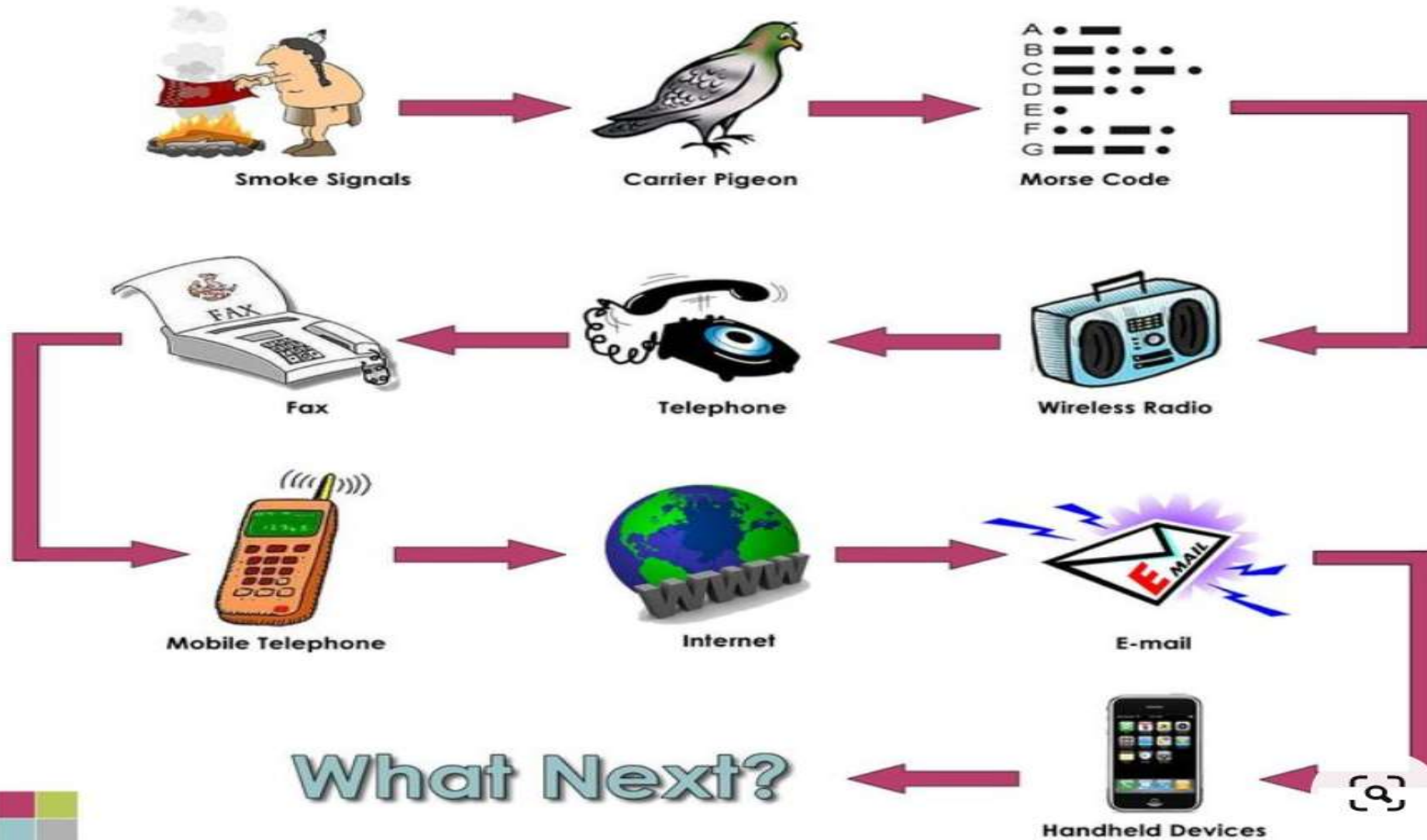


Optical Communication

Introduction

Comminication Timeline



Introduction

❖ The requirements of any Communication System are:

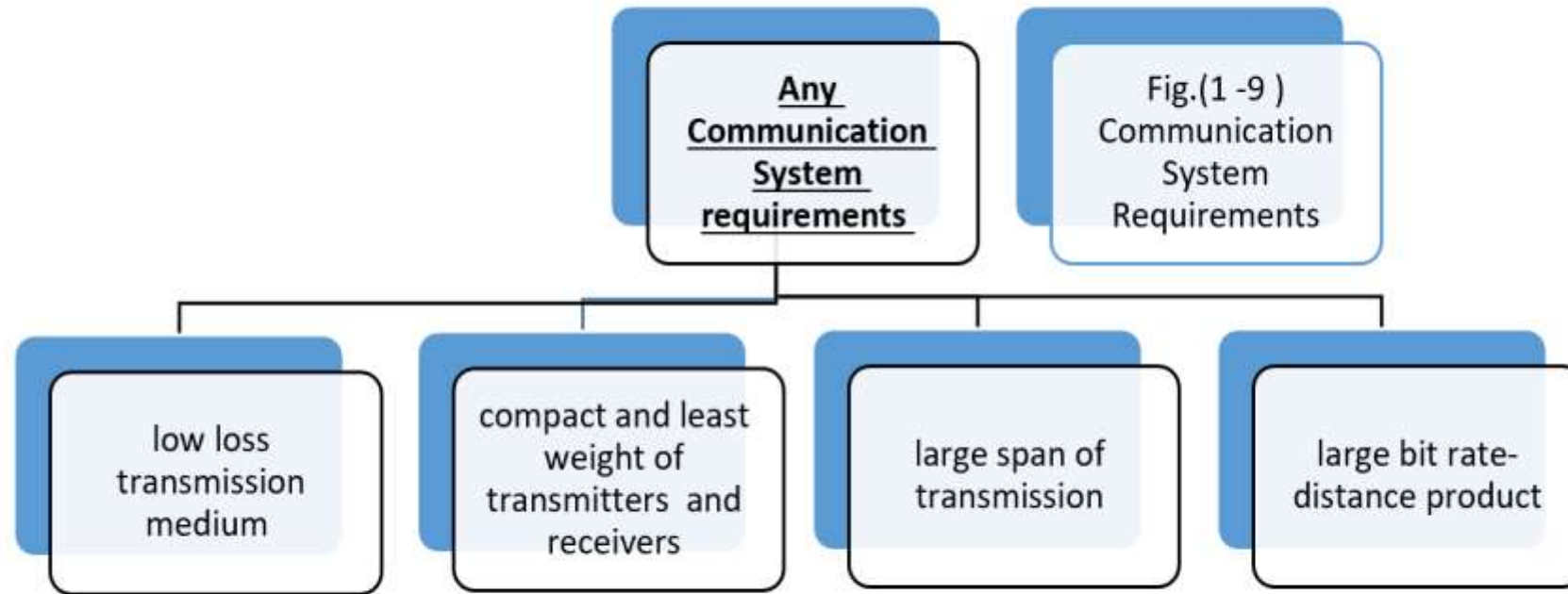
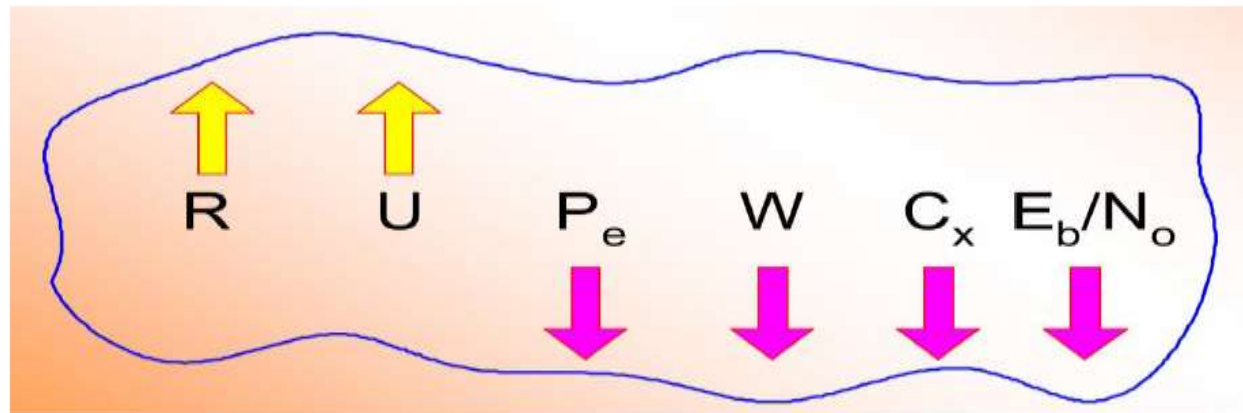


Fig. (1 -9) Communication System Requirements

Goals in Communication System Design

Goals in Communication System Design

- To maximize transmission rate, R
- To maximize system utilization, U
- To minimize bit error rate, P_e
- To minimize required systems bandwidth, W
- To minimize system complexity, C_x
- To minimize required power, E_b/N_o



Classification of Transmission Media

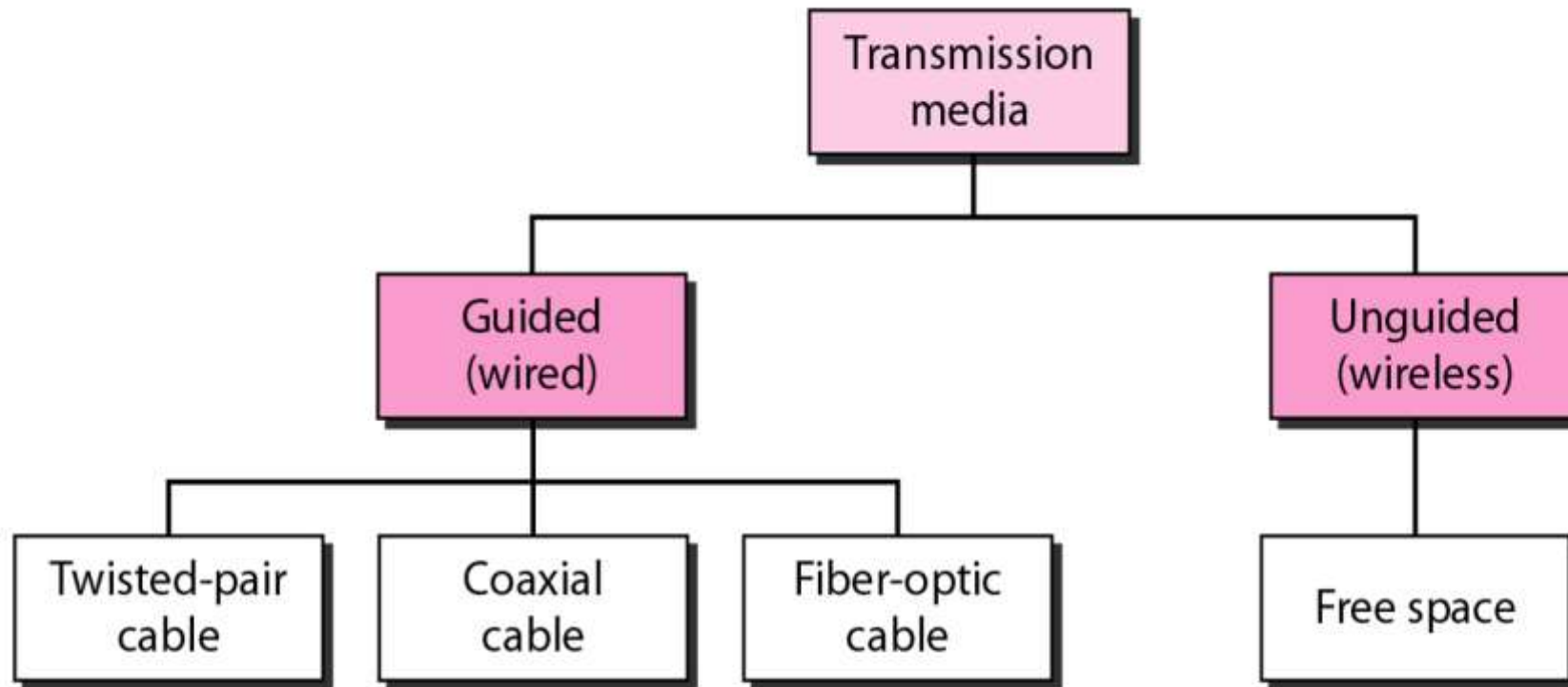
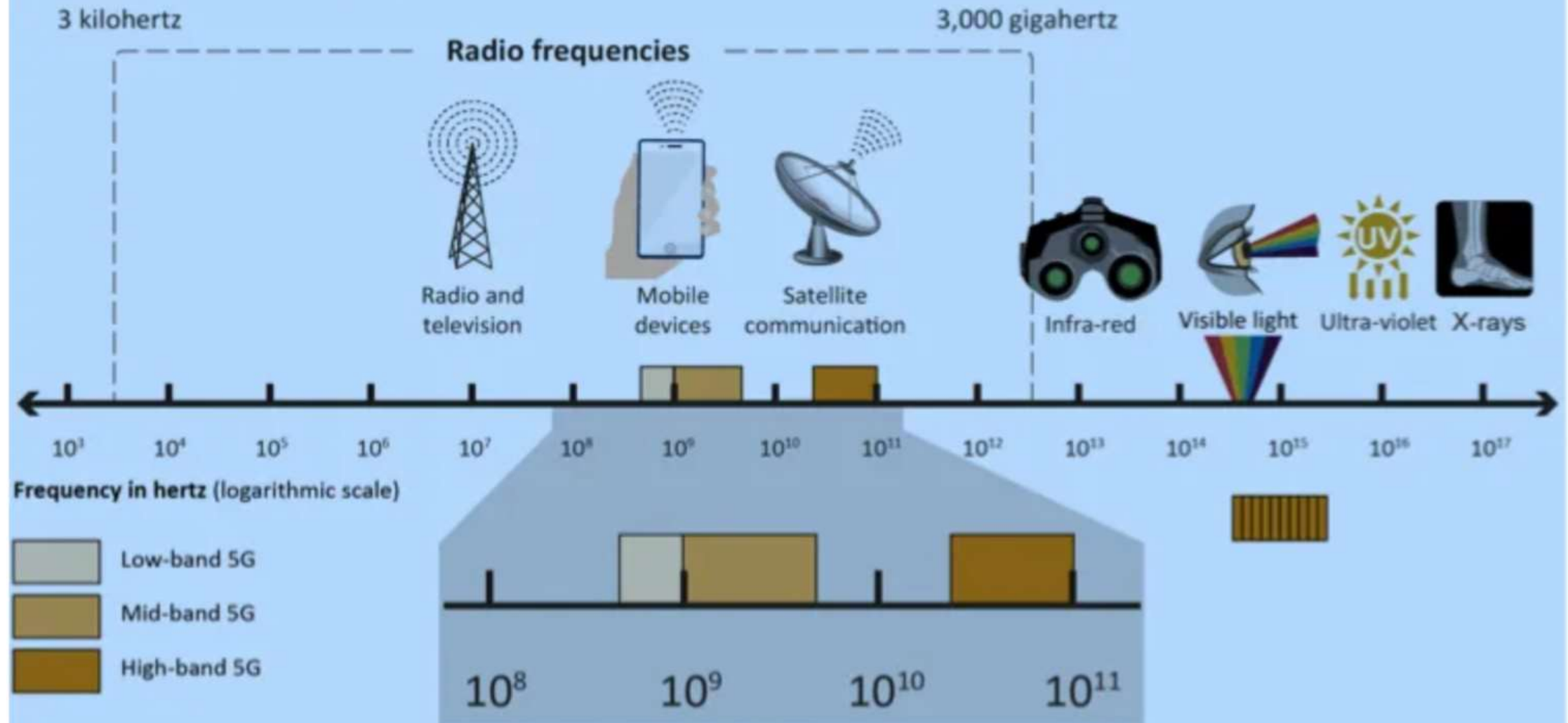


Fig. (1 -10) Classes of transmission media

+ Free Space Optical communication

Electromagnetic spectrum

Figure 2: Electromagnetic spectrum



Optical Communication

- **Optical communication using fibers is performed in the frequency range of 1 THz to 1000 THz (microwaves to ultraviolet).**
- **An optical fiber can offer a transmission bandwidth in excess of 100 GHz.**
- **Spectrum allocations are arrived at by an international agreement.**

Optical communications

- Optical Communication is the most modern mode of wired communication.
- Optical communication is also the youngest mode of communication. However its capabilities supersede all other modes of communication.
- Before optical communication the most of the communication was in radio and microwave domain which has frequency range orders of magnitude lower than the optical for the electromagnetic spectrum.

History

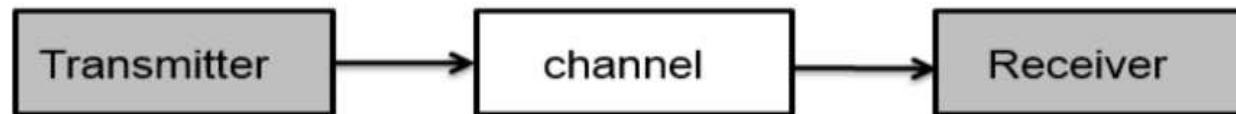
- It 1870 John Tyndall state that light can be guided along the curve of a stream of water and the total internal reflected light gets confined to the water stream and the stream appears luminous.
- In 1950, the transmission of images through optical fibers was realized in practice
- In 1966 Charles Kao and George Hockham proposed the transmission of information over glass fiber.
- The invention of solid state lasers in 1970 made optical communications practicable.

Fiber optics is a technology in which signals are converted from electrical to optical signals, transmitted through a thin glass fiber and reconverted into electrical signals.

