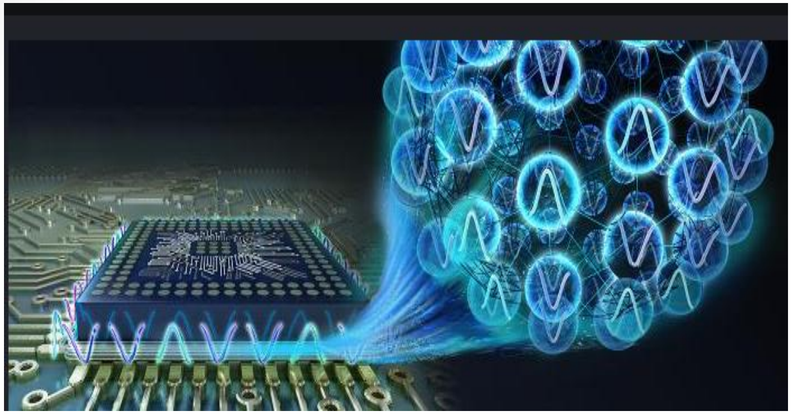
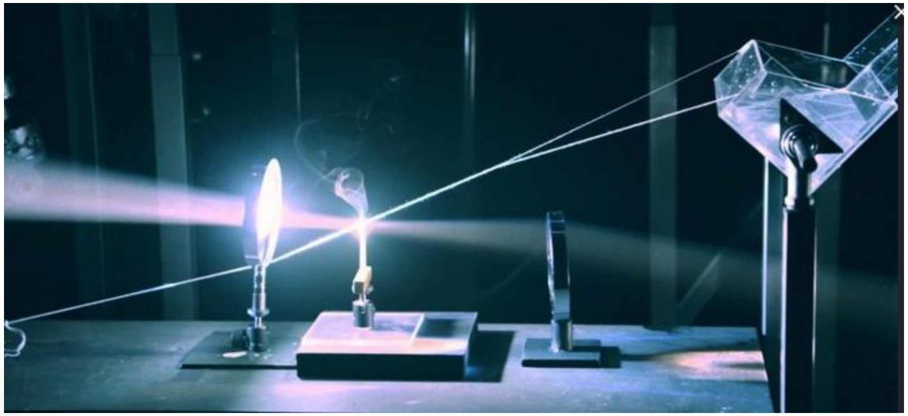


Engineering Physics (PHY109)



Course overview

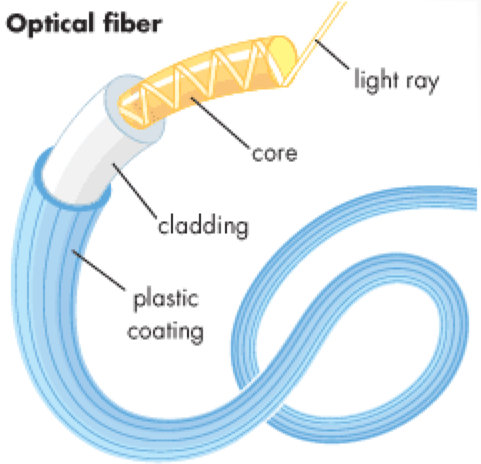
L: 3 T:1 P:0 Credits:4

- **Unit 1: Electromagnetic theory**
- **Unit 2: Lasers and applications**
- **Unit 3: Fiber optics**
- **Unit 4: Quantum mechanics**
- **Unit 5: Waves**
- **Unit 6: Solid state physics**

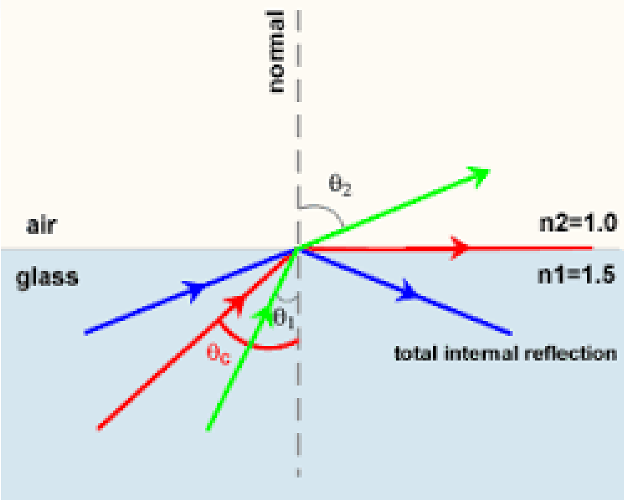
Unit-3: Fiber optics

Unit-3: Fiber optics

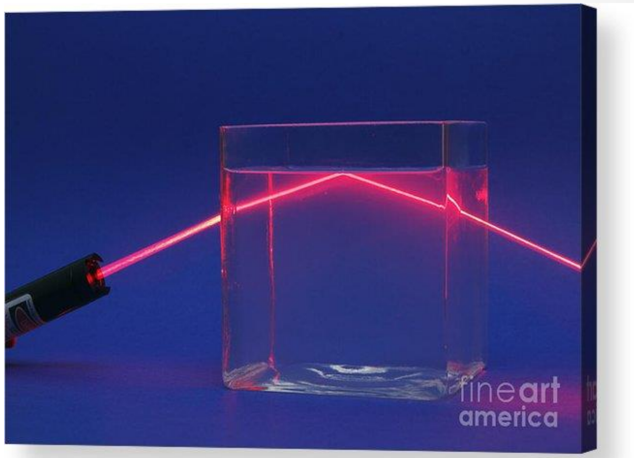
- Introduction to optical fiber
- Optical fiber as a dielectric wave guide
- Total internal reflection
- Acceptance angle & Numerical aperture
- Relative refractive index
- V-number
- Step index and graded index fibers
- Losses associated with optical fibers
- Application of optical fibers

