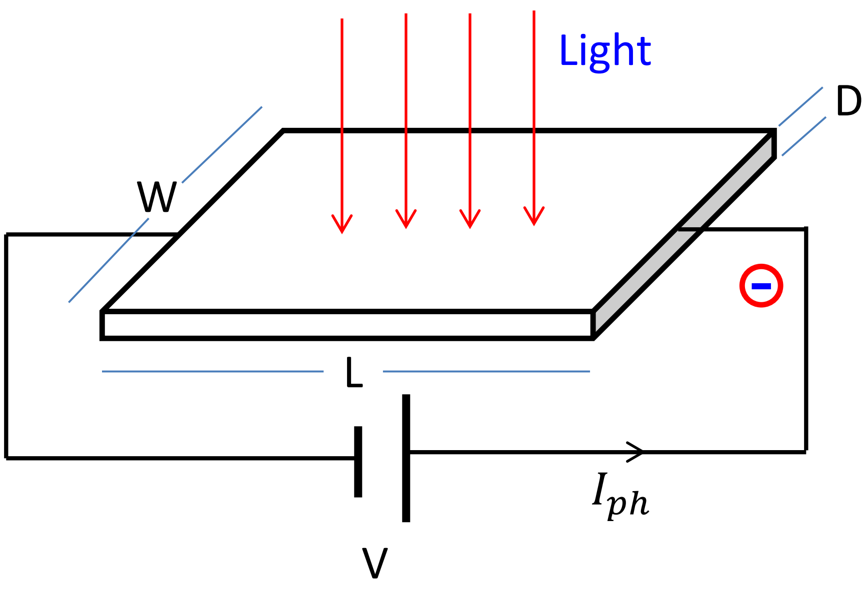
Consider an n-type S.C. where P_o is the incident radiation power. Then the transmitted power after penetrating a thickness D is (**$P_o\, e^{-\alpha D}$**).

The absorbed power ("useful") is

$$\boldsymbol{P_o[1 - e^{-\alpha D}]}$$

The number of photons absorbed per sec

$$N_{ph} = \frac{P_o[1 - e^{-\alpha D}]}{hf} = \frac{P_o[1 - e^{-\alpha D}]\lambda}{hc}$$



Photodetectors

- Assuming unity internal quantum efficiency, then each of these absorbed photons will generate an electron-hole pair(EHP) per sec. If G_{ph} is the photogeneration rate of EHP per unit volume then

$$G_{ph} = \frac{N_{ph}}{Vol} = \frac{P_o[1 - e^{-\alpha D}]\lambda}{hc \times LWD}$$

- In steady state conditions, i.e. constant illumination from the laser, we will reach steady state when there is no net change in the excess carrier concentration:

$$\frac{d\Delta p_n}{dt} = G_{ph} - \frac{\Delta p_n}{\tau_r} = 0 \quad \Rightarrow \Delta p_n = \tau_r G_{ph}$$

Assuming that the injection is high $\Rightarrow \tau_r = 1/\alpha_r \Delta p_n$, thus:

$$\Delta p_n = \tau_r G_{ph} = \frac{G_{ph}}{\alpha_r \Delta p_n} \quad \Rightarrow \quad \therefore \Delta p_n = \sqrt{\frac{G_{ph}}{\alpha_r}} = \sqrt{\frac{P_o[1 - e^{-\alpha D}]\lambda}{\alpha_r \times hc \times LWD}}$$

Photodetectors

- The photoconductivity is the increase in the conductivity $\Delta\sigma$ due to the absorbed light:

$$\Delta\sigma = q\mu_e \Delta n_n + q\mu_h \Delta p_n$$

$$\Delta\sigma = q\Delta p_n(\mu_e + \mu_h) = q(\mu_e + \mu_h)\sqrt{\frac{P_o[1 - e^{-\alpha D}]\lambda}{\alpha_r \times hc \times LWD}}$$

- We can express the increase in conductivity in terms of the light intensity (power density W/m²) $I_o = P_o/(WL)$

$$\Delta\sigma = q(\mu_e + \mu_h)\sqrt{\frac{I_o[1 - e^{-\alpha D}]\lambda}{\alpha_r \times hc \times D}} \quad \Rightarrow \Delta\sigma \propto \sqrt{I_o}$$

α is the absorption coefficient

α_r is the recombination coefficient.

