MODULE – 1: Fundamentals of Optoelectronic devices

Lasers - Expression for energy density using Einstein coefficients (derivation), Condition for laser action, Requisites for laser system, Construction and working of He-Ne Laser, Advantages and its limitations. Application of laser: Laser in range finder. Numerical Problems

Optical Fibers: Structure, Principle and light guiding mechanism, Acceptance angle and Numerical aperture (derivation), V-number and Modes of propagation (qualitative), Types of optical fibers and their characteristics, Attenuation and its types, Application of optical fiber: Point-point communication, Numerical Problems

LASER is the acronym for Light Amplification by Stimulated Emission of Radiation.
The principle of LASER is Stimulated Emission.

The basic properties of laser are

- LASER light is nearly a monochromatic beam
- It is unidirectional beam
- It is a coherent beam where all waves are exactly in phase with one another
- It consists of high directionality and hardly diverges.
- It exhibits high brightness
- Laser is extremely intense; hence by Laser, we can achieve very high energy density.

Matter Radiation Interaction:

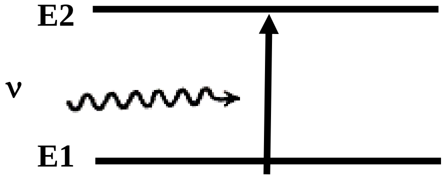
When radiation interacts with matter, it leads to the transition of a quantum system such as an atom or molecule from one energy state to another.

Consider two energy states E_1andE_2, (E2 > E1) of a system. An electron at the energy stateE_1 is exited to E_2, when it absorbs a light photon of energy ΔE = (E_2-E_1). If an electron makes a transition from the higher energy state E_1, a light of photon of energy ΔE = E_2-E_1 is emitted. In both cases, the frequency of the photon involved is $\nu = \frac{\Delta E}{h} = \frac{E_2 - E_1}{h}$

There are three possible ways in which the interaction of radiation and matter can take place.

1. Induced (stimulated) absorption

Induced adsorption is a process where the atom in a lower energy state rises to a higher energy state by absorbing a suitable photon.



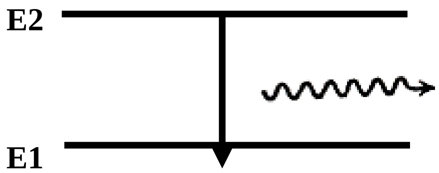
Consider two energy states with energies E_1 and E_2. Let a photon of energy, ΔE = E_2-E_1 be incident on the atom. The atom absorbs the energy of the photon and its energy becomes equal to $E_1+\Delta E = E_2$. Hence it makes a transition to the exited state E_2. This is called induced absorption.

Induced absorption can be represented as

$$\text{atom} + \text{photon} \rightarrow \text{atom}^* \qquad \text{(* represents the excited state)}$$

2. Spontaneous emission:

Spontaneous emission is an process in which an atom in the higher energy state falls to the lower state by emitting a photon on its own.



Consider an atom in the excited state, the atom voluntarily emits a photon of energy ΔE equal to (E_2-E_1) and falls to the energy state E_1. The emission where an atom emits a photon without any aid by external agency is called spontaneous emission. The photons emitted may have any direction and phase. Hence they are incoherent.

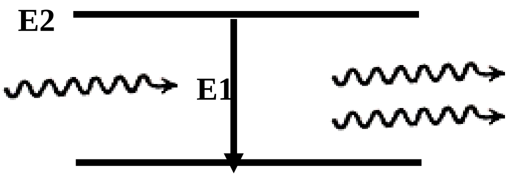
This process can be represented as

$$\text{atom}^* \rightarrow \text{atom} + \text{photon}$$

Note: 1) Life time of atoms in higher energy state is usually very small of the order of 10^{-8} sec.
2) If there is an assembly of atoms, the radiation emitted spontaneously by each atom has a random direction and random phase. Therefore radiation emitted by spontaneous emission is incoherent. (Eg: glowing electric bulb)

3. Stimulated emission:

Stimulated emission is a process of the emission of a photon by a system under the influence of a incident photon of suitable energy, due to which the system transits from a higher energy state to a lower energy state.

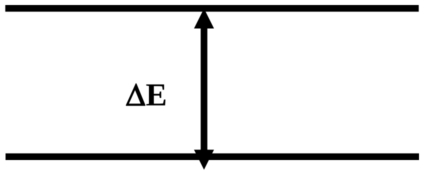


Consider an atom in the exited state with energy E_2. Let a photon of energy $\Delta E = E_2 - E_1$ interacts with this atom. As a result, the atom emits a photon and transits to the lower energy state. The emitted photon will have same phase, energy and direction of movement as that of the incident photon." The electromagnetic waves associated with the two photons will have same phase and thus they are coherent. This kind of emission is responsible for laser action.

This process can be represented as

$$\text{atom}^* + \text{photon} \rightarrow \text{atom} + 2\,\text{photon}$$

Energy density using Einstein's coefficients:



Consider two energy states E_1 and E_2 of a system of atoms ($E_1 < E_2$). Let N_1 be the number of atoms in the energy state E_1 and N_2 be in E_2 per unit volume of the system. Then N_1 and N_2 are called the number density of atoms in the energy states E_1 and E_2 respectively. Let $d\nu$ be the energy of the incident radiation per unit volume of the system where radiations lie in the frequency range ν to $\nu + d$, then $'U_\nu'$ is called the energy density of frequency "ν".

<u>Case (1): Stimulated absorption</u>:

The rate of stimulated absorption depends on (a) the number density of lower energy state

(b) The energy density $'U_\nu'$.

Rate of absorption = $B_{12} N_1 U_\nu$ → (1)

Where B_{12} → Einstein's Coefficient of induced absorption.

<u>Case (2): Spontaneous emission:</u>

The rate of spontaneous absorption depends only on the number density of the higher energy state i.e., N_2.

Rate of spontaneous emission = $A_{21} N_2$ ----------- (2)

where A_{21} → Einstein's coefficient of spontaneous emission.

<u>Case 3: Stimulated emission:</u>

The rate of stimulated absorption depends on a) Number density of higher energy state

b) The energy density $'U_\nu'$.