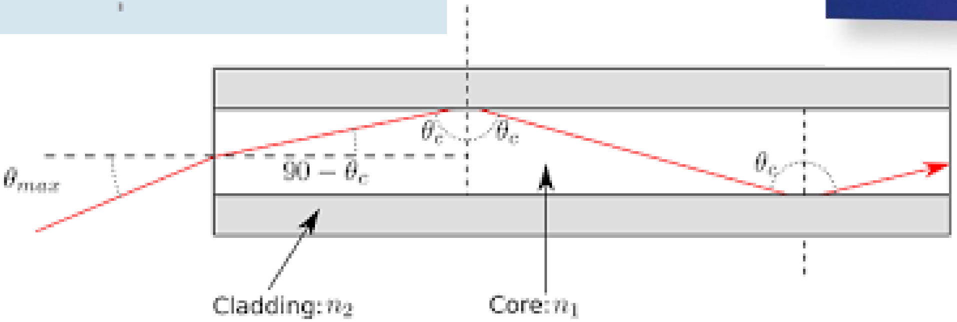


Refraction→TIR



Total internal reflection



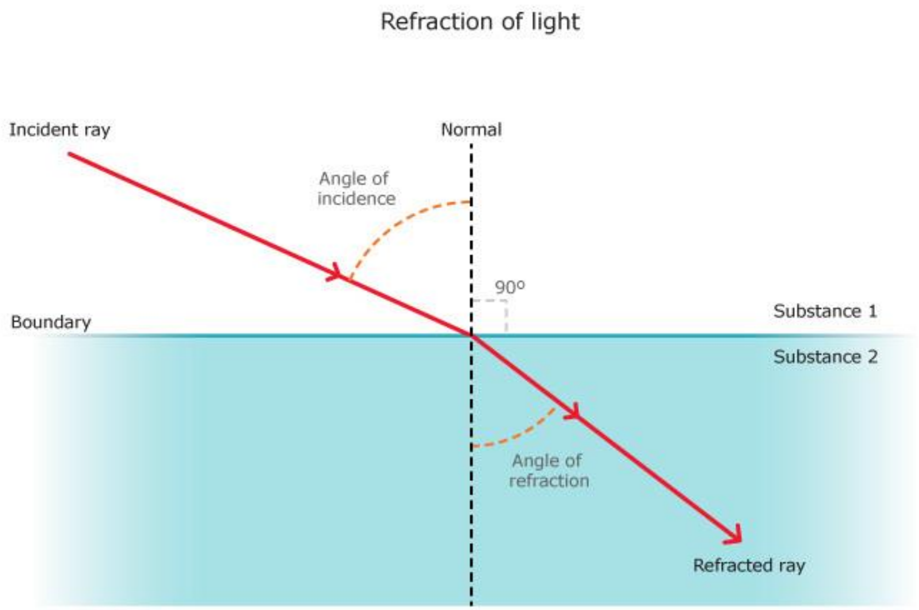


High speed data transfer

CO3: discover the concepts of physics in understanding fiber optics

Key phenomena

- Refraction: phenomenon of light, being deflected in passing through the interface between one medium and another or through a medium of varying density



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Refractive indices

- In optics, the *refractive index* or *index* of *refraction* of a material is a dimensionless number that describes how light propagates through that medium. It is defined as

$$\boxed{n=c/v}$$

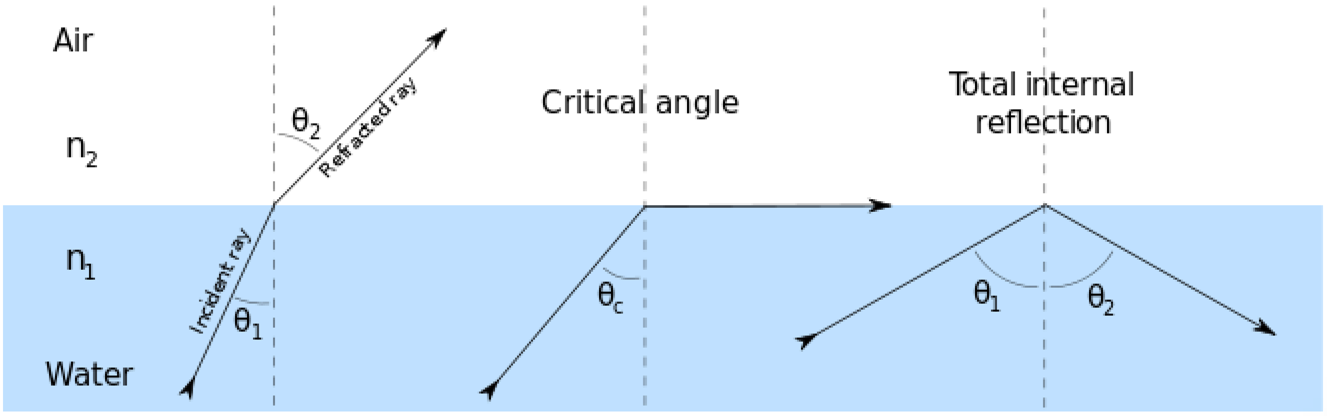
Where,

c is the speed of light in vacuum and

v is the phase velocity of light in the medium.

Critical angle

- The incident angle at which the angle of refraction is equal to 90’ is called critical angle
- Glass core+plastic cladding has critical angle of 82’
- Which means light rays having incident angle more than 82 will get internal reflection



Introduction

- Many years, radiowaves and microwaves were being used as a carrier waves in communication systems
- However, energy of light waves gets dissipated in open atmosphere, hence cannot travel long distance
- Hence, guiding channel is required (just like a metal wire is required to guide electrical current)
- Firstly, in 1960 first ever fibre optical telecommunication was conceptualized with the help of laser

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Introduction

- Hence the purpose is solved by optical fiber
- Def: a very thin glass or plastic cable designed to guide light waves along the length of the fiber
- As long as the refractive index of the fiber is greater than that of its surrounding medium, the light will undergo total internal reflections to travel at the opposite end of the fiber

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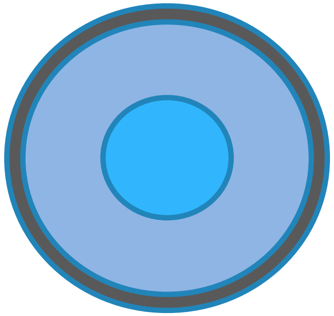
Introduction

