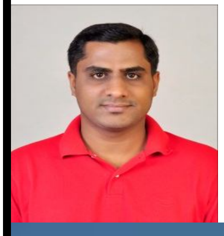
OPTICAL FIBER COMMUNICATION

10EC72/10TE72



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Unit-1

OVERVIEW OF OPTICAL FIBER COMMUNICATION

INTRODUCTION

- Communication is defined as the transfer of information from one point to another.
- when information is to be conveyed over a distance, a communication system is usually required.
- within a commn s/m the information transfer is achieved by super imposing or modulating the infn on to a electromagnetic wave, which acts as a carrier signal.
- This modulated signal is then transmitted to the required destination where it is recieved & original signal is obtained by demodulation.
- Optical communication is most modern mode of wired communication
- Before communication was in radio & microwave frequencies of magnitude lower than optical frequencies.

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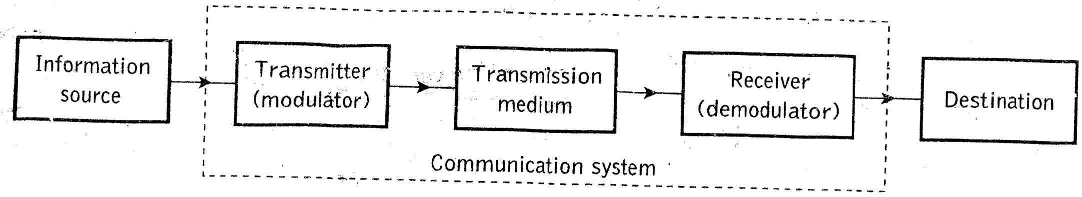
- Optical fiber communication is defined as method of transmitting infⁿ from one place to another by sending pulses of light through an optical fiber.
- Fiber optics is a branch of optics that deals with the study of propogation of light through transparent di-electric waveguides
- An optical fiber is a glass or plastic fiber that carries light along its length.
- optical fibers work on the principle of Total Internal Reflection (TIR)

THE GENERAL SYSTEM

Describe block diagram of an optical fibre transmission link and explain function of each element in the link (DEC13,JAN14,JUNE15) [6/8M]

- An optical communication s/m is similar in basic concept to any time of communication system.
- A block schematic of general commn s/m is shown in the figure below:



- The commn s/m consists of a transmitter or modulator linked to the infn source, the transmission medium & a reciever or demodulator at the destination point.
- The infn source provides an electrical signal derived from the message signal
- Transmitter comprising of electrical & electronic components converts the signal into a suitable form for propogation over the transmission medium.
- The transmission medium can consists of a pair of wires, a coaxial cable or a radio link through free space down which the signal is transmitted to the reciever.

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- It must be noted that in any transmission medium the signal is attenuated or suffers loss & is subject to degradation due to contamination by random signals & noise.
- Therefore in any communication system there is maximum permitted distance b/w the TxR & RxR beyond which the s/m effectively ceases to give intelligible commn.

OPTICAL FIBER COMMUNICATION SYSTEM

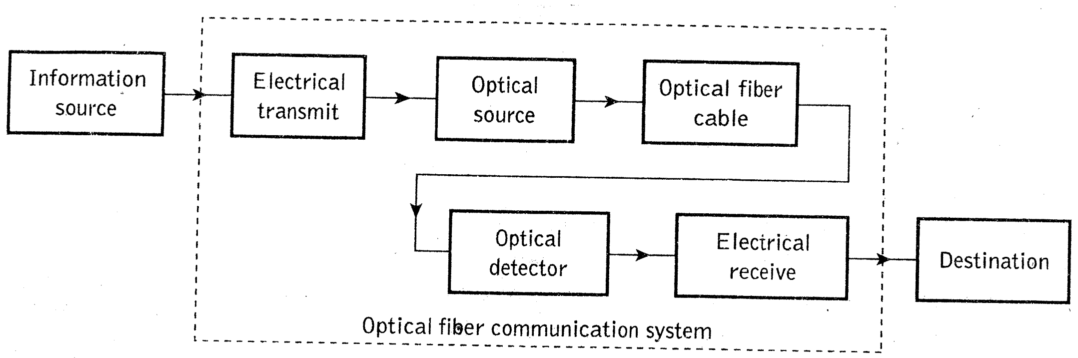

Figure (a) The general communication system. (b) The optical fiber communication system

- In this case the infn source provides an electrical signal to a transmitter comprising an electrical stage which drives an optical source to give modulation of light wave carrier.

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- The optical source provides the electrical-optical conversion may be either a semiconductor laser or light emitting diode (LED)
- The transmission medium consists of an optical fiber cable & RxR consists of a optical detector which drives a further electrical stage & hence provides demodulation of optical carrier.
- Photodiodes, photo transistors & photoconductors are utilized for the detection of the optical signal & the optical-electrical conversion.
- The optical carrier may be modulated using either an analog or digital signal.
- Block schematic of a typical digital optical fiber link:

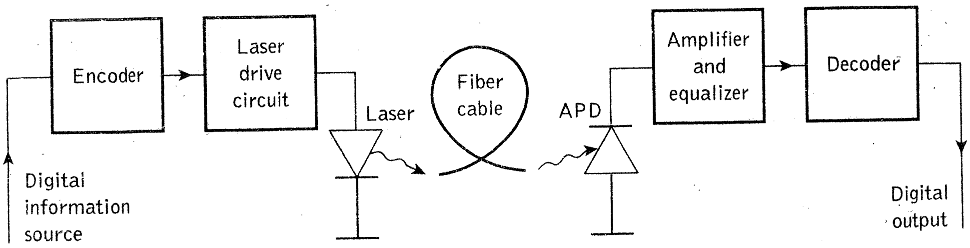

Figure A digital optical fiber link using a semiconductor laser source and an avalanche photodiode (APD) detector

- Initially, the digital input signal from infn source is suitably encoded for optical transmission.

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- The laser drive circuit directly modulates the intensity of the semiconductor laser with the encoded digital signal. Hence a digital optical signal is launched into the optical fiber cable.
- The avalanche photodiode (APD) detector is followed by a front-end amplifier & equalizer or filter to provide gain as well as linear signal processing & noise bandwidth reduction.
- Finally, the signal obtained is decoded to give the original digital information.

Difference in analog & digital modulation of the optical carrier:

- Analog modulation involves the variation of the light emitted from the optical source in a continous manner.
- with digital modulation discrete changes in the light intensity are obtained.
- Analog modulation with an optical fiber commn s/m is less efficient, requiring a far higher SNR at the reciever than digital modulation.
- Analog optical fiber commn links are generally limited to shorter distances & lower BW's than digital links

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ADVANTAGES, DISADVANTAGES & APPLICATIONS OF OFC

1. **What are the advantages ,applications and disadvantages of optical fibre compared to copper cables? (Jan10,June13,June 14) [6/8M]**
2. **List disadvantages of copper wire at optical frequency range (Dec12) [6M]**
3. **Discuss advantages of OFC? (Jul11,Dec11,June12,June 10,Dec10) [6M]**

Advantages :

i) Enormous Potential Bandwidth :

Information carrying capacity of TxR s/m is directly proportional to carrier frequency of transmitted signals.

The optical carrier frequency in the range of 10^{13} to 10^{16} Hz which yeilds a far greater potential transmission BW than metallic cable systems.

ii) Small size and weight :

Size of fiber ranges from 10 μm to 50 μm. Space occupied is small compared to conventional electrical cables.

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Optical fibers are much lighter than corresponding copper cables.

iii) Electrical Isolation:

Optical fibers which are fabricated from glass or plastic polymer, are electric insulator.

They do not exhibit earth loop & interface problems.

They do not pick any electro-magnetic wave or high current lightening.

Also suitable in explosive environment.

iv) Immunity to interference & cross talk:

Optical fibers form a dielectric waveguide & therefore free from electromagnetic interference. Operation of OFC s/m is unaffected by transmission through an electrically noisy environment.

And cross talk is negligible even when many fibers are cabled together.

v) Signal security

The light from optical fibers does not radiate significantly & therefore they provide a high degree of signal security.

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vi) Low Transmission Loss:

Due to usage of ultra low loss fibers its loss less transmission.

vii) Ruggedness and flexibility:

Fiber cable can be easily bent or twisted without damaging it.

The fiber cables are superior interms of handling, installation, storage, transportation, maintainence, strength & durability.

viii) System Reliability & ease of maintainence:

Low loss property of OF cables reduces requirement for intermediate repeater or line amplifiers to boost Txd signal strength.

Made of silicon glass which does not undergo any chemical reaction or corrosion.

ix) Potential Low cost:

Fibers are made of silica which is available in abundance.

∴ There is no shortage of material

Disadvantages:

1. Lack of Bandwidth Demand
   Its economical only when the entire bandwidth is fully utilized.

2. Difficulty in splicing:
   The small size of fibers & cables creates difficulties with splicing & forming connectors.

3. complex Testing procedure:
   Due to small size of fibers, testing procedures tends to be more complex.