Therefore, rate of stimulated emission $\propto N_2 U_\nu$

$$= B_{21} N_2 U_\nu \text{ --------------- (3)}$$

where B_{21} is the Einstein's coefficient of stimulated emission.

At thermal equilibrium,

the rate of absorption= Rate of spontaneous emission+ Rate of stimulated emission.

ie $B_{12}N_1U_\upsilon = A_{21}N_2 + B_{21}N_2U_\upsilon$

ie $U_\upsilon(B_{12}N_1 - B_{21}N_2) = A_{21}N_2$

$$\therefore U_\upsilon = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2}$$

Or $U_\upsilon = \frac{A_{21}}{B_{21}}\left[\frac{1}{\frac{B_{12}N_1}{B_{21}N_2}-1}\right]$ ---------------------- (4)

According to Boltzmann's law we have

$N_2 = N_1 e^{-\left(\frac{E_2-E_1}{KT}\right)} = N_1 e^{-\frac{h\upsilon}{KT}}$

$$\therefore \frac{N_1}{N_2} = e^{h\nu/kT} \text{-------------(5)}$$

Therefore equation (4) becomes

$$U_\upsilon = \frac{A_{21}}{B_{21}}\left[\frac{1}{\frac{B_{12}}{B_{21}}e^{\frac{h\upsilon}{KT}}-1}\right] \quad \text{----------------- (6)}$$

According to Planck's law of radiation

$$U_\nu = \frac{8\pi h\nu^3}{C^3}\left[\frac{1}{e^{\frac{h\nu}{KT}}-1}\right] \quad \text{-------------------- (7)}$$

Comparing equation (6) and (7) we have

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{C^3}, and\, \frac{B_{12}}{B_{21}} - = 1$$

➔ $B_{12}=B_{21}=B$ ---------- (8) and $A_{21}=A$

The identity (8) implies that the probability of induced absorption is equal to the probability of stimulated emission.

Therefore, we can write the expression for energy density in terms of Einstein's A & B coefficients as

$$U_\upsilon = \frac{A}{B\left[e^{\frac{h\nu}{hT}} - 1\right]}$$

Condition for Laser action:

1. <u>Population inversion:</u>

Population inversion is the state of a system in which the number of atoms in the higher energy level is greater than the number of atoms in the lower energy state.

Under normal condition, the population is more in lower state. But for stimulated emission and hence for lasing action more atoms must be present in the exited state by some artificial methods known as pumping.

Normal state **Population inversion state**

2. <u>Metastable state:</u>

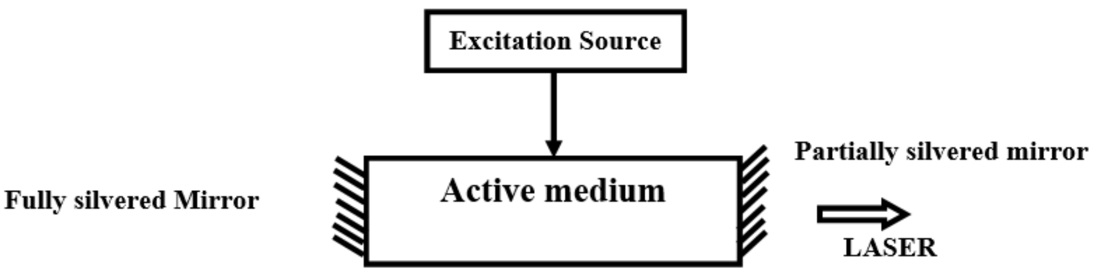
An excited energy between the ground state and one of the ordinary excited state having longer time of about 10^{-3} to 10^{-2} sec is called the metastable state. The existence of this state is very essential for creating population inversion. .

Requisites of a laser system

In the laser system, there are mainly three requisites. The details of the same are as follows:

1) An **excitation source** provides energy in an appropriate from for pumping the atoms to higher energy levels. If the pumping is achieved by light energy input, then it is called optical pumping (Ruby laser). If the pumping is achieved by electrical energy input, then it is called electrical pumping (He-Ne laser).
2) **Active medium**. A medium in which light gets amplified is known an active medium. The medium may be solid, liquid or a gas. It contains atoms having at least one metastable state along with ground state and other ordinary excited states.

3) <u>Laser cavity (Resonating cavity):</u>

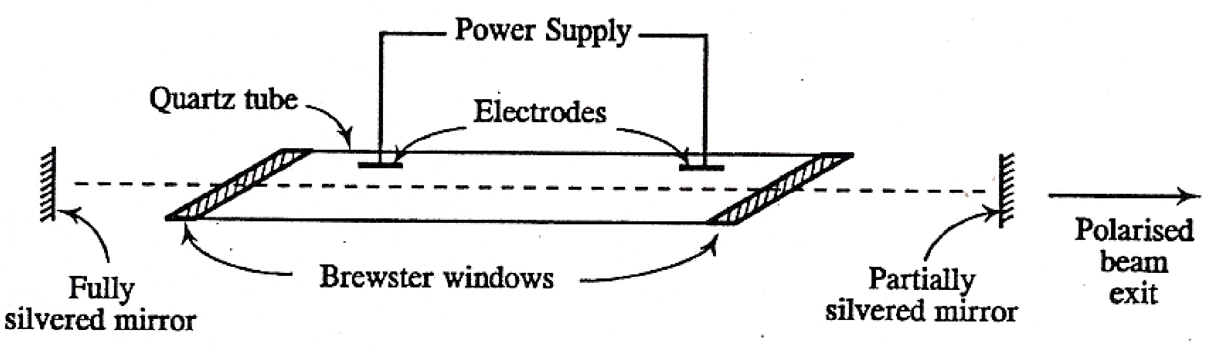


A laser device consists of an active medium bound between two parallel mirrors, one is perfect reflector and other one is partially reflector. The mirrors reflect the photon to and fro through the active medium. Thus, the two mirrors provide the optical feedback.

Inside the cavity two types of waves exist, one moving towards the right and other to the left. These waves interfere constructively or destructively depending on the phase difference. In order to arrange for constructive interference, the distance ‘L’ between the two mirrors should be such that the cavity should support an integral number of half wavelength, i.e. $L = m\frac{\lambda}{2}$, where **m** is an integer. This results in the amplification of stimulated emission of radiation which is the laser light.

