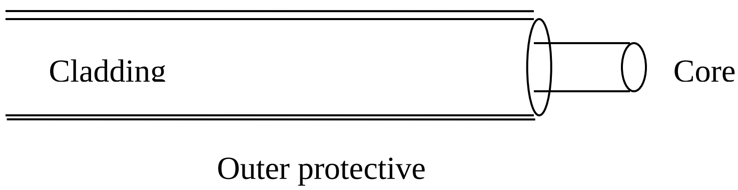
Optical fibres

A thin flexible and transparent wire prepared for light propagation is called optical fibre. The optical fibre has been constructed for the following reasons:

- The light wave cannot traverse long distance in air without any losses.
- To make loss less light wave communication, the optical waves can be guided through optical fibre.

The optical fibre can be used for the many of industrial application and medical applications as well. The optical fibre consists of two media kept one inside the other. The centre transparent medium of optical fibre is called "core" and the outer is cladding. The refractive index of core will be always higher than the refractive index of cladding.



1. The propagation of light in optical fibre.

The light propagates through optical fibre through "Total internal reflection". The total internal reflection appears due following reasons.

- When light traverse from optically rarer medium (like air) to denser medium (glass) the refracted ray moves towards the normal drawn on the interface of media as in Snell's law. Conversely, if light traverse from denser to optically rarer medium, the refracted ray moves away from the normal drawn on the interface of the medium fig.(1a)
- If the angle of incidence increases (fig.1b), to certain value for which the refracted ray happen to be on the interface of medium. The angle of incidence s known as critical angle (θ_c)(fig.1c).
- If the incident angle (fig.1d) increases more than critical angle, then the refracted ray falls on the same denser medium with no refraction. "This reflection of light is called total internal reflection".

Thus, following are the conditions for total internal reflection:

1. The ray of light should be traverse from denser to rare medium.
2. The incident angle should be more than the Critical angle ($\theta_i > \theta_c$).

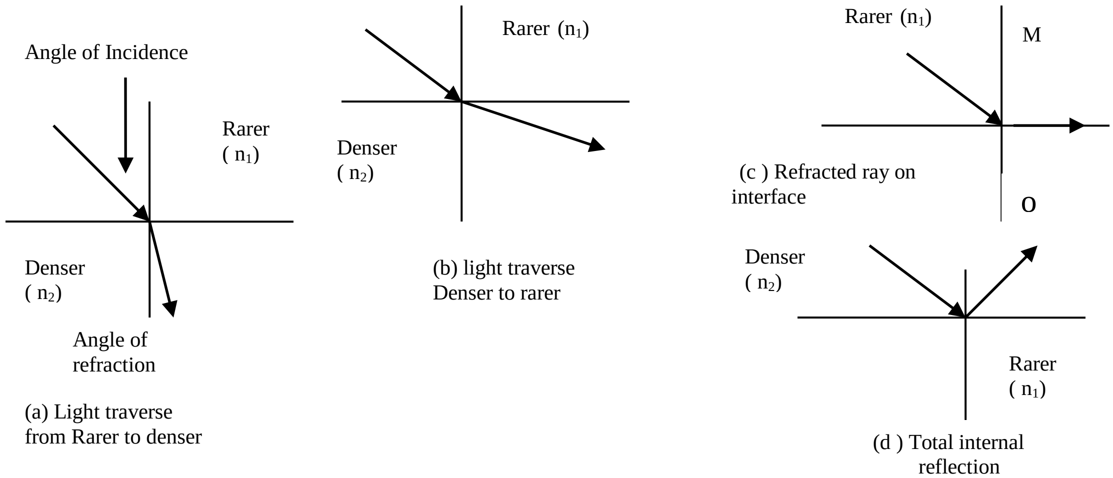


Fig.1 propagation of light from rarer to denser medium

Total internal reflection

If the incident ray exceeds the critical angle, the refraction would be turned in to reflection called total internal reflection. The critical angle is used for the mathematical expression to the occurrence of total internal reflection (fig.1c)

$$n_1 \sin\theta_i = n_2 \sin 90^0 \quad \text{(from Snell's law)}$$

$$\sin\theta_i = \frac{n_2}{n_1} \quad \text{Since, } \sin 90^{\circ} = 1$$

$$\sin\theta_c = \frac{n_2}{n_1} \quad \text{Since, } \theta_i = \theta_c$$

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

Therefore, to propagate the light through optical fibre, the incident angle should be made higher than the critical angle at various points on the core, so that the light can be traversed by the total internal reflection at those points.