4. High investment cost:
   The initial cost of installation is very high compared to all other systems.

Applications:

1. Public n/w applications:
   provides variety of appl^n for OFC s/m like trunk n/w, junction n/w, submerged plans.

2. Military applications:
   can be used in military mobiles such as air craft, ships & tanks.

3. Civil Applications:
   These transmission techniques may be utilized on railways & along pipe & electric power lines.

4. Consumer applications:

major application is within automotive electronics.

5. Industrial applications:

OF SIMS are successfully applied in nuclear testing applications

6. Optical sensor SIMS:

can be employed for monitoring & telemetry in industrial environments.

7. Local area networks:

OFC technology is finding application with LANs to meet the on-site requirements of large commercial organizations.

RAY THEORY

Explain the ray theory of optical fiber, with help of neat diagram. [8M]

1. Total Internal Reflection (TIR)

Its an optical phenomenon that occurs when a ray of light strike boundary at an angle larger than critical angle with respect to normal, all the light is reflected.

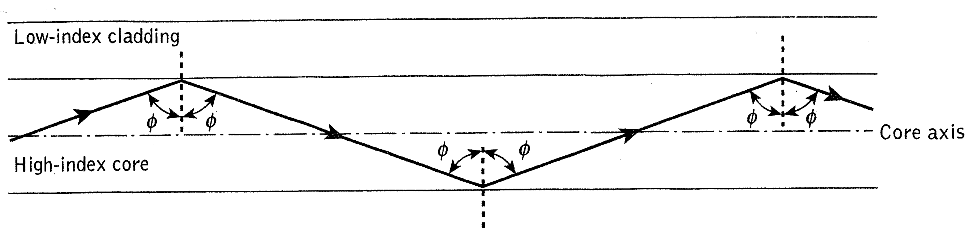

Figure The transmission of a light ray in a perfect optical fiber

- The figure illustrates transmission of light ray in an optical fiber via a series of total internal reflections at the interface of silica core & cladding.
- The ray has an angle of incidence ϕ at the interface which is greater than critical angle and is reflected at the same angle to the normal.

2. Acceptance Angle:

- It is the angle at which light ray must enter the optical fiber to undergo total internal reflection (TIR)
- The geometry concerned with launching the light ray is shown in the fig:

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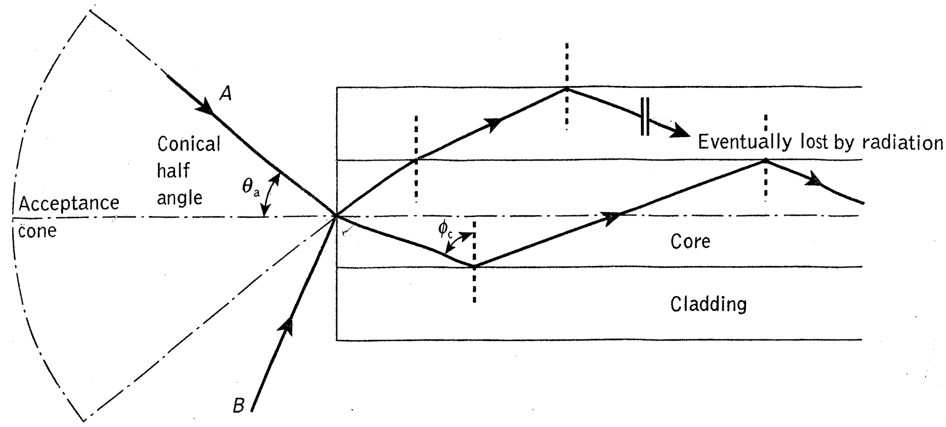

Figure The acceptance angle θ_a when launching light into an optical fiber

- Fig illustrates a meridonial ray A at the critical angle ϕ_c which enters the fiber core at an angle θ_a to the fiber axis & is refracted at the air-core interface before transmission to core-cladding interface at critical angle.
- Also shows incident ray B at an angle greater than θa is refracted into cladding & lost by radiation.

3. Numerical Aperture (NA):

NA indicates the light gathering capability of an optical fiber.

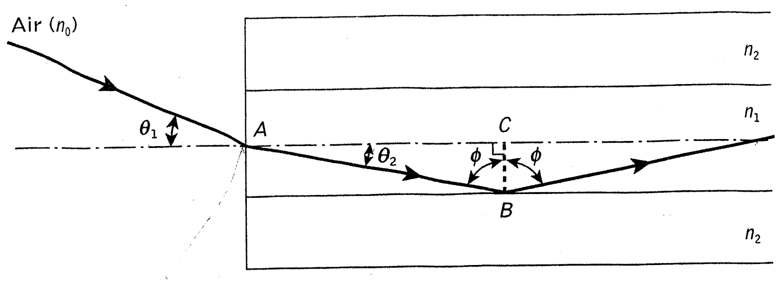

Figure The ray path for a meridional ray launched into an optical fiber in air at an input angle less than the acceptance angle for the fiber

Fig. shows a light ray incident on the fiber core at an angle θ_1 to the fiber axis that is less than acceptance angle θ_a.

- A ray enters the fiber from a R.I. n_0 & the fiber core has R.I. n_1 slightly greater than cladding R.I. n_2.
- Consider refraction at the air-core interface & using Snell's Law:

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

Consider the right angled triangle ABC:

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

ϕ is greater than critical angle at core cladding interface

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

$$\sin^2\phi + \cos^2\phi = 1$$

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

For TIR, ϕ becomes equal to critical angle. θ_1 becomes acceptance angle for fiber θ_a.

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

NA is defined as:

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

NA can also be given in terms of relative refractive index difference Δ.

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

$$\simeq \frac{n_1 - n_2}{n_1} \quad \text{for } \Delta \leq 1$$

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

4. Skew Rays

- The category of ray exists which is transmitted without passing through fiber axis.
- These rays follow a helical path through the fiber.

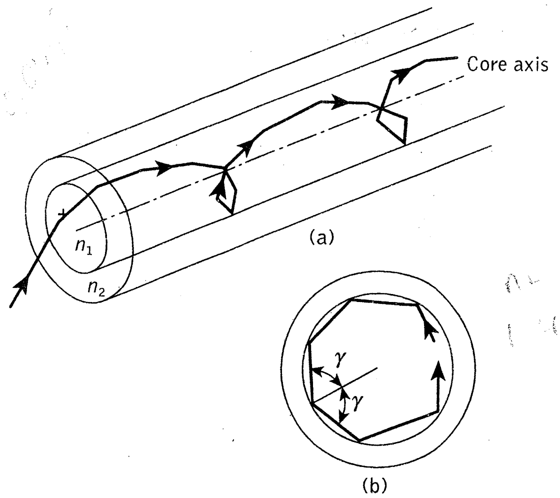

Figure The helical path taken by a skew ray in an optical fiber: (a) skew ray path down the fiber; (b) cross-sectional view of the fiber

- The helical path traced through the fiber gives a change in direction of 2γ at each reflection.
- γ is angle b/w projection of ray in 2D & radius of the core.
- The point of emergence of skew rays from fiber in air will depend upon number of reflections they undergo.

$$\sin\theta_{as} = \frac{n_1}{n_0}\frac{\cos\phi_c}{\cos\gamma} = \frac{n_1}{n_0\cos\gamma}\left(1-\frac{n_2^2}{n_1^2}\right)^{1/2}$$

$$n_0 \sin\theta_{as}\cos\gamma = (n_1^2 - n_2^2)^{1/2} = NA$$

$n_0 = 1$ $\quad \sin\theta_{as}\cos\gamma = N.A.$

For meridonial rays $\cos\gamma = 1$

$\theta_{as} = \theta_a$

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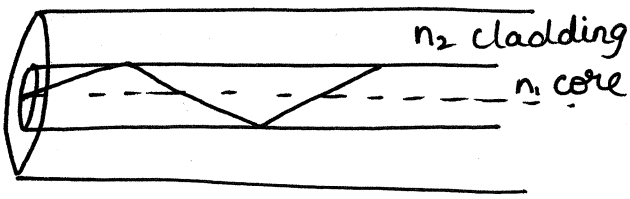
Note:



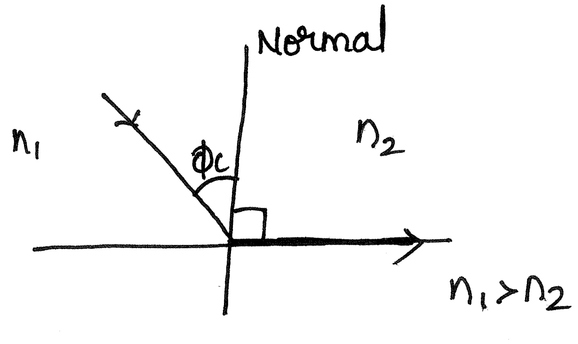
Meridonial Rays:

Light ray is launched in a plane containing the axis of the fiber.
The light ray after Total Internal Reflection travels in the same plane.
These light rays always cross/intersect the axis of the fiber.
These are called Meridonial rays.

Critical Angle

The angle of incidence from denser to rarer medium at which the angle of refraction is 90°.