Helium-Neon Laser:

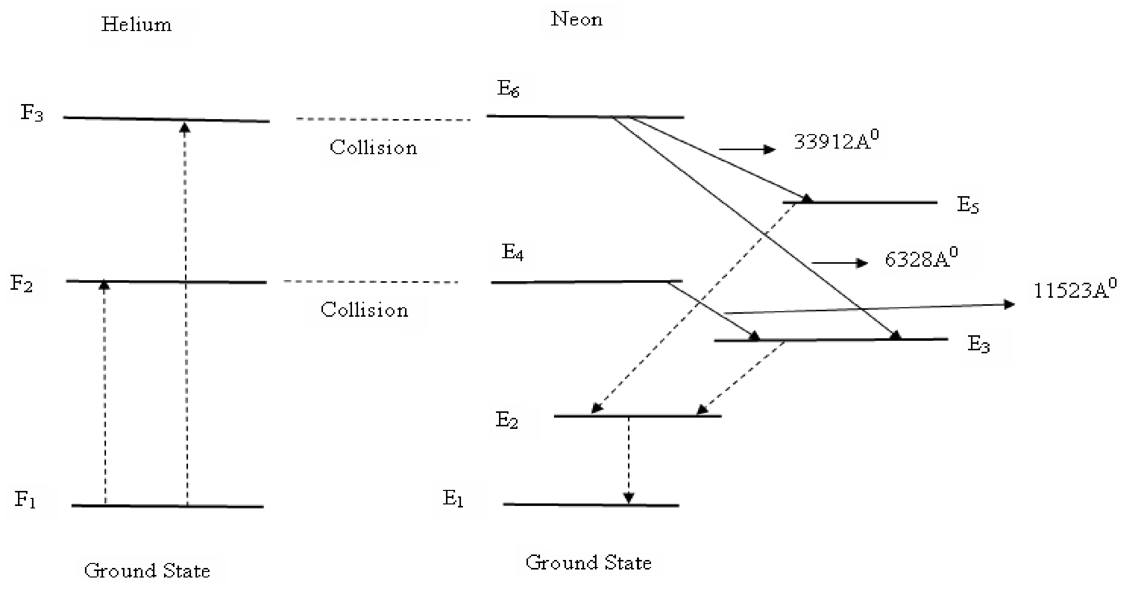
Construction:



HELIUM - NEON LASER

It consists of a narrow quartz tube of about 1m long and 1.5 cm in diameter. A mixture of helium and neon in the ration 10:1 is taken in the tube. The tube has two parallel mirrors, one fully reflecting and other partly reflecting fixed at either end. An electric discharge is produced in the gas by means of electrodes, connected to a high voltage dc source.

Working:



When an electric discharge is produced in the gas, electrons are released. These free electrons are accelerated towards the anode, during which they collide with the gaseous atoms in the tube. Since the helium (He) concentration is higher, the collisions are more in these atoms. Hence, He atoms will be exited to the higher energy levels F_2 and F_3 from the ground state. The atom remains in the metastable states F_2 and F_3 for a longer time, which increases the population of these states.

Some of the He atoms in F_2 and F_3 states transfer their energy to ground state Neon atoms in collisions. Due to this Ne atoms get excited to E_4 and E_6 levels. Here, there is a greater probability of collisions between He atoms in the F_2 and F_3 state and Ne atoms in the E_1 state. Thus, E_4 and E_6 levels of Ne get highly populated. This creates a population inversion between the higher states (E_6 and E_4) with respect to the lower states (E_5 and E_3) of neon atoms. Now the lasing action takes place in the following transitions.

a) Transitions from E_6 to E_5 level give rise to a wavelength of 33912 A^0 which is in IR region.

b) Transitions from E_6 to E_3 level give rise to a wavelength of 6328A^0 which is red light in the visible region.

c) Transitions from E4 to E3 level give rise to a wavelength of 11523A^0 which is in IR region.

The atoms from E_5 and E_3 levels undergo spontaneous transitions to E_2 level which is a metastable state of Neon by releasing photons. These photons will excite the atoms of E_2 back to E_5 and E_3 levels. This will affect the population inversion of E_5 and E_3 levels. To overcome this difficulty, a very narrow tube is taken to enable efficient depopulation of E_2 level. In the He-Ne laser, the output is a continuous wave beam.

Advantages:

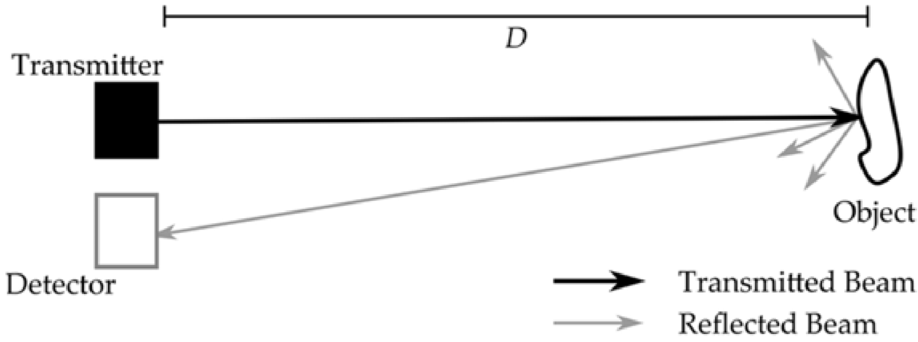
- It is low-cost laser
- It has frequency stability
- It can operate continuously without the need of cooling system
- It has good coherence property

Disadvantages (Limitations):

- It has moderate power output
- The efficiency of laser is low
- It is low gain laser system
- It requires high voltage for its operation.

Applications of Laser:

A rangefinder is a device that measures the accurate distance from the observer to a target for the purposes of surveying, auto-focusing or accurately aiming a weapon. It makes use of the characteristic properties of the laser beam, namely, monochromaticity, high intensity, coherency, and directionality. Laser range finders are used to get accurate information about the enemy target without the knowledge of the enemy personals. The computer interfaced rangefinders can calculate the distance of the target within 1% of the actual distance.



Construction and working:

A schematic diagram of a typical LASER range finder is as shown in the figure above. It consists of source, receiver, and display unit. A high-power laser pulse is directed towards the enemy target from the transmitting part of the range finder. The beam gets reflected from the surface of the target which is collected by a receiver. The receiver consists of photomultiplier, photodetector and filter. A suitably tuned optical interference filter present in the receiver eliminates the background noise. The pure signal is amplified by the photomultiplier tube. The time for to and fro motion of beam is measured by a built-in clock which is then converted in to the distance.

