SUBJECT:
OPTICAL COMMUNICATION
SUB. CODE:
BEC057
BRANCH: ECE
SEM: 5TH

II - Signal loss in optical fibers.

① **Attenuation** → It is expressed in the logarithmic unit of dB decibel.

- Decibel is used for comparing two power levels for a particular optical wavelength.
- Decibel (Attenuation) is defined as the ratio of input/transmitted optical power P_i into a fiber to o/p/received optical power P_o from the fiber.
- No. of decibels (dB) $= 10 \log_{10}\left(\frac{P_i}{P_o}\right)$ $\Rightarrow \log_{10}\frac{P_i}{P_o} = \left(\frac{dB}{10}\right)$ $\Rightarrow \frac{P_i}{P_o} = 10^{(dB/10)}$
- Benefits of log unit → $\times$ & $\div$ $\Rightarrow$ + & −
  power & roots $\Rightarrow$ $\times$ & $\div$

⇒ • Attenuation is expressed in decibels/length. (dB/Km)

$$\alpha_{dB} L = 10 \log_{10}\left(\frac{P_i}{P_o}\right)$$

α_{dB} → signal attenuation per unit length in decibels.
L → fiber length.

Q. $P_i = 120\,\mu W$ | Length of the fiber = 8 km
$P_o = 3\,\mu W$ |

ⓐ overall signal attenuation/loss in decibels (assuming no connectors or splices)

signal attenuation $= 10 \log_{10}\frac{P_i}{P_o} = 10 \log_{10}\frac{120\times10^{-6}}{3\times10^{-6}}$

$= 10 \log_{10} 40 = 10\times1.6 = \underline{16\,dB}$

ⓑ signal attenuation per km for the fiber.

$\alpha_{dB} L = 16\,dB$

$\alpha_{dB} = \frac{16\,dB}{L} = \frac{16}{8} = 2\,dB/Km$

ⓒ The overall signal attenuation for a 10 km optical link using the same fiber with splices at 1 km intervals each giving an attenuation of 1 dB.

$\alpha_{dB} = 2\,dB/Km \Rightarrow$ if $L = 10$ $\alpha_{dB} L$ (of loss incurred along 10 km)

$= 2\times10 = \underline{20\,dB}$

at 1 km interval → link has nine splices (joints) each with an attenuation of 1 dB. Therefore the loss due to the splices is 9 dB.

⇒ overall signal attenuation for the link is

signal attenuation = 20 + 9 = 29 dB.

(d) the numerical input/output power ratio in (c).

$$\frac{P_i}{P_o} = 10^{29/10} = 10^{2.9} = \underline{794.3}$$

⇒ Many mechanisms are responsible for signal attenuation within optical fiber.

- Material composition, purification technique & waveguide structure

Areas 1) Material absorption, 2) Material scattering < linear / Nonlinear

3) curved microbending loss (4) mode coupling radiation losses

5) losses due to leaky modes. (6) Losses at connectors & splices.

Material Absorption Losses in silica glass fibers.

- It is related to material composition and fabrication process for the fiber.
- Absorption of light may be < intrinsic / extrinsic

intrinsic → caused by the interaction with one or more of the major components of the glass.

extrinsic → caused by impurities within the glass.

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visible spectrum → V 0.4 μm R 0.7 μm (~~10^{14} f < 10^{16}~~