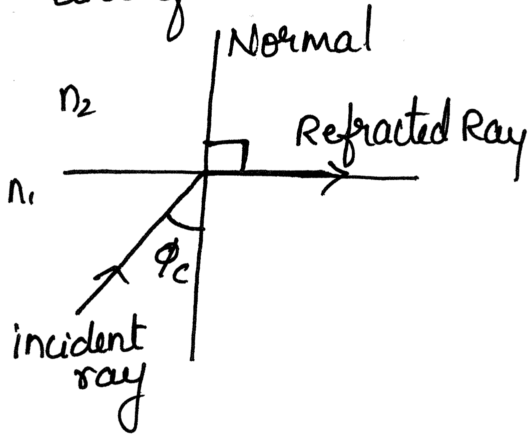
$$\frac{n_2}{n_1} = \frac{\sin\phi_1}{\sin 90^\circ} = \sin\phi_c \Rightarrow \boxed{\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)}$$



Snell's Law

The ratio of sine of angle of incidence to that of sine of angle of refraction to normal give refractive index of interface.

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



Relative Refractive Index Difference:

Ratio of R.I. difference b/w the core & cladding to the R.I. of the core of an optical fiber.

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

$$\Delta n_1 = n_1 - n_2$$

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

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

$$= \sqrt{n_1 \Delta (n_1 + n_2)}$$

$\because\ n_1 \simeq n_2,\ (n_1 + n_2) \simeq 2n_1$

$\Rightarrow\ NA = \sqrt{2n_1^2 \Delta} \qquad \Rightarrow \boxed{NA = n_1\sqrt{2\Delta}}$

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V-number

The number of modes supported for propogation in the fiber is determined by a parameter called V-number.

Fiber is surrounded by a medium of R.I. no, then expression is:

$$V = \frac{2\pi a}{\lambda} n_0 \sqrt{n_1^2 - n_2^2}$$

$$V = \frac{2\pi a}{\lambda} n_0 (NA)$$

If n_0 is air then,

$$\boxed{V = \frac{2\pi a}{\lambda} (NA)}$$

$a \Rightarrow$ radius of the core

Derive numerical aperture of a step indexed fibre from Snell's law? (July15,Jan10) [6/7M]

Derive the expressions for N.A of a step indexed fibre in terms of acceptance angle , core and cladding refractive indices & further in terms of each element in the link? (June 15,Jan14) [6M]

Derive necessary mathematical condition that the angle of incidence must satisfy for the optical skew rays to propagate in a step indexed fibre? (June 10) [8M]

Describe the different types of optical fibre waveguide structure using ray theory with neat labelled diagrams. Explain the light propagation? (June 11) [8M]

Define acceptance angle & critical angle? (Jul14) [3M]

CYLINDRICAL FIBER

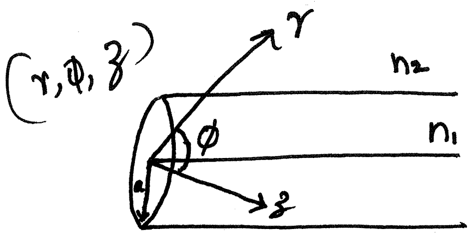
- Limitation of Ray model: even after TIR, there will be some field in cladding.

Wave Model:

→ Propogation of light inside the fiber, treating light as an E.M. wave.
Here optical energy gets guided i.e; the energy propogates along axis of core.

→ For optical fiber communication:
consider cylindrical coordinate s/m (r, ϕ, z),
if propogates in z direction ⇒ fields have definite distributions in (r, ϕ)

→ we use maxwell's equation:
we assume equations which govern the electromagnetic radiations inside the fiber are source free.



→ Optical fiber is dielectric waveguide that operates at optical frequencies

→ According to type of materials used:
- plastic or silica fibers

→ According to band width requirements
- low
- medium
- high
- ultra high fibers

→ As per operating classes.
- Single mode
- Multimode

→ Depending on R.I. variation:
- step Index
- Graded Index.

Modes

→ The propogation of light along a waveguide is described in terms of a set of guided electromagnetic waves, called modes of wave guides.

(or) A set of guided EM waves is called the modes of an optical fiber.

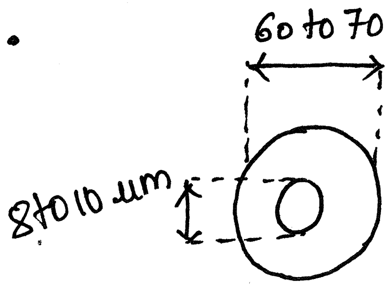
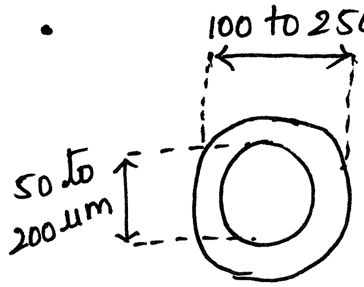
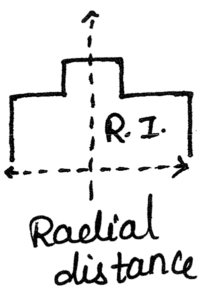
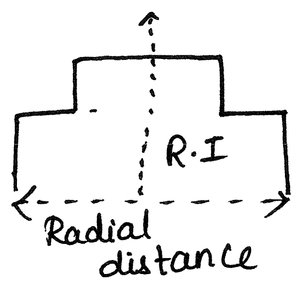
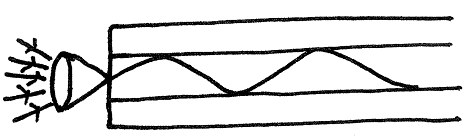
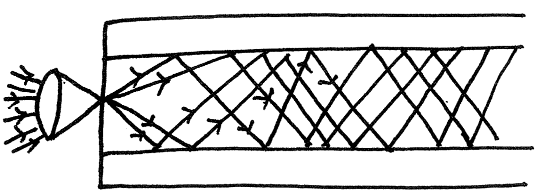
Explain the structure of single mode & multi mode step indexed fibre & graded indexed fibre optical fibre with cross section & ray path? (Dec10) [7M]

With neat and labelled diagrams explain the different types of optical fibres considering number of modes & material composition of the core? (Dec11) [8M]

Distinguish between:
Single mode v/s Multimode Fibres
Step Indexed v/s Graded Indexed Fibres (Jan14) [8M]

Explain what is meant by Graded Indexed optical fibre ? Using simple ray theory concept, indicate major advantages of this type of fibre with regard to multimode propagation? (Dec13) [6M]

Single Mode Fiber	Multi Mode Fiber
• only a single fundamental mode propogates in the fiber	• More than one modes propogate in the fiber.
• Have higher bandwidth	• Limited by bandwidth
• Do not exhibit any dispersion	• Limited by modal dispersion.
• Data transfered is low	• Data transfered is high

Single mode fiber	Multimode fiber
• Cheap	• Costly compared to single mode.
• Used in submarine cable s/m.	• Used in telephone links
•  Geometry	•  Geometry
• R.I. profile 	• R.I. profile 
• Ray propogation 	• Ray propogation 

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Step index Fiber

→ The R.I of core is uniform throughout & undergoes step change at core cladding boundary.

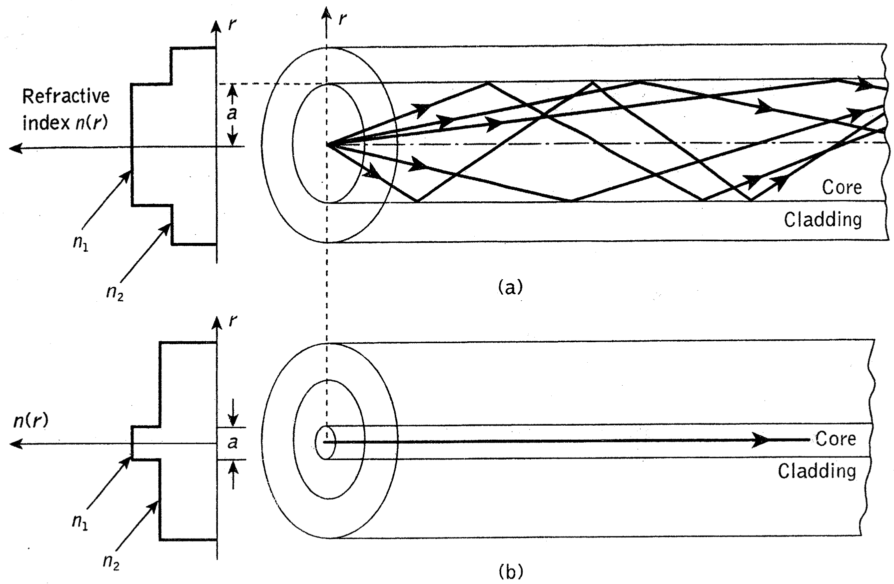

Figure The refractive index profile and ray transmission in step index fibers: (a) multimode step index fiber; (b) single-mode step index fiber

→ Light rays propogating through fiber are in the form of meridonial rays.

