Fibre Optics and Lasers

2.1 Introduction

The field of fibre optics communications has exploded over the past two decades. Fibre is an intergal part of modern-day communication infrastucture can be found along roads, in buildings, hospitals and machinery.

The fibre itself is a strand of silica based glass, its dimensions are similar to those of a human hair, surrounded by a transparent cladding. Light can be transmitted along the fibre over great distance at very high data rates providing an ideal medium for the transport of information. This section will provide explanations for some of the terms associated with the field of fibre optic engineering for telecommunications.

optical Fibre

Optical fibres are glass or plastics as thin as human hair, designed to guide light waves along their length. An optical fibre works on the principle of total internal reflection. When light enters through one end of the fibre it undergoes successive total internal reflections from side wall and travels down the length of the fibre along a zigzag path. A small fraction of light may escape through side walls but a major fraction emerges out from the other end of the fibre.

A practical optical fibre has in general three coaxial regions. The innermost region is the light guiding region known as the core. It is surrounded by a coaxial middle region known as the cladding. The outermost region is called the sheath. The refractive index of cladding is always lower than that of the core. The purpose of cladding is to make the light to be confined to the core. Light launched into the core and striking the core to cladding interface at greater than critical angle will be reflected back into the core. Since the angles of incidence and reflection are equal, the light will continue to rebound and propagate through the fibre. The sheath protects the cladding and the core from abrasions, contamination and the harmful influences of moisture. In addition it increases the mechanical strength of the fibre.

Optical fibres are constructed either as a single fibre or a flexible bundle or a cable. A fibre bundle is a number of fibres in a single jacket. Each carries light independently. The cross-sectional view of a typical telephone communication cable is shown in figure 2.1. It contains six fibres and has an insulated steel cable for providing tensile strength. Each optical fibre consists of a core surrounded by cladding which in turn is coated with an insulating jacket. The fibres are thus individually buffered and strengthened, six insulated copper wires are distributed in the space between the fibres. They are used for electrical transmission if required. The fibres are wrapped with mylar type to bend the assembly. The assembly is then fitted in a corrugated aluminium sheath which acts as a shield. A polyethylene jacket is applied over the top.

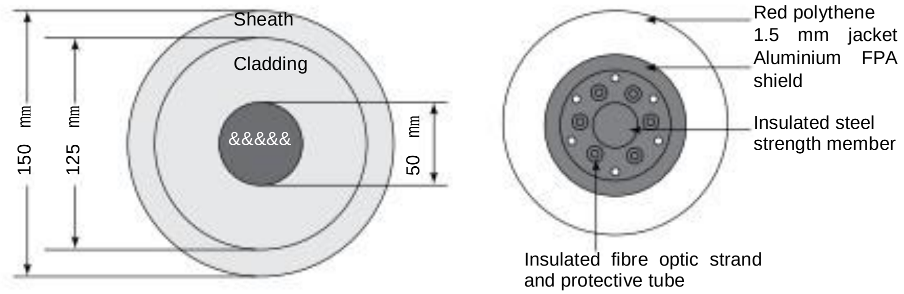

Fig. 2.1

Snell's Law in Refraction

Whenever a ray of light travels from rarer medium (say air) into denser medium (say glass) it bends towards the normal drawn at the interface as shown in Fig. 2.2. The angle of incidence -*i* is greater than the angle of refraction - *r*; and the ratio of; (sin *i* / sin *r*) is constant (*n*). *This constant* (*n*) *is called the refractive index of the second medium with respect to the first medium.*

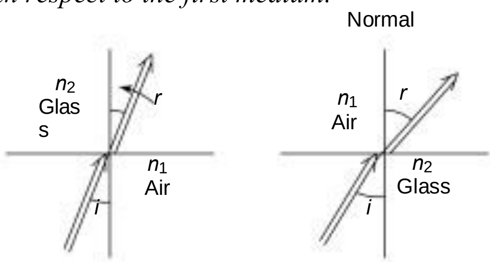

Fig. 2.2 Phenomenon of refraction: (*A*) Refracted ray bends towards normal and - *r* < - *i* (*B*) Refracted ray bends away from normal and - *r* > - *ik.*