optical fiber comm → 0.8 μm – 1.7 μm

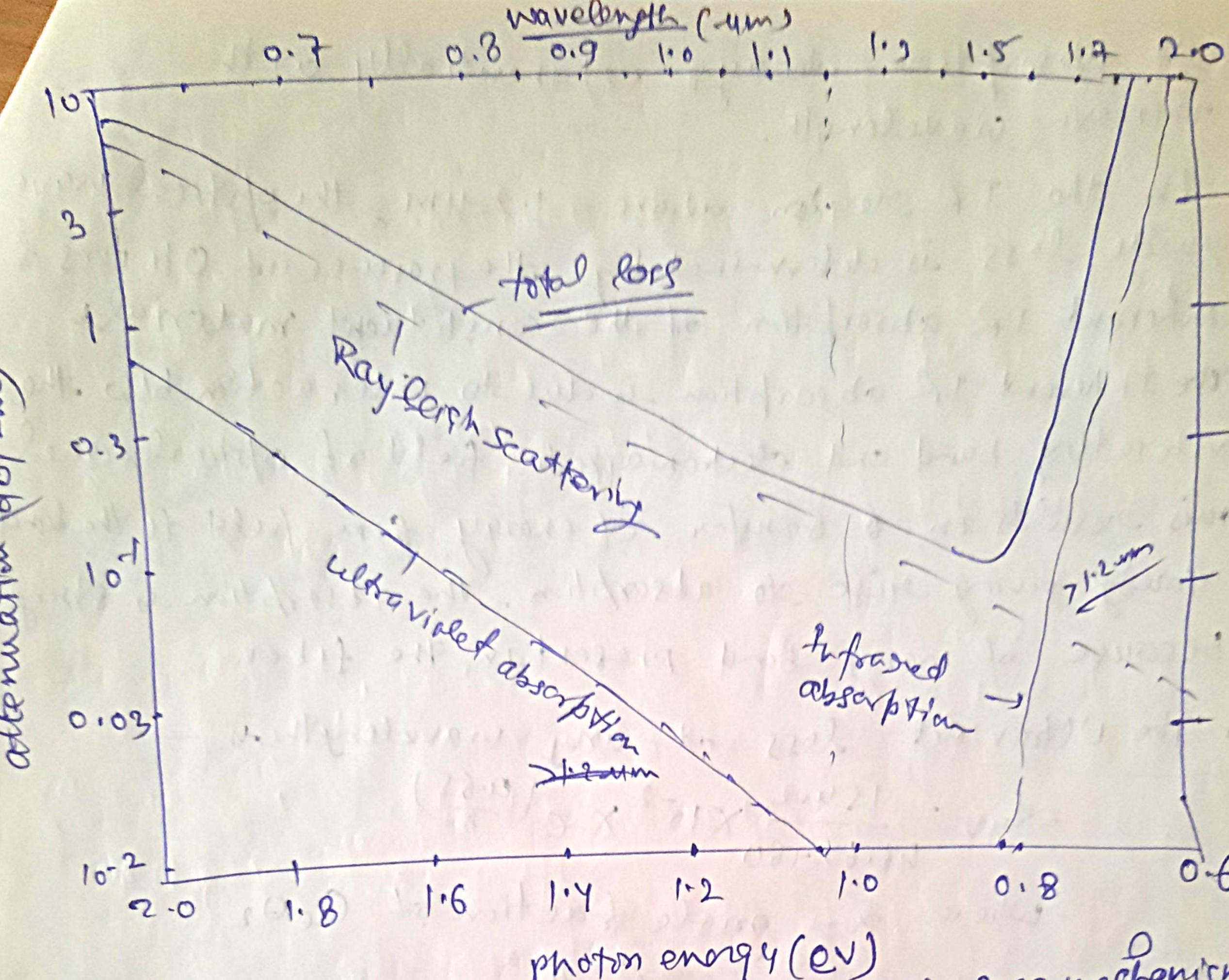

Fig: the attenuation spectra for the intrinsic loss mechanism in pure $GeO_2 - SiO_2$ glass.

Intrinsic Absorption -

It occurs when material is in absolutely pure state, no density variation and inhomogenities. The intrinsic absorption sets fundamental lower limit on absorption for any particular material.

- It results from electronic absorption band in UV region and from atomic vibration band in near infrared region.
- There are associated with the band gaps of amorphous (अनाकार) glass material.

Absorption occurs when a photon interacts with an electron in the valance band and excites it to a higher energy level

UV absorption decays exponentially with increasing wavelength.

- In the IR region above 1.2 μm, the optical waveguide loss is determined by the presence of OH ions & inherent IR absorption of the constituent materials. The Inherent IR absorption is due to interaction b/w the vibrating band and electromagnetic field of optical signal this results in transfer of energy from field to the band, thereby giving rise to absorption. The absorption is strong because of many band present in the fiber.

- The Ultraviolet loss at any wavelength is –

$$\alpha_{uv} = \frac{154.2}{46.6x+60} \times 10^{-2} \times e^{\left(\frac{4.63}{\lambda}\right)}$$

where $x \rightarrow$ mole fraction of GeO_2

$\lambda \rightarrow$ operating wavelength

$\alpha_{uv} \rightarrow$ dB/Km

- The loss in IR region (above 1.2 μm) is.

$$\alpha_{IR} = 7.01 \times 10^{11} \times e^{\left(\frac{-48.48}{\lambda}\right)}$$

→ expression is defined for $GeO_2 - SiO_2$ glass fiber.

Intrinsic Material → 1) no charge carrier at 0K
2) VB is filled with e⁻ and conduction band is empty.
3) No impurities & lattice defects.

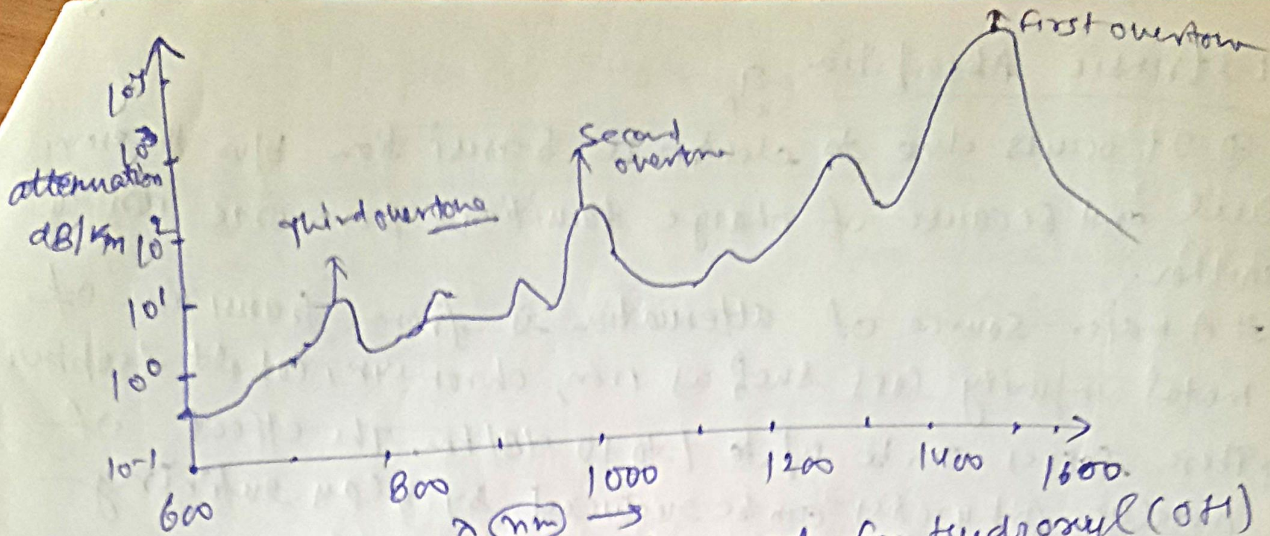

Fig: The absorption spectrum for hydroxyl (OH) group in silica.