To achieve the above, the size of core should be adjusted suitably which causes different types of optical fibre based on size, (no. of modes) refractive index and modes of propagation.

1.2 Classification

In the optical fibres the materials used, refractive index and mode of propagation of light are used for classification as follows:

1.2.1 Material Based optical fibres,

The material based classification results to the following types:

1. Plastic made fibres.
2. Glass made fibres.

The plastic made fibres are obtained from polymers of transparent to light, flexibility and interaction less to light etc,.

For example poly methyl metha acrylate (PMMA), polyethylene (PE), polystyrene (PS) are used as core materials.

Glass made fibre is also fabricated from flexible glass as core with suitable drawing technique in presence of impurities. Therefore, the above types of optical fibres are limited to some application.

1.2.2 Classification of optical fibres based on refractive index

The types of optical fibre can be classified based on the refractive index are

1. Step index fibres.
2. **Graded index fibres.**

Step index

If the refractive index of core remains the same from the centre of the core to the core-cladding interface; those optical fibres are known as step index fibres (fig.2a). The distance from centre of core to interface of fibre vs. refractive index is shown as below:

Graded index

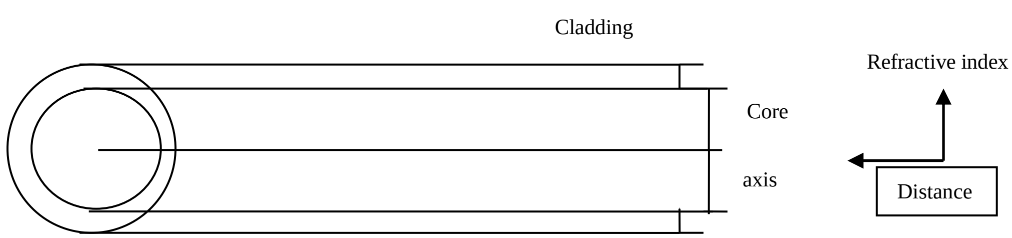


Fig.2a Step Index fibre profile

These types are made of varying refractive index of core material. Therefore, the refractive index changes with distance form the centre of fibre to core-cladding interface. The profile of above is as shown in the fig 2

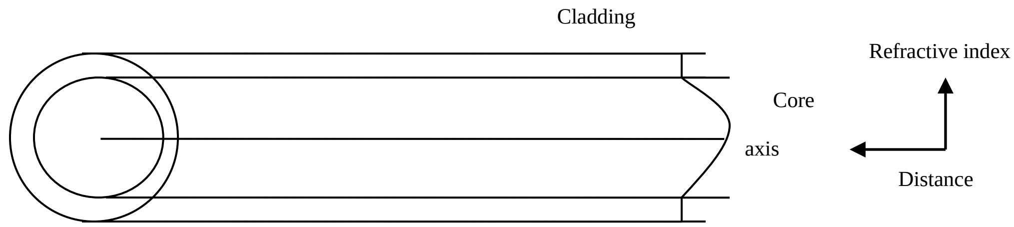


Fig.2b Graded Index fibre profile

1.2.3 Modes of propagation based optical fibre

Based on modes of propagation of light through core, the following are the types of optical fibre identified.

- Single mode fibres
- Multimode fibres

Single mode fibres

Considering the light as electromagnetic radiation, the possible modes of propagation are transverse electric (TE) modes and transverse magnetic (TM) modes. Among them, the TE_{10}, TE_{11}, TE_{01} and TM_{10}, TM_{11}, TM_{01} are possible, within which the modes TE_{10} and TM_{11} are significant. If the core size is adjusted to allow only one mode of light wave propagation is single mode fibre, whose profile (fig.2c) is shown below:

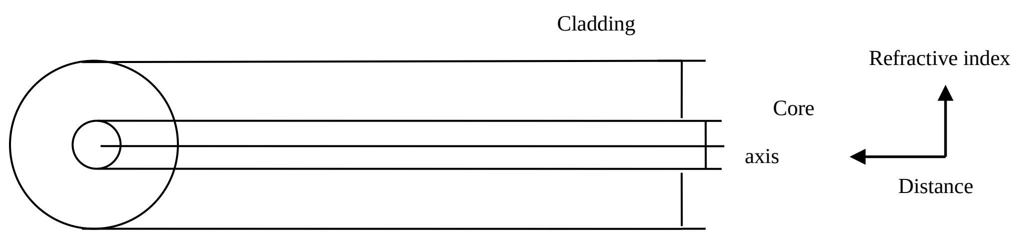


Fig.2c Single mode fibre profile

Multi mode optical fibre

If the core size has been adjusted to allow more than one mode of propagation of light wave is multimode fibre. The profile of multimode fibres is as shown below:

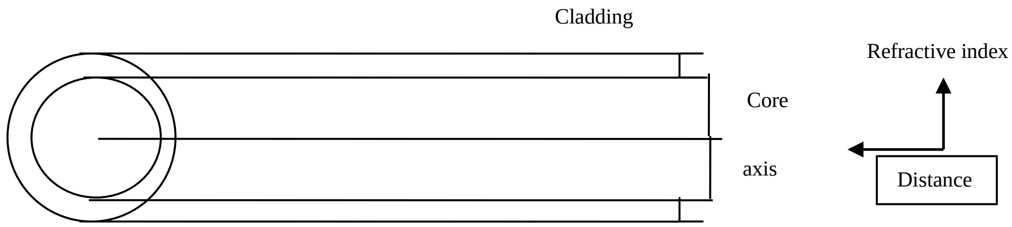


Fig.2d Multi mode fibre profile

Combination of optical fibres

The refractive index of core and mode of propagation of light in optical fibre is used to form combination types of optical fibre.

- Step index-single mode fibres
- Step index-multi mode fibres
- Graded index-Single mode fibres
- Graded index-Multi mode fibres

1.3 Parameters of optical fibres

The parameters of optical fibres are:

- Radius of the core
- Numerical Aperture
- Acceptance angle

1.3.1 Radius of the core

The size of optical fibres plays crucial role in the light wave propagation through fibre. Therefore, radius of the core is significant to decide mode of propagation in fibre. The thickness/diameter of the core can be measured in spite of measurement of radius. For the purpose the profile projector can be used.

1.3.2 Numerical aperture (NA)

Numerical aperture (NA) is a light gathering property of optical fibre, which gives the quantity of light that brought into the centre of optical fibre in terms of incidence angle. To calculate NA, consider a longitudinal section of fibre as in fig.(3). Let n_0, n_1, n_2 are the refractive indices of air (outside optical fibre), core and cladding respectively.

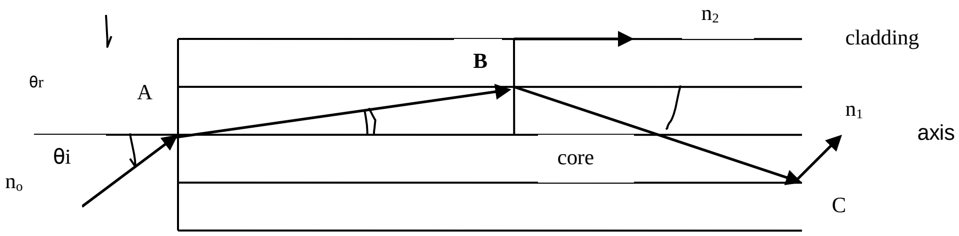


Fig.3 Longitudinal Section of optical fibre

θ_i , θ_r are incidence angle and refracted angle of the light through fibre.

Applying Snell's law at A

$$n_0 \sin\theta_i = n_1 \sin\theta_r$$

$$\sin\theta_i = \frac{n_1}{n_0}\sin\theta_r = \frac{n_1}{n_0}\sqrt{1-\cos^2\theta_r} \qquad (1)$$

Applying Snell's law at B

$$n_1 \sin(90-\theta_r) = n_2 \sin 90$$

$$n_1 \cos\theta_r = n_2$$

$$\cos\theta_r = \frac{n_2}{n_1} \qquad (2)$$

Substituting (2) in (1)

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

$$\sin\theta_i = \frac{1}{n_0}\sqrt{n_1^2-n_2^2}$$

$$\therefore NA = \sin\theta_i = \frac{1}{n_0}\sqrt{n_1^2-n_2^2}$$

or

$$NA = \sin\theta_i = \sqrt{n_1^2-n_2^2} \qquad \text{(Where } n_0 = 1 \text{ for air)} \qquad (3)$$

1.3.3 Acceptance angle

It is a semi vectorial angle that formed by the set of incident rays at the centre of fibre, which helps to decide the size of core.