- Uses glass, plastic, threads or fibres to transmit data

Core (n_1) [glass]

Cladding (n_2) [optical material]

Sheath [plastic protecting material]



$n_1 > n_2$ (total internal reflection)

Dielectric waveguide

- An optical fibre is a dielectric waveguide with a **very high bandwidth**
- A **Waveguide** that consists of a **Dielectric** material surrounded by another **dielectric** material, such as air, glass, or plastic, with a lower refractive index
- It guides electromagnetic waves in an optical spectrum, the same way as microwaves are guided by rectangular or cylindrical metallic waveguides
- An optical fibre confines the propagating waves inside it by utilizing the property of total internal reflection of light from a dielectric interface

Relative refractive index

- Fractional refractive index

- If the refractive index of the core material is n_1 and that of cladding material is n_2, a quantity Δn_r is defined as,

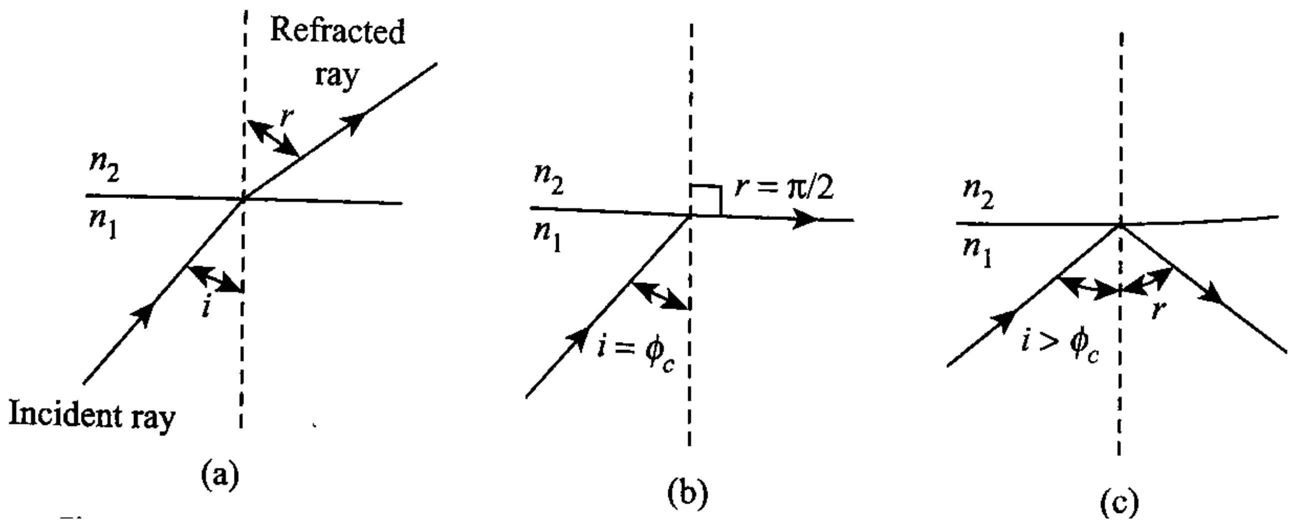
$$\boxed{\Delta n_r = (n_1 - n_2)/n_1}$$

Total internal reflection

- Refraction is governed by Snell's law

$$n_1 \,\mathrm{Sin}(i) = n_2 \,\mathrm{Sin}(r)$$

- Def: Phenomenon of re-entering of the refracted ray into the medium from which the ray incident on the interface originated is called *total internal reflection*



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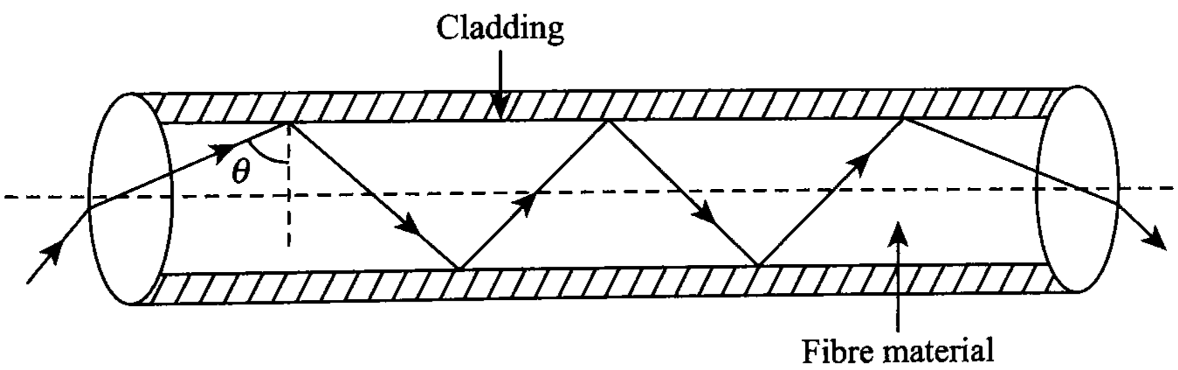
Total internal reflection

- Snell's law for TIR

$$\sin(i=\theta_c)/\sin(r=90)=n_2/n_1$$

$$\sin(\theta_c)= n_2/n_1$$



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Acceptance angle

- $\Phi=(\pi/2)-\theta$
- Acceptance angle=Half angle α_m (corresponding to θ_c)