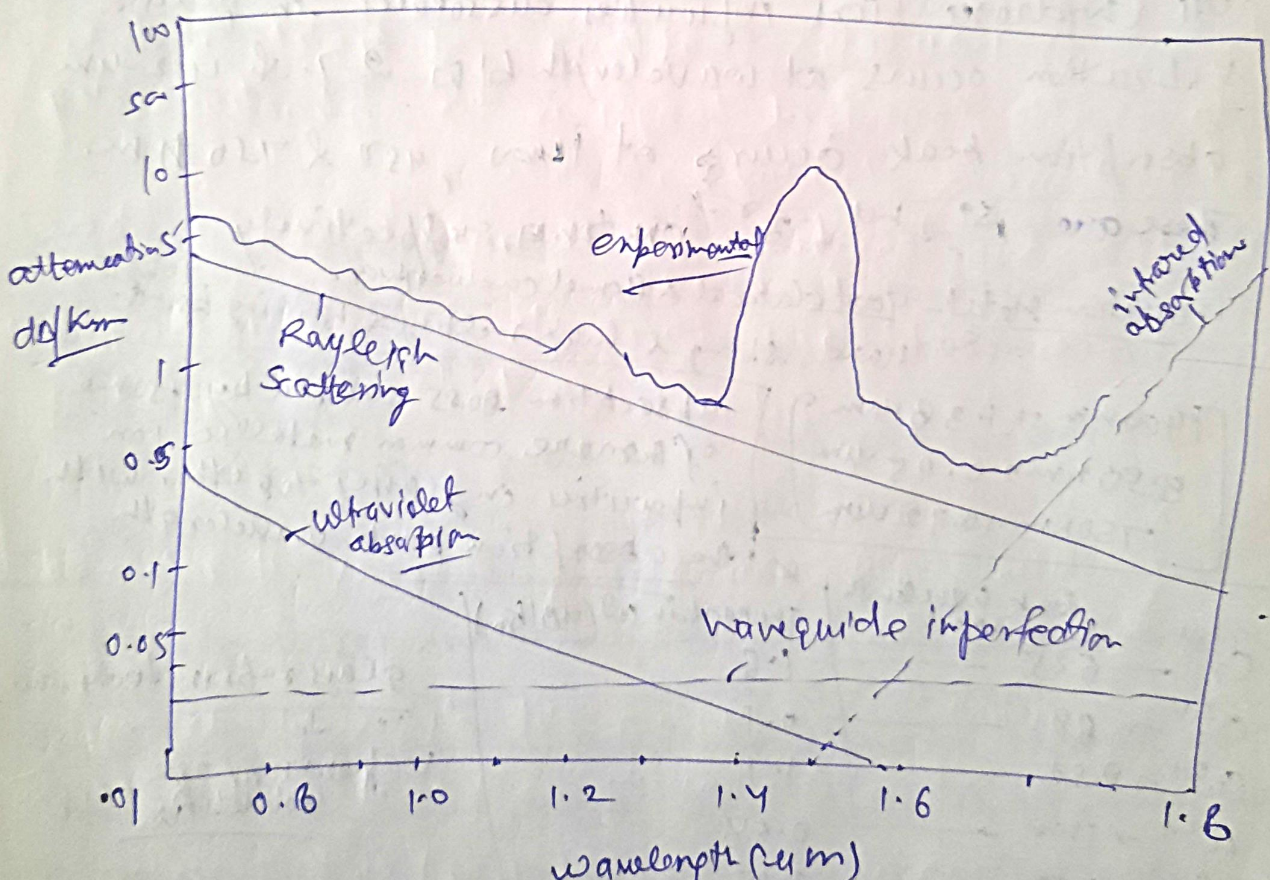

Fig: The measured attenuation spectrum for an ultra-low-loss single mode fiber (solid line) with calculated attenuation spectra for some of the loss mechanisms contributing to the overall fiber attenuation (dashed & dotted line)

Extrinsic Absorption

⊕ It occurs due to electronic transition b/w the energy level and because of charge transitions from one ion to another.

A major source of attenuation is from transition of metal impurity loss such as iron, chromium, cobalt & copper. These losses can be upto 1 to 10 dB/km. The effect of metallic impurities can be reduced by glass refining techniques (Transition metal - group 3-12 D-block)

- Another major extrinsic loss is caused by absorption due to OH (hydroxyl) ions impurities dissolved in glass. Vibration occurs at wavelength b/w 2.7 & 4.2 μm
- absorption peak occurs at 1400, 950 & 750 nm. These are 1st, 2nd & 3rd overtones respectively.

Transition metal - good electrical & thermal conductivity. high melting & boiling temp. → Hard, strong & high melting

1400 nm → 1.38 μm
950 nm → 0.95 μm
750 nm → 0.72 μm

absorption loss caused by some of the more common metallic ion impurities in glasses, together with the absorption peak wavelength

	Peak wavelength (nm)	& one part in 10^9 (dB/km)
Cr^{3+}	625	1.6
C^{2+}	685	0.1
Cu^{2+}	850	1.1
Fe^{2+}	1100	0.68
Fe^{3+}	400	0.15
Ni^{2+}	650	0.1
Mn^{3+}	460	0.2
V^{4+}	725	2.7

glass refining technique
↓
vapour phase oxidation

Types of Scattering Losses

- Linear Scattering Losses
  - Rayleigh Scattering
  - Mie Scattering
  - due to non-ideal properties of manufactured fiber.
- Non-linear Scattering Loss
  - Stimulated Brillouin Scattering
  - Stimulated Raman scattering

degree of scattering →
1) size of particle (m)
2) wavelength. (λ)

LSL
⇒ Linear scattering mechanism cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly in different mode.
→ light does not continue to propagate within fiber core but is radiated from the fiber.

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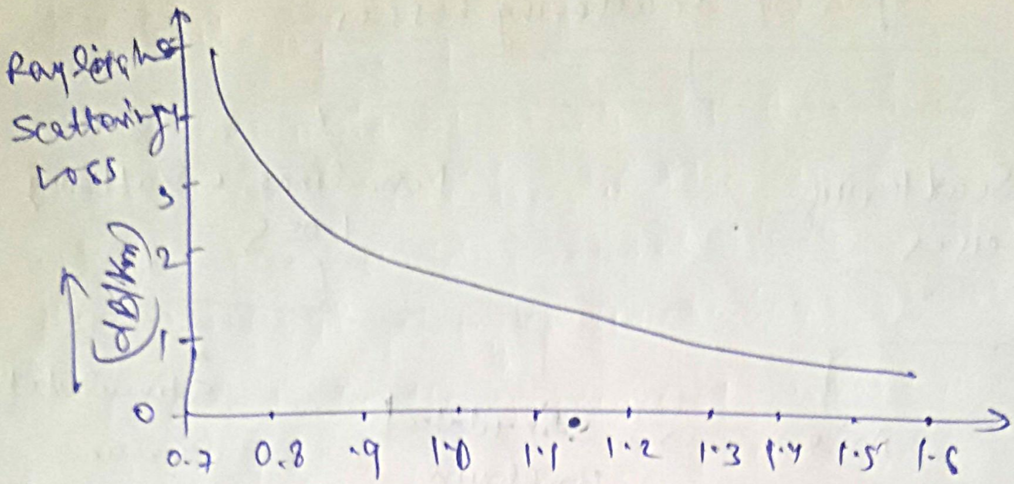
* scattering losses exist in optical fiber because of microscopic variation in the material density and composition.
As glass is composed by randomly connected network of molecules and several oxides (SiO_2, GeO_2, P_2O_5). These are the major cause of compositional structure fluctuation
at results to variation of refractive index and Rayleigh type scattering of light

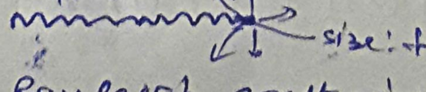


fig! Scattering Loss

* R.S.L → Rayleigh scattering of light is due to small localized changes in the refractive index of the core & cladding material.
There are two causes during the manufacturing of fibers

① due to slight ~~change~~ fluctuation in mixing of ingredients Random changes are impossible to eliminate completely.