Photodetectors

- The change in conductance ΔG can be given by

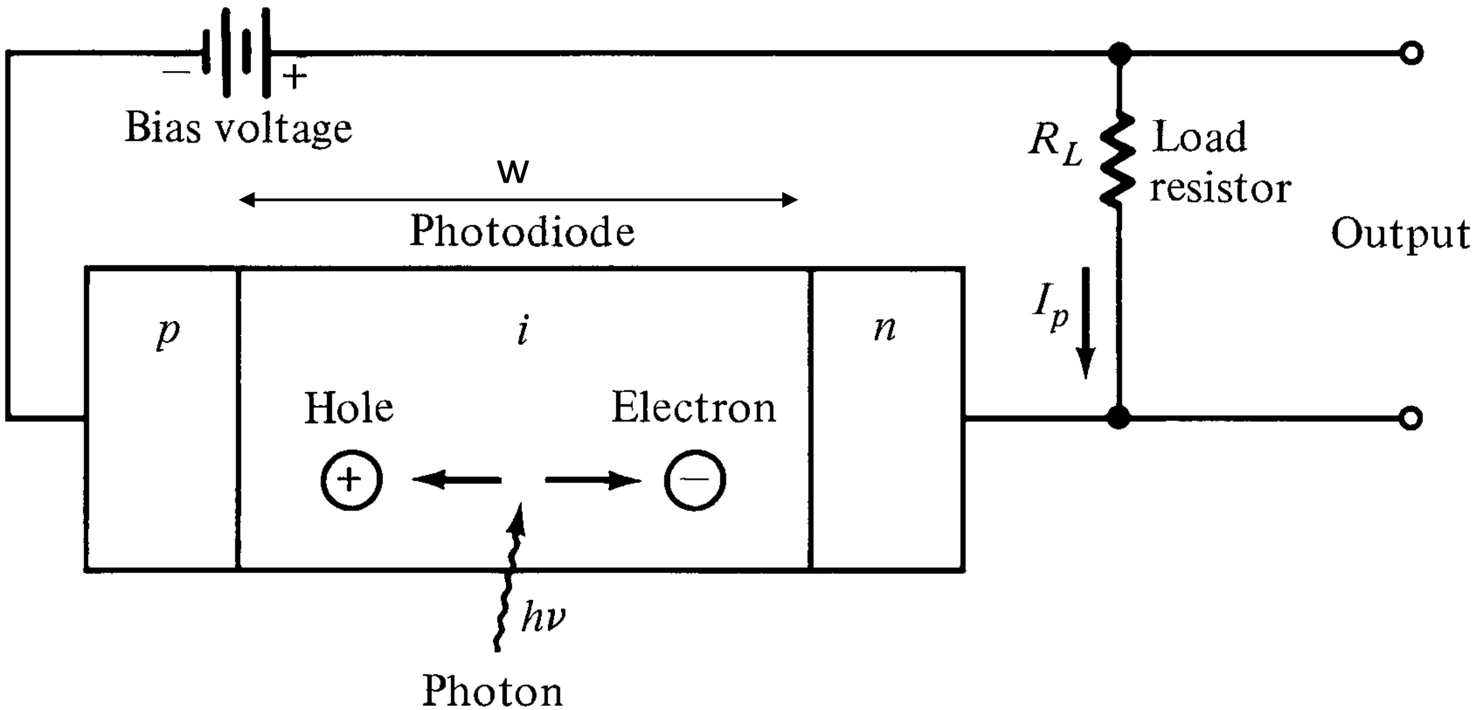
$$\Delta G = \frac{A\Delta\sigma}{L} = \frac{WD\Delta\sigma}{L}$$