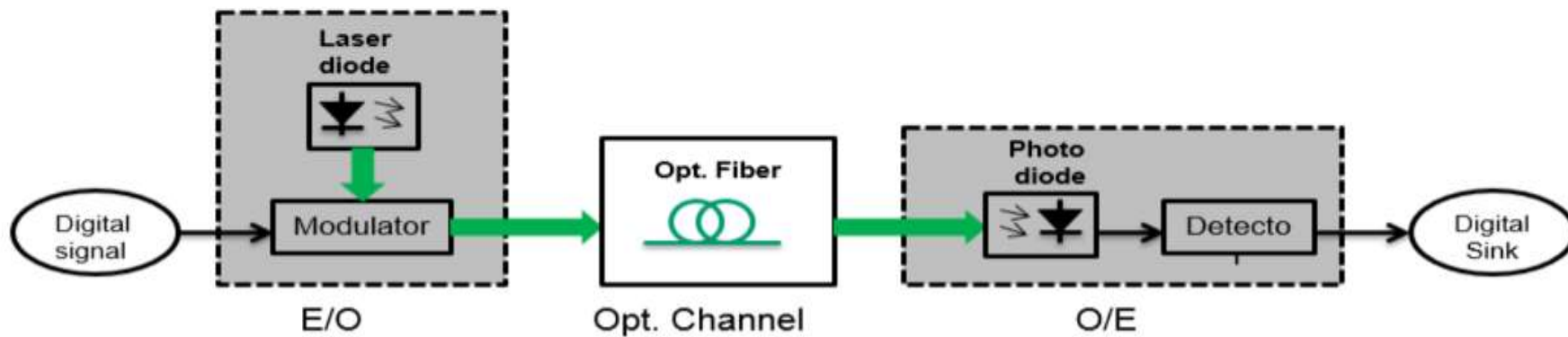
Optical Communication System

Optical Communications System

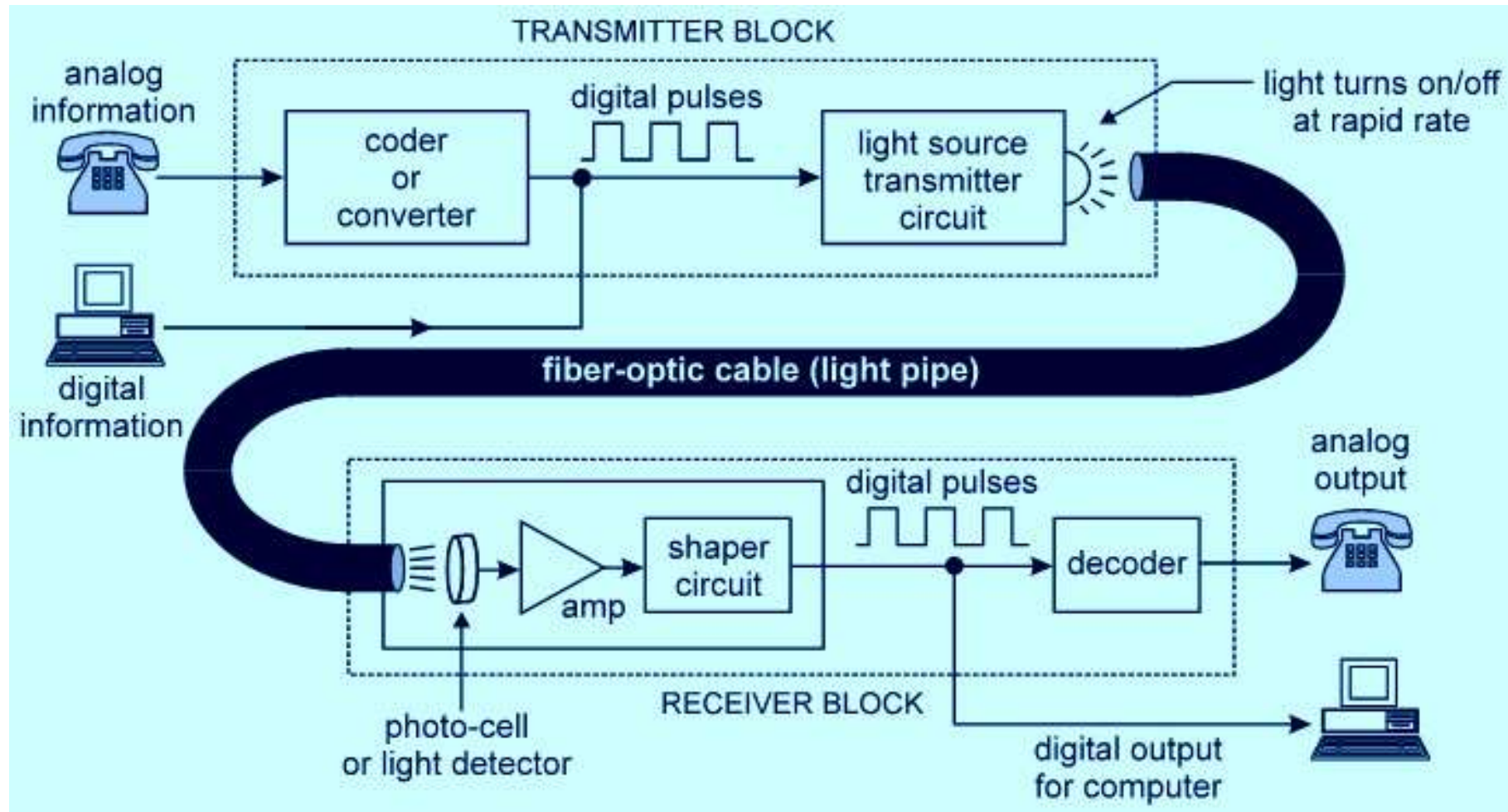
- Conventional communications system



- Optical communications system



General Block diagram of Fiber communication system



Transmission Media alternative to the optical Communication

Transmission media Alternative to the Optical Communication

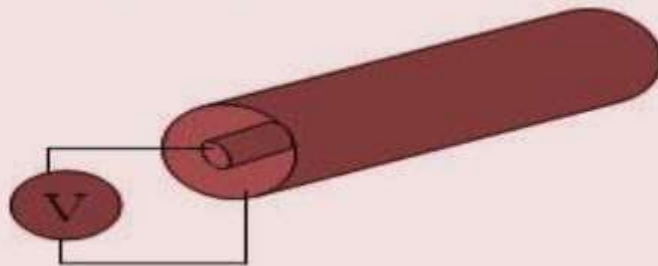
There are various wired and wireless media used for long and short distance communication. Their broad characteristics are summarized in the following.

Twisted Pair: (point-to-point)



Telephone Lines
Low data rate
High EMI
Lossy at RF

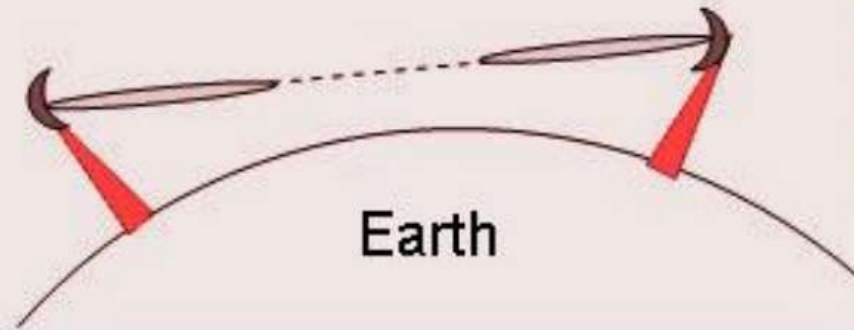
Co-axial Cable (point-to-point)



LAN
Data rates few Mbps
Low EMI
Moderate loss

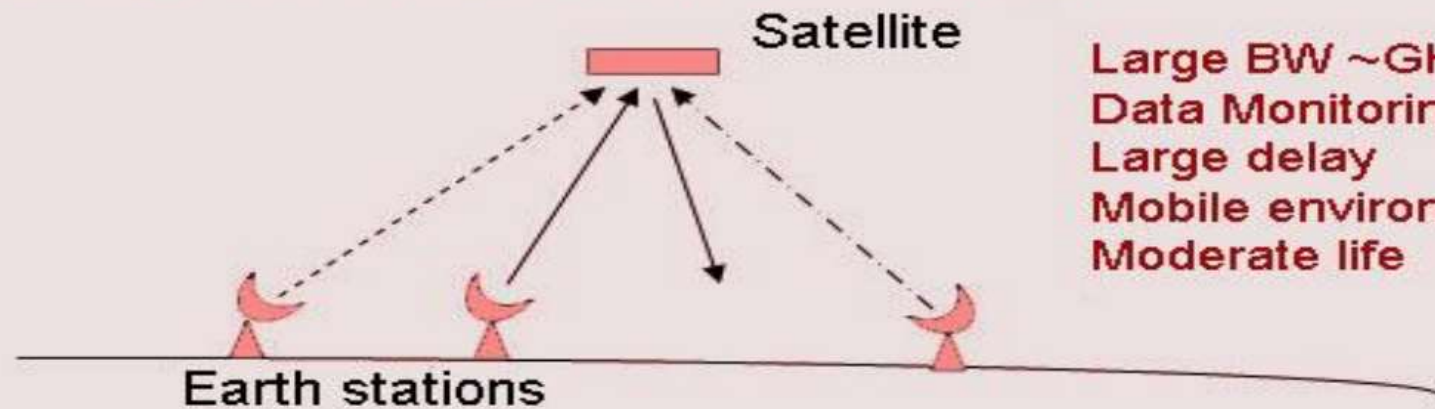
continue

Microwave Link (point-to-point)



Long distance
Large BW
Line-of-sight
High free-space loss

Satellite Communication (point-to-multi-point)



Large BW ~GHz
Data Monitoring
Large delay
Mobile environment
Moderate life

Continue

- The first two media have a very limited bandwidth.
- Microwave links and Satellite communication has comparable bandwidths as in principle their mode of operation is same but the spatial reach of satellite is far greater.
- Before Fiber optic communication became viable, satellite communication was the only choice for long distance communication.

Comparison of satellite and optical communication

Satellite vs Fiber Optics

Satellite

- Point to Multi-point
- BW ~ GHz
- Maintenance free
- Short life ~7-8 Yr
- No upgradeability
- Mobile, air, sea

Fiber Optics

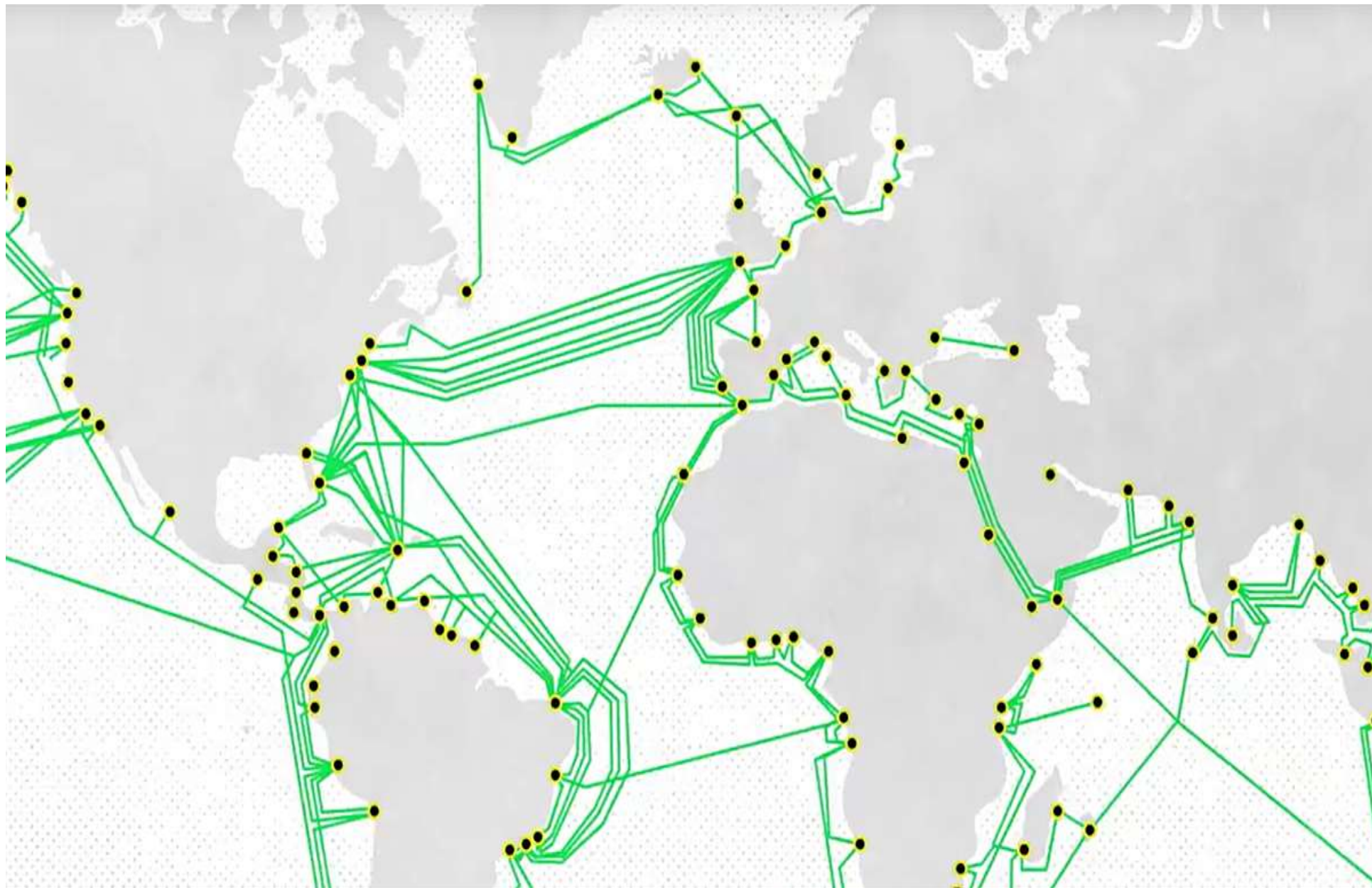
- Point to point
- BW ~ THz
- Needs Maintenance
- Long life
- Upgradeable
- On ground only

(One common misconception is that most of our information is transmitted through satellites,

*but **fiber optic cables** actually form the backbone of the internet, transmitting about **99%** of all data.)*

Today, there are over 420 submarine cables in service, stretching over 700,000 miles (1.1 million km**) around the world.**

The network is clustered around information economy hotspots like Singapore and New York, but cables connect to just about anywhere.





How fiber cable is longer ?

Earth circumference = 40000 km •

Glob fiber optic length = 1000000 km •

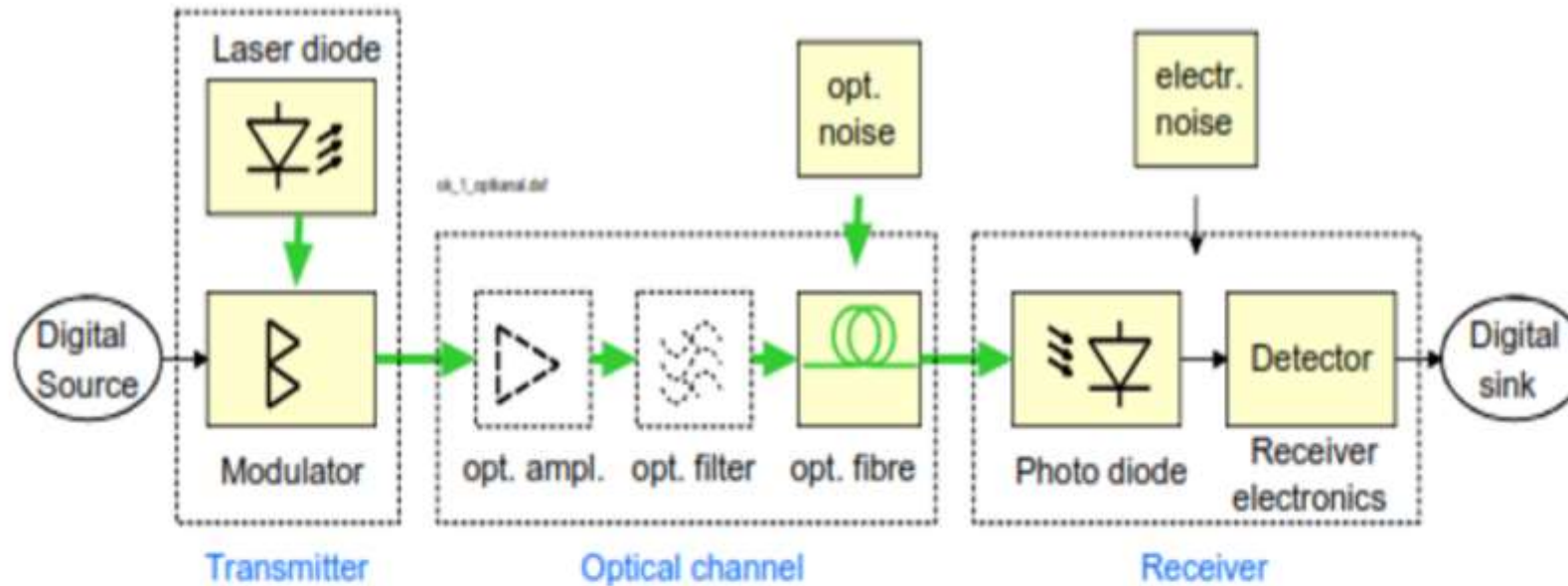
The percentage is **25** times •

.