② slight change in density.
→ When light ray strike such zones, it gets scattered in all direction
→ The amount of scattering depends on depends on the size of discontinuity compared with λ of light
→ shorter wavelength (highest freq) suffers more scattering.



Rayleigh scattering.

for single component glass.

Rayleigh scattering loss →

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F$$

Rayleigh scattering coeff.

λ → optical wavelength

n → ref. index of the medium

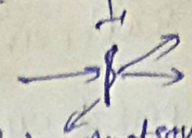
p = average photo elastic coeff.

β_c = iso thermal compressibility at fictive temp T_F → fractional differential change in volume due to change in pressure

K = Boltzmann's constant

Iso. Compression → thermodynamic process. T = constant ($P \propto \frac{1}{V}$); $V \downarrow$ & $P \uparrow$

Photoelasticity



Property of some transparent materials, such as glass, or plastic, while under stress, to become doubly refracting.

Isothermal → $\Delta T = 0$. Temp of the system remains constant; change in temp = 0

PV = constant
$PdV + VdP = 0$
$\Rightarrow -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right) = \frac{1}{P} = K$

T_F → defined is the temp at which the glass can reach a state of thermal equilibrium and is closely related to anneal temp. → badx ...

transmittivity (transmission loss factor)

(i) $\mathcal{L} = \exp(-\gamma_R L)$

L → length of the fiber.

$L = 1$ Km $= 10^3$ m

$\lambda \uparrow \Rightarrow$ RSL ↓

Attenuation due to Rayleigh scattering (dB/Km) →

$$\text{Attenuation} = 10 \log_{10}\left(\frac{1}{\mathcal{L}}\right)$$

Mie scattering. 1

Non perfect cylindrical structure of the waveguide & fiber imperfection (i.e. irregularities in core-cladding interface, core-cladding refractive index differences along the fiber length, diameter fluctuations, strains & bubbles)

⇓

Scattering occurs at inhomogenities.

⇓

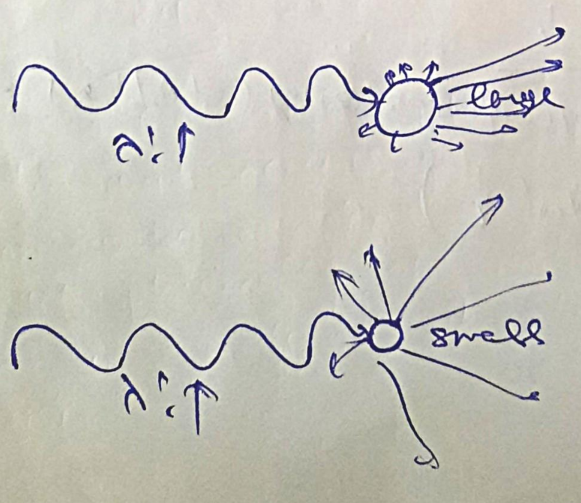
When the scattering inhomogenities size is > $\frac{\lambda}{10}$

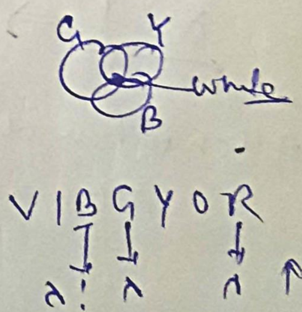
the scattering created by such inhomogenities is mainly in the forward direction and is called mie-scattering.

Depending upon the fiber material, design & manufacture, Mie scattering can cause significant losses.

The inhomogenities may be reduced by —

1. removing imperfection due to the glass manufacturing process.
2. carefully controlled extrusion (disturbance) and coating of fiber
3. increasing the fiber guidance by increasing the relative refractive index difference.

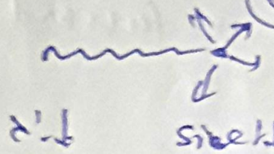




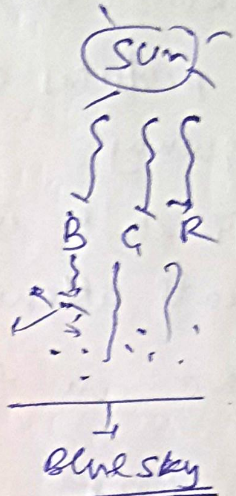
<u>Scattering</u> → When light impinging on a rough surface, may be deflected in all direction with loss of coherence & phase.

degree of scattering ← size of particle, wavelength

(RS) (uniform)



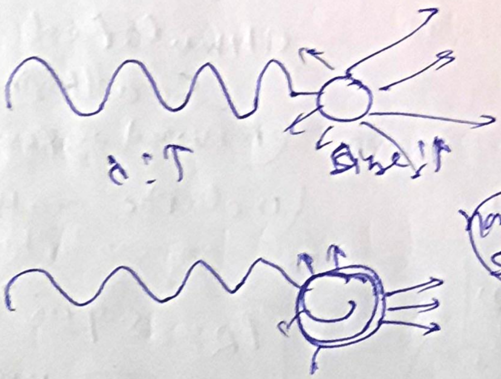
RS (blue color)



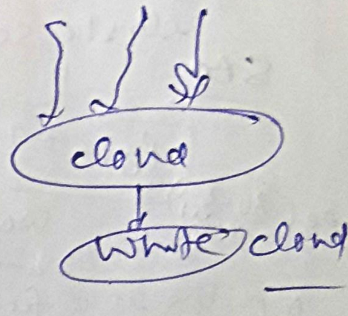
<u>elastic</u> ⇒ energy same after scattering