$$\therefore Photocurrent = I_{photo} = \Delta I = V\Delta G$$

Photodetectors

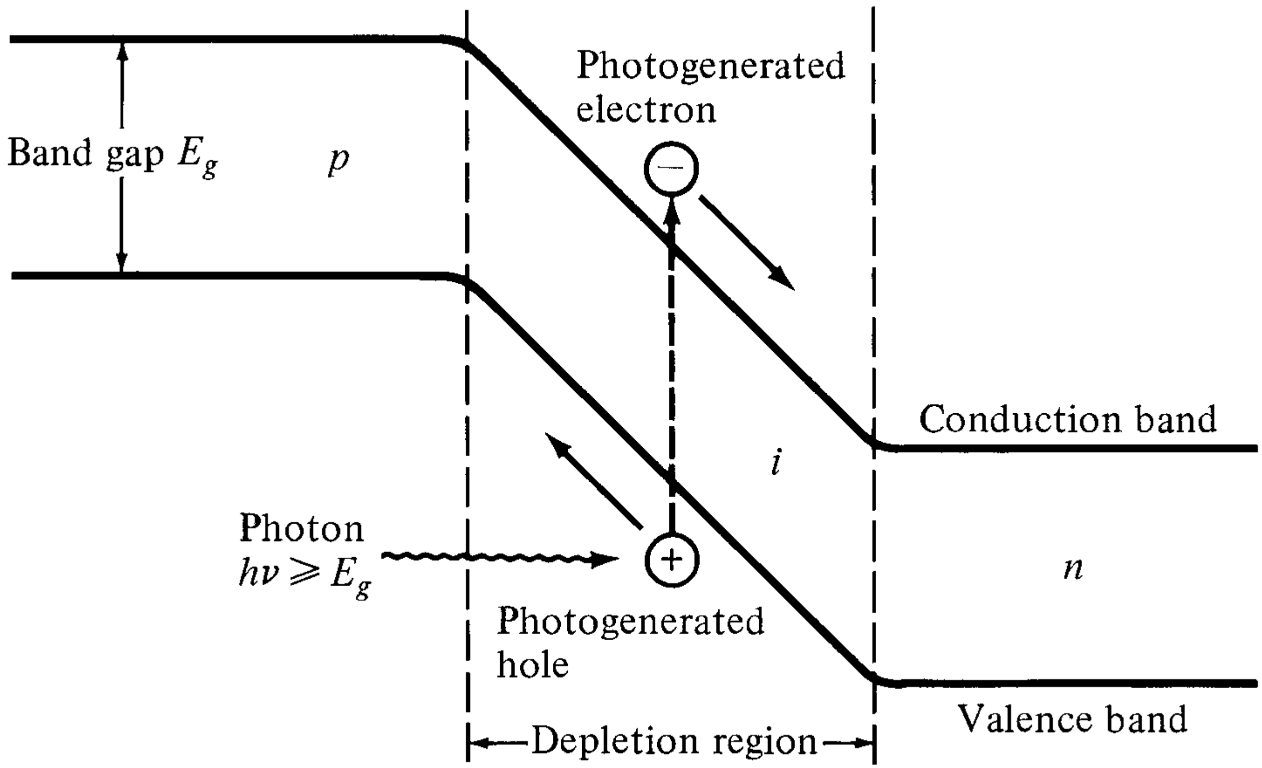
Example: a photoconductive film of n-type GaAs doped with 10^{13} cm^{-3} donors, L = 2 mm, W = 1 mm, D = 5 µm. The sample has electrodes attached to its ends which are connected to 1 V supply. The GaAs photoconductor is uniformly illuminated over the surface area (2 mm x 1 mm) with a 1 mW laser radiation of wavelength λ = 800 nm. α_r for GaAs is 7.21×10^{-16} $m^{-3}s^{-1}$. α is 5×10^3 cm^{-1}. $\mu_e = 8000\ cm^2$/Vs and $\mu_h = 400\ cm^2$/Vs. the energy gap is E_g = 1.43eV

pin Photodetector



The high electric field present in the depletion region causes photo-generated carriers to Separate and be collected across the reverse –biased junction. This give rise to a current Flow in an external circuit, known as **photocurrent**.