Advantages and Disadvantages of optical communication

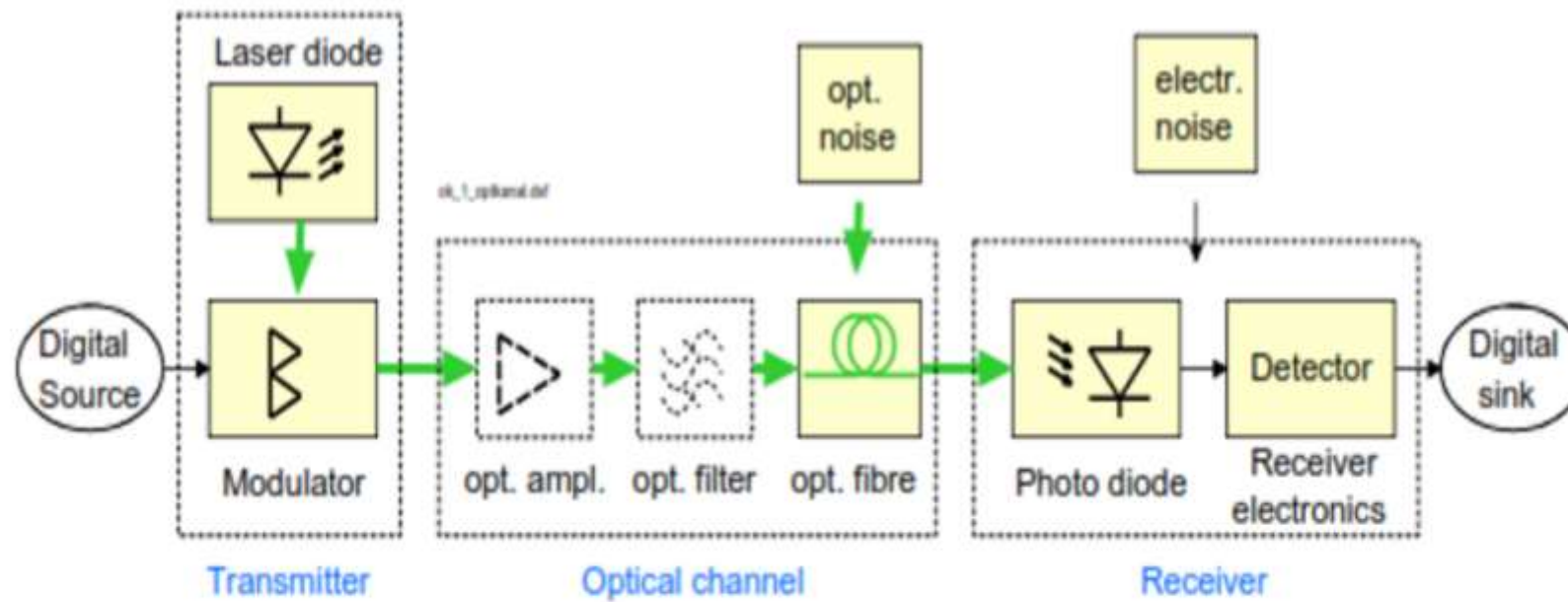
Advantages	Disadvantages
1. <u>Much Higher Bandwidth</u> (Giga bit per second (Gbps)) - Thousands of channels can be multiplexed together over one strand of fiber 2. <u>Immunity to Noise</u> - Immune to electromagnetic interference (EMI). 3. <u>Safety</u> - Doesn't transmit electrical signals, making it safe in environments like a gas pipeline. 4. <u>High Security</u> - Impossible to "tap into." 5. <u>Less Loss</u> - Repeaters can be spaced 75 miles apart (fibers can be made to have only 0.2 dB/km of attenuation) 6. <u>Reliability</u> - More resilient than copper in extreme environmental conditions. 7. <u>Size</u> - Lighter and more compact than copper. 8. <u>Flexibility</u> - Unlike impure, brittle glass, fiber is physically very flexible. 9. <u>Non-Flammable.</u> 10. <u>Light signals.</u>	1. <u>High initial cost</u>: The initial installation or setting up cost is very high compared to all other systems. 2. <u>Maintenance</u> and repairing cost: The maintenance and repairing of fiber optic systems is not only difficult but expensive also.

General Block Diagram of Basic Optical Transmission System



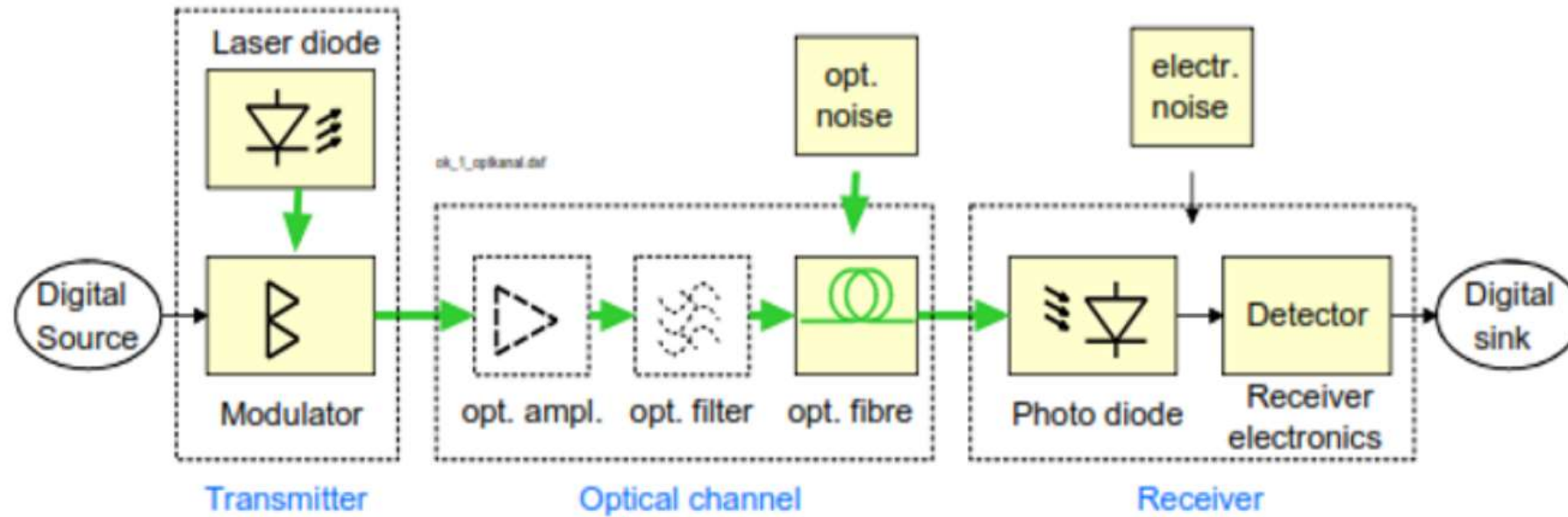
Basic optical transmission link with transmitter, Channel and receiver. We have optical signals (thick, green) and electrical signals (thin, black). Optical signals are (sinusoidal) carrier at optical frequency (THz). Electrical signals represent the transmitted and received signals, which are associated with digital data modulation.

General Block Diagram of Basic Optical Transmission System



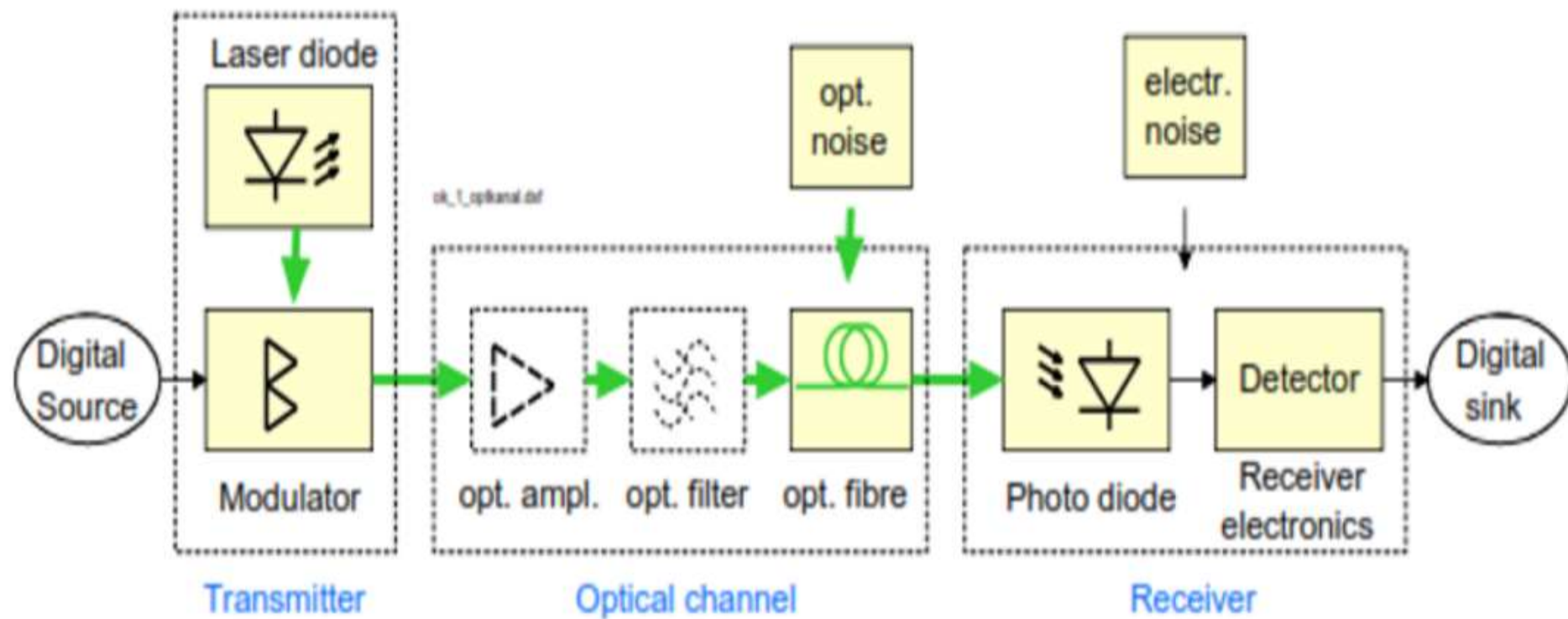
Laser Diode: produces nearly single frequency light with well defined wavelength = carrier signal at frequency ($f_c = C/\lambda_c$). f_c in the range of several hundred THz (1 THz = 10^{12} Hz). The light wave, i.e. the electromagnetic wave is often simply called “electrical field”.

continue



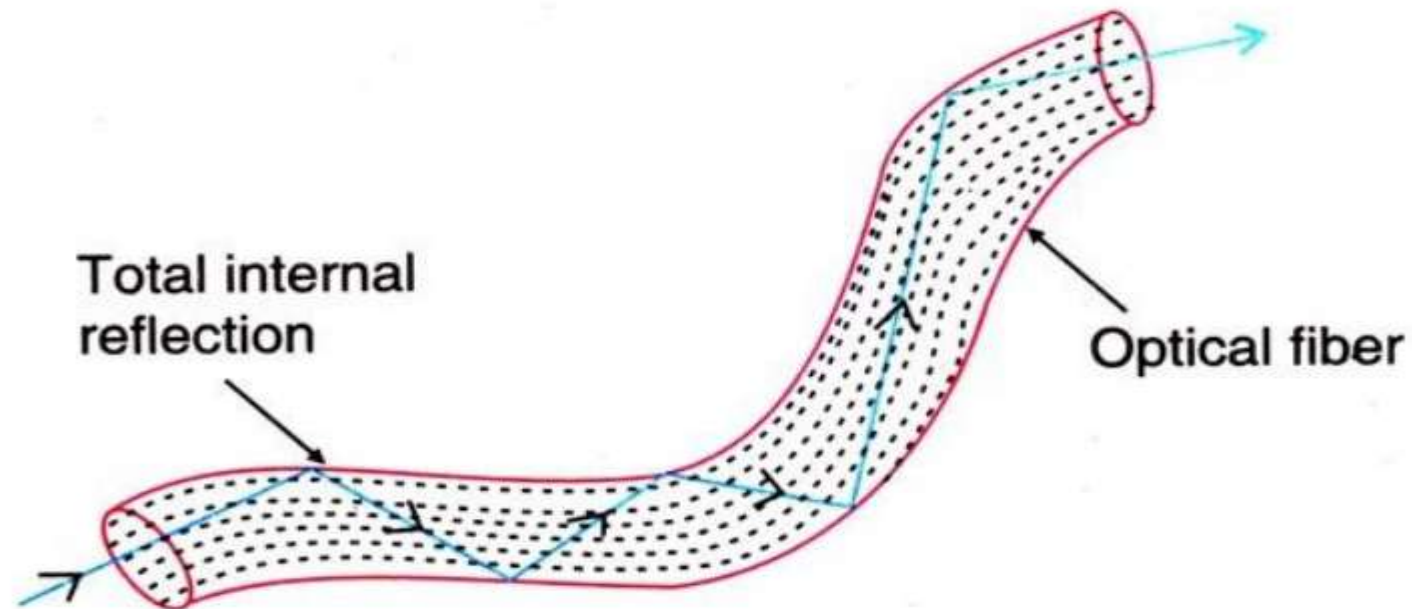
Modulator: Electrical-to-optical convertor in which the digital signal (electrical) is modulated on the carrier (here light). Most modulators have the capability to modulate the power of the light. I.e. the instantaneous optical power (=light intensity = $|E(t)|^2$) is proportional to the modulating data signal of e.g. 10 Gb/s. With binary signal “1”=light on, “0”=light nearly off (On-Off Keying and Intensity Modulation). Implementation, either *direct modulation* of laser diode forward current or by a separate *external modulator* (as shown above).

continue



Optical Fiber

- **Definition:** An optical fiber is a cylindrical wave guide made of transparent dielectric, (glass or clear plastic), which guides light waves along its length by total internal reflection. It is very thin like human hair, approximately $70\mu\text{m}$ or 0.003 inch diameter. The thin strand of a metal is called a wire and a thin strand of dielectric materials is called a Fiber.



Optical fiber (OF)

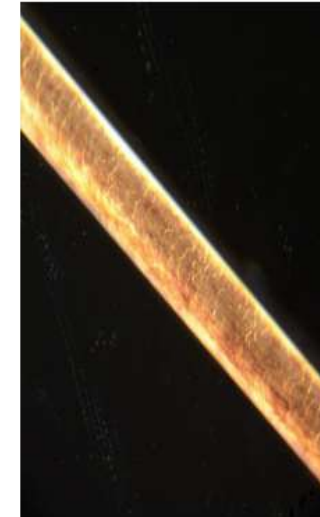
Fiber-optic communication is a method of transmitting information from one place to another by sending pulses of light through an optical fiber. The **light forms an electromagnetic carrier wave that is modulated by a signal to carry information.**

Optical Fiber :

An optical fiber or optical fibre 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.



Fig. (1-1). a). optical
fiber diameter: 8 -200 μm



b). human hair
diameter: 50-120 μm

Principle

- Light propagate in optical fiber from one of its ends to the other end is based on the principle of total internal reflection.

When light enters at one end of the fiber, it undergoes successive total internal reflection from side walls and travels along the length of the fiber in a **zigzag** path.

A small fraction of light may escape through sidewalls but a major fraction emerges out from the exit end of the fiber. Light can travel through fiber even if it is bent.

continue

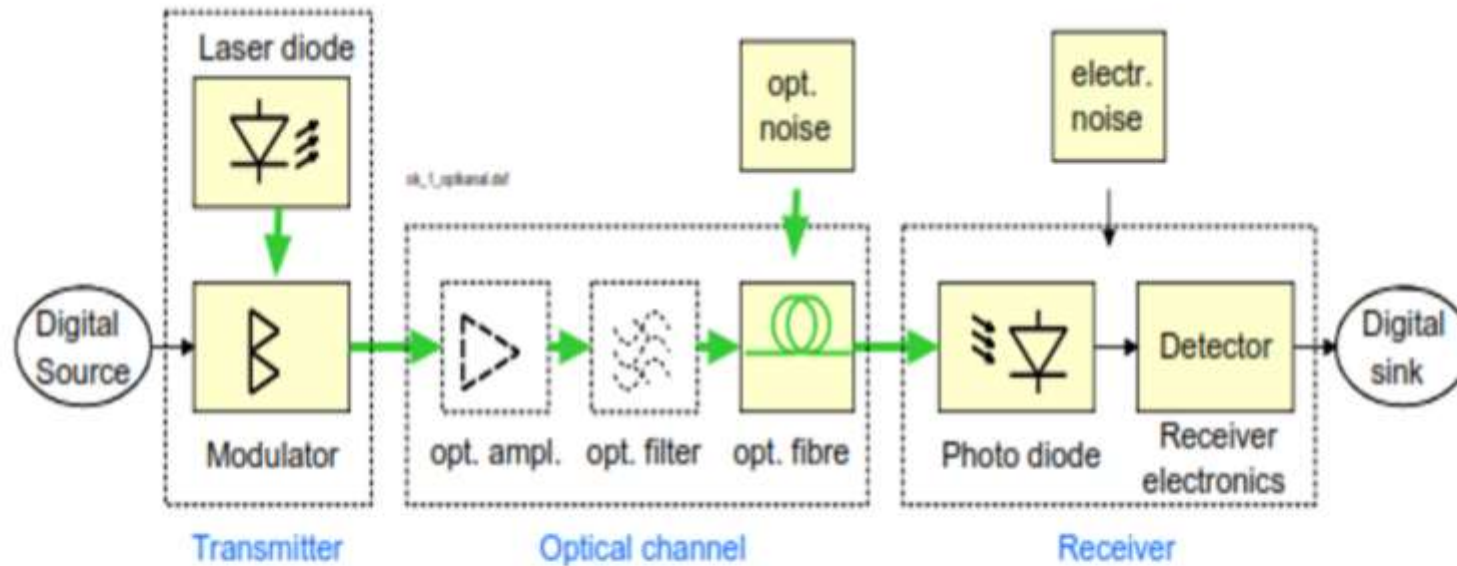


Photo diode: Optical-to-electrical conversion by detecting the power of the received signal (envelope detector). The received instantaneous light power results in a proportional electrical signal (photo current)

Noise: Is present in the optical domain (mainly from optical amplifier) as well as in the electrical domain (from electronics) and from photo diode itself (shot noise)

Optical fiber basic structure:

Each optical fiber stand has three components inside: (Fig.1-3)

1. **Core** : thin glass center of the fiber where light travels. Size of the core is varying between 8 and 63 microns. Most important specification of the core is the **index of refraction** which is the value for light bending passing through the material and for the speed of that light could travel through material with.
2. **Cladding**: outer optical material surrounding the core. Cladding is having lower refractive index than the core. It allows light to stay inside the fiber and not escape into cladding, since it will be reflected. The core, and the lower-refractive-index cladding, are typically made of high-quality silica glass, though they can both be made of plastic as well.

Structure of Fiber Optic cable

- A practical optical fiber is cylindrical in shape (see figure 2a)
- It has in general three coaxial regions as shown in figure 2b.