From $\quad NA = \sin\theta_i = \sqrt{n_1^2-n_2^2}$

$$\sin\theta_i = \sqrt{n_1^2-n_2^2}$$

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

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

1.4Applications of optical fibres in industry and medicine

1.4.1 Optical fibre in communication

The conventional method of communication has more limitation toward signal security and also affected by change in atmospheric factors. To overcome these limitations and factors, te optical fibres are introduced in communication system. In optical fibre communication the protocol consist of transmitter unit and receiving unit in the system.

The transmitter unit

The transmitter unit contains light source, signal to be transmitted, light modulator, amplifiers and coupler. Similarly, the receiver unit consists of couplers, light detectors, amplifiers, filters and output device. The transmitter unit and receiver unit are connected by suitable optical fibre. The layout of optical fibre communication is shown in the fig.4

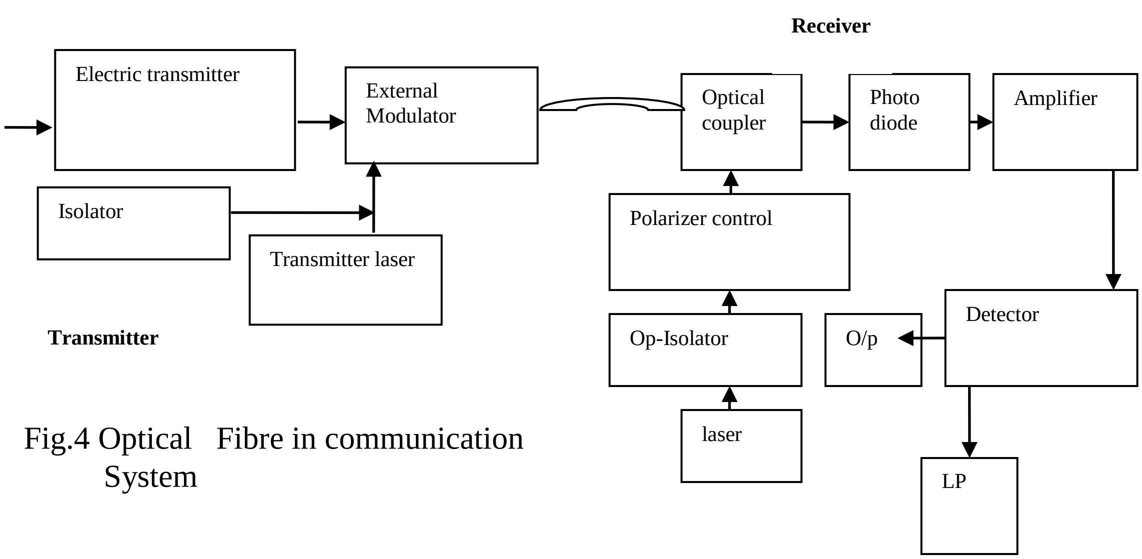


Fig.4 Optical Fibre in communication System

The signal

The signal to be transmitter can be voice, music as audio or movie as video signals. Generally, the signals will be in analog form which can be converted to digital using A/D converters in the transmitter.

The optical communication system (fig) system consist of transmitter unit containing digital source, electrical transmitter, laser as light source, modulator and transmitter channel.

In receiving end, the light detector, amplifier, optical coupler and the de modulator are available.

In transmitter, the digital signal will be converted in to electrical signal, which modulates optical carrier wave through transmitter wave by laser in terms of intensity, frequency or phase.

Modulator

In the modulator the mixing of signal with optical carrier wave takes place. The modulation can be

- Simple ON-OFF keying (OOK)
- Amplitude shift keying (ASK)
- Frequency shift keying (FSK)
- Phase shift keying (PSK)
- Multi level modulation keying (MMK)

The function of the modulator may be electro optic or acoustic optic phenomenon.