SOLVED EXAMPLES:

1. **The average output of laser source emitting a laser beam of wavelength of 632.8 nm is 10 mW. Find the number of photons emitted per second by the laser source.**

Given: Wavelength of laser, λ = 632.8 nm

Power output = 10 mW = 10 x 10^{-3} W

To find: No. of photons emitted/second, N = ?

Solution: We know that the energy difference,

$$\Delta E = h\nu = \frac{hc}{\lambda}$$

$$= \frac{6.63 X 10^{-34} X 3 X 10^{8}}{632 X 10^{-9}}$$

$$= 3.147 \times 10^{-19} \text{ J}$$

This energy difference is the energy of each photon. If N is the number of photons emitted per second to give a power o/p of 10 mW, then

$$N \times \Delta E = 10\ mW = 10 \times 10^{-3}$$

$$\therefore N = \frac{10\ X\ 10^{-3}}{3.147\ X\ 10^{-19}}$$

$$N = 3.178 \times 10^{16}$$

$\therefore$ The number of photons emitted per second = 3.178×10^{16}

2. A pulsed laser emits photons of wavelength 780 nm with 15 mW average power/pulse. Calculate the number of photons contained in each pulse if the pulse duration is 15 nSec.

Given: Wavelength of laser, λ = 780 nm

Power output = 15 mW = 15×10^{-3} W

Duration of eac pulse = t = 15 nSec = 15×10^{-9} Sec

To Find: No. of photons in each pulse, N = ?

Solution: $\Delta E = h\nu = \frac{hc}{\lambda}$

$$= \frac{6.63\ X\ 10^{-34} X\ 3\ X\ 10^{8}}{780\ X\ 10^{-9}}$$

$$= 2.55 \times 10^{-19}\ J$$

Now, we have energy of each pulse,

E = power x duration of the pulse

E= P x t = $15 \times 10^{-3} \times 15 \times 10^{-9}$

E= 2×10^{-10} J

If N is the number of photons in the pulse, then

$$N \times \Delta E = E$$

$$N = \frac{E}{\Delta E} = \frac{2\ X\ 10^{-10}}{2.55\ X\ 10^{-19}} = 7.84 \times 10^{8}$$

$\therefore$ The number of photons emitted in each pulse is = 7.84×10^{8}

3. A laser operating at 6328 Å emits 4.154 x 10^{16} photons per second. Calculate the output power of the laser if the input power is 100 watt. Also, find the percentage power converted into coherent light energy.

Given: Wavelength of laser, λ = 6328 Å

No of photons emitted per second, n = 4.154×10^{16}

Input power, P_{in} = 100 W

To Find: % of power converted into laser, P_E = ?

Solution: **We have, energy of each photon =** $E = \frac{hc}{\lambda} = \frac{6.63\ X\ 10^{-34} X\ 3\ X\ 10^{8}}{6328\ X\ 10^{-10}}$

$$= 3.143 \times 10^{-19}\ J$$

But, o/p power = Energy emitted/Second

= (No of photons emitted / second) x energy of each photon

= nE = $4.154 \times 10^{16} \times 3.143 \times 10^{-19}$

= 0.013 W

% of power $= \frac{output\ power\ of\ laser}{input\ power}\ X\ 100$

$= \frac{0.013}{100}\ X\ 100$

∴ The percentage power converted into light energy = 0.013

4. A medium in thermal equilibrium at 325 K has two energy levels with a wavelength separation of 1μm. Find the ration of population densities of the upper and lower levels.

Given: Thermal equilibrium, T = 325 K

Wavelength separation, $\lambda = 1 \times 10^{-6}$ m

To Find: $\frac{N2}{N1} = ?$

Solution: we know that $\frac{N2}{N1} = e^{-\frac{h\nu}{kT}}$

Since $\lambda = \frac{c}{\nu}$; $\nu = \frac{c}{\lambda}$

∴ $\nu = \frac{3X\,10^8}{10^{-6}} = 3 \times 10^{14}$

Now $\frac{N2}{N1} = e^{-\frac{(6.623\,X\,10^{-34})X\,(3\,X\,10^{14})}{1.38\,X\,10^{-23}X\,325}}$

$$\frac{N2}{N1} = 1.4\,X\,10^{-21}$$

∴ The ration of population density = 1.4×10^{-21}

5. The ratio of population of two energy levels is 1.059 x 10^{-30}. Find the wavelength of the light emitted at 340 K lower levels.

Given: Thermal equilibrium, N2/N1 = 1.059×10^{-30}

To Find: Wavelength of light, $\lambda = ?$

Solution : we know that $\lambda = \frac{c}{\nu}$

$Also,\ \frac{N2}{N1} = e^{-\frac{h\nu}{kT}}$

$1.059 \times 10^{-30} = e^{-\frac{(6.623\,X\,10^{-34})X\,(3\,X\,10^{14})}{1.38\,X\,10^{-23}X\,340}}$

$1.059 \times 10^{-30} = e^{(-1.45\,X\,10^{-13})\nu}$

Or ln $1.059 \times 10^{-30} = -1.45 \times 10^{-13} \times \nu$

Or $\nu = 4.76 \times 10^{14}$

Now $\lambda = \frac{3\,X\,10^8}{4.76\,X\,10^{14}}$ = 630.2 nm

∴ The wavelength of light emitted = 630.2 nm

OPTICAL FIBERS

Introduction:

A conventional method of long-distance communication uses radio waves (10^6 Hz) and micro waves (10^{10} Hz) as carrier waves. A light beam acts as carrier wave which is capable of carrying far more information since optical frequencies are extremely large (10^{15} Hz).

Optical fibers are essentially light guides used in optical communication as waveguides. With the development of laser and flexible fiber, optical fibers are being used extensively for various communication applications. The principle behind the transmission of light waves in an optical fiber **is total internal reflection**. Fiber optic communication has significant advantages over the transmission by conventional coaxial cables. The loss of signal strength is considerably less in optical fibers and hence permits transmission over long distances. Use of light waves in place of radio and microwave has improved the speed of communication.