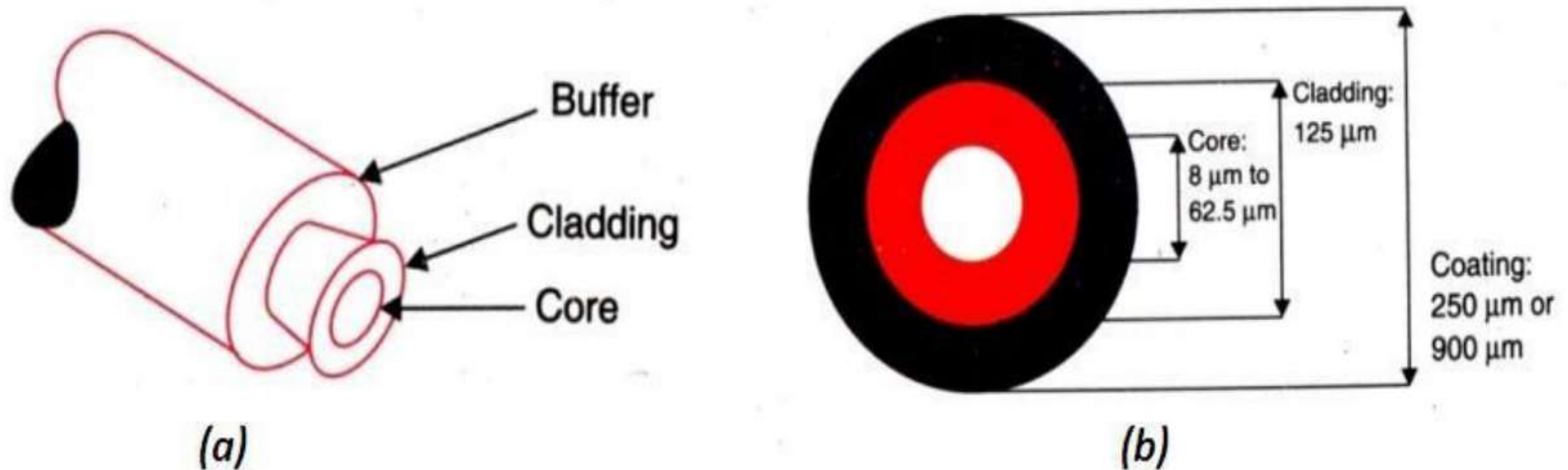


Figure : (2)

Continue

Core:

- The innermost cylindrical region is the light guiding region known as the **core**.
- In general the diameter of the core is of the order of $8.5\text{ }\mu\text{m}$ to $62.5\text{ }\mu\text{m}$

Cladding:

- The core is surrounded by a coaxial middle region known as the cladding.
- The diameter of the cladding is of the order of $125\text{ }\mu\text{m}$.
- The refractive index of cladding (n_2) is always lower than that of core (n_1).
- Light launched into the core and striking the core –to-cladding interface at angle greater than critical angle will be reflected back into the core.
- When the angles of incidence and reflection are equal, the light will continue to rebound and propagate through the fiber.

Necessity of cladding

- **The actual fiber is very thin and light entering a bare fiber will travel along the fiber through repeated total internal reflections at the glass-air boundary. However, bare fibers are used only in certain applications. For use in communications and some other applications, the optical fiber is provided with a cladding.**

The cladding maintains uniform size of the fiber, protects the walls of the fiber from chipping, and reduces the size of the cone of light that will be trapped in the fiber.

The cladding performs the following important functions:

- **Keeps the size of the fiber constant and reduces loss of light from the core into the surrounding air.**
- **Protects the fiber from physical damage and absorbing surface contaminants**
- **Prevents leakage of light energy from the fiber through evanescent waves.**
- **Prevents leakage of light energy from the core through frustrated total internal reflection.**
- **Reduces the core of acceptance and increases the rate of transmission of data.**
- **A solid cladding, instead of air, also makes it easier to add other protective layers over the fiber.**

Continue

Buffer:

- The outermost region is called the sheath or a protective buffer coating.
- It is a plastic coating given to the cladding for extra protection.
- This coating is applied during the manufacturing process to provide physical and environmental protection for the fiber.
- The buffer is elastic in nature and prevents abrasions.
- The coating varies in size from 250 μm or 900 μm .

In short

- Core is the inner light-carrying member
- Cladding is the middle layer-which serves to confine the light to the core.
- Buffer coating surround the cladding, which protects the fiber from physical damage and environmental effects.

Core:

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- The coating varies in size from $250\text{ }\mu\text{m}$ or $900\text{ }\mu\text{m}$.

continue

3. **Buffer Coating** : is simply a protective layer that is protecting core and cladding from the fracture.

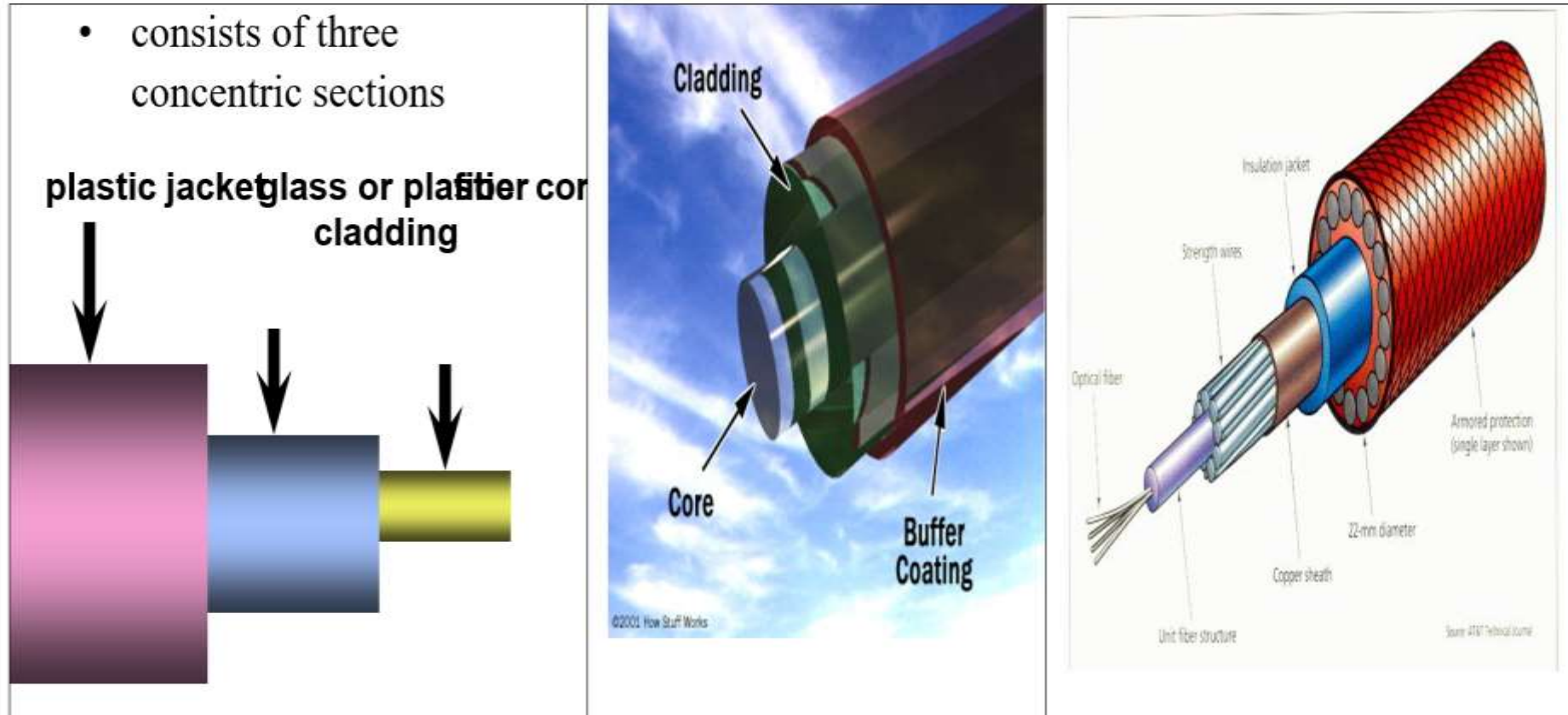
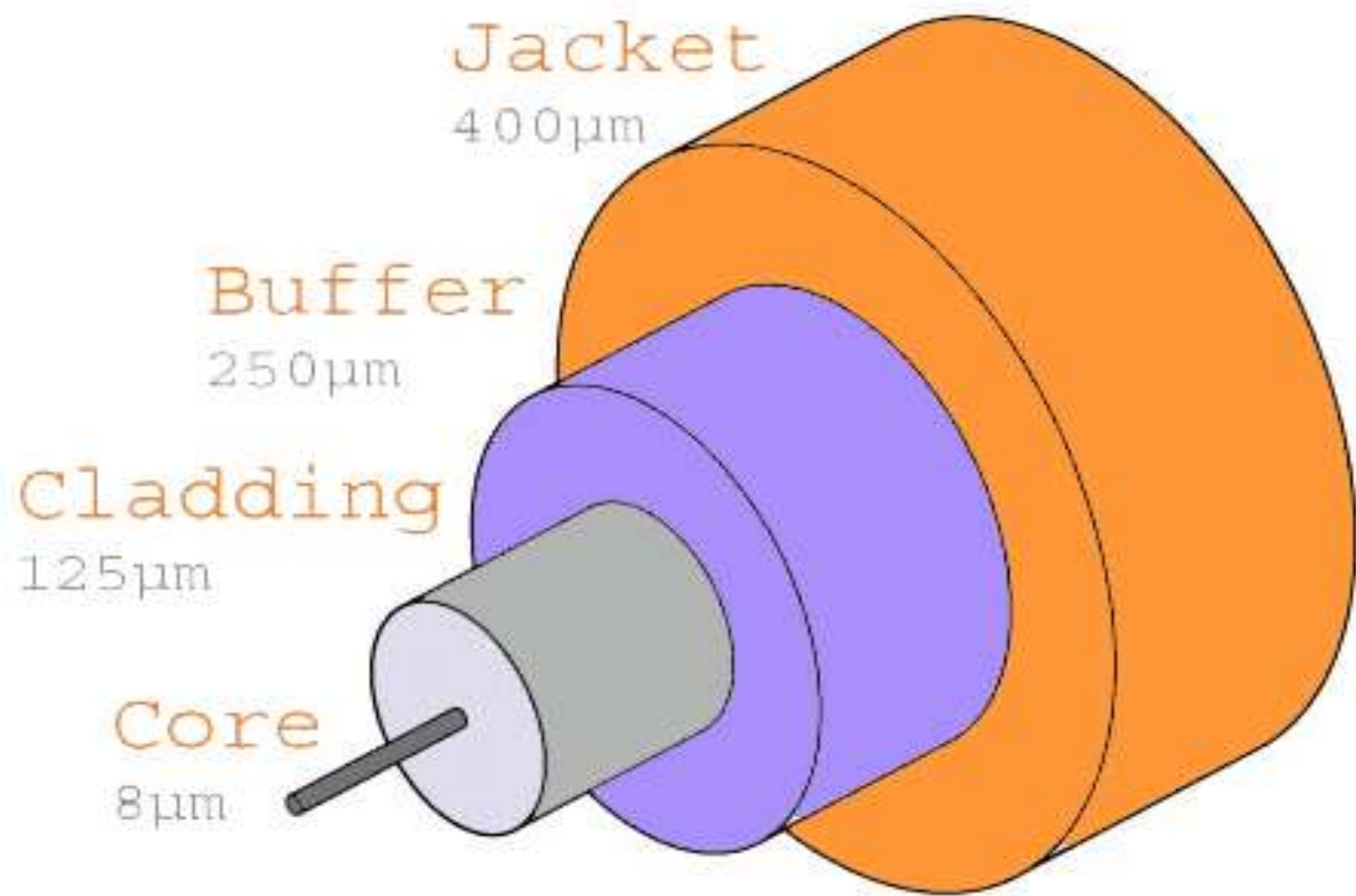


Fig. (1-3) Optical Fiber Construction



Optical Fiber System operation

- **An optical fiber is used to transmit light signals over long distances. The role of a light transmitting medium is similar to a coaxial cable or wave guide used in microwave communications.**

Optical fiber requires a light source for launching light into the fiber at its input end and a photo detector to receive light at its output end. As the diameter of the fiber is very small, the light source has to be dimensionally compatible with the fiber core.

Light emitting diodes and laser diodes, which are very small in size, are used as the light sources.

Continue

- The electrical input signal is in general of digital form. It is converted in to optical signal by varying the current flowing through the light source. Hence, the intensity of the light emitted by the source of modulated with the input signal and the output will be in the form of light pulses

The light pulses constitute the signal that travel through the optical fiber. At the receiver end, semiconductor photo diodes, which are very small in size, are used for detection of these light pulses. The photo detector converts the optical signal into electrical form. Thus a basic optical fiber system consists of LED /laser diode, optical fiber cable and a semiconductor photodiode.

Optical fiber Applications:

Fiber optic cables have revolutionized the world of network communication ever since their inception **nearly 4 decades ago**.

Some of the most popular applications of fiber optic cables are listed below:

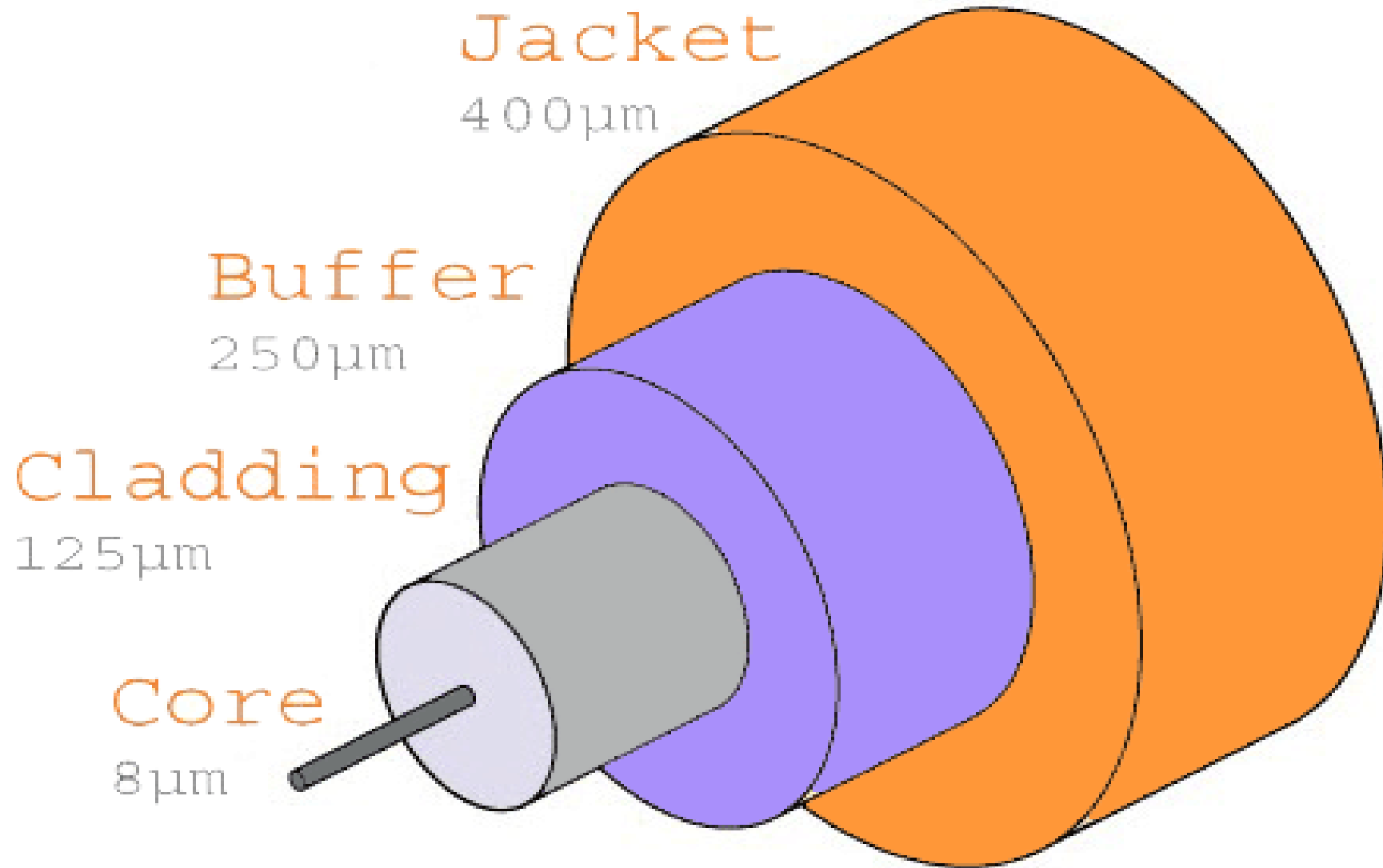
1	Internet	6	Lighting and Decorations
2	Cable Television, CCTV	7	Mechanical Inspections
3	Telephone	8	Military and Space Applications
4	Computer Networking: LAN, WAN	9	Automotive Industry and sensors
5	Surgery and Dentistry	10	Industrial process control system