Energy-Band diagram for a *pin* photodiode



Photocurrent

- Optical power absorbed, $P(x)$ in the depletion region can be written in terms of incident optical power, P_0 :

$$P(x) = P_0(1 - e^{-\alpha_s(\lambda)x})$$ [6-1]

- Absorption coefficient $\alpha_s(\lambda)$ strongly depends on wavelength. The upper wavelength cutoff for any semiconductor can be determined by its energy gap as follows:

$$\lambda_c(\mu\text{m}) = \frac{1.24}{E_g(\text{eV})}$$ [6-2]

- Taking entrance face reflectivity into consideration, the absorbed power in the width of depletion region, *w*, becomes:

$$(1 - R_f)P(w) = P_0(1 - e^{-\alpha_s(\lambda)w})(1 - R_f)$$

Responsivity

- The primary photocurrent resulting from absorption is:

$$I_p = \frac{q}{h\nu} P_0 (1 - e^{-\alpha_s(\lambda) w})(1 - R_f) \quad [6\text{-}3]$$

- Quantum Efficiency:

$$\eta = \frac{\#\text{ of electron-hole photogenerated pairs}}{\#\text{ of incident photons}}$$

$$\eta = \frac{I_P / q}{P_0 / h\nu} \quad [6\text{-}4]$$

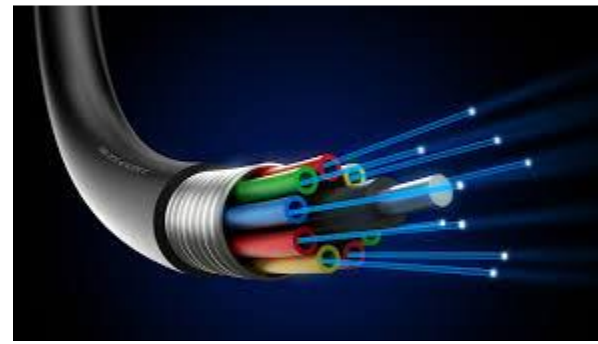
- **Responsivity:**

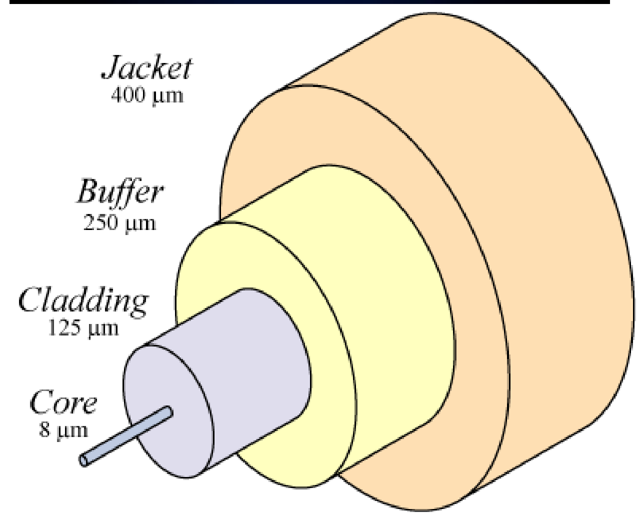
$$\Re = \frac{I_P}{P_0} = \frac{\eta q}{h\nu} \quad [\text{A/W}] \quad [6\text{-}5]$$