Receiver unit

The output of transmitter can be connected to the optical fibre which ends at receiver.

The receiver unit can be two type, they are:

- Homodyne receiver
- Heterodyne receiver

In homodyne receiver, one way communication is encouraged where as the heterodyne receiver encourages to transmit and receive the signal in a single receiver unit. If the transmitted signal alone be received through the receiver whose frequency synchronize with the local laser frequency, it will be homodyne receiver ($f_s = f_l$).

Heterodyne receiver

If the transmitted signal be received through the receiver whose frequency does not synchronize with the local laser frequency, it will be heterodyne receiver ($f_s \neq f_l$). The homodyne and heterodyne receivers are shown in present fig

Transmitter laser

To achieve high bit rate and long range data transmission with low error rate a single mode transmitter laser can be used as in fig.5

Isolators

There can be undesired reflection between transmitter lasers to the external modulator. To avoid the consequence as reflection this improves laser emission spectrum. Further, it causes quality deterioration which causes quality of transmission. To avoid above, a optical isolation is used across external modulator and transmitter laser.

External modulators

The direct modulation technique contain semiconductor component such devices directly modulates using injection current by charge carriers in terms of intensity amplitude and frequency adding additional noise.

The above can be avoided in external modulators.

.Optical coupler

The optical coupler mixes the receiving signal and local light wave from laser to improve system performance, quality of emission spectrum of laser. This optical coupler has 2 inputs through super imposed optical waves and one output to photodiode

Photodiode

The photo diode gives electric current corresponding to optical input power. Normally, PIN diodes or avalanche diode (APD) are used. Among them, the PIN diodes are significant due to input optical power proportional to square of input electric field.

It generates electric current proportional to optical input power. For the purpose PIN and APD are used. The gain of APD is improved by performance of coherent optical radiation PIN diodes are used in practice. As the optical power is proportional to the square of the electric field, the superposing of two fields is linear. In photodiodes current also contain an immediate frequency which referred as IF signals.

Inter mediate Frequency (IF) filters

The IF signal, the difference of local laser frequency and frequency of received light are significant in the present communication system.

To get homodyne detection, care should be taken to get phase and frequency to match.

To get heterodyne detection, the signal should be selected by IF filter and the demodulated with respect to amplitude/frequency or phase.

All type of demodulator can be used. The output of demodulator may also contain noise which can be eliminated by low pass filter.

Output device

The filtered nose will be sampled and hold receives the signal after filter to be connected to output device.

1.5 Some losses in optical fibres

The optical fibre does not experience the loss in terms of intensity of light. However, the presence of impurities, scattering at the edges, geometry of structure and dispersion of light causes some losses.

Transmission loss/attenuation (α)

If the intensity of light at the second end of the optical fibre be I_{out} and intensity at first end be I_{in}

The attenuation, $\alpha = -\log\left(\frac{I_{out}}{I_{in}}\right)$

In decibel the attenuation, $\alpha = -\frac{10}{L}\log\left(\frac{I_{out}}{I_{in}}\right)dB$

Other possible losses in optical fibre

The possible losses are absorption, scattering, radiation losses and geometric losses.

The absorption loss

The absorption losses appears as

- Extrinsic losses
- Intrinsic losses
- Atomic defect losses

Extrinsic losses

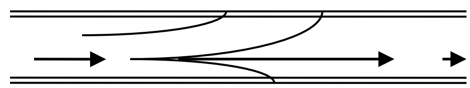
The extrinsic loss appears due to presence of impurities which absorbed the light. The impurities may be due to presence of Fe, Cr, Co and Cu in the core material. The impurities could absorb the energy that may reemit the absorbed energy during the de excitation in different wavelength which causes loss of intensity to original light of specific wavelength.

Intrinsic loss

Since, the fibre core itself absorbs some quantity of energy which is known as intrinsic loss.

Scattering and radiation losses

Since, optic fibre contains glass as core, where impurities are present. The scattering of light at these impurities causes Raleyeigh scattering where the energy of scattered wave directly proportional to 4th power ($E = 1/\lambda^4$) of wavelength. Therefore, small change of energy causes 4th power of wavelength. The loss of energy at couplers and interfaces are known as radiative losses.