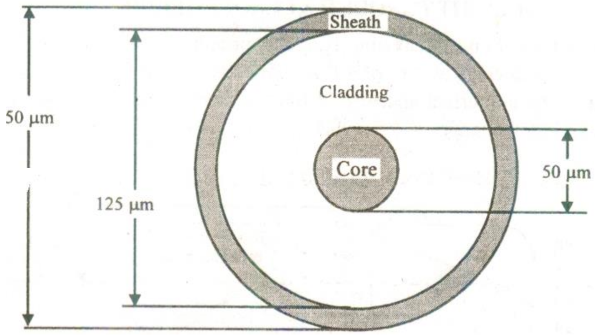
Basic principle:

The basic principle of optical fiber is multiple **total internal reflections**. When a ray of light travels from a denser to a rarer medium, at an angle of incidence greater than the critical angle for the pair of media, the ray is reflected into the denser medium. This property is called **total internal reflection**. Light signals are transmitted through optic fibers by multiple total internal reflections

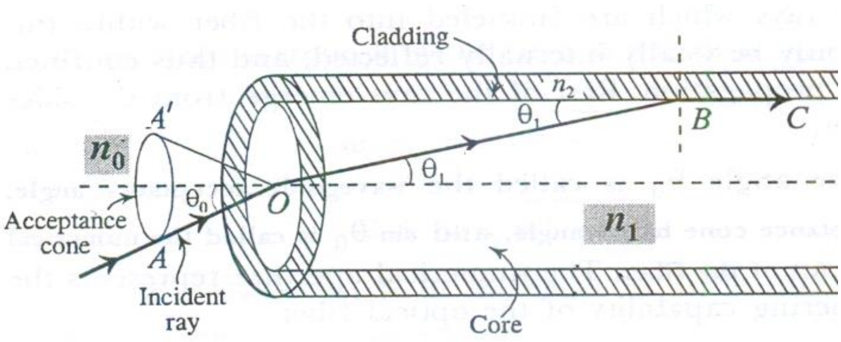
Structure:

An optical fiber is a transparent fiber made of glass or plastic. It is designed to guide light waves along its length. An optical fiber works on the principle of total internal reflection. When light enters one end of the fiber, it undergoes successive total internal reflections from sidewalls and travels down the length of the fiber along a zigzag path.

A practical optical fiber has in general three coaxial regions. The innermost region is the light guiding region known as the **core.** It is surrounded by a coaxial region known as **cladding**. The outermost region is called the **sheath**. The refractive index (RI) of core (denoted by n_1) is always greater than that of the cladding (denoted by n_2). The purpose of cladding is to make the light to be confined to the core. The sheath protects the cladding and the core from contamination, abrasions, harmful influence of moisture. It also provides a mechanical strength to the fiber.



Light guiding mechanism in optical fibers:

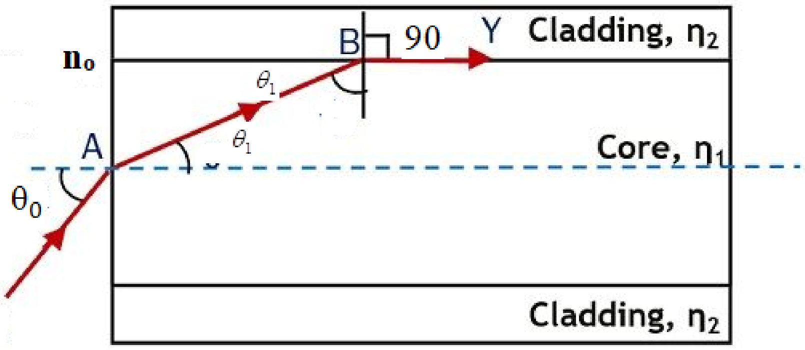


Consider an optical fiber into which light is launched at one end from a medium of RI n_0. Let n_1 be the RI of core and $n_2$be that of the cladding. Let a ray of light is launched into the fiber at angle θ_i with respect to the axis of the fiber. The light ray refracts at an angle θ_1 and strikes the core – cladding interface at an angle of $90-\theta_1$. If $90-\theta_1$is greater than the critical angle for the core – cladding interface, the ray undergoes total internal reflection at the interface. Let the angle θ_i is adjusted to a particular angle such that $90-\theta_1$ is equal to the critical angle for the core – cladding interface. Therefore, all light rays entering into the fiber at angles less than θ_0 will undergo total internal reflection when incident at the core-cladding interface.

The angle θ_0 is called the **acceptance angle**. "***It is the maximum angle that a light ray can have relative to the axis of the fiber and propagates down the fiber***".

Sine of the acceptance angle θ_0 $(sin\theta_0)$ is called the numerical aperture (NA) of the fiber. It represents the light gathering capacity of the optical fiber.

Expression for Angle of Acceptance and numerical Aperture:



Consider an optical fiber into which light is launched from a medium of RI $\mathbf{n_o}$. Let $\mathbf{n_1}$ be the RI of core and $\mathbf{n_2}$ be that of the cladding.

Let a ray of light enters the fiber at an angle θ_0 known as acceptance angle with respect to the axis of the fiber. The light ray refracts at an angle θ_1 and strikes the core – cladding interface at an angle of $(90 - \theta_1)$ which is equal to the critical angle for the core – cladding interface.

Applying Snell's law at 'A'

$$\frac{sin\theta_0}{sin\theta_1} = \frac{n_1}{n_0}$$

$$sin\theta_0 = \frac{n_1}{n_0}(sin\theta_1)$$

$$sin\theta_0 = \frac{n_1}{n_0}\left(\sqrt{1 - cos^2\theta_1}\right) ------(1)$$

Applying Snell's law at 'B'

$$n_1 \sin(90 - \theta_1) = n_2 \sin 90$$

$$cos\theta_1 = \frac{n_2}{n_1} ------(2)$$

Substituting (2) in (1)we get,

$$sin\theta_0 = \frac{n_1}{n_0}\left(\sqrt{1 - \left(\frac{n_2}{n_1}\right)^2}\right)$$

$$sin\theta_0 = \frac{n_1}{n_0}\left(\sqrt{\frac{n_1^2 - n_2^2}{n_1^2}}\right)$$

$$sin\theta_0 = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

By definition, sine of the angle of acceptance is known as numerical aperture (N.A)

$$N.A. = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

If the medium surrounding the fiber is air, then $n_0 = 1$

$$\mathrm{N.A.} = \sin\theta_0 = \sqrt{n_1^2 - n_2^2}$$

If θ_i is the angle of incidence of an incident ray w.r.t. the axis of the fiber, then ray will be able to propagate,

if $\theta_i \langle \theta_0$

if $\sin\theta_i \langle \sin\theta_0$

or $\boxed{\sin\theta_i \langle N.A.}$

This is the **condition for propagation.**

Fractional Index Change (Δ):

It is the ratio of the RI difference between the core and cladding to the RI of core of an optical fiber,

i.e. $\Delta = \frac{n_1 - n_2}{n_1}$; Where; $n_1 \rightarrow$ RI of core, $n_2 \rightarrow$ RI of cladding.