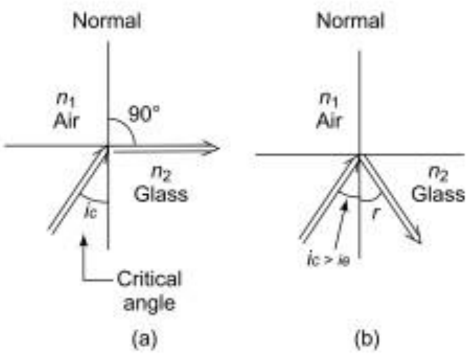

Fig. 2.3 (a) Whenever a ray of light has -*r* = 90º, then - i_c is called critical angle. (b) At an angle greater than critical angle, there is no refraction but internal reflection.

In more general way it is written as,

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1} \quad \text{i.e.,} \qquad \text{i.e., } n_1 \sin i = n_2 \sin r$$

where n_2 is the refractive index of the second medium (glass) and n_1 is the refractive index of the first medium (air). This is known as *Snell's law*.

2.2 total Internal reflection

If a ray of light is incident at an angle i in denser medium (of refractive index n_2) the refracted ray will bend away from normal in rarer medium (of refractive index n_1), as shown in Fig. 2.3(b) the Snell's law is written as,

$$\frac{\sin i}{\sin r} = \frac{n_1}{n_2} \qquad \text{OR} \quad n_2 \sin i = n_1 \sin r$$

If a ray of light is incident at such an angle (say - i_c) that the angle of refraction becomes - $r = 90^\circ$ then,

$$\sin i_c = \frac{n_1}{n_2}$$

where - i_c is known as *critical angle*. The value of critical angle depends upon the values of refractive indices (n_1 and n_2) of two media.

If a ray of light in denser medium is directed at an angle greater than critical angle -i_c, the ray of light does not suffer refraction in rarer medium. But it is reflected back into the denser medium. This reflection is called the *total internal reflection*.

In total internal reflection the intensity is not diminished, hence the phenomenon of total reflection is used in fibre optics.

Fibre Structure

The diagram shows the typical structure of a fibre used for communication links. It has an inner glass core with an outer cladding. This is covered with a protective buffer and outer jacket. This design of fibre is light and has a very low loss, making it ideal for the transmission of information over long distances.

light in a Fibre

The light propagates along the fibre by the process of total internal reflection. The light is contained within the glass core and cladding by careful design of their refractive indices. The loss along the fibre is low and the signal is not subject to electromagnetic interference which plagues other methods of signal transmission, such as radio or copper wire links.

The signal is, however, degraded by other means particular to the fibre such as dispersion (described below) and non-linear effects (caused by a high power density in the fibre core).

Basic Parts of a Fibre

Core: It is a single solid dielectric cylinder of radius with refractive index n_1 known as core:

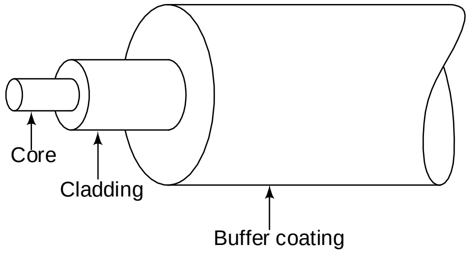

Fig. 2.4

Cladding (as a rarer medium)

The core is surrounded by a solid dielectric cladding having a refractive index $n_2 < n_1$. Cladding reduces the scattering losses due to dielectric discontinuities at the core surfaces. It provides the mechanical strength to the fibre. The cladding is made up of either glass or plastic materials.

Buffer

Most fibres are encapsulated in a plastic material. The encapsulating material is called buffer coating. The buffer adds further mechanical strength to the fibre. This also avoids the random microscopic or sharp bends when the fibres are corporated into cables or when supported in some other structures.

In the step index fibre may enter at different angles of incidence with the axis travelling different path lengths and emerging out a different times. This results in pulse dispersion i.e., an input pulse gets widened as it travels along the fibre.

The path travelled by the ray is shown. In gradient fibre, the path is completely different from the step index fibre which actually relies on total internal reflection.