$RS \propto \frac{1}{\lambda^4}$

(Mie S)



(non uniform scattering)



Non-linear Scattering Losses

* When optical power is transferred from one mode to other mode or same mode with different freq, Non linear scattering happens.
* This scattering takes place either in forward or backward direction.
* It produces optical gain but there is a shift in frequency.
* This shift in freq. results loss of signal and creats attenuation.
* There are two types of non-linear scattering,

SBS
Stimulate Brillouin Scattering
(backward direction)
elastic scattering of photon

SRS
Stimulated Raman Scattering
(forward ~~& Reverse~~ direction)
(inelastic scattering of photon)

SBS

$$P_B = 4.4\times10^{-3} d^2 \lambda^2 \alpha_{dB} \nu$$ Watts

d & $\lambda \rightarrow \mu m$
$\alpha \rightarrow dB/Km$
$\nu \rightarrow GHz$

$P_B = 80 \times 10^{-3}$ mW

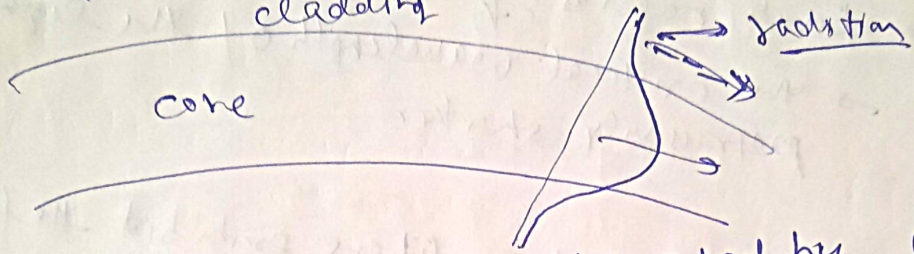
$$P_R = 5.9\times10^{-2} d^2 \lambda \alpha_{dB}$$ Watts

$P_R = 1.38$ W

* A photon is a form of energy but the phonon is a mode of oscillation that occurs in lattice structures.
* A photon can be considered as a wave & a particles which are phisically observable intity.
* A phonon is a mode of vibration, which is neither a wave nor

Bending Losses in fibers

Optical fibers suffers radiation losses at bends or curves on their paths. This is due to the energy in the evanescent field at the bend exceeding the velocity of light in the cladding and hence guidance mechanism is inhibited, which causes light energy to be radiated from fiber.



* The loss can generally be represented by a radiation attenuation coeff. given by.

$$\alpha_r = C_1 \exp(-C_2 R)$$

* wher $R \rightarrow$ radius of curvature of the fiber bend & C_1 & C_2 are constants which are independent of R.
* Furthermore large bending losses tend to occur at a ~~circuit~~ critical radius of curvature R_c which may be estimated as —

$$R_c \simeq \frac{3 n_1^2 \lambda}{4\pi (n_1^2 - n_2^2)^{3/2}}$$ for multimode fiber

It may be observed from the expression that the bending losses may be reduced by —

(1) Designing fibers with large relative refractive index differences.

(2) operating at the shortest wavelength possible

Radius of curvature for single mode fiber

$$R_{cs} = \frac{20\lambda}{(n_1 - n_2)^{3/2}} \left(2.748 - 0.996 \frac{\lambda}{\lambda_c}\right)^{-3}$$

λ_c = cut off wavelength ~~of~~ for single mode fiber

when bend radius ↓

→ the critical wavelength of the light becomes progressively shorter.

ex Two step index fibers exhibit the following parameters –

(a) A multimode fiber with a core refractive index of 1.500, a relative refractive index diff of 3% and an operating wavelength of 0.82 um.

(b) An 8-um core diameter single-mode fiber with a core refractive Index the same as (a), a relative refractive Index difference of 0.3% and an operating wavelength of 1.55um

Estimate the critical radius of curvature at which large bending losses occur in both cases.

sol

Relative Ref Index diff :

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

$$n_2^2 = 2.250 - 0.06 \times 2.250$$

$$= 2.115$$

for multimode fiber critical radius of curvature

$$R_c \simeq \frac{3n_1^2 \lambda}{4\pi(n_1^2 - n_2^2)^{3/2}} = \frac{3 \times 2.250 \times 0.82 \times 10^{-6}}{4\pi \times (0.135)^{3/2}} \approx 9 \mu m$$

$n_1 = 1.5$ | $\Delta = .3\%$ | $n_2^2 = 2.225 - (0.006 \times 2.25)$

$n_1^2 = 2.225$ | $= .003$ | $= 2.237$

$\Delta^2 = .006$

the cut off wavelength for single mode fiber

$$\lambda_c = \frac{2\pi a n_1 (2\Delta)^{1/2}}{2.405}$$

$$\left[\lambda_c = \frac{2\pi a n_1 (2\Delta)^{1/2}}{V_c} \right]$$ $V_c \rightarrow$ cutoff normalised freq. $V_c = 2.405$

$$= \frac{2\pi \times 4 \times 10^{-6} \times 1.5 (0.06)^{1/2}}{2.405}$$

$$= 1.214 \mu m$$

$$R_{cs} = \frac{20 \times 1.55 \times 10^{-6}}{(0.043)^{3/2}} \left(2.748 - \frac{0.996 \times 1.55 \times 10^{-6}}{1.214 \times 10^{-6}} \right)^{-3}$$

$$= 34 \text{ mm}$$

Kerr Effect → It is due to the nonlinear response of the material. It means that the index of the silica is now depending on the optical field propagation through it

- the power dependence of refractive index is responsible for the Kerr Effect
- Depending upon the type of I/P signal the Kerr Non-linearity has three different effects such as -

SPM (self phase Modulation)

CPM (cross phase Modulation)

FWM (four wave mixing)

→ The non-linearity is due to refractive index is known as Kerr Non-linearity.

→ The non-linearity produces a carrier induced phase modulation of the propagating signal which is called Kerr Effect.