Construction of optical fiber cable

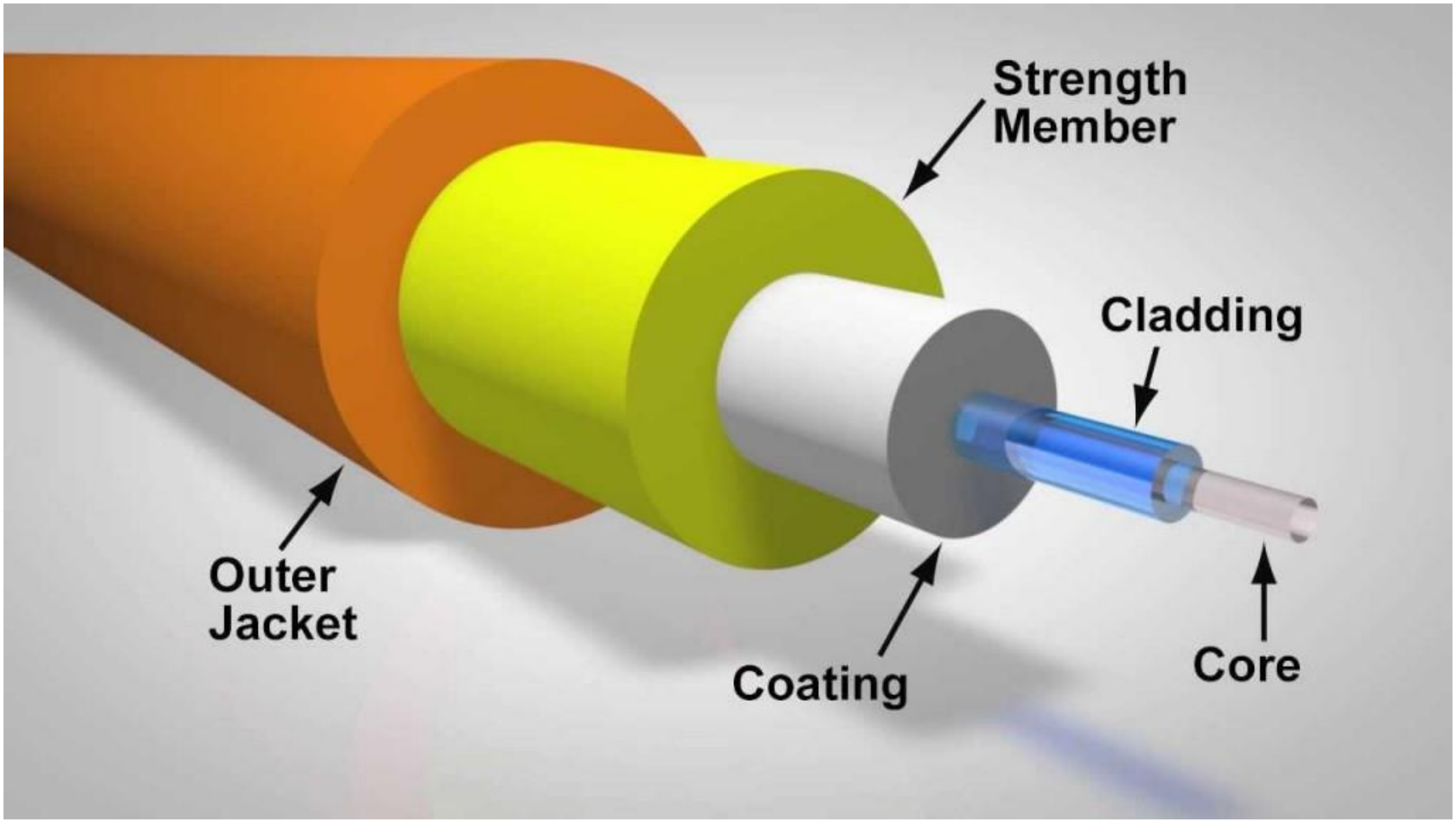
An optical fiber (American spelling) or fibre (British spelling): is cylindrical dielectric waveguide that transmits light along its axis, by the process of total internal reflection

- The fiber consists of a denser core surrounded by a cladding layer
- For total internal reflection to confine the optical signal in the core, the refractive index of the core must be greater than that of the cladding
- The boundary between the core and cladding may either be abrupt, in step-index fiber, or gradual, in graded index fiber
- The fiber is encased in an insulating jacket which protects it from moisture and provide some mechanical strength





What is optical Fiber?