→ R.I. profile is given by:

$$n(r) = \begin{cases} n_1 & r < a \text{ (Core)} \\ n_2 & r \geq a \text{ (Cladding)} \end{cases}$$

Single Mode:

Advantage: Low intermodal dispersion as only one mode is transmitted.

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Multimode Step Index Fiber:

→ Advantages:

- use of spatially incoherent optical sources.
- larger N.A. as well as core diameters, facilitating easier coupling to optical sources
- lower tolerance requirements on fiber connectors.

→ Multimode step index fiber allow propogation of finite number of guided modes

→ Number of modes dependent upon physical parameters of fiber & wavelength of light which are included in normalized frequency V for the fiber.

Number of modes guided is given by:

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

→ Majority of the guided modes operate far from cut off & are confined to the fiber core, thus most of optical power is carried in the core region.

→ The properties of cladding do not affect the propogation of these modes.

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Graded Index Fiber

→ In this type, the R.I. of core is made to vary in parabolic manner such that maximum value of R.I. is at centre of core.

→ Light rays propogating through it is in the form of skew rays.

→ R.I. profile:

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

α is profile parameter which gives the characteristic R.I. profile of fiber core.

If, $\alpha = \infty$, R.I profile is of step index fiber

$\alpha = 2$, R.I. profile is parabolic

$\alpha = 1$, R.I profile is triangular.

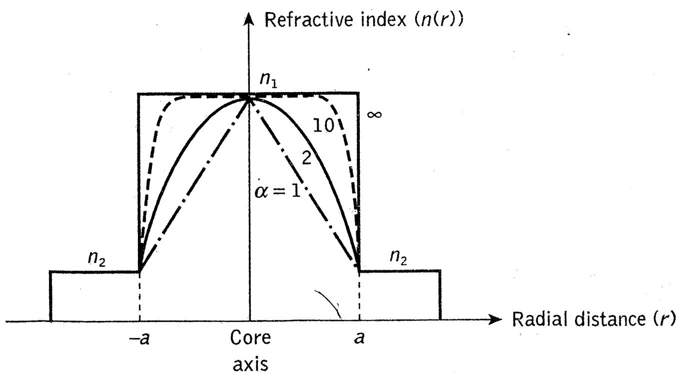

Figure Possible fiber refractive index profiles for different values of α (given in Eq. (2.75))

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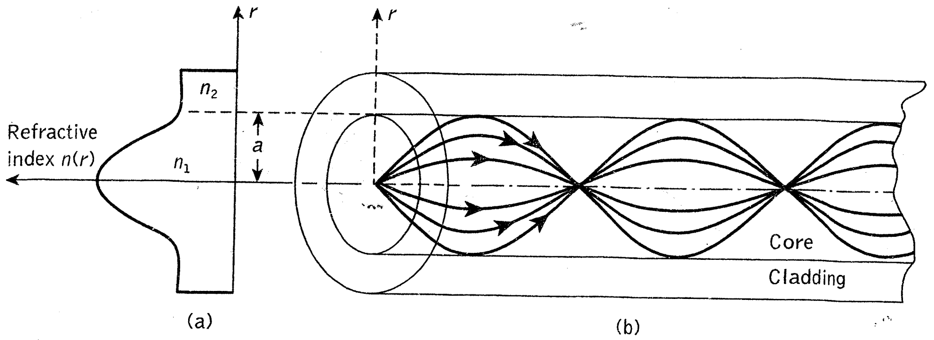

Figure The refractive index profile and ray transmission in a multimode graded index fiber

→ Multimode graded index fiber exhibit less intermodal dispersion than multimode step index fibers due to their refractive index profile.

→ Although many different modes are excited in the graded index fiber, the different group velocities of modes tend to be normalized by the index grading.

→ Number of modes is given by:

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

$$\boxed{M_g \simeq \frac{V^2}{4}}$$

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Step Index Fiber	Graded Index Fiber
• R.I. of core is uniform throughout & changes abruptly at the cladding boundary.	• R.I. of the core is a function of the radial distance from the fiber center.
• They may have bandwidth of 50MHz	• They may have band width of 200, 400, 600MHz or more
• Attenuation is more	• Attenuation is less
• Typical core size: single mode : 8 to 12 um multimode : 50 to 200 um	• Typical core size: multimode: 50 to 100 um
• cladding size: single mode: 125 um multimode: 125-400 um	• Cladding size: multimode: 125-140 um
• $\Delta = \frac{n_1 - n_2}{n_1}$	• $\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$
• coupling efficiency is higher	• Lower coupling efficiency.
• Pulse Spreading is more	• pulse spreading is less.
• diagrams previously drawn	• diagrams previously drawn

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Single Mode Fibers :

→ Advantage : Signal dispersion caused by delay differences b/w different modes in a multimode fiber is avoided.

→ The transmission of a single mode fiber must be designed to allow propogation of only one mode, while all other modes are attenuated by leakage or absorption.

→ The cut off normalized frequency in step index fiber occurs at $\boxed{V_c = 2.405}$.

→ Single mode propogation in step index fiber is over the range :

$$0 \leq V < 2.405$$

→ Graded index fibers may also be designed for single mode operation.

The cut off value of normalized frequency V_c to support a single mode in a graded index fiber is given by :

$$V_c = 2.405\left(1 + 2/\alpha\right)^{1/2}$$

Cut off wavelength :

The frequency suitable for single mode fiber is given by :

$$V = \frac{2\pi}{\lambda} a\,(NA) \quad \text{— (1)}$$

Rearranging the eq^n

$$\lambda = \frac{2\pi a}{V_c}(NA)$$

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

V_c is the cutoff normalised frequency

λ_c is wavelength above which particular fiber becomes single-mode

Obtaining the inverse relationship:

$$\frac{\lambda_c}{\lambda} = \frac{V}{V_c}$$

$V_c = 2.405$

$$\boxed{\lambda_c = \frac{V\lambda}{2.405}}$$

Mode-field Diameter & Spot Size:

Explain Mode Field Diameter of a Single Mode Fibre? (July13) [6M]

→ The mode field diameter (MFD) is an important parameter for characterizing single mode ~~fibers~~ properties which take into account the wavelength dependent field penetration into the fiber cladding.

→ It is a function of optical source wavelength, core radius & R.I. profile of the fiber.

→ This is used to predict fiber properties such as splice loss, bending loss, cut off wavelength & waveguide dispersion.

→ For step index & graded single mode fibers operating near the cut off wavelength λ_c, the field is approximated by Gaussian distribution.

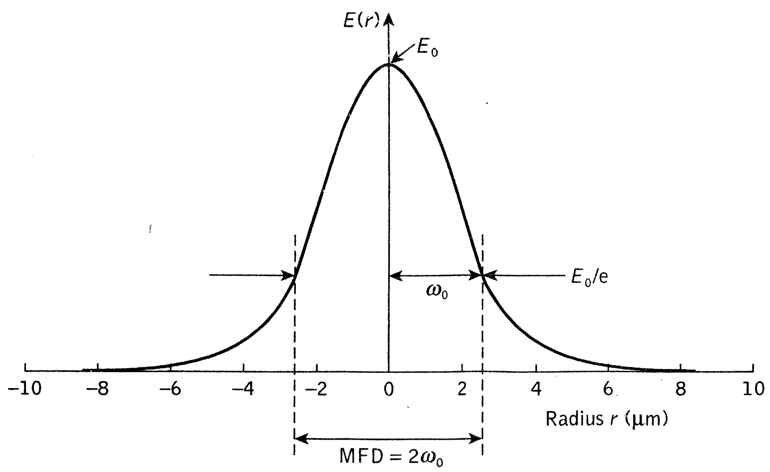
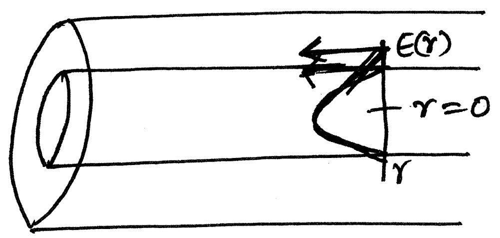


Figure Field amplitude distribution $E(r)$ of the fundamental mode in a single-mode fiber illustrating the mode-field diameter (MFD) and spot size (ω_0)

→ MFD is generally taken as distance b/w opposite $1/e = 0.37$ field amplitude points & power $1/e^2 = 0.135$ in relation to values on fiber axis.



→ Another parameter related to MFD is spot size w_0.

$$MFD = 2w_0$$

$w_0 \Rightarrow$ nominal half width of i/p excitation.

FIBER MATERIALS

Explain briefly what are the different fibre materials used in optical fibre communication? (Dec10,June12) [7M]

With a neat labelled diagram explain photonic crystal fibres in optical fibre communication? (June12) [7M]

Differentiate between glass fibre & plastic fibres. In case of Glass Fibre how R.I can be varied? (June13) [4M]

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Briefly explain the structure of fibre optic cable? [6M]

→ Requirements while selecting materials of optical fibers:

1. Must be possible to make long, thin, flexible fibers from the material
2. Material must be transparent at a particular optical wavelength in order for fiber to guide light efficiently.
3. Physically compatible materials that have slightly different R.I. for core & cladding must be available.