Geometrical loss

Due to bending of optical fibres there are 2 types of losses from macroscopic bending and microscopic bending. If the fibre be rounded as big circle of known radius of curvature, the loss may be less called macroscopic bending loss.

For small bending of fibre the loss of energy in microscopic bending is larger. Some time the irregularities in the dimensions cause geometrical losses.

Dispersion loss

In the transmission of light through optical fibres the pulse width varies due to dispersion of light through the core. The loss of intensity caused as result of dispersion of light is due to

- Material dispersion
- Waveguide dispersion
- Inter modal dispersion

Material dispersion

The refractive index of core causes the changes in the wavelength/frequency called material dispersion. If narrow pulse passes trough fibre, causes broadening of pulse width due to material property. It can be overcome by highly monochromatic source of light. The single mode fibre could reduce the material dispersion to maximum extent.

Waveguide dispersion

The optical fibre can be considered as circular wave guide where refractive index varies with modes of propagation with wavelength causes wave guide dispersion.

Intermodal dispersion

The optical power in the pulsed wave distribution over the mode of light through the fibre decreases during the propagation, these changes are known as intermodal dispersion.

1.6 Optical fibres as sensors

Generally, optic sensor consists of light source, optical fibres and detector. The sensors are Two types viz., active sensors and passive sensors.

The physical changes directly changes the electrical responses called active sensors; where as the physical changes are indirectly recorded to sensing is called passive sensors.

Temperature sensor

The light can be arranged to fall on reflecting surface and the associated phase angle is be measured. The reflecting surface can be varied using temperature variation, which causes additional phase angle to light wave as seen in the fig.5. When light thrown on the reflector by optical fibre, the initial and final response can be compared for measure of temperature by relative correlation.

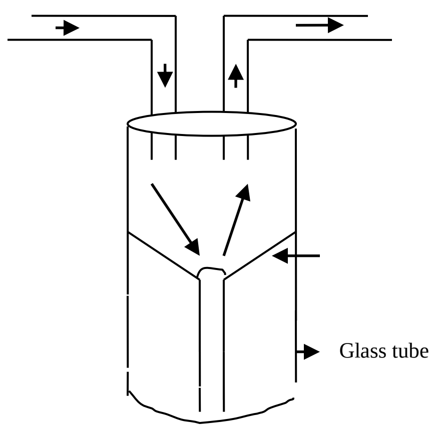


Fig.5 Temperature sensor

Displacement sensors

The light is sent through transmitting fibre and further it is allowed to fall on moving target. The light ray falls on the surface and gets reflected. The incident ray could mix with reflected wave and forms standing wave to which the phase angle shift can be measured. The fig indicates displacement sensors.

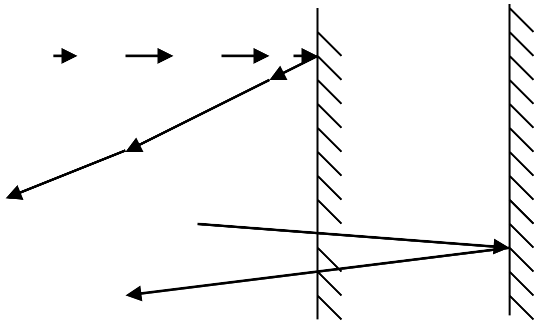


Fig.6 Displacement sensor

Optical fibres in medicine

Endoscope

The endoscope is a instrument through which small surgery could be performed. The construction details are given as in fig.7. The ray of light is obtained using laser the light is partially allowed to pass through optical fibre kept inside the tube as shown in the figure. The output of fibre is connected to lens system and then to prism to split the object. The reflected light can be obtained using polished prism and returning ray will be visualize to get the real position of inner organs.