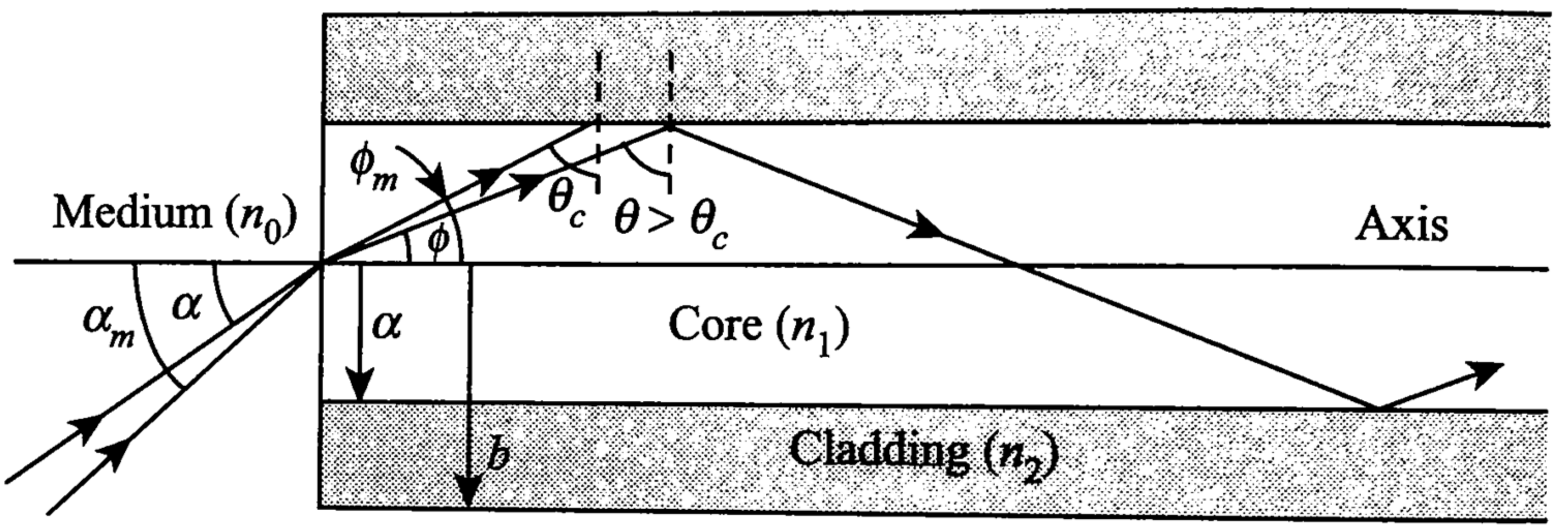
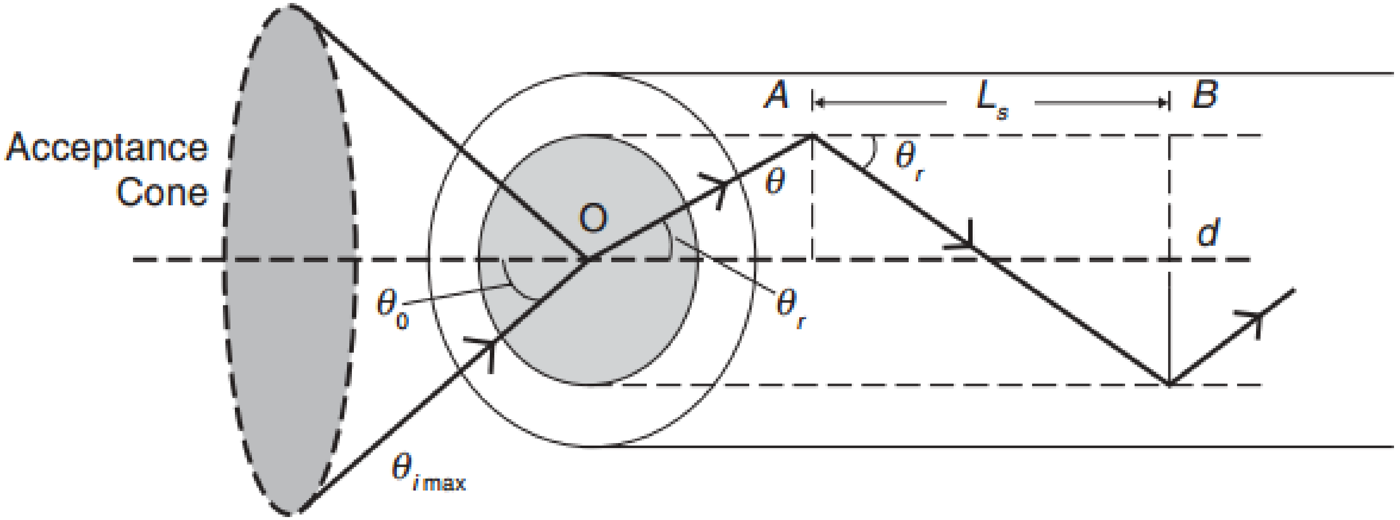
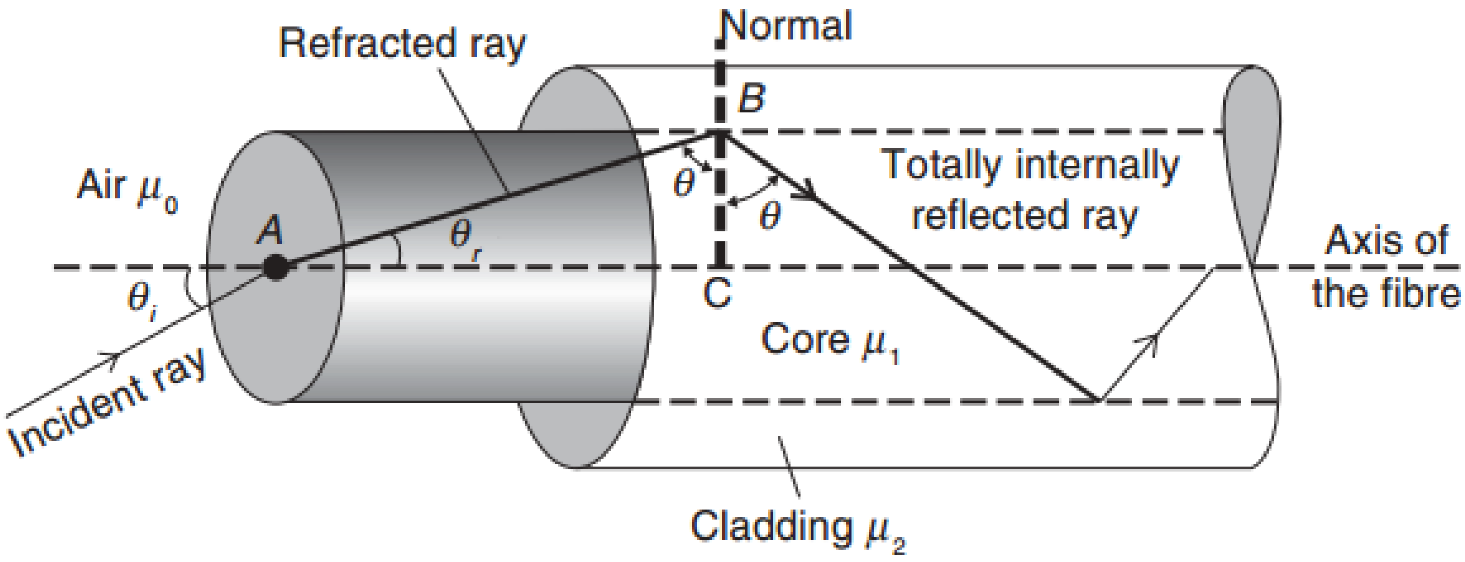