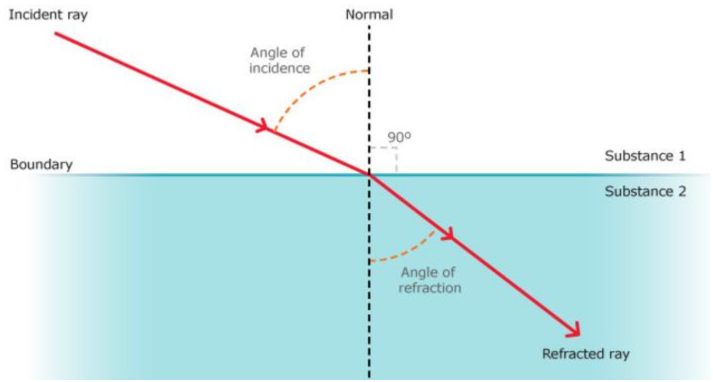


Construction of optical fiber cable

- **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.

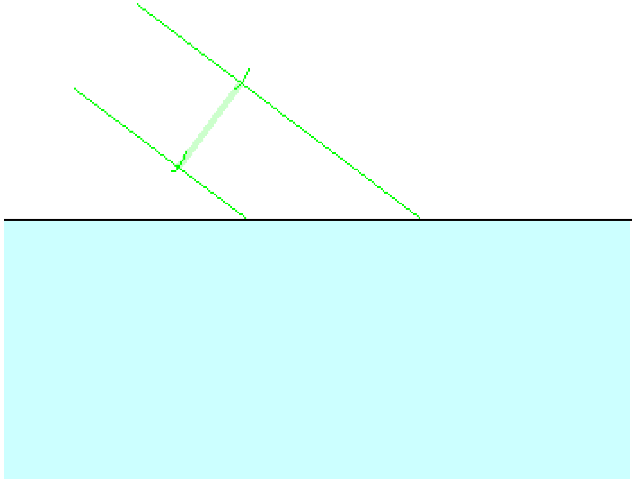
Total internal reflection (TIR)

The light which is transmitted usually changes direction when it enters the second material. This bending of light is called refraction and it depends upon the fact that light travels at one speed in one material and at a different speed in a different material



$$n = \frac{c}{v} = \frac{1/\sqrt{\mu_o \varepsilon_o}}{1/\sqrt{\mu_o \mu_r \varepsilon_o \varepsilon_r}}$$

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



where
n is the refractive index
c is the speed of light in a vacuum
v is the speed of light in the material

Total internal reflection (TIR)