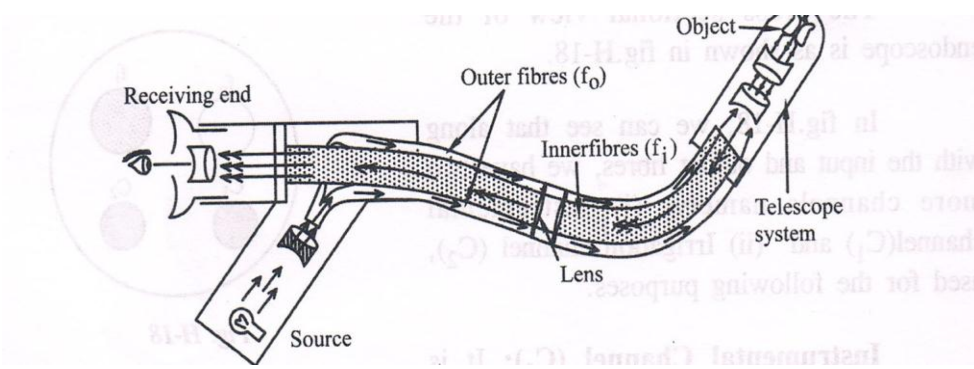


Fig.7 Endoscope

Question bank

1. What is meant by population inversion? *(AU,Chennai,Apr2009)*

The no. of atoms in the ground state will be more than that the atom in the excited state and it is called ideal state of atom. The he reverse of this a state of achieving more no. of atoms in the higher energy level than that of the lower energy is called population inversion.

2. What are coherent sources? *(AU Tricy Jan 2010)*

Coherent sources are the sources which have same wavelength and frequency. It has correlation with the amplitude and phase at any point with any other point in propagation.

3. What are Einstein's coefficients? *(AU Jan 2009)*

The Einstein's coefficients A and β account for spontaneous and stimulated emission/ absorption probabilities of light by a system of dissimilar particles. It is also explains the importance of meta stable states and condition for laser action.

6. Define meta stable state? *(AU Jan 2009)*

It is the state for which the life time of electron is more than the excited state, i.e, it is the semi stable which lies between the excited state and the lower state.

7. Distinguish between spontaneous and stimulated emission?(AU,Jan2011,12,13)

The spontaneous emission

The atom in the excited state returns to ground state thereby emitting a photon without any external inducement is called spontaneous emission. The emitted photons can move randomly

The radiation given out so less intense and are incoherent

Photons are not in phase

The stimulate emission

An atom in the excited state is induced to return to ground state thereby resulting in two photons of same frequency and energy is called as stimulated emission.

The emitted photons move in same direction and they are highly directional, the radiation is highly intense mono chromatics and coherent photons are in phase.

8. Define coherent length and coherent time? How are they related to each other?(AU2003)

The max. Length up to which two wave trains have correlations with the amplitude and phase is called coherent length and the time up to which they are correlated is called coherent time they are also related as coherent length

9. What are the characteristics of light (AU2009,12,13)

The four important characteristics of the laser beams are: It is highly directional it has high intensity the beam is purely monochromatic it has coherence

10. State some of the applications of lasers in engineering and/industry?(2012)

Higer power lasers are useful for blast holes, Cracks flows, blow holes etc. in the materials

They are used to test the presence of pores Cracks flows, blow holes etc., in the materials

they are used for welding

11. Classify different types of laser with respect to active medium
Gas laser-CO2 laser(AU2002)
Solid state laser-semiconductor laser as Ga-As
Solid laser0Nd-YAG laser

12. What are the difference between the homo and hetero junction laser(2009,10)
Homo junction lasers are made up of single crystals, power out put is low, pulsed & continuous and high current density,
The hetero junction lasers may contain polycrystal,power out put is high,continuous,low threshold current density

13. Give some application of laser in medical field(2009)
Lasers are used in microsurgery and bloodless operations,treatment of detached retina and cancer treatment

14.what are the advantages of Nd-YAG lasers?(2012)
Low excitation threshold potential,it has higher thermal conductivity than ruby rod,high pulse repetition rate, quasi continuous waves and high efficiency

Part-B

1. What are Einstein coefficients for atomic transition? derive relation
2. Explain the principle, structure and working of Nd-YAG laser with energy level diagram
3. Describe the structure and principle wit working of co2 laser:
4. Draw suitable diagram explain how laser action is achieved in homo junction and hero junction Ga-as laser.

Optical fibre

Part A

1. Give four applications of optical fibre(2000)
1. Used in displacement sensor,2. Used in the fluid level indication sensor
3. Pressure sensors and 4.temperature sensors

2. Explain the basic principle of optical fibre communication(2000)
Total internal reflection is used in fibre optic communication. When light travels from a denser to rarer medium at a particular angle of incidence called critical angle the ray emerges along the surface of separation. The angle of incidence exceeds the critcal angle the incident ray is reflected in the same medium and this phenomenon is called total internal reflection.