Fig. 5.3 Propagation of light in optical fibre

Acceptance cone

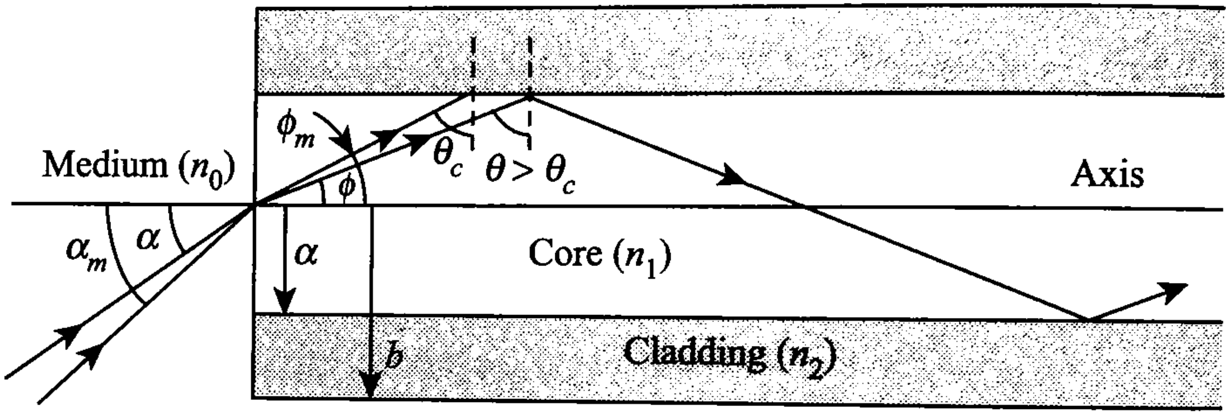


Acceptance angle



Numerical aperture & Acceptance angle

- Application of Snell's law at the core-air interface



$$n_0 \sin\alpha = n_1 \sin\phi$$

$$n_0 \sin\alpha_m = n_1 \sin\phi_m$$

$$\phi_m = \frac{\pi}{2} - \theta_c$$

The use of Eq. (5.6) in Eq. (5.5) yields the following expression:

$$n_0 \sin \alpha_m = n_1 \cos \theta_c \tag{5.7}$$

We can write that

$$\cos \theta_c = [1 - \sin^2 \theta_c]^{1/2} \tag{5.8}$$

The use of Eq. (5.3) in Eq. (5.8) leads to the following expression:

$$\cos \theta_c = \left[1 - \frac{n_2^2}{n_1^2}\right]^{1/2}$$

which gives the following relation:

$$\cos\theta_c = \frac{\left(n_1^2 - n_2^2\right)^{1/2}}{n_1} \tag{5.9}$$

Substitution of Eq. (5.9) into Eq. (5.7) results in the following expression:

$$n_0 \sin \alpha_m = n_1 \frac{\left(n_1^2 - n_2^2\right)^{1/2}}{n_1}$$

which implies that

$$n_0 \sin \alpha_m = (n_1^2 - n_2^2)^{1/2} \tag{5.10}$$

The term $n_0 \sin \alpha_m$ is called the *numerical aperture* (NA) for an optical fibre. The numerical aperture decides the light-gathering capacity of a fibre. Thus, we can write the following expression:

Numerical aperture

$$NA = (n_1^2 - n_2^2)^{1/2} \tag{5.11}$$

Let us define a quantity called relative refractive index difference Δ by the following expression:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \tag{5.12}$$

The use of Eq. (5.12) in Eq. (5.11) leads to the following relation:

$$NA = n_1\sqrt{2\Delta} \tag{5.13}$$

Numerical aperture is a measure of the quantity of light that can be collected by an optical fibre. The light-gathering capability of an optical fibre increases with an increase in its numerical aperture. From Eqs (5.10) and (5.11), it is clear that NA = sin α_m for $n_0 = 1$. Since the maximum value of sin α_m can be 1, NA cannot exceed 1. For $\alpha_m = 90$, NA = 0; that is, the fibre completely reflects the incident light. Numerical apertures of practical optical fibres generally fall in the range of 0.2–1.

Numerical

(1) for an optical fibre with a glass core (n_1=1.5) and a fused quartz cladding (n_2=1.46), determine the (1) critical angle, (2) acceptance angle and (3) NA. The source to fibre medium is air