PRINCIPLES OF LIGHT PROPAGATION THROUGH OPTICAL FIBER

introduction

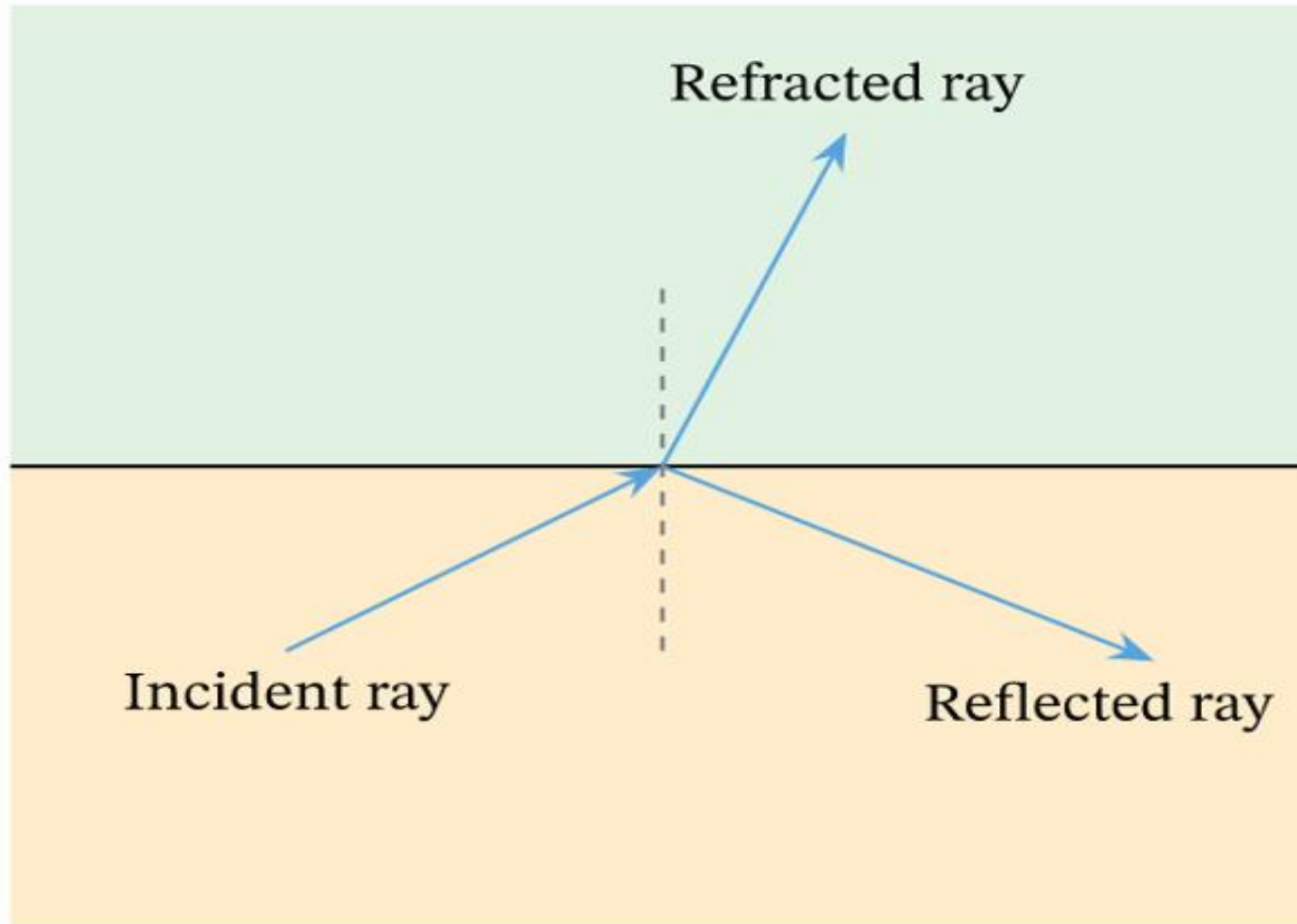
Fiber optic Cable construction



Optical fiber construction

- Optical fiber construction shows that, the cable consists of two main parts, **core and cladding**.
- These two materials have different refractive properties(**Refractive Index**).
- Refractive index (n) tells how *fast or slow* light travels through the material.
- Optical boundary is a surface that separates two materials with different refractive indexes.
- Most light rays **both reflect and(or) refract** when they encounter a boundary between two materials.
- These depends on **refractive index of the material** **and** **angle of ray incident**.

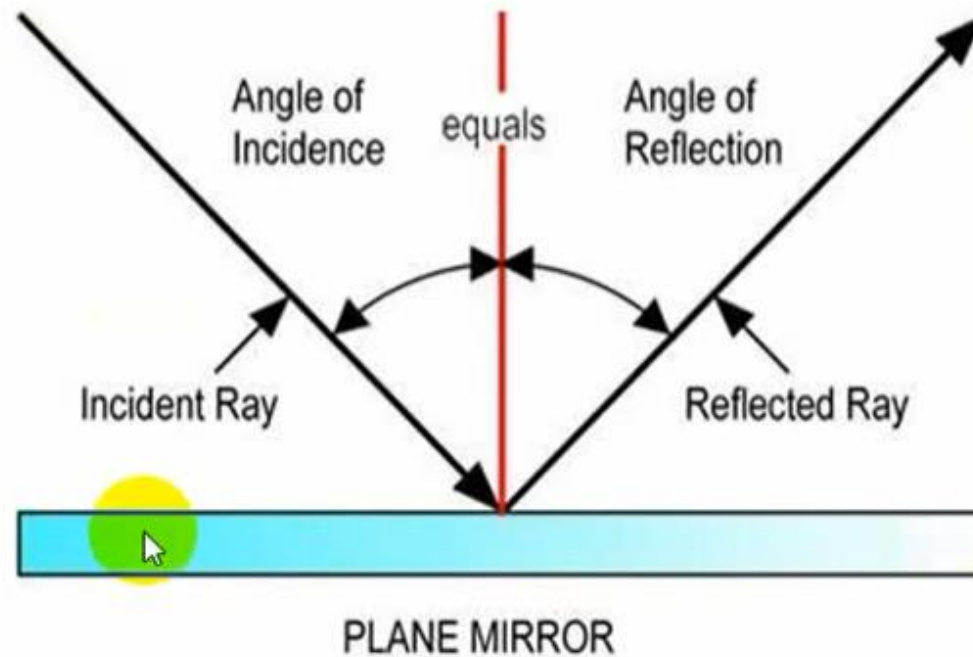
Light propagation through different media with Different Refractive Index



Reflection, Refraction, and Snell's Law

Law of Reflection:

- The angle of incidence equals to the angle of reflection



Reflection, Refraction, and Snell's Law

Refraction:

- Light will bend when it changes mediums because its velocity is changed once it leaves the vacuum.

Refractive Index (n):

- Is the ratio of the speed of light in vacuum to the speed of light in a medium.

$$n = \frac{\text{speed of light in the vacuum}}{\text{speed of light in the medium}}$$



Reflection, Refraction, and Snell's Law

Snell's Law

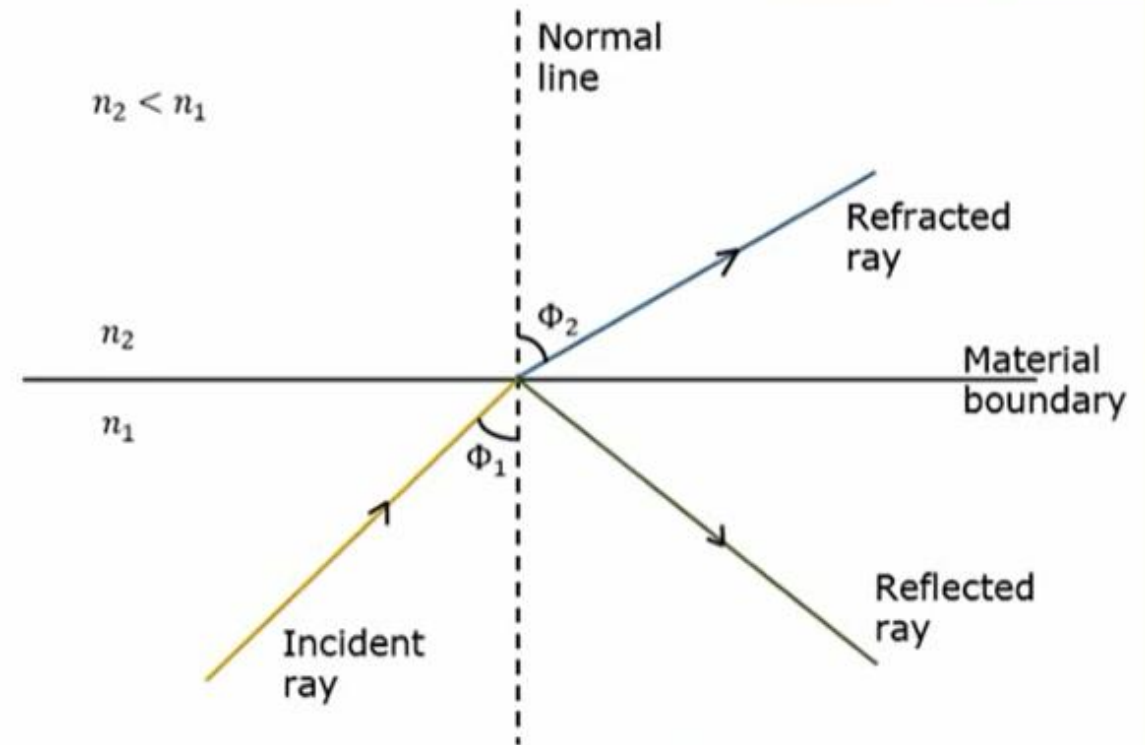
$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

n_1 : refractive index for incident medium

n_2 : refractive index for refracted medium

ϕ_1 : angle of incidence

ϕ_2 : angle of refraction

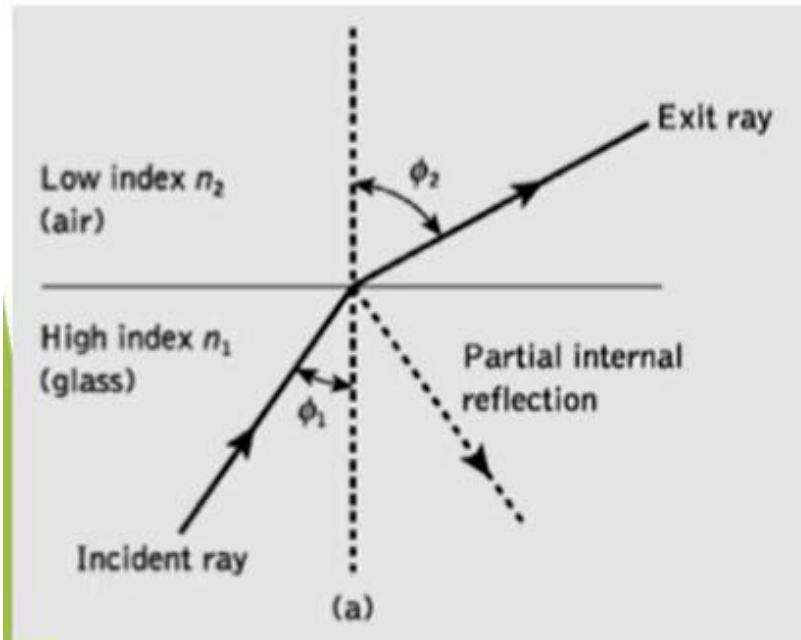


Ray Transmission Theorem/Refraction

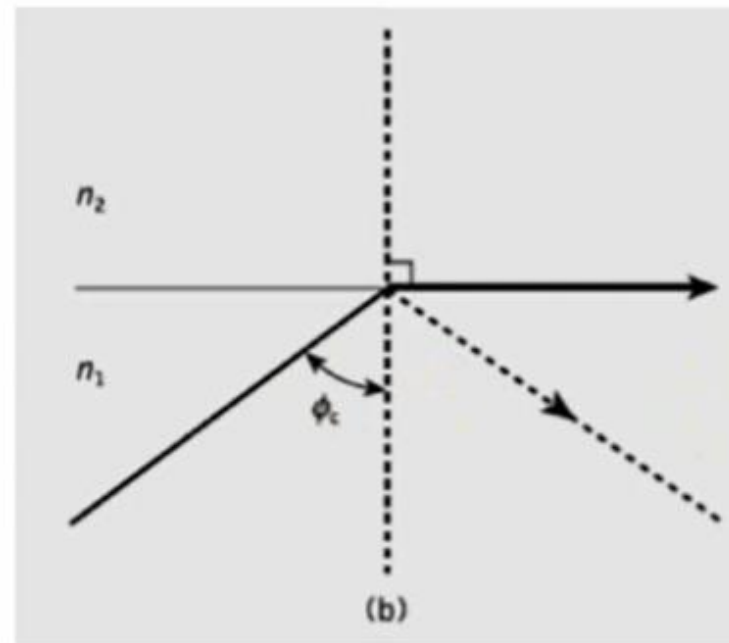
- When light travels from one medium to another it changes speed and is **refracted**.
- If the light rays are travelling from a less dense material to a dense medium they are refracted towards the normal and if they are travelling from a dense to less dense medium they are refracted away from the normal.
- As the angle of incidence increases so does the angle of refraction.
- When the angle of incidence reaches a value known as the critical angle the refracted rays travel along the surface of the medium or in other words are refracted to an angle of 90° .

Ray Transmission Theory

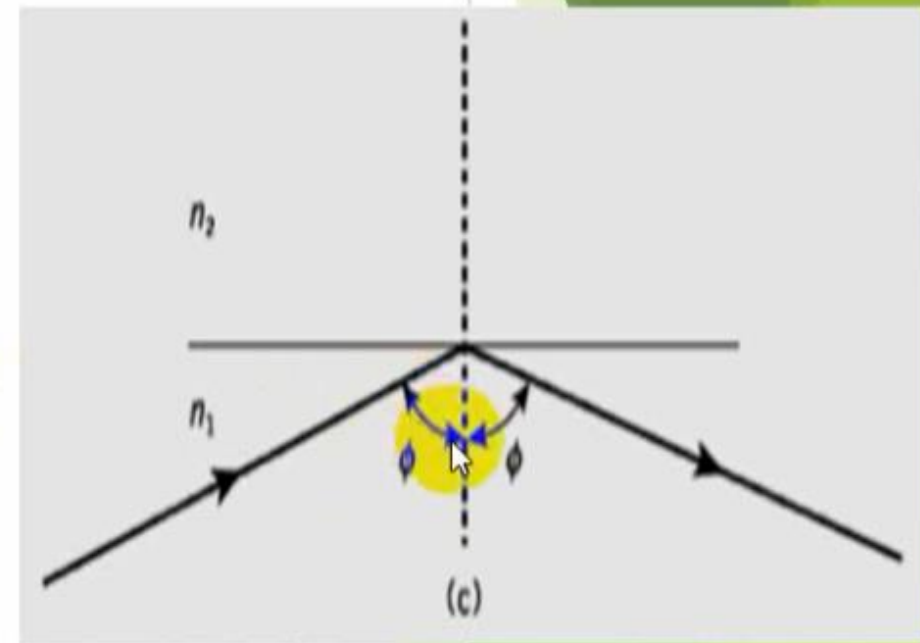
A: Partial Internal Reflection



B: Critical Angle



C: Total Internal Reflection



Activate Windows
Go to Settings to activate Windows.

Critical Angle

- When the angle of incidence(Φ_1) is progressively increased, there will be progressive increase in refractive angle (Φ_2)
- At some condition (Φ_1) , the refractive angle (Φ_2) becomes 90 degree to the normal.
- When this happens the refracted ray travels along the interface.
- The angle Φ_1 at which Φ_2 become 90 is called critical angle and denoted by Φ_c .

Angle of Incident – Critical angle relation

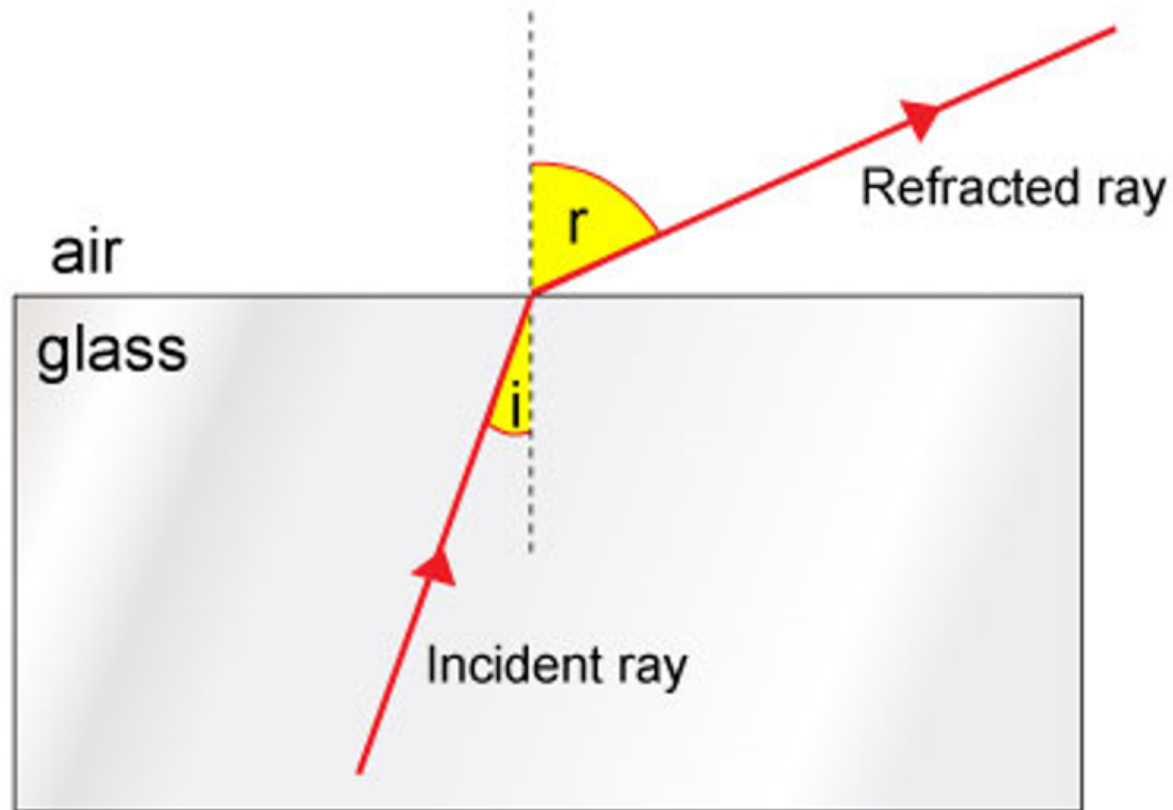
- **There are three cases:**

1. Angle of incidence **Less** than the critical angle

2. Angle of incidence **Equal** to the critical angle

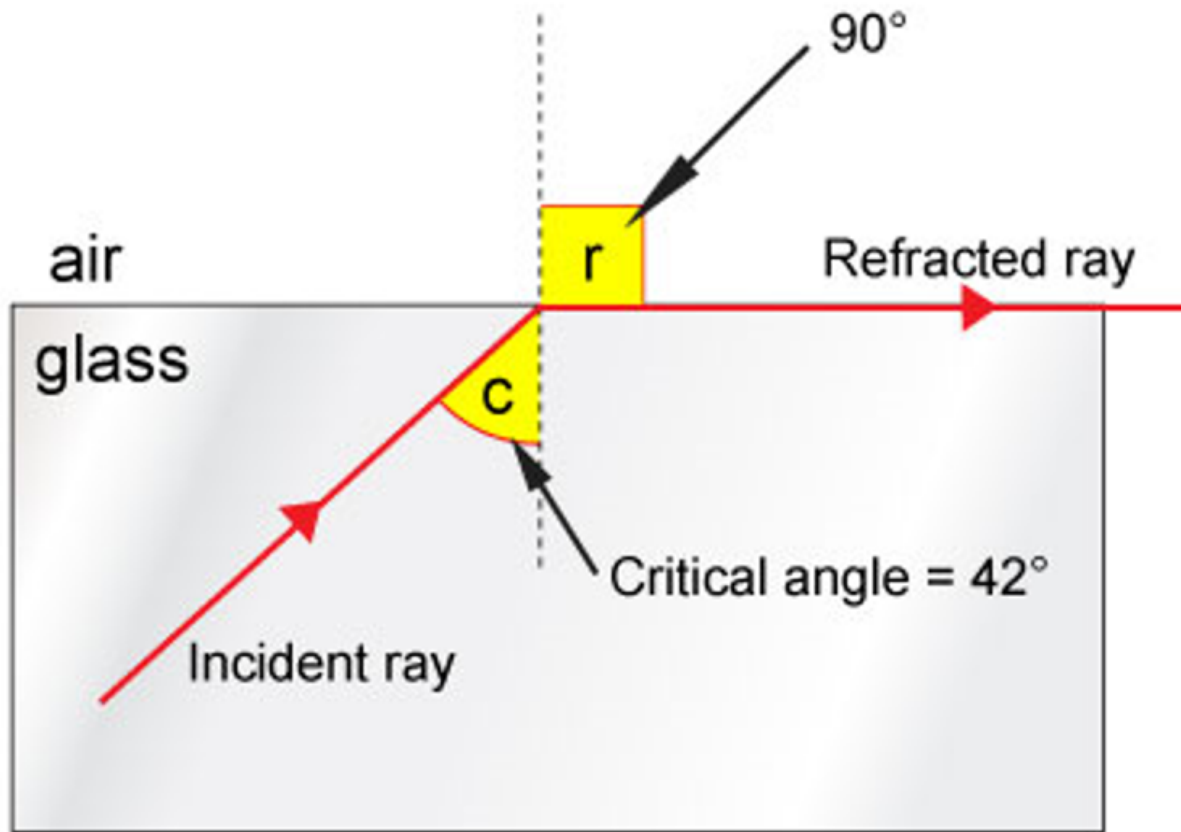
3. Angle of incidence **Greater** than the critical angle