$n = n_0 + n_2 I$

$n_2 = \frac{P}{V}$

$$n_{eff} = n_0 + n_2\left(\frac{P}{A_{eff}}\right)$$

n_0 → ordinary refractive index of material / linear Refractive index

n_2 → non-linear index coeff

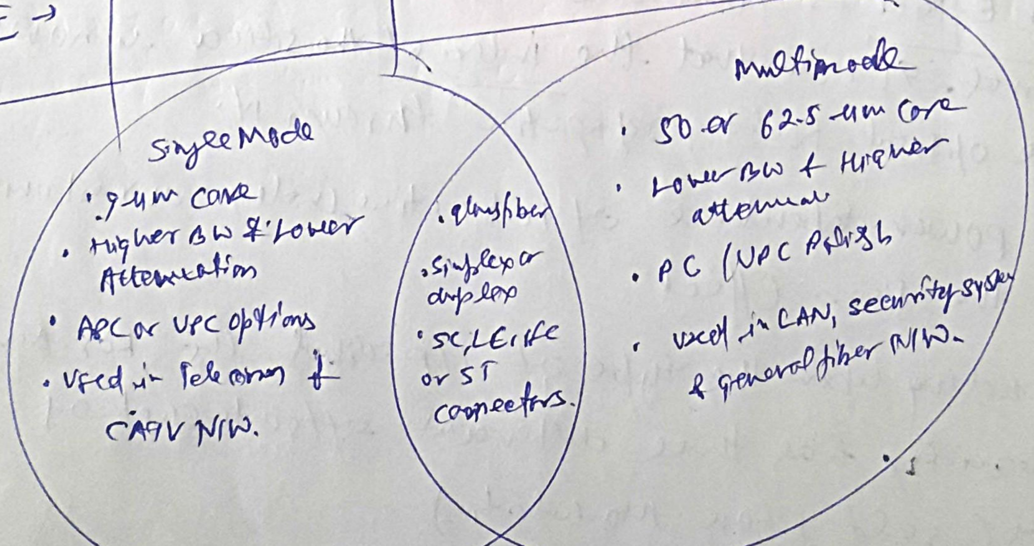
(P ↑)

P = optical power

A_{eff} → Effective Mode Area ⊕ core cross sectn

Step Index fiber Vs Graded Index fibers

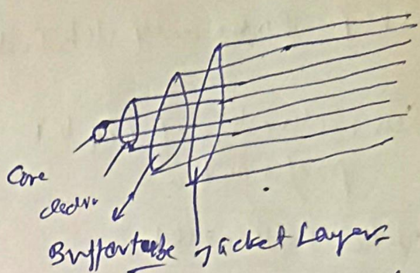
Parameter	Step I.F.	Graded Index
(1) Def →		



Parameter	Single Mode	Multi Mode
fiber cost	Low	High
system cost	High	Low
Loss	Low	High
BW	High	Low
Distance	up to 60 km	up to 2 km
Transmission speed	supports up to 40G (single pair)	supports up to 400G single pair

G → GBPS

→ SMF are more expensive than MMF



→ Used in data centers, universities, campuses, office buildings, Industrial plants, electric companies etc

SMF → 1) Used for long distance comm.

2) core diameter → 8.3 — 10 um ≈ 9 um has one mode of transmission

3) has one mode of transmission

4) due to small core & single light wave propagation → signal attenuation is less & speed of Transmission is highest.

5) Typical band wavelength → 1310 or 1550 nm

6) It has light source with a narrow spectral width.

7) It is also called mono mode optical fiber / single mode optical waveguide / unimode fiber.

8) SMF is useful for WDM / wave Division multiplexing /

MMF 1) It is used for short distances less than 500 m (have different modes of propagation)

2) MMF ways → OM$_1$, OM$_2$, OM$_3$, & OM$_4$.

3) Each Multimode type have different data rates, link length & BW for specific App^n.

4) MMF core diameter → 62.5 um (OM$_1$) & 50 um (OM$_2$/OM$_3$/OM$_4$)

5) for long distance > 914.4 m (3000 ft), multipath of light can cause signal distortion at Rx end.

6) It has bigger core diameter. (50-100 u)

7) Light waves are dispersed into numerous paths or modes as they travel as they travels through the core typically 850nm / 1310nm

Differences - ① Light Propagation Differences

2) SMF have only step index | MMF have step index & graded index

→ less reduction of light propagation | more reduction of light propagation

② Optic Differences

→ Laser diode based source | LED based source.

single mode connectors have higher stringent alignment | MMF - connector have lower stringent alignment

3) Deployment Cost Diff

which one to choose → (Distance requirement)

1) In a data centre → MMF

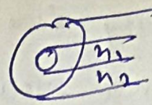
for long distances → (1km, 40km, 80km & further | So cost ret?

2) $Cost_{SMF} > Cost_{MMF}$ | ③ $(Tr. Rate)_{SMF} > (Tr Rat)_{MF}$

4) $(Dist)_{SMF} > (Dist)_{MMF}$ 50

5) SMF & MMF are not compatible → You can not mix MMF & SMF b/w two endpoints

Step Index fibers. (1)