Types of optical fibres

Classified into three major categories based on following parameters

A. Raw material of the fibre
B. Number of modes of propagation of signal
C. Refractive index profile

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Types of optical fibres

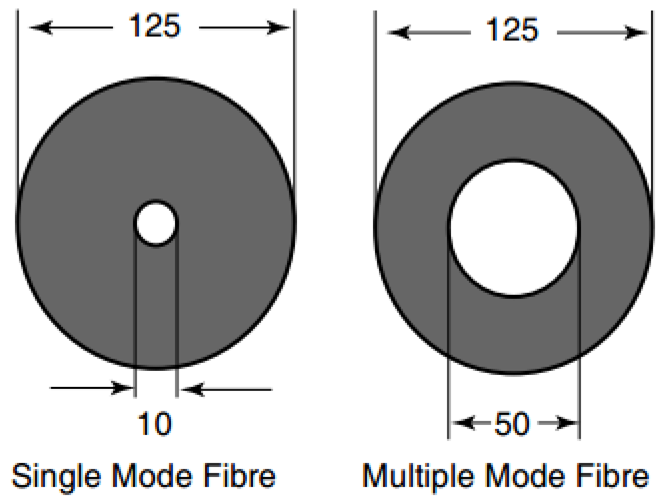
A. Raw material of the fibre

1. Glass (if the optical fibre is made by fusing mixture of metal oxides and silica glasses…known as a glass fibre)eg: GeO_2-SiO_2 core and SiO_2 clad, SiO_2 core and P_2O_3-SiO_2 clad
2. Plastic (Polystyrene and acrylate compound used to make…) inexpensive, highly flexible, tough, long life…possessed more attenuation compared to glass fibres…eg. Polystyrene core and methylmethacrylate clad, polymethyl-methacrylate core and co-polymer clad

Types of optical fibres

B. Number of modes of propagation of signal

1. Single mode optical fibre
2. Multimode optical fibre



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Single mode optical fibre

- Is designed to carry <u>only one signal of light</u>
- This signal may contain different range of WLs
- Typical core diameter: 8-10 μm
- Cladding diameter: 125 μm
- Small difference in the refractive indices of core and cladding
- Only laser light can be used as a signal which propagates through single mode optical fiber
- Long distance
- Low attenuation losses

Multimode optical fibre

- More than one signal can be propagated
- Advantageous over single mode fiber
- Large core diameter makes it easier to connect such multimode fiber cables (end-to-end connections)
- Mostly used for communication over shorter distances
- Data rates: 10 Mbit/s to 10 Gbit/s (upto 600m)

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Types of optical fibres

C. Refractive index profile

1. step index optical fibre
2. graded index optical fibre

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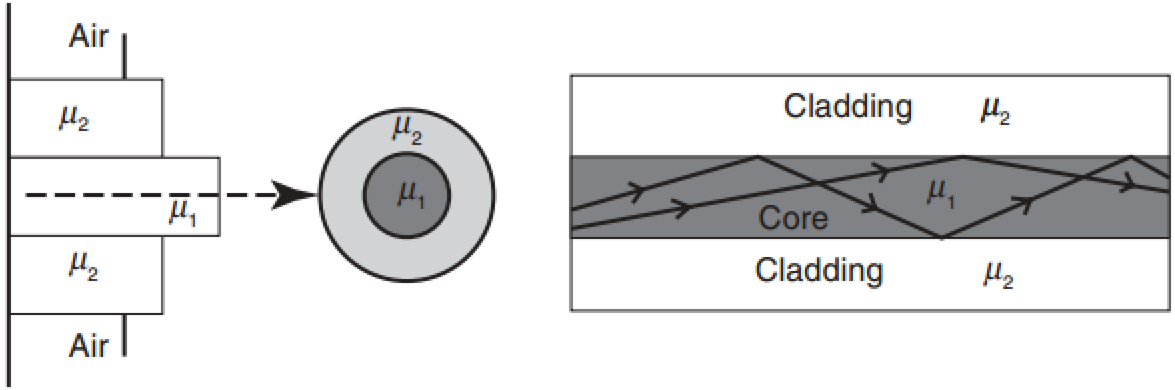
Step index optical fibre

- Core diameter 2a
- Cladding diameter 2b
- Refractive index has a step function profile over radial axis
- NA: 0.2-0.29

2a = 50-100 μm

2b = 118-140 μm



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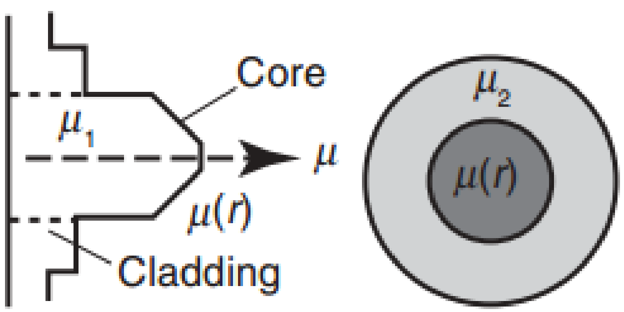
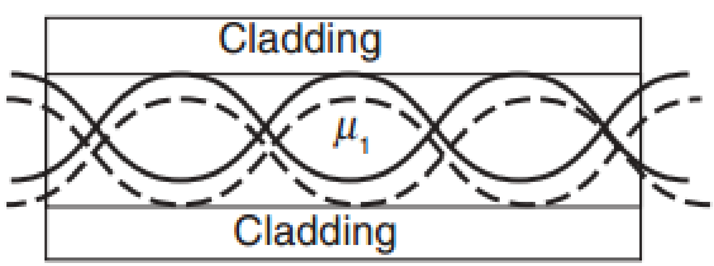
Graded index optical fibre

- Overcomes-Multipath dispersion (will discuss in losses)
- The refractive index at the core-cladding interface changes gradually
- Light rays follow a helical path
- High bandwidth
- Low distortion

2a = 50-62.5 μm

2b = 125 μm





Further classifications

- Step index-single mode (SISM) 10/120 m
  - Small NA
  - Negligible dispersion
  - High bandwidth
  - High cost
  - Under sea installation, submarine cables, long distance communication

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Further classification are

- Step index-multimode (SIMM) 200/300 μm
    - Large NA
    - High dispersion
    - Low bandwidth
    - Suffer from inter-mode dispersion loss
    - Low cost

Further classification are

- Graded index-multimode (GIMM) 200/250 μm
  - Reduced losses
  - Low attenuation
  - Medium bandwidth
  - Small NA
  - Cost high
  - Intercity trunk between telephone offices