1. Angle of incidence less than the critical angle



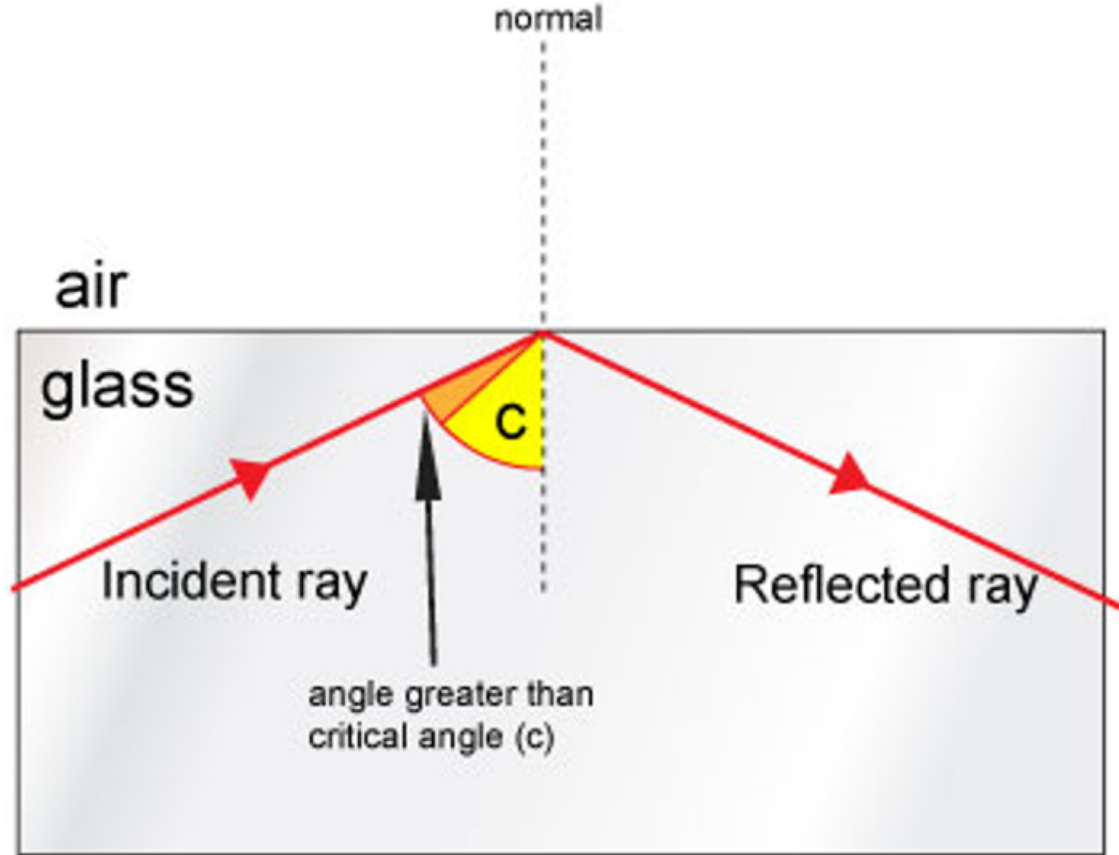
When the angle of incidence of the light ray leaving the glass is less than the critical angle, the light ray speeds up on leaving the glass and is refracted away from the normal.

2. Angle of incidence equal to the critical angle



When the angle of incidence of the light ray reaches the critical angle (42°) the angle of refraction is 90° . The refracted ray travels along the surface of the denser medium in this case the glass.

3. Angle of incidence greater than the critical angle



When the angle of incidence of the light ray is greater than the critical angle then no refraction takes place. Instead, all the light is reflected back into the denser material in this case the glass. This is called **total internal reflection**.

- The critical angle is defined as the minimum angle of incidence (ϕ_1) at which the ray strikes the interface of two media and causes an angle of refraction (ϕ_2) equal to 90° . Fig. 2.2.4 shows critical angle refraction.

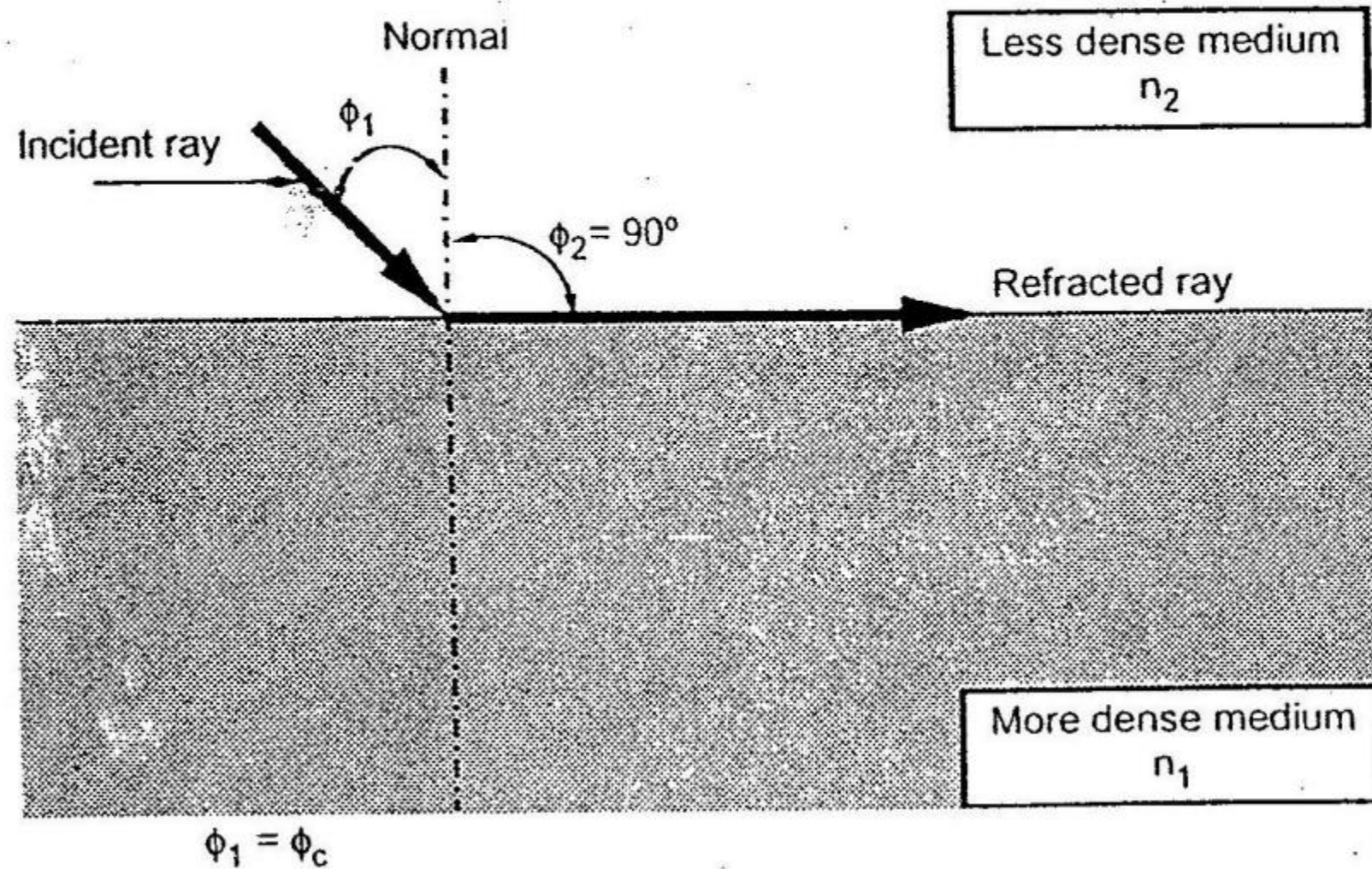


Fig. 2.2.4 Critical angle

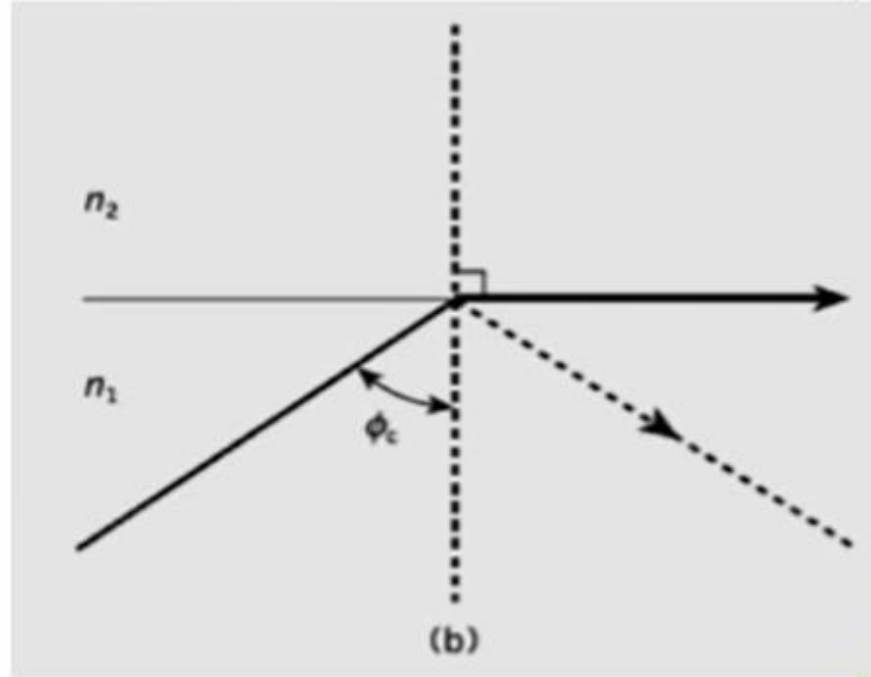
Critical Angle

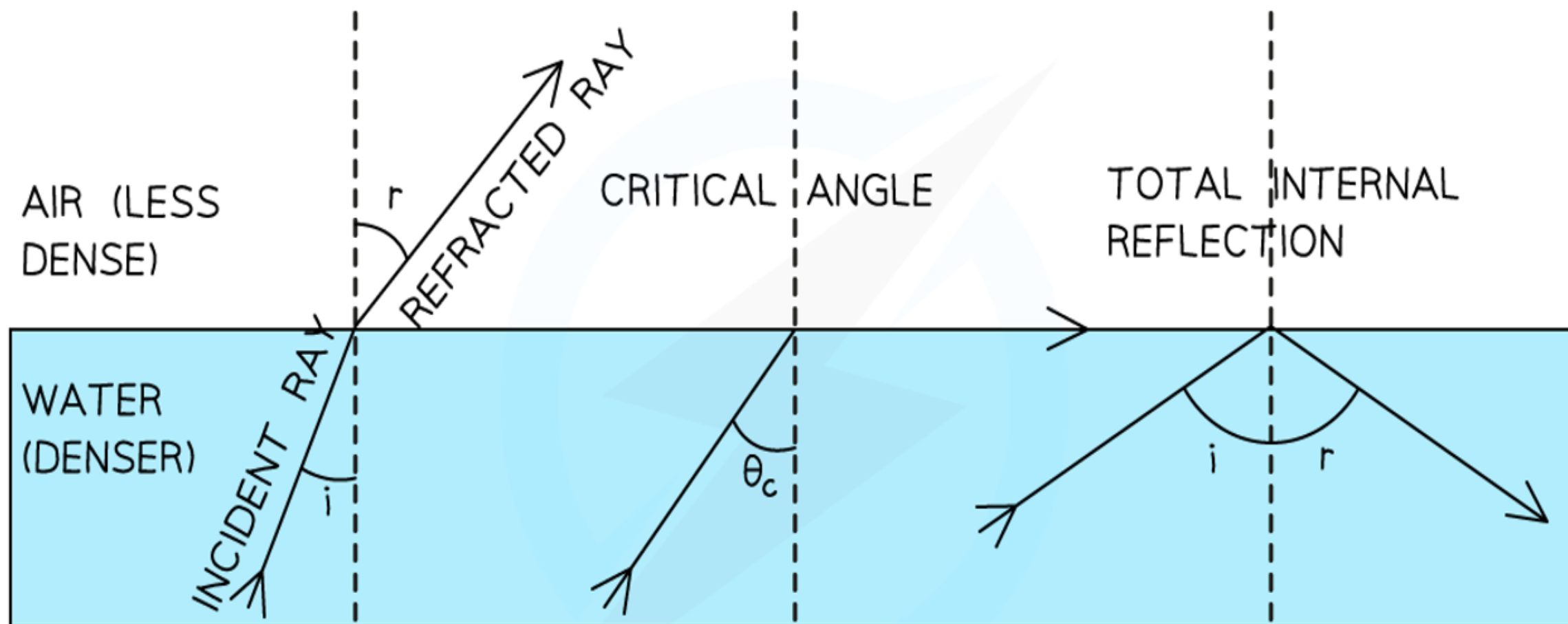
$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

$$n_1 \sin \phi_c = n_2 \sin 90$$

$$\sin \phi_c = \frac{n_2}{n_1}$$

$$\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$





$$i < \theta_c$$

$$i = \theta_c$$

$$i = r$$
$$i > \theta_c$$

Total Internal Reflection (TIR)

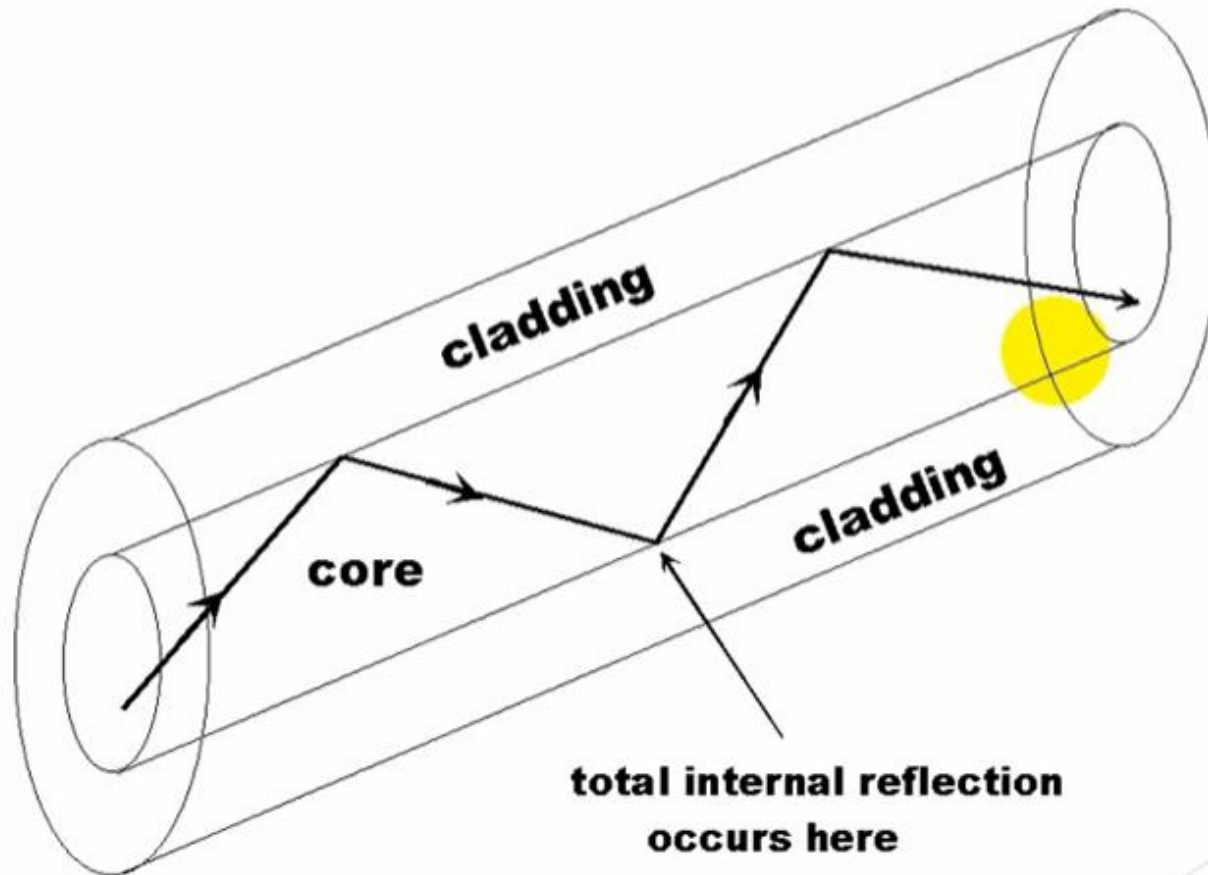
- When the incident angle is increased beyond the **critical angle**, the light ray does not pass through the interface into the other medium.
- This gives the effect of **mirror** exist at the interface with no possibility of light escaping outside the medium.
- In this condition angle of reflection (θ_2) is equal to angle of incidence (θ_1) .
- This action is called as **Total Internal Reflection (TIR)** of the beam.
- It is TIR that leads to the propagation of waves within fiber-cable medium.
- TIR can be observed only in materials in which the velocity of light is less than in air.