Fibre optic Materials

Any material that is used for the synthesis of an optical fibre must satisfy some important qualities such as the following:

(i) The material must be transparent at a particular optical wavelength in order to guide optical pulses along the fibre.

(ii) It should be possible to make thin, flexible and long fibres from the material.

(iii) It should be physically possible to produce core and cladding having a slight difference in refractive indices by doping some impurities.

Among the various materials investigated for the preparation of optical fibres, glass and plastics seem to be highly competitive satisfying many requirements.

While glass (silica or silicate) has less attenuation over long distances, plastic fibres have a greater mechanical strength than that of glass fibres. Thus, depending upon the nature of applications optical fibres made of both glass and plastics are used these days.

For producing glass optical fibres, silica is preferred as the basic material whose refractive index is 1.458 (at 850 nm). Using suitable dopants of fluorine or other oxides such as B_2O_3, GeO_2 and P_2O_5, core materials with higher refractive indices can be produced. Silica is used as the cladding for the core materials. Thus, the common optical fibres made of glass materials are:

(i) P_2O_5-SiO_2 core and SiO_2 cladding

(ii) GeO_2-SiO_2 core and SiO_2 cladding

(iii) GeO_2-B_2O_3-SiO_2 core and B_2O_3-SiO_2 cladding, and so on.

Some of the advantages of glass fibres are its resistance to deformation at temperatures as high as 1000° C, high resistance to breakage from thermal shock, good chemical durability and its utility in both visible and IR region of optical pulses.

Recently fluoride glasses having extremely low transmission losses at IR wavelengths have been reported. Fluoride glasses belong to a general family of halide glasses in which the anions are from Group VII elements of periodic table, namely, fluorine, chlorine, bromine, etc. This material forms the core of a glass fibre. To make a lower refractive glass for cladding, one partially replaces ZrF_4 by HaF_4. Although fluoride optical fibres offer low losses, it is very difficult to make a lengthy optical fibre.

It is also possible to develop optical fibres having *glass core* and *plastic cladding*. These types of fibres are useful for long-term applications where losses are normally low. Silica is used as a core, while silicone resin having a lower refractive index compared to silica is used for forming the cladding. Another popular cladding polymer material is perfluoronated ethylene propylene whose refractive index is 1.338 (at l = 850 nm), making this sort of fibre a potential candidate for many applications.

In addition to this, all-plastic multimode step index fibres are also available. Although these types of optical fibres show higher attenuation losses, the toughness and durability of plastic materials allow the production of optical fibres from plastic materials too. Some examples of this type are:

(i) A polysterene core (n_1 = 1.60) and a methyl methacrylate cladding (n_2 = 1.49) to give NA to 0.60.

(ii) A polymethyl methacrylate core (n_1 = 1.49) and a cladding made of its copolymer (n_2 = 1.40) to give NA of 0.50.

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There are two types of optical fibres

1. SMF
2. MMF

A single mode fibre has a smaller core diameter and can support only one mode of propagation.

On the other hand, a multimode fibre has a larger core diameter and supports a number of modes.

Multimode fibres are further distinguished on the basis of index-profile. A multimode fibre can be either a step index type or graded index GRIN type. Single mode fibre is usually a step index type.

1. Single Mode Step Index Fibre

A single mode step index fibre has a very fine thin core of uniform refractive index of a higher value which is surrounded by a cladding of lower refractive index. The refractive index changes abruptly at the core cladding boundary because of which it is known as step index fibre.

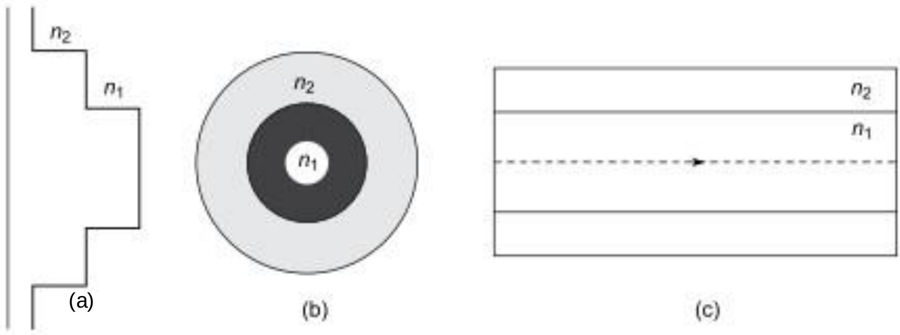


Fig. 2.5

The fibre is surrounded by an opaque protective sheath. A typical SMF has a core diameter of 4 mm. Light travels in SMF along a single path, i.e., along the axes obviously it is zero order mode that is supported by a SMF. A SMF is characterized by a very small value of D. It is of the order of 0.002.