V-number

- Def: a normalized frequency parameter, which determines the number of modes in a step-index fiber
- Unit less quantity
- Often used in the context of step-index fibers

$$v_n = \pi \frac{d}{\lambda} NA = \frac{\pi d}{\lambda} \sqrt{\mu_1^2 - \mu_2^2}$$

where

- λ is the wavelength
- *d* is the diameter of the fiber core
- NA is the numerical aperture

V-number

- For V values below ≈ 2.405, a fibre supports only one mode, single mode optical fibre

- Multimode fibers can have much higher V numbers. For large values, the number of supported modes of a step-index fiber can be calculated approximately as

$$m_m = \frac{v_n^2}{2}$$

Types of rays

1. Meridional
   - Plane of propagation contains axis of the optical fibre
   - Even under TIR ray will continue to travel in that plane
2. Skew
   - In which the plane of propagation does not contain axis of optical fibre

Splicing

- The process of forming a permanent joint between two optical fibre is called splicing

<u>Used</u>

(1) To increase the length of the optical fibre

(2) To repair a broken optical fibre

<u>Two ways of splicing</u>

(1) Fusion splicing (electric arc as a heating source)
(2) Mechanical splicing (capillary and adhesive of same refractive index)

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Power losses in optical fiber

- Attenuation
  - Absorption
  - Scattering
  - Bending
  - Dispersion

Attenuation (Power loss)

- Loss of optical power while light travels along the fibre is known as attenuation
- Signal attenuation is defined as the ratio of optical input power (P_i) to the output power (P_o)
- The causes of attenuation in an optical fibre are ***absorption, scattering*** and ***bending losses***
- Each mechanism of loss is influenced by the properties of fibre material and fibre structure
- However, loss is also present at ***fibre connections***
- Unit of attenuation: decibles/kilometre i.e., dB/km

Absorption loss

- The following relation defines the signal attenuation or absorption coefficient in terms of length L of the fibre

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

- Length L of the fibre is expressed in kilometers
- Absorption losses over a length L of fibre can be described by the usual exponential law for light intensity (or irradiance) I.

$$I = I_0 e^{-\alpha L}$$

- I_0 is the initial intensity or the irradiance of the light

Absorption loss

- Absorption of light by core and cladding of a fibre is the main source of attenuation

1. Atomic imperfection in glass composition
2. Intrinsic absorption
3. Extrinsic absorption

Scattering loss

- Due to microscopic variation in material density, random variation in refractive index and structural inhomogeneity or defects during manufacturing

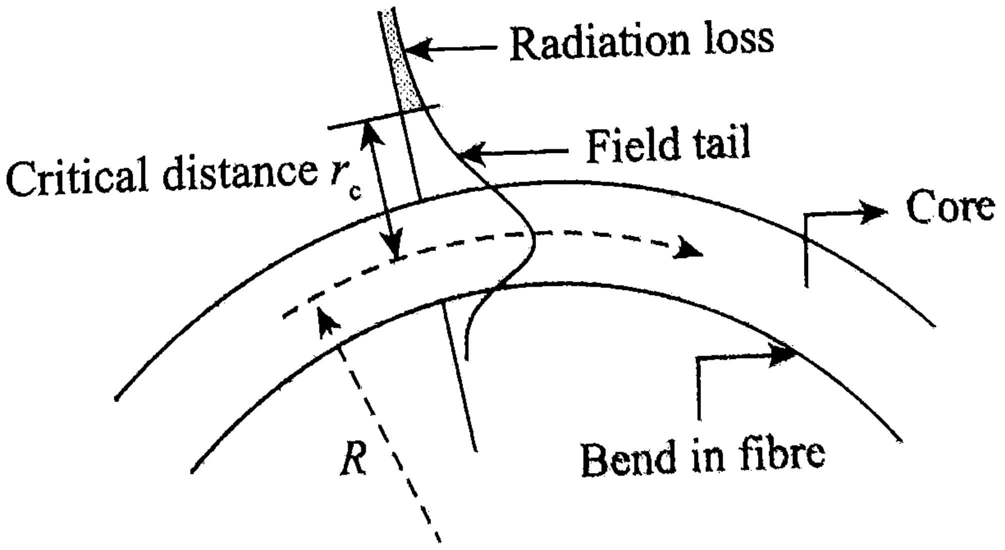
- This variations may be considered as small scattering objects/particles embedded in an otherwise homogeneous material

Types: Linear & non-linear scattering

1. Linear (more power→more loss due to scattering)
2. Non-linear (no such linear trend !)

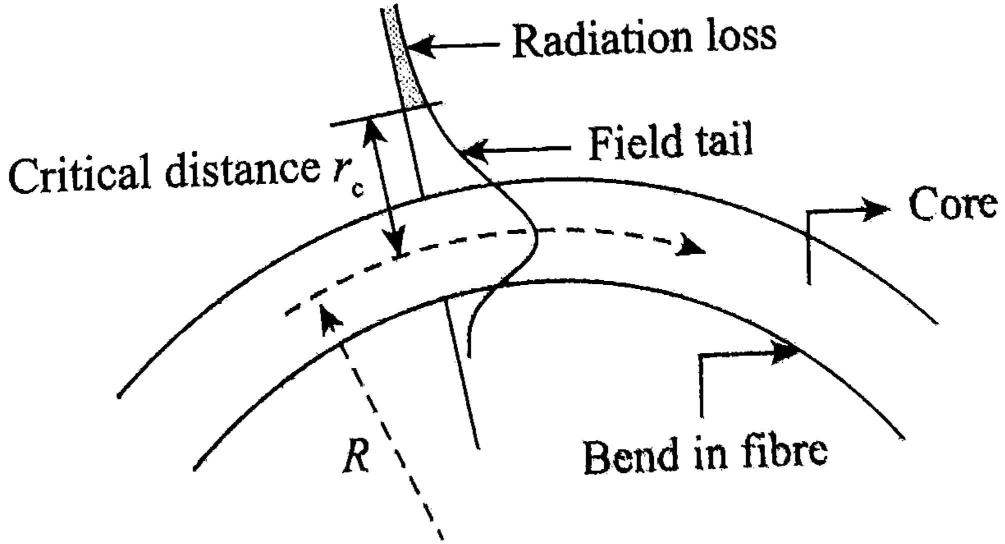
Bending loss

1. Macro-bending (bends with radii much larger than the radius of optical fibre)
2. Micro-bending (bends with radii of the order/less of/than the radius of optical fibre)