→ Materials of fibers are made of glass consisting of either silica (SiO_2) or silicate

→ Plastic fibers are less widely used because of their substantially higher attenuation than glass fibers

→ Plastic fibers used in short distance application.

Glass Fibers :

→ Glass is made by fusing mixtures of metal oxides, sulfides or selenides, resulting material is randomly connected molecular n/w rather than ordered structure.

→ Due to this random order, glasses do not have well defined melting points.
It remains solid upto several hundreds of degrees of centigrade.
As temperature increases, glass begins to soften & becomes viscous liquid.

→ The largest category of optically transparent glasses consists of oxide glasses ⇒ Silica (SiO_2)
it has R.I. of 1.458 at 850nm.

→ Either fluorine or oxides are added to silica to form the R.I. difference for core & cladding

→ Doping of : GeO_2 & P_2O_5 increases the R.I.
Flourine or B_2O_3 decreases the R.I.

Egs of combination :

$GeO_2 - SiO_2$ core SiO_2 cladding
$P_2O_5 - SiO_2$ core SiO_2 cladding

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SiO_2 core $B_2O_3-SiO_2$ cladding

$GeO_2-B_2O_3-SiO_2$ core $B_2O_3-SiO_2$ cladding

→ Raw material for silica is high purity sand.

some of desirable properties are:

- resistance to deformation at temperatures
- high resistance to breakage from thermal shock.
- Good chemical durability
- High transparency in both visible & infra red region.

Active Glass Fibers

→ Incorporating rare Earth elements into passive glass gives new optical & magnetic properties.

→ This allow it to perform amplification, attenuation & phase retardation on light passing through it.

→ 2 commonly used materials for fiber lasers are erbium & neodymium.

→ The ionic concentrations of rare-earth elements are low to avoid clustering effects.

→ we can use optical source which emits at an absorption wavelength to excite electrons at higher energy levels.

Plastic Optical Fibers

→ The growing demand for delivering high speed services led to create high Bandwidth graded index polymer (Plastic optical fibers)

→ The core of these fibers is either polymethyl-methacrylate or perfluorinated polymer

→ These fibers are hence referred to as PMMA POF or PF POF.

→ They exhibit greater optical signal attenuations but they are tough & durable.

→ Compared to silica fibers core diameters of plastic fibers are 10-20 times larger. In expensive plastic injection-moulding technologies used to fabricate connectors, splices & transceivers.

PHOTONIC CRYSTAL FIBERS [PCF]

→ Initially this fiber was called as Holey fiber & now as photonic crystal fiber or micro structured

→ The difference b/w this & conventional fiber is the cladding.

→ Core regions of a PCF contain air holes.

→ The size & spacing of holes in the microstructure & the R.I. of its constitutent material determine the light guiding characteristics of photonic crystal fibers.

→ For PCF effective R.I. of cladding depends on wavelength, size & pitch of the holes.

Index-Guiding PCF:

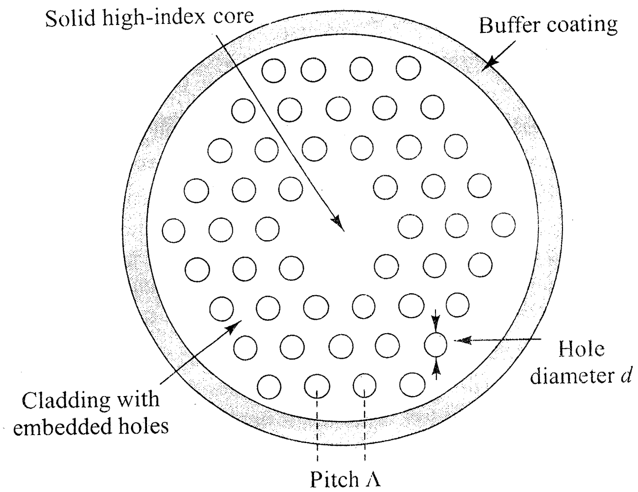

Fig. *Cross-sectional end view of the structure of an index-guiding photonic crystal fiber*

→ It has solid core that is surrounded by a cladding region which contains air holes running along the length of the fiber.

→ The holes have a diameter 'd' & a pitch 'Λ'

→ Although, the core & cladding are made of same material, air holes lower the effective index of refraction in cladding region.

→ It creates a step index optical fiber

→ Operational advantages:

- very low losses
- ability to transmit high optical power levels
- high resistance to darkening effects from nuclear radiation.

Photonic Bandgap Fiber : (PBG)

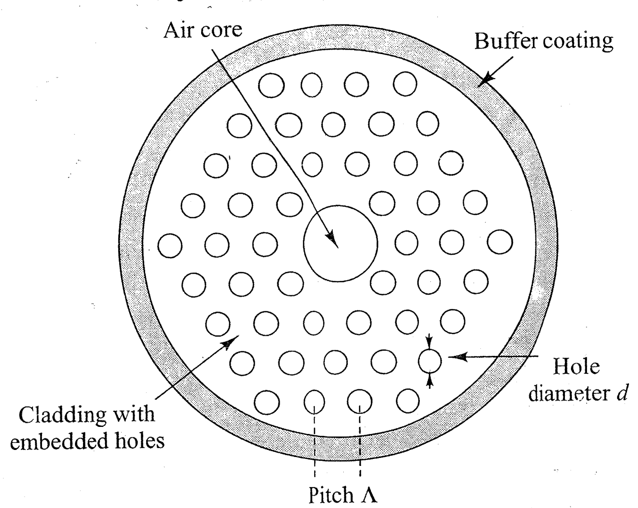

Fig. *Cross-sectional end view of the structure of a photonic bandgap fiber*

→ It has a hollow core & cladding region, has air holes running along length of fiber.

→ Functional principle of PBG is to block electrons occupying bandgap region.

→ The hollow core acts as a defect in the photonic bandgap structure, creates a region in which the light can propogate.

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FIBER OPTIC CABLES

→ Fibers need to be incorporated in some type of cable structure.

→ cable structure depends on whether cable is to be pulled into underground or intra building ducts, buried directly in the ground, installed on outdoor poles or submerged under water.

Cable structures

→ Important mechanical property : Maximum allowable axial load on cable, determines length of cable.

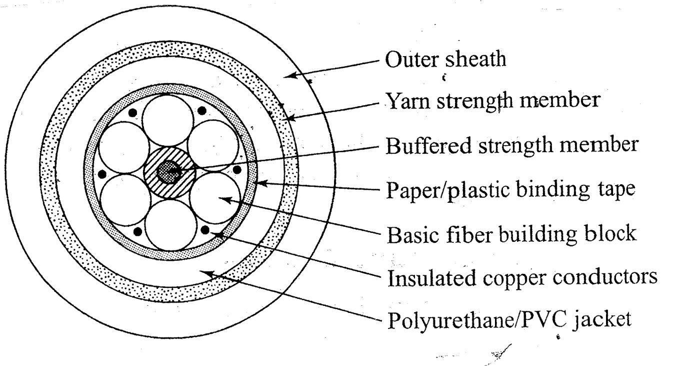

Fig. *A typical six-fiber cable created by stranding six basic fiber-building blocks around a central strength member*

→ Fig. shows typical 6-fiber cable created by six building blocks around a central strength member.

→ Outer sheath protects the fiber cable from atmospheric & other external effects.

→ Yarn strength member is used to avoid effects of EMI or to reduce cable width.

→ PVC jacket is tough that provides crush resistance & handles any tensile stresses applied to the cable.

→ Paper binding tape binds & encapsulates the fiber grouping together.

→ The insulated copper conductor & fiber building block are wound loosely around central buffered strength member.

Two basic optic cable structures:

1) Tight buffered cable:

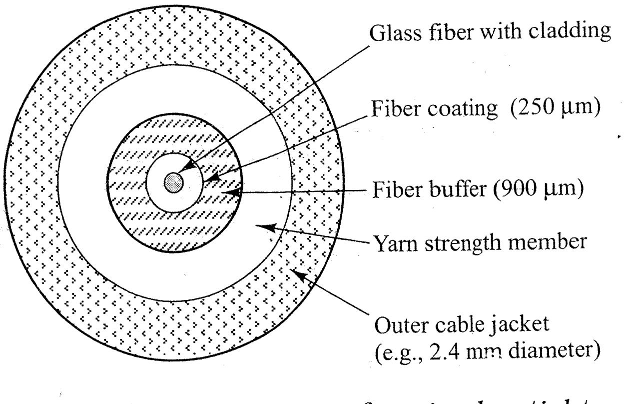

Fig. *Construction of a simplex tight-buffered fiber cable module*

→ Each fiber is individually encapsulated within its own 900 μm diameter plastic fiber structure.

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→ 250 µm protective coating provides excellent moisture & temperature performance & permits direct termination with connectors.

→ used for indoor applications.