Relation between N.A. and Δ:

We have numerical aperture,

$$N.A. = \sqrt{n_1^2 - n_2^2}$$

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

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

i.e. $n_1\Delta = n_1 - n_2$

$\therefore$ $N.A. = \sqrt{(n_1 + n_2)n_1\Delta}$

Since $n_1 \approx n_2$; $n_1 + n_2 \approx 2n_1$

Hence $N.A. = \sqrt{2n_1 n_1 \Delta} = n_1\sqrt{2\Delta}$

i.e. $\boxed{N.A. = n_1\sqrt{2\Delta}}$

Modes of propagation:

Light propagates as an electromagnetic wave through an optical fiber. All waves having ray directions above the critical angle will be trapped within the fiber due to total internal reflection. But all such waves do not propagate along the fiber. There is certain ray directions allowed for the propagation. ***These allowed ray directions or possible number of path of light in optical fibers is known as modes of propagation***. The paths are zigzag paths excepting the axial direction. The number of modes that a fiber will support depends on the diameter of the core and wavelength of the wave being transmitted.

Normalized frequency (V – number):

It is the relation between fiber size, the refractive indices and the wavelength of light propagating through the fiber. It is given by,

$$\boxed{V = \frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2}}$$

Were, $d \rightarrow$ diameter of the core; $n_1 \rightarrow$ RI of the core; $n_2 \rightarrow$ RI of the cladding; $\lambda \rightarrow$ Wavelength of light.

Since $\sqrt{n_1^2 - n_2^2} = N.A.$ we can write

$$V = \frac{\pi d}{\lambda} NA$$

The number of modes supported by a fiber is given by

$$\boxed{M_N = \frac{V^2}{2}}$$

Refractive index profile is a curve which represents the variation of refractive index with respect to the radial distance from the axis of the fiber.

Types of optical fibers:

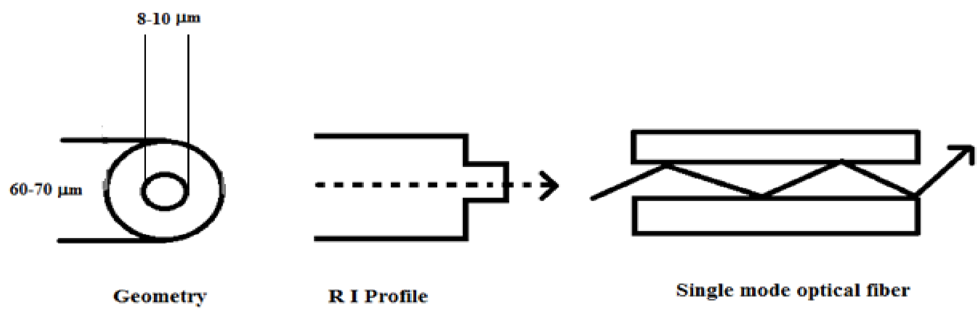
Depending on the RI profile and number of modes that a fiber can support, we have three types of optical fibers. They are

1. Step index single-mode fiber
2. Step index multi-mode fiber
3. Graded index multi-mode fiber

1. Step index single mode fiber:

A step index single mode fiber has a core diameter of about 8 to 10 μm and external diameter of cladding is 60 to 70 μm. The RI of the core has a uniform value. The cladding also has a uniform RI but slightly lesser than that of the core. The RI of the fiber changes ***abruptly*** at the core – cladding interface. Hence it is called a step index fiber. This fiber can support only one mode of propagation along its axis. Hence it is called a single mode fiber.

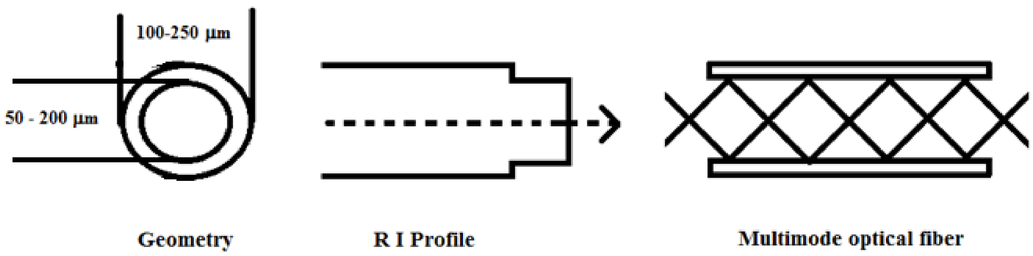
Due to narrow diameter of the fiber only laser can be used as the source of light with these fibers. There is no intermodal dispersion in the fiber. These are widely used in submarine cable systems.



2. Step index multi mode fiber:

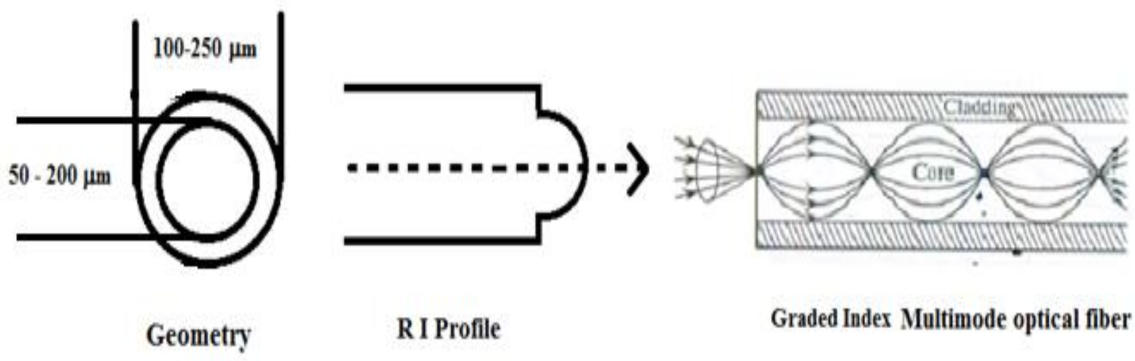
This fiber has a core diameter of 100-250 μm. The RI remains uniform in the core and cladding region. But the RI changes ***abruptly*** at the core – cladding interface. Because of larger diameter, this fiber allows many modes to propagate through it.