Bending loss

- Electric field tail goes into cladding
- Field tail needs to travel faster than the speed of light due to curve
- It will get removed for distance above critical distance in the form of radiation loss



Dispersion loss

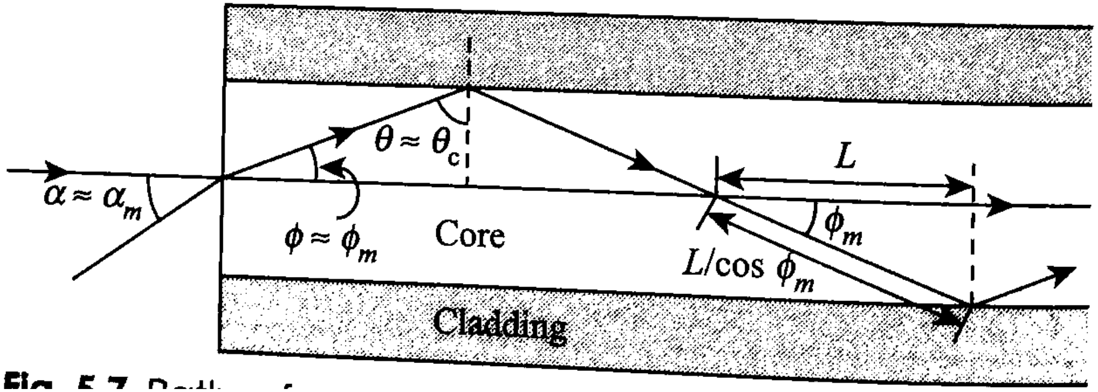
- The spreading of pulses of light as they propagate along a fibre is called dispersion
- In optics, dispersion is the phenomenon in which the phase velocity of a wave depends on its frequency
- Such medium is called a dispersive medium
- The dispersive effects in a single mode fibre are much smaller than a multimode fibre

Dispersion loss

- Due to dispersion, optical pulses in optical fibres spread and hence the signals degrade over long distances
- There are several factors that cause dispersion in optical fibres
- For example, in multimode fibres, different axial speeds of different transverse modes cause intermodal dispersion that limits the performance of the fibre
- Dispersion limits the bandwidth of the fibre because the spreading optical pulses limit the rate that pulses can follow one another on the fibre and still remain distinguishable at the receiver

Dispersion loss

- Multipath time dispersion
- Pulse broadening
- $\Delta t/L = n_1(n_1-n_2)/n_2c$



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Advantages of fibre optics

- Can carry more data compared to metal cable (due to larger bandwidth)
- Less susceptible than metal cables to external interferences
- Much thinner and lighter than metal wires
- Data can be transferred digitally
- Low attenuation, be used to send data at larger distances

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Applications

(1) Communication: OF are used to carry signals in optical communications due to their unique features, viz. large channel capacity, wide bandwidth, good electrical isolation, no cross talks.

Telephone, television, satellite and computer links rely heavily on fibre optics technology

Scanning

- OF can be used to measure the distribution of light intensity over an illuminated area
- The input end of the OF scans the area of interest and the light output at the other end of OF is fed to photodetector
- The variation of the photodetector output will reveal the light intensity distribution

Medical instruments

- Used in medical instruments to examine internal body cavities such as stomach and bladder (endoscope)
- Useful in the study of tissues and blood vessels far below the skin
- Bloodless surgery (as a laser opthalmoscope) for retinal welding

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Coupler

Can be used for coupling two circuits without introducing a direct electric link

- LED act as a load in the primary circuit, so that a light output is obtained
- OF collects the light and transmit to a photodetector, which converts incoming light to an electrical signal
- Thus produced electrical signal drives the secondary circuit corresponding to the output from the primary

Display and illumination

- OF are employed to carry light from the source to the display unit

- Also used to illuminate dials when measuring instruments are used in dark/dim light

Energy transfer

- OF are used in the ultraviolet region for spectroscopic work and also used to transfer optical energy from the source to the point of application of heat

No of modes…

- n_1=1.43
- n_2=1.36
- WL=631 nm
- a=5 um
- Find number of modes that can be propagated using this fibre

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Attenuation loss…

- An optical signal of 9 mW is injected into a fiber. The outcoming signal from the other end is 4500 μW. calculate the attenuation loss (in dB)

(Eqn) Loss=-10 $\log_{10} (P_{out}/P_{in})$

Ans: 3.01 dB

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Attenuation loss…

- An OF of length 150 m has input power of 10 μW and output power of 8 μW. Calculate the loss in dB/m.

- 0.970 dB/150 m

Ans: 0.0065 dB

Attenuation loss…

- A communication system uses a 10 km fiber having a loss of 2.3 dB. Calculate the output power if the input power is 900 μW.
- Power loss: 2.3 dB/km
- 23 dB/10 km
- P_{in} = 900 μW
- Ans: P_{out}=1.79 μW

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Pulse broadening…

- n1=1.5
- n2=1.47
- Find pulse broadening per unit length of OF..
- $\Delta t/L = (n1/n2)(n1-n2)/c$
- Ans: 10.2×10^{-11} s/m

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Numerical

(2) The NA of an optical fibre is 0.5 and core refractive index 1.54. determine (1) refractive index of cladding (2) relative refractive index (RI)

Numerical

(3) An optical fibre has NA of 0.2 and a cladding refractive index of 1.59. Find the acceptance angle for the fibre in water (water refractive index is 1.33)

Power losses: Attenuation

- Def: Power loss per length of fibre

P_{in}=input power to the fibre

P_{out}=output power

- Power loss (in dB)= $-10 \log(P_{out}/P_{in})$

Attenuation loss (in dB/km) =

$A = -(10/L) \log(P_{out}/P_{in})$ or $L= -(10/A) \log(P_{out}/P_{in})$

$P_{out} = P_{in} * 10^{(-AL/10)}$


Good luck