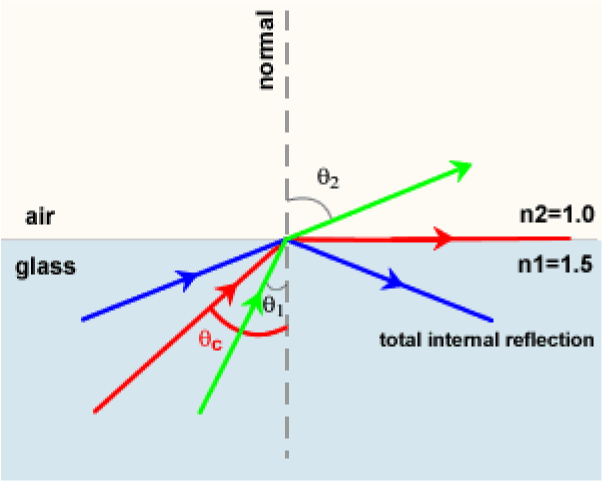
Critical angle

Form Snell's law $n_1 \sin\theta_1 = n_2 \sin\theta_2$

Since $n_1 > n_2$ ***then***

$$\sin\theta_2 = (n_1/n_2)\sin\theta_1$$

$$\theta_2 > \theta_1$$

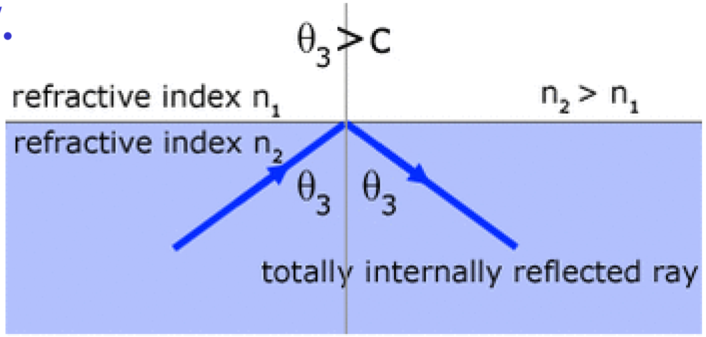


when $\theta_1 = \theta_c$ *; the critical angle at which TIR occurs*

then: $n_1 \sin\theta_c = n_2 \sin 90 = n_2$

hence $\sin\theta_c = n_2/n_1$

if $\theta_1 > \theta_c$ *then the ray is completely reflected in medium 1.*



Hence conditions for light ray propagating through an optical fiber core are :

1. ***the core index is dense and greater than the cladding index***
2. ***incident angle of ray with normal to the core-cladding interface*** $\theta_1 > \theta_c$

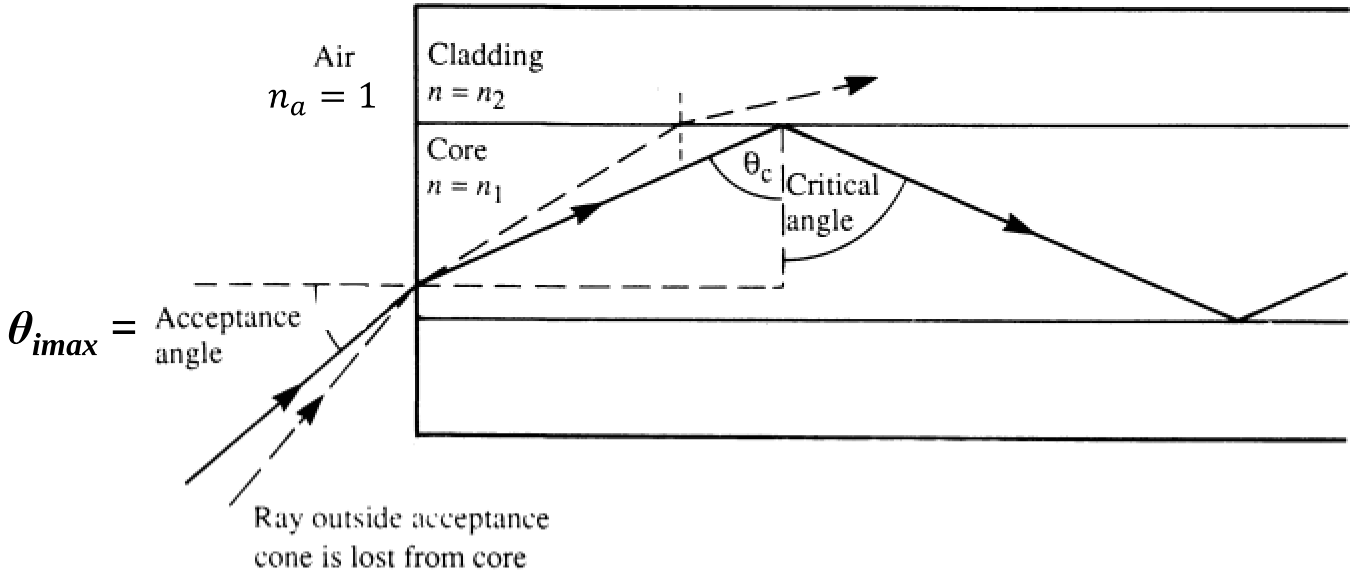
Total internal reflection (TIR)