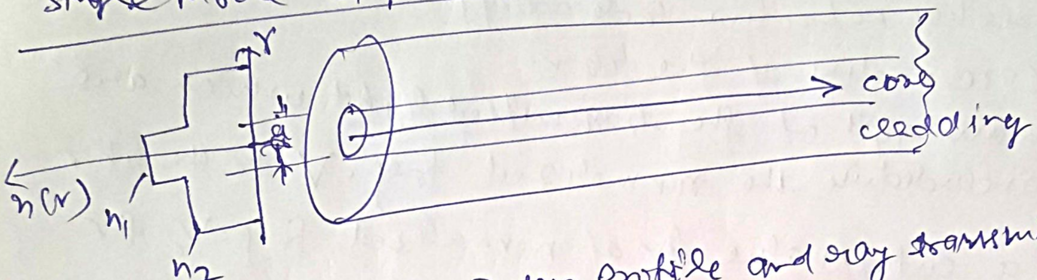


$n_1 > n_2$

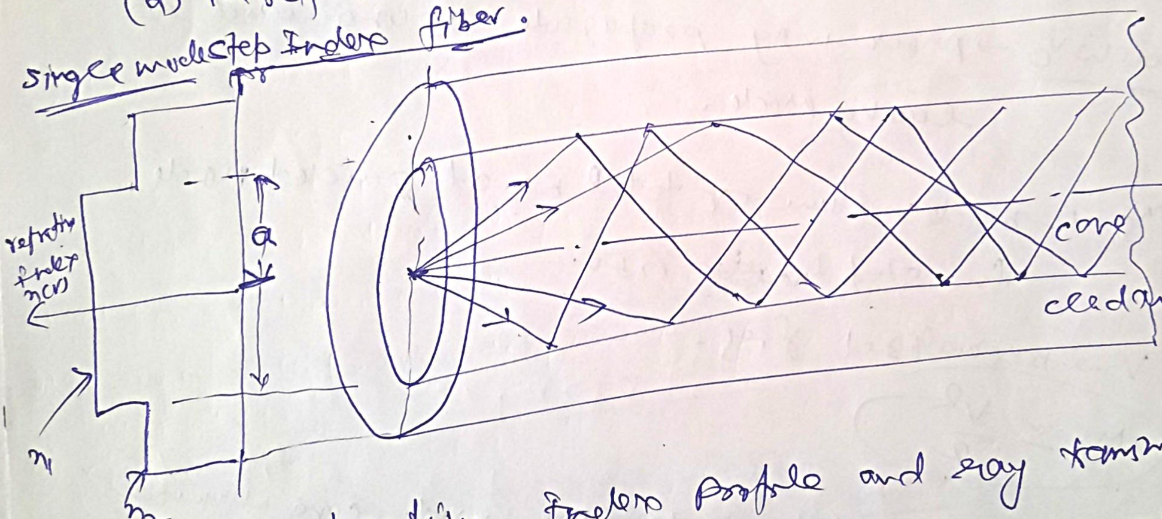
a → core diameter

n(r) → refractive index profile | $n(r) \begin{cases} n_1, r < a \text{ (core)} \\ n_2, r > a \text{ (cladding)} \end{cases}$

Single Mode Step Index fiber.



(a) The refractive index profile and ray transmission in single mode step index fiber.



(b) The refractive index profile and ray transmission in Multimode step index fiber.

core → 50–200 um
cladding – 125–400 um.

SM step I.F (core → 8–12 um; cladding → 125 um)

- → Propagation of only one transverse EM Mode (HE_{11})
- → Core diameter → 2–10 um
- → LOW Intermode Dispersion (Broadening of transmitted light pulses)
- → SMF for HBW
  - ↳ Coupling not efficient

MM SIF

- → core diameter ≥ 50 um.
- → many different possible ~~path~~ Ray paths through the fiber.
- → Dispersion due to the differing group velocities of propagating mode.
- → BW Limitation
- → MMF for Lower BW – Advantage. sources (LED) coupling – efficient

MMSIF → easier coupling due to larger NA & dispersion

→ lower tolerance requirement on fiber connectors,

allows the propagation of a finite number of guided modes along the channels.

→ no. of guided modes is dependent upon the physical parameter

- relative refractive index diff.
- core radius of the fiber.
- wavelength of the transmitted light which are included in the normalized freq. V for the fiber.

→ there is a cutoff value of normalized freq. V_c for guided mode.

below V_c → mode may propagate as unguided or leaky mode.

if M_s → mode volume or total no. of guided mode for step index fiber

V → normalized freq.

$$M_s \simeq \frac{V^2}{2}$$

Q A multimode step index fiber with core diameter of 80 um and a relative index of 1.5% is operating at a wavelength of 0.85 um. If the core refractive index is 1.48. Estimate (a) the normalized freq. for the fiber (b) the no. of guided modes

$a = \frac{80}{2} = 40$

⇒ (a) $V = \frac{2\pi}{\lambda} a n_1 (2\Delta)^{\frac{1}{2}} = \frac{2\pi}{0.85\times10^{-6}} \times 40\times10^{-6} \times 1.48 (2\times0.015)^{\frac{1}{2}}$

$= 75.8$

total no. of guided mode

$M_s = V^2/2$

$= \frac{(75.8)^2}{2} = \frac{5745.6}{2} = 2873$

⇒ This fiber has V = 76 gives 2873 ≈ 3000 guided Modes

Graded Index fiber.

→ It do not have a constant refractive Index in the core.

→ It is called Inhomogeneous core fibers.

The Refractive Index variation

$$n(r) = \begin{cases} n_1 \left[1 - 2\Delta \left(\frac{r}{a}\right)^{\alpha}\right]^{\frac{1}{2}} & r < a \text{ (for core)} \\ n_1 \left[(1 - 2\Delta)\right]^{\frac{1}{2}} = n_2 & r \geq a \text{ (for cladding)} \end{cases}$$

a → radius of core

Δ ⇒ relative refractive Index difference

α → Profile Parameter of refractive Index

when α = ∞ ⇒ step Index profile

α = 2 ⇒ parabolic "

α = +1 → triangular "