2) Loose Tube fiber cable:

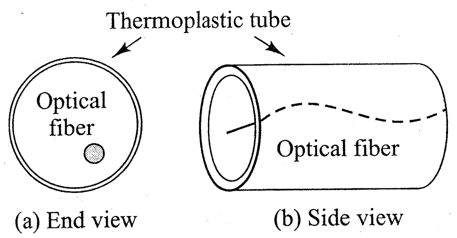

Fig. *Concept of a loose-tube cable configuration*

→ One or more standard coated fibers are enclosed in thermoplastic tube & has inner diameter larger than fiber diameter.

→ Fibers in tube are slightly longer than cable to isolate from any stretching of surrounding cable caused by temperature change, wind force etc.

Ribbon Cables

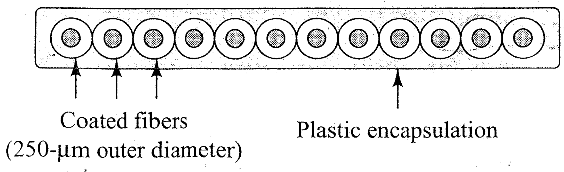

Fig. *Example of a twelve-fiber ribbon cable module*

→ Extension of tight buffered cable.
→ It facilitates splicing.
→ Number of ribbons range from 4 to 12. These ribbons are stacked on top of each other to form a densely packed arrangement.

Indoor Cables

→ Indoor cables are used for:
- Connections to printer or servers
- distributing signals when computers are connected in LAN.
- Short patchcords in tele communication

→ 3 Types of indoor cables:

1) Interconnect Cable:

→ cable is flexible, compact & light weight with tight buffered construction.
→ popular type is duplex cable - 2 cables encapsulated in a outer PVC jacket.

2) Breakout or Fanout Cable

→ consists of 12 tight buffered cables stranded around a central strength member.
→ Allows easy installation of connectors on

individual fibers & hence routing the individually terminated fibers to separate pieces of equipment can be achieved easily.

3) Distribution cable:

→ Has individual grouping of tight buffered fibers stranded around central strength member.

→ They enable grouping within cable to be branched to various locations.

→ Designed for wide range of n/w applications such as sending data, voice & video signals.

Outdoor Cables:

→ outdoor installations include aerial, duct, direct-burial & underwater applications

→ These cables consists of loose tube structure

3 Types

1) Aerial cable

→ intended for mounting outside b/w buildings or on poles

→ 2 popular designs are:

• Self supporting: internal strength permits cable to be strung b/w poles without any additional support mechanism.

• Facility Training : Separate wire or strength member is strung b/w poles is lashed or clipped to this member.

2. Armored Cable

→ used for direct-burial or underground-duct applications

→ consists of one or more layers of steel wire or steel-sheath protective armoring below a layer of polyethylene jacket.

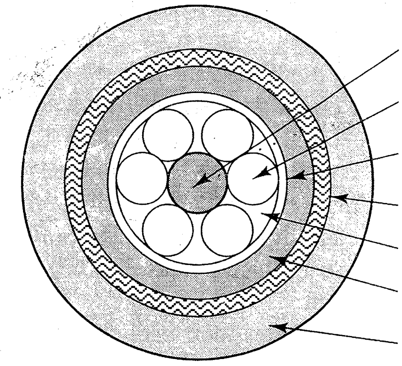

Fig. *Example configuration of an armored outdoor fiber optic cable*

→ Provides additional strength to the cable but also protects from gnawing animals such as squirrels or burrowing rodents, which often cause damage to underground cables.

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3. Underwater or Submarine Cables:

→ used in rivers, lakes and ocean environments.

→ These cables are normally exposed to high water pressures which have much more stringent requirements.

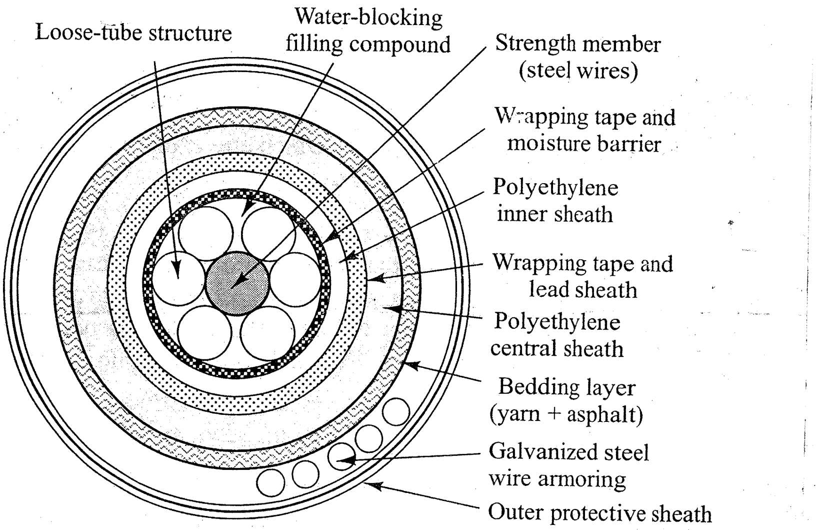

Fig. *Example configuration of an underwater fiber optic cable*

→ consists of various water blocking layers, protective inner polyethylene sheets & heavy outer armor jacket.

→ cables in ocean must have additional layer of armoring & contain copper wires to be provided for optical regeneration.

Speciality Fibers

→ Speciality fibers are designed to intract with light & thereby manipulate or control some characteristic of an optical signal.

→ The light manipulation applications include optical signal amplification, optical power coupling, wavelength conversion, pressure & fluid levels.

→ For light control applications a speciality fiber can be insensitive to bends, redirect specific wavelengths or provide high attenuation for fiber terminations.

→ speciality fibers can be either multimode or single-mode design.

→ optical devices that use speciality fibers are optical light TxR, light signal modulators, optical recievers, wavelength multiplexers, optical power attenuators etc..

Examples of speciality Fibers:

1. Erbium-doped Fiber:

Application: Gain medium for OF amplifiers.

These fibers have erbium ions + silica material to form basic block of OF amplifier.
Higher erbium concentration allow the use of shorter fiber length, small cladding & higher NA.

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2. Photo sensitive Fiber:

Application: Fabrication of fiber Bragg gratings

- Germanium & boron ions are doped with fiber material.
- R.I. changes when exposed to UV light.
- Fiber Bragg grating is periodic variation of R.I. along fiber axis.
- Fiber bragg grating applications include light coupling mechanisms, wavelength add/drop modules, chromatic dispersion compensation modules.

3. Bend insensitive Fiber:

Application: Tightly looped connections in device packages.

- sensitivity to bending loss decreases due to high NA, which decreases MFD.
- This confines optical power more tightly within the core.

4. Termination Fiber:

Application: Termination of open optical fiber ends.

- optical device with multiple ports will have one or more unused open branches.
- Back reflections from these ports cause instabilities & this can be suppressed using termination fiber.

5. Polarization-preserving fiber:

Application: Pump lasers, polarization-sensitive device sensors.

- Optical fibers state of polarization fluctuates as light propagates through the fiber.
- But polarization preserving fibers have a special core design that does not vary the polarization as light propogates through it.

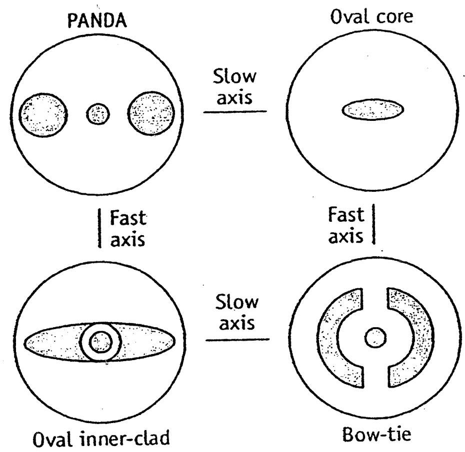

Figure Cross-sectional geometry of four different polarization-maintaining fibers

- Figure illustrates geometry of four different-polarization maintaining fibers.
- Light circles represent the cladding & dark areas are core.
- Goal in each design is to create fast & slow axes in core.

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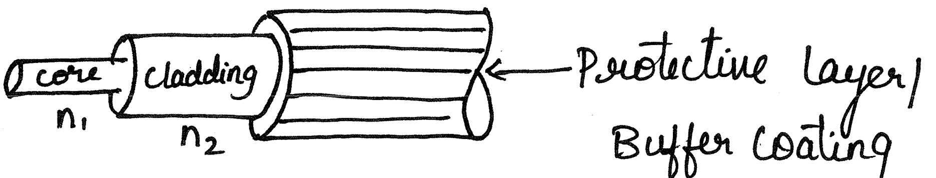
- Each of these axes will guide light at a different velocity.

6. High index fibers:
   Application : Fused couplers, short-λ sources, DWDM devices

7. Photonic crystal fibers:
   Application : switches, dispersion compensation.

OPTICAL FIBER CONFIGURATION:



→ An optical fiber is a cylindrical waveguide operating at optical frequencies.
→ Dielectric cylinder of radius 'a' & refractive index n_1 is known as core of fiber
→ core is surrounded by glass of slightly lower R.I. n_2 ($n_2 < n_1$) known as cladding
→ Cladding reduces scattering losses & adds mechanical strength to the fiber.
→ Buffer provides strength to OF & gives protection from environment changes.