The step index multimode fiber can accept either a laser or LED as source of light. It is used in data links which has lower band width requirements.



3. Graded Index multimode fiber:

It is a multimode fiber with a core consisting of concentric layers of different refractive indices. Therefore, RI of the core decreases with distance from the fiber axis. The RI of the cladding remains uniform. The RI profile and the modes of propagation are shown in fig. such a RI profile causes a periodic focusing of light propagating through the fiber. Either a laser or a LED can be the source for these fibers.



Attenuation:

The loss of power suffered by the optical signal as it propagates through the fiber is called **attenuation.**

The attenuation or fiber loss is due to the following factors:

1. Absorption losses
2. Scattering losses
3. Radiation or bending losses

1. Absorption Losses:

The loss of signal strength occurs due to absorption of photons during its propagation. Photons are absorbed by

a) Impurities in the silica glass of which the fiber is made of.

b) Intrinsic absorption by the glass material itself.

a. Absorption by impurities:

The impurities that are generally present in fiber glass are iron, chromium, cobalt, copper etc. During signal propagation when photons interact with these impurities, the electrons absorb the photons and get excited to higher energy levels. Later these electrons give up their absorbed energy in the form of light photons with variation in phase and results in loss of optical power.

b. Intrinsic Absorption

The fiber material itself has a tendency to absorb light energy however small it may be. Hence there will be a loss and is known as intrinsic absorption.

2. Scattering Losses:

The optical power is lost due to the scattering of photons. This scattering is due to the non-uniformity in the density of the fiber material, which leads to the variation in the RI of the fiber. Structural inhomogeneities and defects created in the fiber can also cause scattering. The loss of light energy by scattering is found to be wavelength dependent. It decreases with increase in the wavelength of light to be transmitted through the fiber.

3. **Bending Losses (Radiation Losses):**

Radiation losses occur due to bending of fiber. There are two types of bends

a) Microscopic bends

b) Macroscopic bends

Microscopic bends are caused during manufacturing as well as due to the applied stress on the fiber. Macroscopic bending arises during the installation of the fiber. At the point of a bend, light will escape to the surrounding medium due to the fact that the angle of incidence at that point becomes lesser than the critical angle.

To minimize these losses, the optical fiber has to be laid without sharp bends and they should be freed from the external stresses by providing mechanical strength through external coverage.

Attenuation Coefficient:

When light travels in a material medium there will always be a loss in its intensity with distance travelled. This loss takes place according to **Lambert's law.**

According to **Lambert's law**, "the rate of decrease of intensity of light with distance travelled in a homogeneous medium is proportional to the initial intensity". If 'P' is the initial intensity and 'L' is the distance propagated in the medium, then

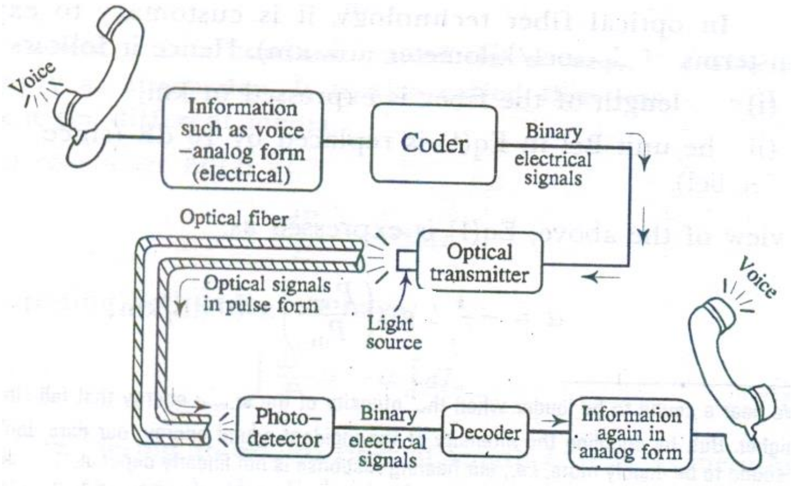
$$-\frac{dP}{dL} \;\alpha\; P$$ (Negative sign indicates that it is decrease in intensity)

Considering a fiber of length 'L' and taking P_{in} as the initial intensity of light launched into the fiber and P_{out} as the intensity of light received at the other end of the fiber, the **attenuation coefficient** is given by

$$\alpha = -\frac{10}{L}\log\left[\frac{P_{out}}{P_{in}}\right] \text{dB/km}$$

Application:

Fiber Optic Communication: ***Point – point communication system using optical fibers***:



In a point - point communication system, we have analog information such as voice of a telephone user. The voice gives rise to electrical signals in analog form coming out of the transmitter section of the telephone. With the help of a coder, the analog signal is converted into binary data. The binary data in the form of a stream of electrical pulses are converted into pulses of optical power by modulating the light emitted by an optical source such as a laser diode or LED. This unit is called optical transmitter, from which the optical power is launched into the fiber.

During the propagation of the signal, attenuation or losses occurs. This may reach a limiting stage beyond which it may not be possible to retrieve the information from the light signal. Hence a repeater is needed in the transmission path. A repeater consists of a receiver and a transmitter. The receiver converts the optical signal into corresponding electrical signal and then it is amplified. These electrical signals are again converted into optical signals and fed into the optical fiber.

At the receiving end the optical signal from the fiber is fed into a photo detector. Hence signal is converted to pulses of electric current. This is then fed to a decoder which converts the binary data into an analog signal, which will be the same information such as voice; which was there at the transmitting end.