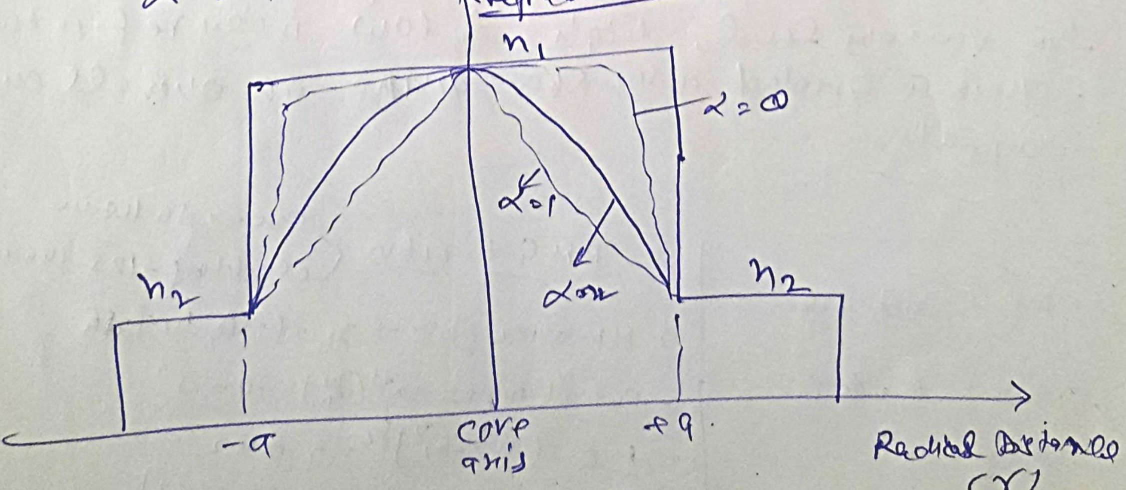


Fig: Possible fiber refractive Index profile for different values of α

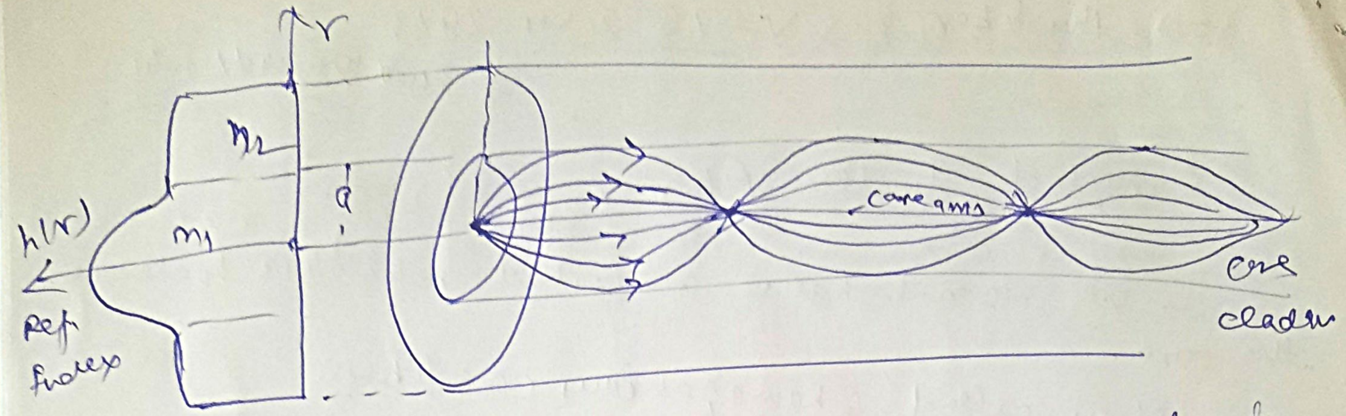
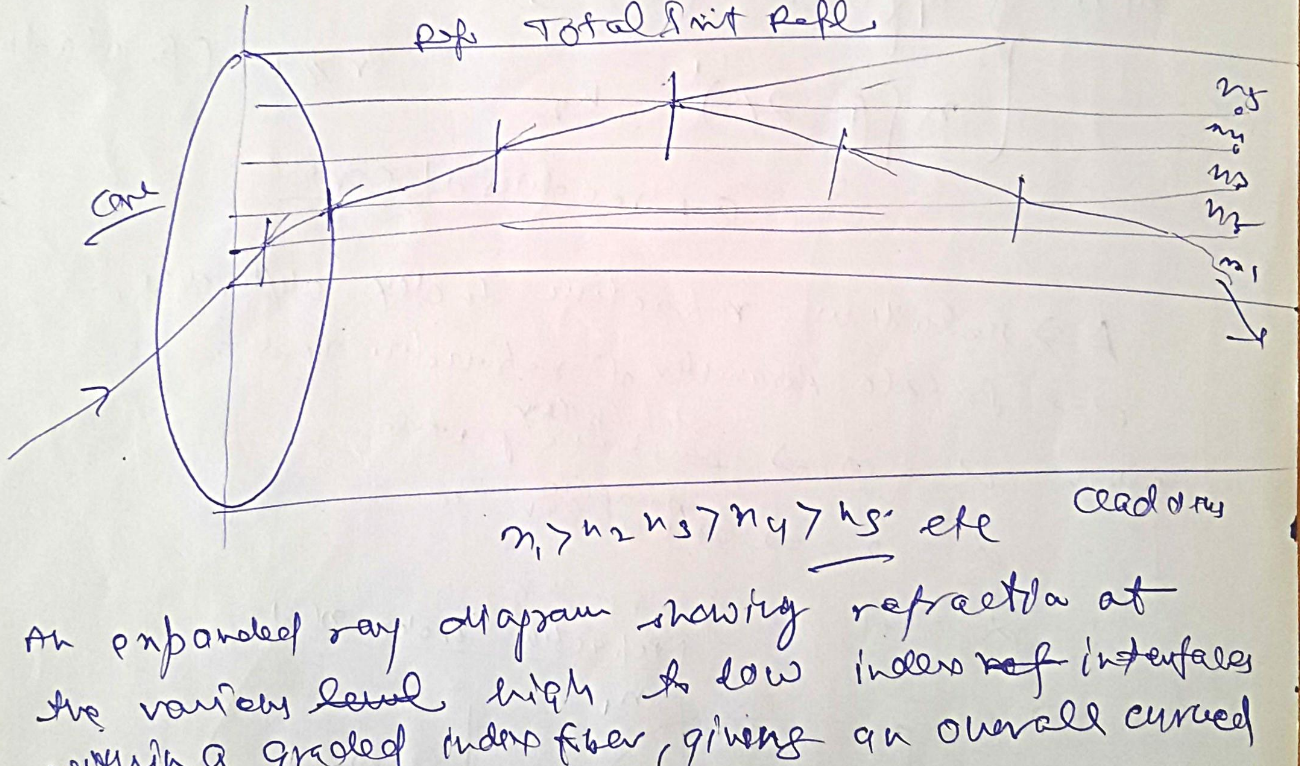


Fig: The ref. index profile & ray transmission in multimode graded index fiber.



$n_1 > n_2\ n_3 > n_4 > n_5$ etc

An expanded ray diagram showing refraction at the various ~~level~~ high to low index ~~ref~~ interfaces within a graded index fiber, giving an overall curved ray path.

SM
MM > Step index fiber
SM
MM > Graded index fi.

MM G. I. fiber < core → 50/100 µm, cladding → 125–140 µm

Q MM silica fiber → $n_1 = 1.46$, $n_2 = 1.46$

(a) Critical angle = $\sin^{-1}\left(\frac{n_2}{n_1}\right) = 80.5°$

(2) N.A $= (n_1^2 - n_2^2)^{1/2} = 0.242$

3) Acceptance angle in air ($n = 1.00$)

$\theta_A = \sin^{-1}(NA) = 14°$