PROBLEMS:

1. A multimode SIF has V number of 75, N.A = 0.3. R.I. of core is 1.458 & operates @ 820nm. Find core radius, RI of cladding, fractional change in R.I. & number of modes propogated.

$\boxed{6M}$ [Dec 09/Jan 10]

→ Given:

$V = 75 \qquad n_1 = 1.458$

$NA = 0.3 \qquad \lambda = 820nm$

i) core radius:

$$V = \frac{2\pi a}{\lambda}(NA)$$

$$a = \frac{V\lambda}{2\pi(NA)} = \frac{75 \times 820 \times 10^{-9}}{2 \times \pi \times 0.3} = \underline{0.326\ \mu m}$$

ii) R.I. of cladding

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

$$(NA)^2 = n_1^2 - n_2^2$$

$$\therefore n_2^2 = n_1^2 - (NA)^2$$

$$= (1.458)^2 - (0.3)^2$$

$$n_2^2 = 2.0357$$

$$n_2 = \sqrt{2.0357} = \underline{1.426}$$

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iii) Fractional change in R.I.

$$\Delta = \frac{n_1 - n_2}{n_1} = \frac{1.458 - 1.426}{1.458}$$

$$= 0.021$$

$$\boxed{\Delta \simeq 2.1\%}$$

iv) Number of modes

$$M = \frac{V^2}{2} = \frac{(75)^2}{2}$$

$$\boxed{M = 2812.5}$$

2. Estimate the maximum core diameter for an OF with R.I. difference of 1.45% & core R.I. of 1.52 in order that it may be suitable for single mode operating at $\lambda = 0.85\,\mu m$. Also calculate λ_c if core diameter is $1.1\,\mu m$.

[6M] [May/June 10]

→ Given: $\Delta = 1.45\%$ $n_1 = 1.52$ $\lambda = 0.85\,\mu m$

i) W.K.T. For SMF: $V = 2.405$

$$V = \frac{2\pi a}{\lambda}(NA) = \frac{2\pi a}{\lambda} n_1 (2\Delta)^{1/2}$$

$$a = \frac{V\lambda}{2\pi n_1 \sqrt{2\Delta}}$$

$\Delta = 1.45\%$
$= 0.0145$

$$= \frac{2.405 \times 0.85 \times 10^{-6}}{2 \times \pi \times 1.52 \times \sqrt{2 \times 0.0145}}$$

$$= \frac{2.0442 \times 10^{-6}}{1.6263}$$

$$\boxed{a = 1.256\,\mu m}$$

$\therefore$ Diameter $= a \times 2 = 1.256 \times 10^{-6} \times 2 = \underline{2.5139\,\mu m}$

ii) Now, given core diameter $= \underline{1.1\,\mu m}$

$$a = \frac{1.1 \times 10^{-6}}{2} = \underline{5.5 \times 10^{-7} m}$$

$$V = \frac{2\pi}{\lambda_c} a n_1 \sqrt{2\Delta}$$

$$\lambda_c = \frac{2\pi a n_1 \sqrt{2\Delta}}{V}$$

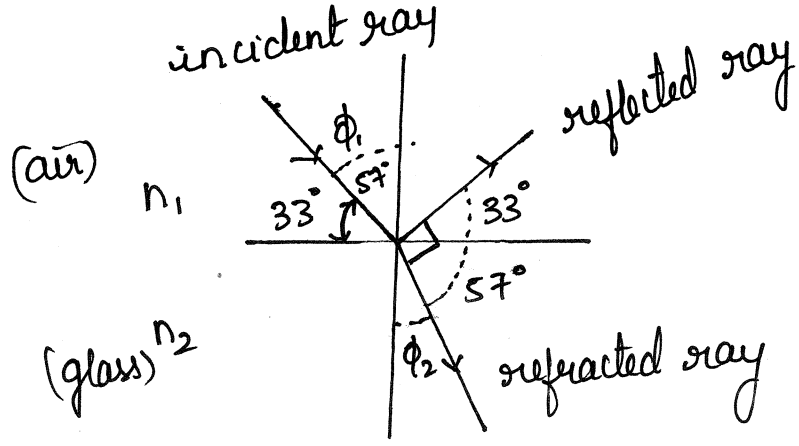
$$= \frac{2 \times \pi \times 5.5 \times 10^{-7} \times 1.52 \times \sqrt{2 \times 0.0145}}{2.405}$$

$$\lambda_c = 3.7193 \times 10^{-7}$$

$$\Rightarrow \boxed{\lambda_c = 0.371\,\mu m}$$

3. Light travelling in air strikes a glass plate @ an angle $\theta_1 = 33°$ where θ_1 is measured b/w the incoming ray & glass surface. If the refracted & reflected beams make an angle of 90° with each other, what is R.I of glass? what is the critical angle. [6M] [Dec 11]

→



Snell's law:

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

$$1 \sin 57° = n_2 \sin 33°$$

$$n_2 = \frac{\sin 57°}{\sin 33°}$$

$$\boxed{n_2 = 1.539}$$

critical angle: $\sin\phi_c = \frac{n_1}{n_2}$ $\qquad \sin\phi_c = \frac{\text{lower index}}{\text{higher index}}$

$$\sin\phi_c = \frac{1}{1.539}$$

$$\phi_c = \sin^{-1}(0.6497) \qquad \boxed{\phi_c = 40.51°}$$

4. A silica glass fiber has a core RI of 1.5 & cladding R.I. of 1.45. Calculate:
a) critical angle for core cladding interface
b) NA of fiber
c) % of light collected by the fiber

[6M] [Dec 12]

→ Given: $n_1 = 1.5$ $n_2 = 1.45$

a) $\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1.45}{1.5}\right) = \underline{75.16^\circ}$

b) $N.A = \sqrt{n_1^2 - n_2^2} = \sqrt{(1.5)^2 - (1.45)^2} = \underline{0.385}$

c) % of light collected by the fiber:

NA ⇒ light gathering capability

$\therefore 0.385 \times 100 = \underline{38.5\%}$

5. A SI MMF with NA of 0.2 supports approximately 1000 modes at a wavelength of 850 nm.
Find a) what is diameter of its core
b) How many modes does fiber support at 1320 nm
c) How many modes does the fiber support at 1550 nm

[4M] [June/July 13]

→ Given: $N.A = 0.2$ $M = 1000$ $\lambda = 850\,nm$

$M = \frac{V^2}{2}$ $V = \sqrt{2M} = \sqrt{2 \times 1000} = \underline{44.72}$

a) $V = \frac{2\pi}{\lambda} a(NA)$

$a = \frac{V\lambda}{2\pi(NA)}$

$= \frac{44.72 \times 850 \times 10^{-9}}{2 \times \pi \times 0.20}$

$\boxed{a = 30.24\ \mu m}$

$\therefore$ diameter $= d = a \times 2 = \underline{60.49\ \mu m}$

b) $\lambda = 1320 nm$

$V = \frac{2\pi \times 3.24 \times 10^{-6}}{1320 \times 10^{-9}} \times (0.2)$

$V = 28.78$

$M = \frac{V^2}{2} = \underline{414.14}$

c) $\lambda = 1550 nm$

$V = \frac{2\pi \times 3.24 \times 10^{-6}(0.2)}{1550 \times 10^{-9}} = \underline{24.51}$

$M = \frac{V^2}{2} = \underline{300.37}$

6. A step index fiber with core & cladding R.I. of 1.44 & 1.42 respectively. Calculate acceptance angle for skew rays which change direction by 150° at each reflection.

[6M] [Dec 13/Jan 14]

→ Given: $n_1 = 1.44$ $\quad 2\gamma = 150°$

$n_2 = 1.42$

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

Acceptance angle: $\phi_0 = \sin^{-1}\sqrt{n_1^2 - n_2^2}$

$$\sin\theta_{as}\cos\gamma = NA$$

$$2\gamma = 150° \Rightarrow \boxed{\gamma = 75°}$$

$$N.A = \frac{n_1 - n_2}{n_1} = \frac{1.44 - 1.42}{1.44} = \underline{0.0138}$$

$$\sin\theta_{as}\cos 75° = 0.0138$$

$$\Rightarrow \theta_{as} = \sin^{-1}\left[\frac{0.0138}{\cos 75°}\right]$$

$$\Rightarrow \boxed{\theta_{as} = 3.0759°}$$

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7. A Graded Index fiber with parabolic R·I has $n_1 = 1.48$ & $n_2 = 1.46$, if core radius is 20 µm, find number of modes at 1300 nm & 1550 nm

[6M] [Dec 13/Jan 14]