Continue

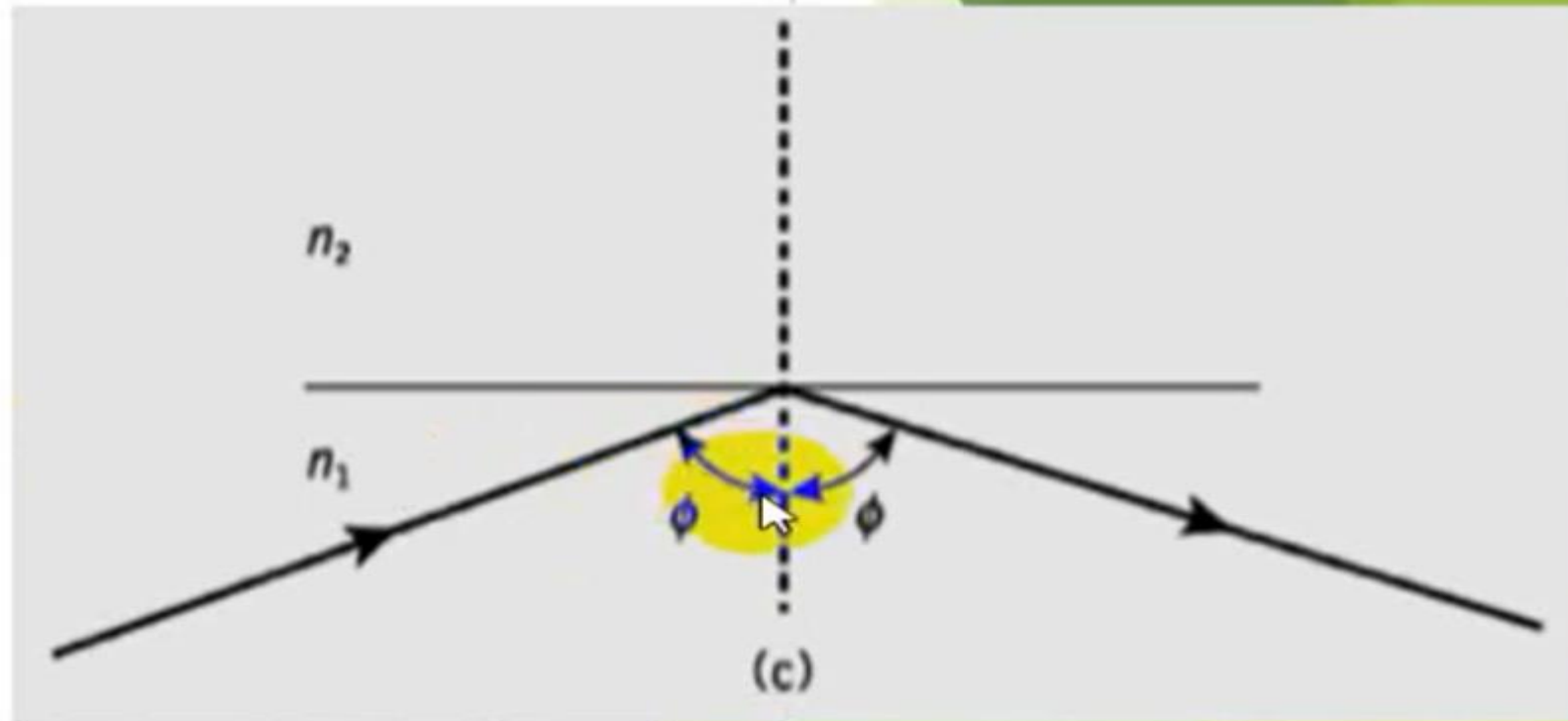
- Sometimes, when light is moving from a denser medium towards a less dense one, instead of being refracted, all of the light is reflected.
- This phenomenon is called total internal reflection
 - Total internal reflection (TIR) occurs when:
 - The angle of incidence is greater than the critical angle and
 - The incident material is denser than the second material
- Therefore, the **two conditions** for total internal reflection are:
 - o The angle of incidence $>$ the critical angle
 - o The incident material is denser than the second material

Principle of Transmitting Light in Fiber Optic

- Reflection (Total Internal Reflection)



C: Total Internal Reflection



⇒ **Example 2.2.1 :** A light ray is incident from medium-1 to medium-2. If the refractive indices of medium-1 and medium-2 are 1.5 and 1.36 respectively then determine the angle of refraction for an angle of incidence of 30° .

Solution : Medium-1 $n_1 = 1.5$

Medium-2 $n_2 = 1.36$

Angle of incidence $\phi_1 = 30^\circ$

Angle of refraction $\phi_2 = ?$

Snell's law : $n_1 \sin \phi_1 = n_2 \sin \phi_2$

$$1.5 \sin 30^\circ = 1.36 \sin \phi_2$$

$$\sin \phi_2 = \frac{1.5}{1.36} \sin 30^\circ$$

$$\sin \phi_2 = 0.55147$$

$$\therefore \phi_2 = 33.46^\circ$$

Angle of refraction = 33.46° from normal.

.. Ans

➡ **Example 2.2.2 :** A light ray is incident from glass to air. Calculate the critical angle (ϕ_c).

Solution : Refractive index of glass $n_1 = 1.50$

Refractive index of air $n_2 = 1.00$

Snell's law : $n_1 \sin \phi_1 = n_2 \sin \phi_2$

$$\sin \phi_1 = \frac{n_2}{n_1} \sin \phi_2$$

From definition of critical angle, $\phi_2 = 90^\circ$ and $\phi_1 = \phi_c$.

$$\therefore \sin \phi_c = \frac{n_2}{n_1} \sin 90^\circ$$

$$\sin \phi_c = \left(\frac{1.0}{1.5} \right) \times 1 = 0.67$$

$$\therefore \phi_c = \sin^{-1} 0.67$$

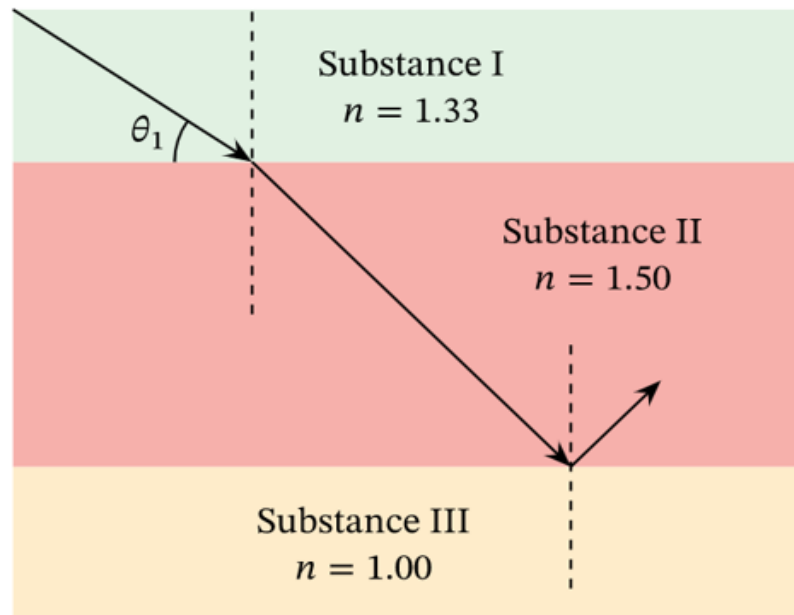
$$\phi_c = 41.81^\circ$$

$$\text{Critical angle } \phi_c = 41.81^\circ$$

... Ans.

Example 4: Relating Angles in Several Optically Different Materials

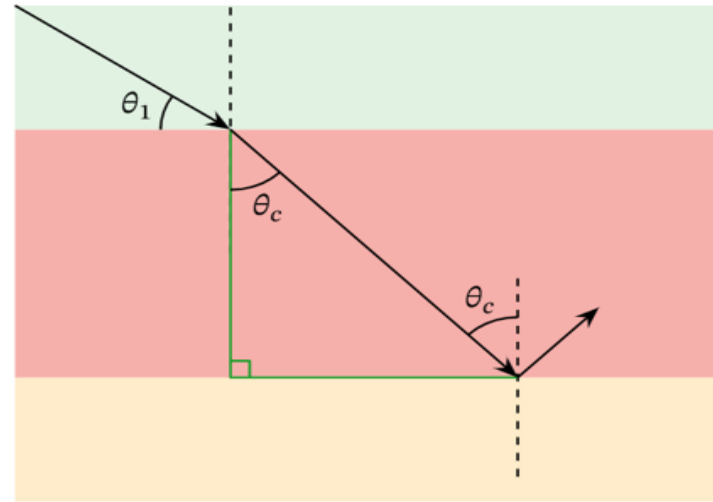
The diagram shows a light ray that is transmitted from substance I to substance II at angle θ_1 to the boundary between the substances. The ray is totally internally reflected back into substance II at the boundary to substance III. For any angle of θ greater than θ_1 , the light ray is transmitted to substance II. Find the angle θ_1 to the nearest degree.



The ray experiences total internal reflection at the boundary between substances II and III, so it must be incident on the boundary at an angle no smaller than the critical angle. We also know that the ray transmits through this boundary when it is incident on the first boundary between substances I and II at an angle larger than θ_1 , so let us think about what this implies. If the angle at θ_1 is made larger, the angle of incidence at the boundary of substances II and III is made smaller. We know that if this angle is made any smaller, the light will not experience total internal reflection; thus, θ_1 is set at a special value so that the angle of incidence between substances II and III is approximate to the critical angle. Since we know the refractive indices of the materials on either side of the boundary, we can calculate the critical angle to learn more about this setup. To calculate the critical angle here, we can rearrange the critical angle formula (from Snell's law) to solve for θ_c and plug in the values $n_r = 1.00$ and $n_i = 1.50$:

$$\theta_c = \arcsin \frac{n_r}{n_i} = \arcsin \frac{1.00}{1.50} = 41.8^\circ.$$

Knowing this, we can use the properties of a right triangle to determine the angle of refraction as the ray passes from substance I to II. Below is a diagram that helps relate these angles to each other using a right triangle, shown in blue. Notice that the vertical leg of the blue triangle is parallel to the surface normal between substances II and III. Because of the alternate interior angles theorem, we know that the top internal angle of the right triangle, which is the angle of refraction for the ray passing from substance I to II, is congruent, or equal, to θ_c . This is shown in the diagram below.



Thus, at this boundary, $\theta_r = 41.8^\circ$, and we also know the indices of refraction for the materials on either side of the boundary, so we can use Snell's law to solve for the angle of incidence there:

$$n_i \sin \theta_i = n_r \sin \theta_r$$

$$\theta_i = \arcsin \left(\frac{n_r}{n_i} \sin \theta_r \right)$$

$$= \arcsin \left(\frac{1.50}{1.33} \sin 41.8^\circ \right)$$

$$= \arcsin\left(\frac{1.50}{1.33} \sin 41.8^\circ\right)$$

$$= 48.7^\circ.$$

Because θ_1 is complementary to θ_i , we can find the value of θ_1 using $90^\circ - 48.7^\circ = 41.3^\circ$.

Rounding to the nearest degree, we have found that $\theta_1 = 41^\circ$.

Beyond using n values to determine the critical angle, it is important to be able to use the critical angle equation to solve for different values, such as the refractive index of a given material. We will practice this in the following example.

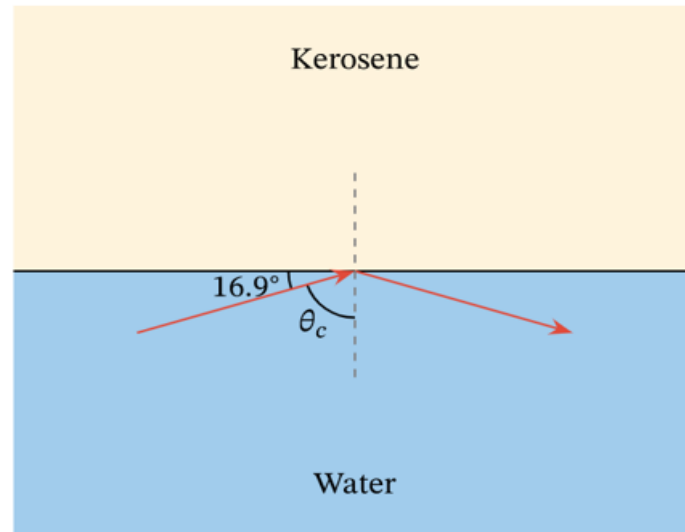
Example 5: Calculating a Refractive Index Using the Critical Angle

Light rays travel through a layer of kerosene floating on the surface of water that has a refractive index of 1.33. Light rays that are incident on the interface of kerosene and water at angles of 16.9° from the surface or less are totally internally reflected. What is the refractive index of the kerosene? Give your answer to two decimal places.

Answer

We have been given the value of an angle, but it is not equal to the critical angle because it is measured relative to the surface rather than the surface normal. However, the critical angle can be easily computed from the angle given because they are complementary:

$$90^\circ - 16.9^\circ = 73.1^\circ.$$



Thus, we know that $\theta_c = 73.1^\circ$. Now that we have a value for the critical angle, and since we know that $n_{\text{water}} = 1.33$, we have two out of the three variables that appear in our equation for the critical angle:

$$\sin \theta_c = \frac{n_r}{n_i}.$$

We can rearrange this equation to solve for one of the n values. Because the light ray is traveling from the kerosene to water, we know that $n_{\text{water}} = n_r$, and we need to solve for n_i , the refractive index of kerosene. To do this, we can multiply both sides of the equation by $\frac{n_i}{\sin \theta_c}$:

$$n_i = \frac{n_r}{\sin \theta_c}.$$

We are now ready to plug in $\theta_c = 73.1^\circ$ and $n_r = 1.33$:

$$n_i = \frac{n_r}{\sin \theta_c} = \frac{1.33}{\sin 73.1^\circ} = 1.39.$$

Therefore, kerosene has a refractive index of 1.39.

⇒ **Example 2.2.3 :** A lightwave is travelling in a semiconductor medium (GaAs) of refractive index 3.6. It is incident on a different semiconductor medium (AlGaAs) of refractive index 3.4 and the angle of incidence is 80° . Will this result in total internal reflection.

Solution : Refractive index of GaAs (n_1) = 3.6

Refractive index of AlGaAs (n_2) = 3.4

Angle of incidence $\phi_1 = 80^\circ$

Snell's law : $n_1 \sin \phi_1 = n_2 \sin \phi_2$

At critical angle $\phi_1 = \phi_c$ and $\phi_2 = 90^\circ$

$$\sin \phi_c = \frac{n_2}{n_1} \sin 90^\circ$$

$$= \frac{3.4}{3.6} \sin 90^\circ$$

$$= 0.945$$

$$\therefore \phi_c = \sin^{-1} 0.945 = 70.81^\circ$$

... Ans.

Since critical angle θ_c is less than angle of incidence ϕ_1 but for total internal reflection (TIR) to exist the incident angle (ϕ_1) must be greater than critical angle (θ_c). In the given problem $\phi_1 = 80^\circ$ and $\theta_c = 71^\circ$, hence TIR will take place.