SOLVED EXAMPLES

1. The refractive indices of core and cladding are 1.49 and 1.47 respectively in an optical fiber. Find the numerical aperture and angle of acceptance.

Given: RI of Core, $n_1 = 1.49$

RI of Cladding $n_2 = 1.48$

To find: Numerical aperture, N.A = ?

Acceptance angle, $\theta = ?$

Solution: We know that the numerical aperture is given by,

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

$$= \sqrt{1.49^2 - 1.47^2}$$

$$= 0.243$$

The angle of acceptance θ is related to N.A. through the equation,

$$\theta = \sin^{-1}(N.A.) = \sin^{-1}(0.243)$$

$$\theta = 14.06$$

The values of numerical aperture and angle of acceptance are 0.243 and 14.06 respectively.

2. An optical fiber has a core material with refractive index 1.57 and its cladding material has a refractive index of 1.54. The light is launched into it in air. Calculate its numerical aperture and acceptance.

Given: RI of Core, $n_1 = 1.57$

RI of Cladding $n_2 = 1.54$

To find: Numerical aperture, N.A ?

Acceptance angle, $\theta = ?$

Solution: We know that the numerical aperture is given by,

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

$$= \sqrt{1.57^2 - 1.54^2}$$

$$= 0.305$$

The angle of acceptance θ is related to N.A. through the equation,

$$\theta = \sin^{-1}(N.A.) = \sin^{-1}(0.305)$$

$$\theta = 17.75$$

3. An optical glass fiber of refractive index 1.48 is to be clad to ensure total internal reflection that will contain light travelling within 6° of the fiber axis. What maximum index of refraction is allowed for the cladding?

Given: RI of Core, $n_1 = 1.48$

Angle between the ray and the fiber axis = 6°

To find: RI of Cladding n_2 =?

Solution: Angle of incidence of the ray at the core and cladding interface = 85°

For grazing incidence,

$n_1 \sin 84° = n_2 \sin 90°$

$1.48 \sin 85 = n_2 (\sin 90° = 1)$

$n_2 = 1.47$

$\therefore$ If $n_2 = 1.47$, the refracted ray grazes along the interface or the ray suffers the total internal reflection since $n_2 < 1.48$.

4. The N.A. of an optical fiber is 0.3 when surrounded by air. Determine the R.I. of its core given the R.I. of the cladding is 1.6. Also find the acceptance angle when the fiber is in a medium of R.I of 1.33.

Given: N.A. while the fiber is in air, $(N.A.)_{air} = 0.3$

RI of Cladding, $n_2 = 1.6$

R.I. of water, $n_o = 1.33$

To find: RI of Cladding n_1 =?

Acceptance angle while the fiber is in water, θ_o = ?

Solution: **In Air, N.A. is given by**

(N.A.)air $= \sqrt{n_1^2 - n_2^2} = 0.3$

$\therefore 0.3 = \sqrt{n_1^2 - 1.6^2}$

Squiring both sides

$0.09 = n_1^2 - 2.56$

$n_1^2 = 2.56 + 0.09 = 2.65$

$n_1 = 1.62$

In water, N.A. is given by

$(N.A)_{water} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} = \frac{0.254}{1.33}$

$(N.A)_{water} = 0.191$

But N.A. = $\sin\theta_0$

$\therefore$ The acceptance angle,

$\theta_0 = \sin^{-1}(N.A.) = \sin^{-1}(0.191)$

$\theta_0 = 11.01°$

5. The angle of acceptance of an optical fiber is 35° when surrounded by air. Find the acceptance when it is in the refractive index of 1.33.

Given: Angle of acceptance in air $\theta_0 = 35°$

RI of refracting medium, $n'_0 = 1.33$

To find: Angle of acceptance while the fiber is in the refractive medium θ'_0 = 1.33

Solution: We have the equation,

$$\sin\theta_0 = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

when the surrounding medium is air, then, $n_o = 1$, $\theta_o = 30°$

$$\sin 35 = \sqrt{n_1^2 - n_2^2}$$

$$0.57 = \sqrt{n_1^2 - n_2^2} \quad \ldots\ldots\ldots (1)$$

For a medium with R.I = 1.33,

$$\sin\theta'_0 = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

where $n_o = 1.33$ $\quad \therefore \sin\theta'_0 = \frac{\sqrt{n_1^2 - n_2^2}}{1.33}$: $1.33 \sin\theta'_0 = \sqrt{n_1^2 - n_2^2}$

………(2)

From eqn (1) and (2), we get

$$1.33\text{in}\theta'_0 = 0.57 \qquad \therefore \theta'_0 = \sin^{-1}(0.57/1.33)$$

$$\theta'_0 = 25.37°$$

6. **The attenuation of light in an optical fiber is 3.6 dB/km. What fraction of its initial intensity remains after i)1km, ii) after 3km?**

Given: Fiber attenuation, α= 3.6 dB/km.

i) After 1 km distance, $(\frac{P_{out}}{P_{in}})$=?

ii) After3 km distance, $(\frac{P_{out}}{P_{in}})$=?

Hint: Fiber attenuation, α= $-\frac{10}{L} log_{10}(\frac{P_{out}}{P_{in}})$ dB/km

(Ans: α=0.436, α=0.0832)

7. **An optical fiber has a core material with RI 1.55 and its cladding material has RI 1.50. The light is launched into it in air. Calculate its N.A, acceptance angle and fractional index change.**

Given: Refractive index of core, n_1=1.55

Refractive index of cladding, n_2=1.50

Numerical aperture, N.A =?

Surrounding medium air, n_0=1

Angle of acceptance, θ_o =?

Fractional index change, Δ=?

Hint:

$$N.A. = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

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

(Ans: N.A= 0.39, θ_o=23º, Δ =0.032)

8. **Find the attenuation in an optical fiber of length 500m, when a light signal of power 100mW emerges out of the fiber with a power of 90mW**.

Given: Length of optical fiber =500m = 0.5km

Input power of signal, P_{in}=100mW=100x10^{-3}W

Output power of signal , P_{out} =90mW=90x10^{-3}W

Fiber attenuation, α= ?

Hint: Fiber attenuation, α= - $\frac{10}{L} log_{10}(\frac{P_{out}}{P_{in}})$dB/km

(ANS: α=0.915dB/km)

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