→ Given: $n_1 = 1.48 \quad n_2 = 1.46 \quad a = 20\,\mu m$

$$\Delta = \frac{n_1 - n_2}{n_1} = \frac{1.48 - 1.46}{1.48} = 0.0135$$

a) at 1300 nm

$$V = \frac{2\pi a (NA)}{\lambda} = \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta}$$

$$V = \frac{2 \times \pi \times 20 \times 10^{-6} \times 1.48 \sqrt{2 \times 0.135}}{1300 \times 10^{-9}}$$

$$\boxed{V = 23.5}$$

$$M = \frac{V^2}{4} = \underline{138 \text{ modes}}$$

b) at 1550 nm

$$V = \frac{2 \times \pi \times 20 \times 10^{-6} \times 1.48 \sqrt{2 \times 0.0135}}{1550 \times 10^{-9}}$$

$$\boxed{V = 19.71}$$

$$M = \frac{V^2}{4} = \underline{97.12 \text{ modes}}$$

8. Calculate maximum value of Δ & n_2 of a SMF of a core diameter 10 μm & core R.I 1.5. The fiber is coupled to a light source with a wavelength of 1.3 μm. V cut off for SM propogation is 2.405. Also calculate acceptance angle

$\boxed{6M}$ [June/July 15]

→ Given:

core diameter = 10 μm $n_1 = 1.5$

⇒ $a = 5\,\mu m$ $\lambda = 1.3\,\mu m$

$V = 2.405$

$$V = \frac{2\pi a(NA)}{\lambda}$$

$$NA = \frac{V\lambda}{2\pi a} = \frac{2.405 \times 1.3 \times 10^{-6}}{2 \times \pi \times 5 \times 10^{-6}} = \underline{0.0995}$$

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

$$(NA)^2 = n_1^2 - n_2^2$$

$$n_2^2 = n_1^2 - (NA)^2$$

$$= (1.5)^2 - (0.0995)^2$$

$$n_2^2 = 2.24$$

$$\boxed{n_2 = 1.49}$$

$$\Delta = \frac{n_1 - n_2}{n_1} = \frac{1.5 - 1.49}{1.5} = 0.00667 \Rightarrow 0.667\,\%$$

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Acceptance Angle:

$$\phi_0 = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)$$

$$= \sin^{-1}\sqrt{(1.5)^2 - (1.49)^2}$$

$$= \sin^{-1}(0.1729)$$

$$\boxed{\phi_0 = 9.957^\circ}$$

9. what is core size & cladding index for manufacturing silica core step index fiber with $V = 70$ & $NA = 0.25$ to be used with LED of 820nm if core is 1.458

[4M] (Dec 13/Jan 14)

→ Given: $V = 70$ $NA = 0.25$

$\lambda = 820nm$ $n_1 = 1.458$

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

$$(NA)^2 = n_1^2 - n_2^2$$

$$n_2^2 = n_1^2 - (NA)^2$$

$$= (1.458)^2 - (0.25)^2$$

$$n_2^2 = 2.063$$

$$n_2 = \sqrt{2.063}$$

$$\boxed{n_2 = 1.436}$$

$$V = \frac{2\pi a (NA)}{\lambda}$$

$$a = \frac{V\lambda}{2\pi (NA)}$$

$$= \frac{70 \times 820 \times 10^{-9}}{2 \times \pi \times 0.25}$$

$$\boxed{a = 36.54 \mu m}$$

10. A multimode SIF supports 75 nodes, having NA = 0.3, $n_1 = 1.458$ operating at 820 nm. Find core radius R.I. of cladding & fractional change in R.I.

→ Given: N.A = 0.3 $n_1 = 1.458$ $\lambda = 820 nm$

$V = 75$

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

$$n_2^2 = n_1^2 - (NA)^2$$

$$= (1.458)^2 - (0.3)^2$$

$$n_2^2 = 2.0357$$

$$\boxed{n_2 = 1.426}$$

$$\Delta = \frac{n_1 - n_2}{n_1} = \frac{1.458 - 1.426}{1.458}$$

$$\boxed{\Delta = 0.0219} \Rightarrow \Delta = 2.19\ \%$$

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$$V = \frac{2\pi a}{\lambda}(NA)$$

$$a = \frac{V\lambda}{2\pi(NA)}$$

$$= \frac{75 \times 820 \times 10^{-9}}{2 \times \pi \times 0.3}$$

$$\boxed{a = 32.62\,\mu m}$$

11. A silica OF with core diameter large enough to be considered by ray theory has a core R.I of 1.5 & a cladding R.I. 1.47. Determine a) critical angle b) acceptance angle c) NA.

→ Given: $n_1 = 1.5$ $n_2 = 1.47$

$$\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1.47}{1.5}\right) = \underline{78.5^\circ}$$

$$NA = (n_1^2 - n_2^2)^{1/2} = \sqrt{(1.5)^2 - (1.47)^2}$$

$$\underline{NA = 0.3}$$

Acceptance angle: $\theta_a = \sin^{-1}(NA)$

$$\theta_a = \underline{17.36^\circ}$$

12. R.I for an OF designed for long distance transmission is 1%. Estimate i) NA

ii) solid acceptance angle in air for fiber when core index is 1.46.

iii) critical angle at core cladding interface within the fiber.

→ Given: $\Delta = 1\%$ $\quad n_1 = 1.46$

$\Delta = 0.01$

i) $NA = n_1\sqrt{2\Delta} = 1.46\sqrt{2\times0.01} = \underline{\underline{0.206}}$

ii) for small angles, the solid acceptance angle, δ in air is

$$\delta \simeq \pi\theta_a^2 = \pi\sin^2\theta_a$$

$$\Rightarrow \delta = \pi(NA)^2 = \pi\times(0.206)^2$$

$$\boxed{\delta = 0.13\,\text{rad}}$$

iii) $$\Delta = \frac{n_1 - n_2}{n_1} = 1 - \frac{n_2}{n_1} = 0.01$$

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

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}(0.99) = \underline{\underline{81.89^\circ}}$$

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13. A OF in air has $NA = 0.4$. Compare acceptance angle for meridonial rays with skew rays which change direction by 100° at each reflection.

→ Meridonial rays:

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

$$= \sin^{-1}(0.4)$$

$$\boxed{\theta_a = 23.6^\circ}$$

Skew rays:

They change direction by $100^\circ \Rightarrow 2\gamma$ at each reflection $\gamma = 50^\circ$

$$\Rightarrow \theta_{as} = \sin^{-1}\left(\frac{NA}{\cos\gamma}\right)$$

$$= \sin^{-1}\left(\frac{0.4}{\cos 50^\circ}\right)$$

$$\boxed{\theta_{as} = 38.5^\circ}$$

14. Multimode step index fiber has core diameter 80 μm R.I. difference 1.5%, $\lambda = 0.85$ μm, core R.I is 1.48.

Find : i) normalized frequency for the fiber.

ii) number of guided modes.

→ Given: diameter = 80 μm $\Delta = 1.5\%$

$a = \frac{80\mu}{2} = 40\,\mu m$ $\Delta = 0.015$

$\lambda = 0.85\,\mu m$ $n_1 = 1.48$

i) $$V = \frac{2\pi a}{\lambda}(NA)$$

$$= \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta}$$

$$= \frac{2 \times \pi \times 40 \times 10^{-6} \times 1.48 \times \sqrt{2 \times 0.015}}{0.85 \times 10^{-6}}$$

$$V = 75.8$$

ii) Num of modes

$$M \approx \frac{V^2}{2} = \frac{(75.8)^2}{2} = 2873 \text{ modes.}$$

if considered

$$V \cong 76 \Rightarrow M = \frac{V^2}{2} = 2888 \text{ modes}$$

15. Graded index fiber has parabolic R.I. profile with core diameter 50 μm & NA = 0.2. Find the number of modes guided at wavelength 1 μm.

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→ Given: core diameter = 50 µm N.A = 0.2

$\Rightarrow a = \frac{50}{2}\mu = 25\ \mu m$ $\lambda = 1\ \mu m$

parabolic profile $\Rightarrow \alpha = 2$

$$V = \frac{2\pi a}{\lambda}(NA)$$

$$= \frac{2 \times \pi \times 25 \times 10^{-6}}{1 \times 10^{-6}} \times (0.2)$$

$$V = 31.4$$

$$M \simeq \frac{V^2}{4} = \frac{(31.4)^2}{4} = 246.49 \simeq \underline{\underline{247}}$$

16. Graded index fiber has R.I. profile $n_1 = 1.5$ & $\Delta = 1\%$. Estimate possible core diameter which allows single mode operation at a wavelength of 1.3 µm.

→ Given: $n_1 = 1.5$ $\Delta = 1\% = 0.01$ $\lambda = 1.3\ \mu m$

$$V = 2.4\left(1 + 2/\alpha\right)^{1/2}$$

$\boxed{\alpha = 2}$

$$V = 2.4\left(1 + \frac{2}{2}\right)^{1/2}$$

$$\boxed{V = 2.4(\sqrt{2})}$$

$$V = \frac{2\pi a (NA)}{\lambda}$$

$$a = \frac{V\lambda}{2\pi (NA)}$$

$$= \frac{V\lambda}{2\pi n_1 \sqrt{2\Delta}}$$

$$= \frac{2.4\sqrt{2} \times 1.3 \times 10^{-6}}{2\pi \times 1.5 \times \sqrt{2 \times 0.01}}$$

$$\boxed{a = 3.3 \mu m}$$