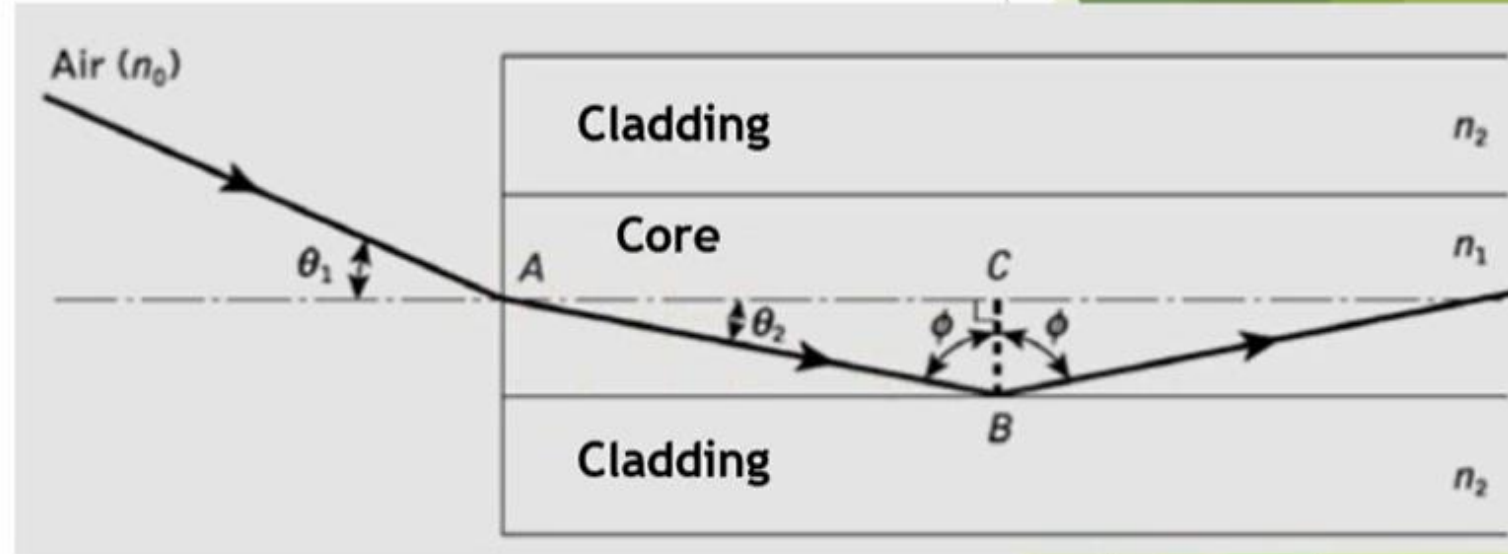
Acceptance Angle (θ_a)

it is the maximum angle of a ray hitting the fiber core which allows the incident light to propagate into the fiber.

$$n_0 \sin \theta_1 = n_1 \sin \theta_2$$

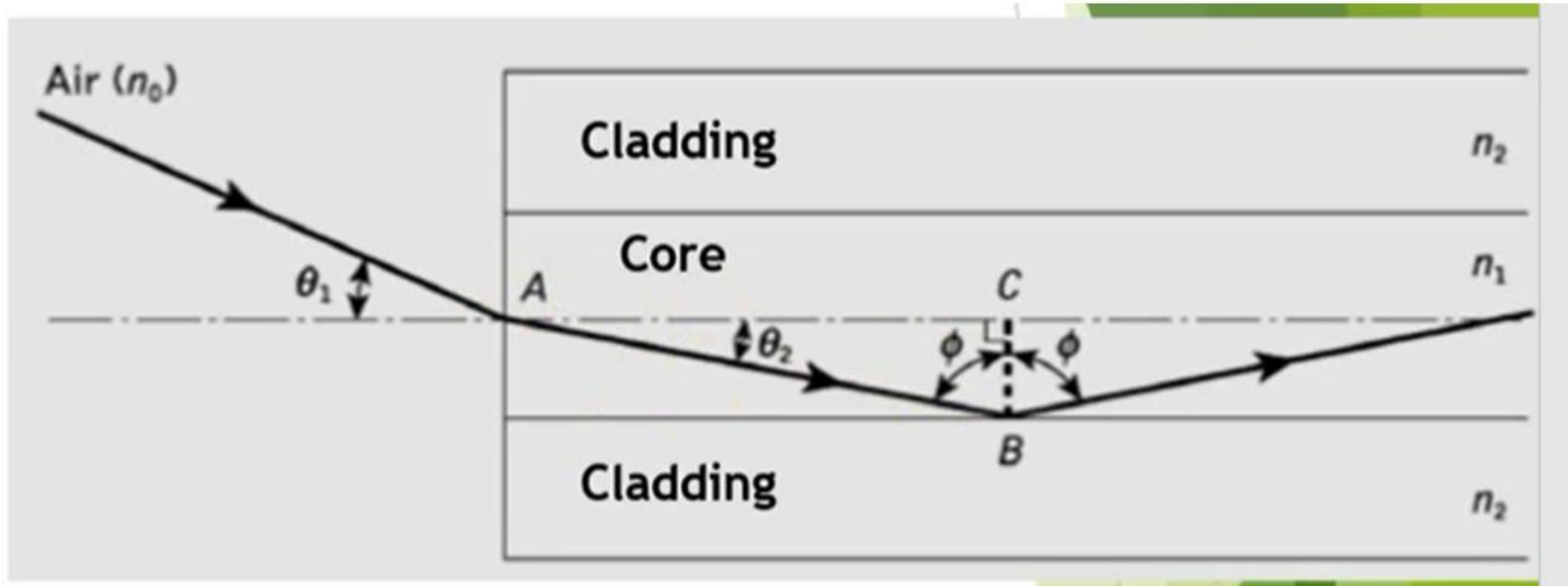
$$\phi = \frac{\pi}{2} - \theta_2$$

$$n_0 \sin \theta_1 = n_1 \cos \phi$$



Acceptance Angle

When a light ray hits Fiber optic core with an incident angle θ_1 , that means it transmits from air to the fiber core (two materials with different refraction index), it refracted with an angle θ_2 .



In this case, Snell's law can be applied

Snell's Law

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

n_1 : refractive index for incident medium

n_2 : refractive index for refracted medium

ϕ_1 : angle of incidence

ϕ_2 : angle of refraction

If incidence angle is θ_1 and refraction angle is θ_2 , Then

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

- Since the incidence ray comes from air (refraction index of air n_0), then $n_1=n_0$
- The refraction index of core is n_1 , then $n_2=n_1$

Thus,

$$n_0 \sin \theta_1 = n_1 \sin \theta_2$$

- Since the ray transmission in optic fiber depends on total internal reflection, i.e., the ray should be reflected at the interface surface between core and clad (point B)

for the triangle ABC, $\theta_2 = 90^\circ - \phi$

$$n_0 \sin \theta_1 = n_1 \sin (90^\circ - \phi) = n_1 \cos(\phi)$$

by using the trigonometric relationship,

$$\sin^2 \phi + \cos^2 \phi = 1 \quad \text{then } \cos \phi = (1 - \sin^2 \phi)^{1/2}$$

$$n_0 \sin \theta_1 = n_1 (1 - \sin^2 \phi)^{1/2} = (n_1^2 - n_1^2 \sin^2 \phi)^{1/2}$$

for total internal Reflection, the angle $\phi \geq \phi_c$

where ϕ_c is the critical angle and $\sin \phi_c = n_2/n_1$

$$\text{then } \sin \phi = n_2/n_1, \quad \sin^2 \phi = (n_2/n_1)^2 = n_2^2/n_1^2$$

$$\text{then } n_0 \sin \theta_1 = (n_1^2 - n_1^2 \cdot n_2^2/n_1^2)^{1/2} = (\underline{n_1^2} - n_2^2)^{1/2}$$

$$n_0 \sin \theta_1 = (\underline{n_1^2} - n_2^2)^{1/2}$$

$$\sin \theta_1 = (1/n_0) \cdot (\underline{n_1^2} - n_2^2)^{1/2}$$

$$\theta_1 = \sin^{-1}((1/n_0) \cdot (n_1^2 - n_2^2)^{1/2})$$

The above equation gives the incidence angle Θ_1 in function of refraction index of air, Cor and cladding

This angle is known as acceptance angle Θ_a , which is the maximum angle of a ray hitting the fiber core which allows the incident light to propagate into the fiber.

$$\Theta_a = \sin^{-1}((1/n_0) \cdot (n_1^2 - n_2^2)^{1/2})$$

With $n_0 = 1$ (air)

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

Or $\sin \Theta_a = (n_1^2 - n_2^2)^{1/2} = \text{Numerical aperture (NA)}$

For calculating acceptance angle from NA

$$\Theta_a = \sin^{-1} (n_1^2 - n_2^2)^{1/2} \equiv \sin^{-1} \text{NA}$$

Let us defined Index difference $\Delta_n = n_1 - n_2$

$$\Theta_a = \sin^{-1} (n_1^2 - n_2^2)^{1/2} \equiv \sin^{-1} ((n_1 - n_2)(n_1 + n_2))^{1/2}$$

If n_1 is near n_2 then $n_1 + n_2 = 2n_1$

$$\text{Hence NA} = \sin \Theta_a = (2n_1 \Delta_n)^{1/2}$$

If we define relative Refractive Index $\Delta = (n_1 - n_2)/n_1$

Then, $\Delta \cdot n_1 = n_1 - n_2$

$$\text{NA} = \sin \Theta_a = (n_1^2 - n_2^2)^{1/2} = ((n_1 - n_2)(n_1 + n_2))^{1/2}$$

$$\text{NA} = \sin \Theta_a = ((\Delta \cdot n_1) (2 n_1))^{1/2} = n_1 (2 \cdot \Delta)$$

Numerical aperture (Na) and its relation to acceptance angle Θ_a

|Again, the acceptance angle was defined as the maximum angle to the fiber core axis at which light ray may enter the fiber axis in order to get propagation inside it.

While Numerical aperture is used to describe the light gathering or light collection ability of optical fiber cable.

Acceptance Angle (θ_a)

$$n_0 \sin \theta_1 = n_1 \cos \phi$$

By using the trigonometrical relationship: $\sin^2 \phi + \cos^2 \phi = 1$

$$n_0 \sin \theta_1 = n_1 (1 - \sin^2 \phi)^{1/2}$$

While $\sin \phi_c = \frac{n_2}{n_1}$, and ϕ becomes equal to the critical angle ϕ_c

$$\text{So, } \sin \phi = \frac{n_2}{n_1}$$

θ_1 becomes the acceptance angle for the fiber θ_a

$$n_0 \sin \theta_a = (n_1^2 - n_2^2)^{1/2}$$

$$NA = n_0 \sin \theta_a = (n_1^2 - n_2^2)^{1/2}$$

Activate Windows
Go to Settings to activate Windows.

Numerical Aperture (NA)

The numerical aperture (NA) of a fiber is defined as the sine of the largest angle an incident ray can have for total internal reflectance in the core.

$$NA = n_0 \sin \theta_a = (n_1^2 - n_2^2)^{1/2}$$

$$NA = n_1 (2\Delta)^{1/2}$$

n_1 : Core refractive index

n_2 : Cladding refractive index

Δ : relative refractive index difference

θ_a : acceptance angle

Summary

Critical Angle

$$\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Acceptance Angle

$$\theta_a = \sin^{-1}\left(\frac{NA}{n_o}\right)$$

Numerical Aperture

$$NA = n_o \sin \theta_a = (n_1^2 - n_2^2)^{1/2}$$

$$NA = n_1 (2\Delta)^{1/2}$$

Example:

A silica optical fiber with a core diameter large enough to be considered by the ray theory analysis has a core refractive index of **1.50** and a cladding refractive index of **1.47**.

Determine:

1. The **critical angle** at the core-cladding interface.
2. The **NA** for the fiber.
3. The **acceptance angle** in air for the fiber.

Answer:

1. The critical angle at the core-cladding interface = ϕ_c

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

$$\phi_c = \sin^{-1} \frac{1.47}{1.50}$$

$$\phi_c = \mathbf{78.5^\circ}$$



Answer:

2. The NA for the fiber.

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

$$NA = (1.50^2 - 1.47^2)^{1/2}$$

$$NA = 0.3$$

3. The acceptance angle in air for the fiber = θ_a

$$\theta_a = \sin^{-1} NA$$

$$\theta_a = \sin^{-1} 0.3$$

$$\theta_a = 17.4^\circ$$



Activate Windows
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Homework:

An optical fiber has a numerical aperture of 0.20 and a cladding refractive index of 1.59. Determine:

1. The acceptance angle for the fiber in water which has a refractive index of 1.33.
2. The critical angle at the core-cladding interface.



Examples on numerical Aperture, Acceptance angle and Critical angle

Examples

Example 1

- A silica optical fiber with a core diameter large enough to be considered by ray theory analysis, Has a core refractive index of 1.5 and cladding refractive index of 1.47.

Determine:

1. The critical angle at core – cladding interface
2. The Numerical Aperture for the fiber
3. The acceptance angle in air for the fiber

$$\rightarrow n_1 = 1.5$$

$$n_2 = 1.47$$

$$\begin{aligned}\rightarrow \text{Critical Angle } \phi_c &= \sin^{-1} \left(\frac{n_2}{n_1} \right) \\ &= \sin^{-1} \left(\frac{1.47}{1.5} \right) \\ &= 78.5\end{aligned}$$

$$\begin{aligned}\rightarrow NA &= \sqrt{n_1^2 - n_2^2} \\ &= \sqrt{1.5^2 - 1.47^2} \\ &= \sqrt{2.25 - 2.16} \\ &= 0.3\end{aligned}$$

$$= \sin^{-1} \left(\frac{1.47}{1.5} \right)$$

$$= 78.5$$

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

$$= \sqrt{1.5^2 - 1.47^2}$$

$$= \sqrt{2.25 - 2.16}$$

$$= 0.3$$

$$\rightarrow \text{Acceptance Angle } \theta = \sin^{-1} NA$$

$$= \sin^{-1} 0.3$$

$$= 17.4^\circ$$

A typical relative refractive index difference for an optical fiber designed for long distance transmission is 1%. Estimate the NA and the solid acceptance angle in air for the fiber when the core index is 1.46. further calculate the critical angle at the core-cladding interface within the fiber.

→ Relative Refractive Index $\Delta = 1\% = 0.01$

→ $n_1 = 1.46$

→ Numerical Aperture

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

$$= n_1 \sqrt{2\Delta} = 1.46 \sqrt{2 \times 0.01} = 0.21$$

Example 2

A typical relative refractive index difference for an optical fiber designed for long distance transmission is 1%. Estimate the NA and the solid acceptance angle in air for the fiber when the core index is 1.46. further calculate the critical angle at the core-cladding interface within the fiber.

→ Relative Refractive Index $\Delta = 1\% = 0.01$

→ $n_1 = 1.46$

→ Numerical Aperture

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

$$= n_1 \sqrt{2\Delta} = 1.46 \sqrt{2 \times 0.01} = 0.21$$

→ Relative Refractive Index

$$\Delta = \frac{n_1 - n_2}{n_1} = 1 - \frac{n_2}{n_1}$$

$$\Rightarrow \frac{n_2}{n_1} = 1 - \Delta = 1 - 0.01 = 0.99$$

→ Critical Angle θ_c

$$\theta_c = \sin^{-1} \left(\frac{n_2}{n_1} \right) = \sin^{-1} (0.99)$$

$$\theta_c = 81.9^\circ$$

Fiber-optic cable

The structure of fiber cable,
single-mode vs multimode,
and their major differences.

Fiber-Optic Cable



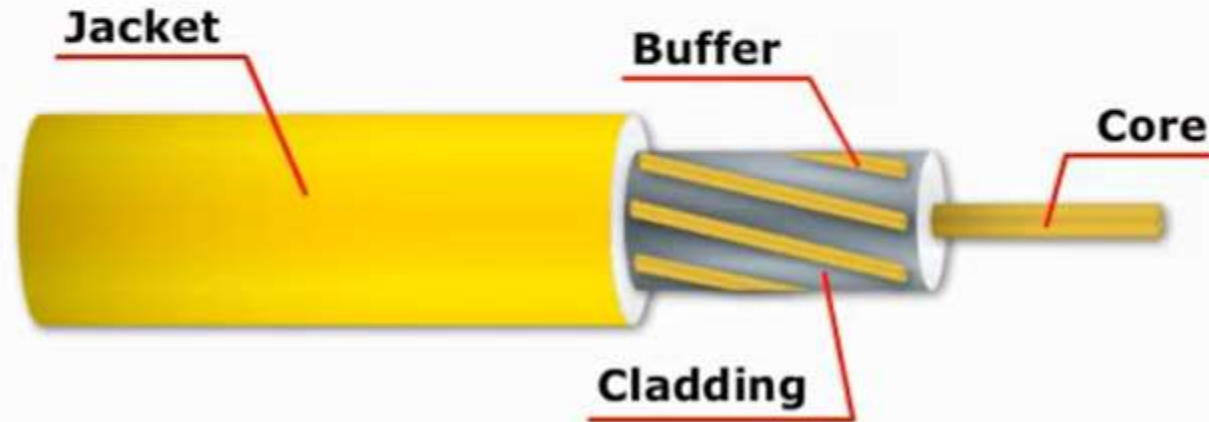
Single-Mode



Multimode

A type of cable that contains one or more optical fibers that are used to carry light. Fiber-optic cables offer significantly higher throughput than copper-based cables, such as coaxial cable or twisted pair cable. Optical fiber may be single-mode or multimode.

Structure Of Fiber-Optic Cable



- **Jacket:** protects inner components
- **Buffer:** used to encapsulate one or more optical fibers providing protection from physical damage
- **Cladding:** the glass or plastic shield around the core. Cladding reflects light back to the core in patterns that vary depending on the transmission mode
- **Core:** a cylinder of glass or plastic and light traveling in the core

Single-mode fiber (SMF)

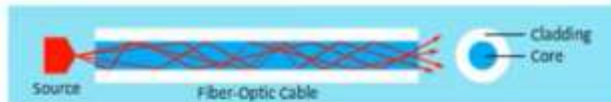
Single-Mode Fiber (SMF)



- High transfer rates over long distances
- Core diameter is about 9 microns. The width of a single human hair ranges from about 20 to 200 microns.
- Laser-generated light travels over one path
- Light does not disperse as signal travels
- Can carry signals many miles before repeating
- Better for long-distance, such as WAN connection
- Internet backbone
- Patch cable: yellow color

Multimode fiber (MMF)

Multimode Fiber (MMF)



- Contains core with larger diameter than single-mode fiber
- Laser or LEDs (light-emitting diodes) generated light pulses travel at different angles
 - Greater attenuation than single-mode fiber
 - Problem: Modal distortion
- Better for short distance
- Patch cable: orange color

Fiber Core Diameter

Optical Fiber Core Diameters

$1\mu\text{m} = 1 \text{ micrometer/micron} = 1 \times 10^{-6} \text{ meter}$



- 1–10 μm – length of a typical bacterium
- 0.125 μm – length of the COVID-19 virus
- 20 to 200 μm – diameter of human hair

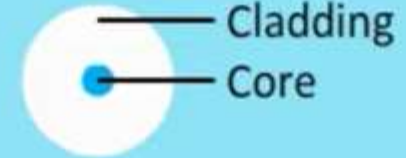
Single-Mode vs Multimode Fiber

Single-Mode

Source



Fiber-Optic Cable



Multimode

Source



Fiber-Optic Cable



Fiber-Optic Cable vs Twisted Pair Cable



Fiber-Optic Cable



Twisted Pair Cable

Benefits over copper cabling:

- Extremely high throughput: 10 Gigabits per second
- Very high noise resistance
- Excellent security
- Able to carry signals for longer distances

Drawbacks:

- More expensive than twisted pair cable
 - Cabling itself more expensive
 - Transmitters and fiber equipment are more expensive
 - Fiber cable installers are more expensive
- Requires special equipment to deal with fiber