3. Distinguish between step-index and graded index fibres(2010,11)
The difference in refractive indices between the core and the cladding is obtained in a single step and hence called step index. The light ray propagate as marginal rays and pass through fibre
The light rays meridian ray propagate as meridian ray propagate as medium rays and pass thought fibre axis
It follows a zig -zag light propagation, low band width Due to non uniform refractive indices. In their difference in refractive indices between the core and the cladding, which gradually increase from centre towards interface and hence called, graded index fibre.

Light propagates in the form of skew rays and does not cross the fibre centre
It has high value of band width.

4. Define acceptance angle(2009)
Acceptance angle is the maximum angle to the axis at which light may enter into the fibre so that it can have total internal reflection inside the fibre.

5. What is the role of cladding in an optical fibre?(2009)
An optical fibre consists of core which is surrounded by cladding. Here, the role of cladding is to make the light to suffer total internal reflection inside the fibre. Satisfying the condition that light should travel from denser to rarer medium.

6. List out factors that causes loss in optical fibre(2009)
During the transmission of light through the optical fibre, three major losses will occur viz., attenuation, Distortions and dispersion, Attenuation is mainly caused due to the absorption, scattering and radiation of light inside the fibers.
Distortion and dispersion occurs due to spreading of light and also due to manufacturing defects.

7. What is meant by endoscope? Mention its use(2010)
The medical endoscope is a tubular optical instrument used to inspect /view the internal parts of human body which are not visible to the eyes normally. The photograph of the internal part can also be taken using endoscope.

8. Define numerical aperture?(2011)
It is light gathering power of optical fibre. it is also measure of light that can be accepted by the fibre

9. Give applications of fibre optic system/(2004)
It can be used in long distance communication for transmission lines
Large no of signal can be accommodated. It can be used in Local area networks LAN and it also be used as sensors in the devices.

10. Mention any four advantages of optical fibre sensors(2006)
It could be used in external interface, used in remote sensing, signal security, compactness

11. Calculate the numerical aperture for the optical fibre whose core refractive index is 1.52 and cladding has 1.43;(2001)

N1=1.52 and N2=1.43

$NA=[(N1)^2-(N2)^2]^{1/2}=1.52^2-1.43^2 =2.3104-2.0449 = 0.5152$

12. Calculate the acceptance angle for the fibre of NA = 0.39?(2003)

Acceptance angle is $\sin(\theta) = 0.39$ and $\theta = \sin^{-1}(0.39)=23^o35'$

13. Differentiate between active and passive fibre optic sensors(2007)
In active sensors the physical parameter to be sensed directly acts on the fibre itself to produce the changes in the transmission characteristics. In extrinsic sensors separate sensing element will be used and the fibre will act as a guiding media to the sensors.

14. Mention any four advantages of optical fibre(2003)
It is light weight, flexile to handle, small in size, non inductive, non conductive and non radiative, high band width can be accommodated, no sort circuit as in line communication

15. What is the condition to the total internal reflection?2003()
Following are the conditions for total internal reflection:

1. The ray of light should be traverse from denser to rare medium. 2.The incident angle should be more than the Critical angle ($\theta_i > \theta_c$).

16. What is mode of propagation in optical fibre(2004)

Considering the light as electromagnetic radiation, the possible modes of propagation are transverse electric (TE) mode and transverse magnetic (TM) mode. Among them, the TE_{10}, TE_{11}, TE_{01} and TM_{10}, TM_{11}, TM_{01} are possible, within which the modes TE_{10} and TM_{11} are significant. If the core size is adjusted to allow only one mode of light wave propagation then it should be single mode fibre.

17. How will you classify the optical fibre (2006)
In the optical fibres the materials used, refractive index and mode of propagation of light are used for classification as follows:

18 Differentiate the single mode and multi mode optical fibre (2010)

In single mode only one mode of propagation is possible, core size is small, and whereas in multi mode more than one mode is possible core size is large.

19. What are the main requirements of light source used in fibre optic communication(2005)

Light produced should be mono chromatic, it must modulate with source of light in modulator, should be high efficiency, and should require small power for the operation.

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