***Acceptance angle* is the maximum angle θ_{imax} which gives just total internal reflection at the core gladding interface**

When $\theta_i = \theta_{imax}$ ➔ $\theta = \theta_c$

When $\theta_i < \theta_{imax}$ ➔ $\theta > \theta_c$ ➔ ***The ray propagate through TIR***

When $\theta_i > \theta_{imax}$ ➔ $\theta < \theta_c$ ➔ The ray penetrates the cladding and lost

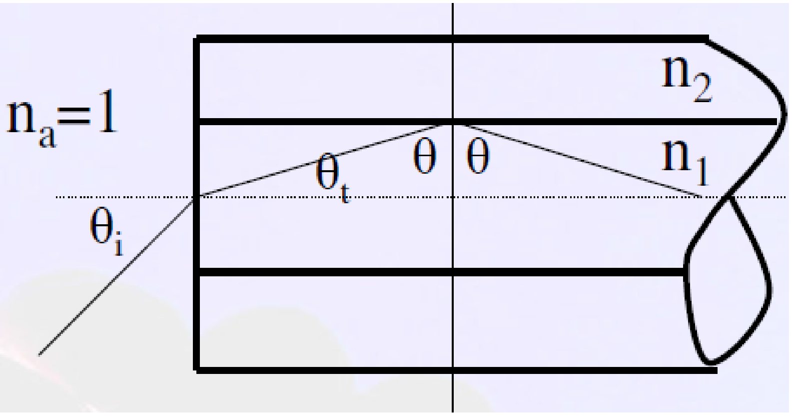


Total internal reflection (TIR)

$n_a \sin\theta_i = n_1 \sin\theta_t$

$\sin\theta_i = n_1 \sin\theta_t$

The minimum value of θ gives reflection is θ_c which gives maximum value of θ_i



$$\sin\theta_{imax} = n_1 \cos\theta_c = n_1\sqrt{1-\sin^2\theta_c}$$

$$= n_1 \sqrt{1-(n_2/n_1)^2}$$

$$= n_1 \sqrt{(n_1-n_2)(n_1+n_2)/(n_1)^2}$$

$$\approx n_1 \sqrt{(n_1-n_2)(2n_1)/(n_1)^2}$$

$$\approx n_1 \sqrt{2(n_1-n_2)/n_1} = n_1\sqrt{2\Delta}$$

$$\Delta = (n_1 - n_2)/n_1$$

the refractive index fractional difference

Or

The relative refractive index difference

***Numerical aperture*: measure the light collecting ability of the fiber**

$$\text{NA} = n_a \sin\theta_{imax}$$

$$\text{NA} = n_1\sqrt{2\Delta} = \sqrt{(n_1^2 - n_2^2)}$$

Total internal reflection (TIR)

Ex1: Derive an expression for the maximum value of n_2 as a function of n_1 that permits all light incident on the end face of a fiber to be propagated. Assume $n_a = 1$ and that the end face is perpendicular to the fiber axis. Calculate this limiting value of n_2 when $n_1 = 1.46$

Solution

$$\text{NA} = n_a \sin\theta_{imax} = \sqrt{(n_1^2 - n_2^2)}$$

Under this condition $\sin\theta_{imax} = 90$ ➔ $\sqrt{(n_1^2 - n_2^2)} = 1$

$$n_2 = \sqrt{(n_1^2 - 1)}$$

If $n_1 = 1.46$ then $n_2 = 1.0638$