2. Multimode Step Index Fibre

A multimode step index fibre is very much similar to the single mode step index fibre except that its core is of bigger diameter. A typical fibre has a core diameter of 100 mm. Light follows zigzag paths inside the fibre. Many such zigzag paths of propagation are permitted in a MMF. The *NA* of a MMF is larger as core diameter of the fibre is larger, it is of the order of 3.

3. Multimode Graded Index Fibre

A graded index fibre is a multimode fibre with a core consisting of concentric layers of different refractive indices therefore the refractive index of the core varies with distance from the fibre axis. It has high value at the centre and falls off with increasing radial distance from the axis. In case of GRIN fibres, the acceptance angle and numerical aperture decrease with radial distance from the axis (Fig. 2.8). For fibres of parabolic index profile, the numerical aperture is given by

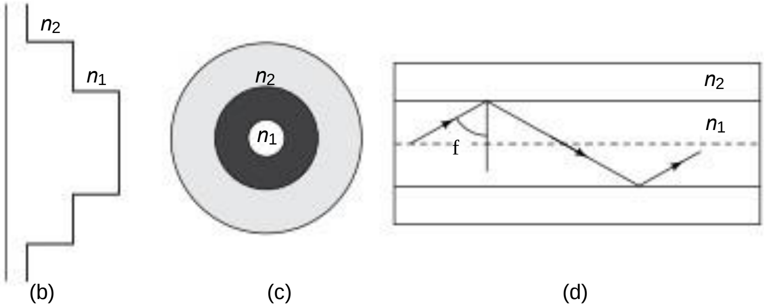


Fig. 2.6

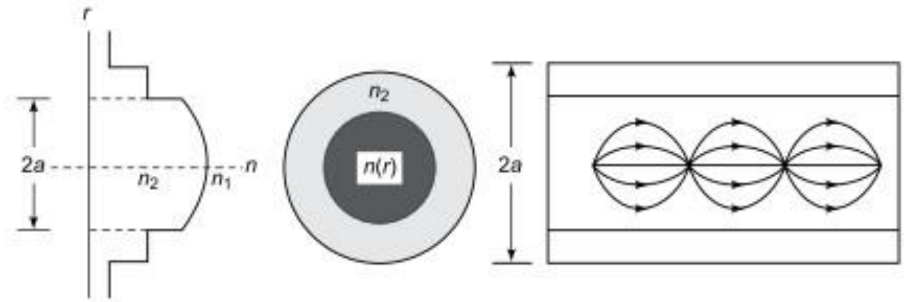


Fig. 2.7

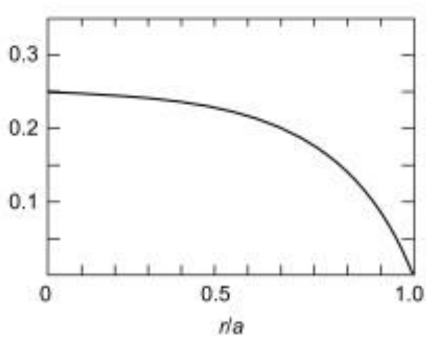


Fig. 2.8 Illustration of variation of numerical aperture of a parabolic index fibre.

$$NA = n_1 (2D)^{1/2} \sqrt{1-(r/a)^2}$$

Conventionally, the size of an optical fibre is denoted by writing its core diameter and then its cladding diameter, with a slash in between. Typical sizes of SI fibres are 50/125, 100/140, 200/230 and of GRIN fibres 50/125, 62.5/125 and 85/125. A 100/140 fibre has a 100 m*m* core and a 140 mm cladding.

Comparison between Single Mode and Multimode Fibres

Single Mode	Multimode
1. It supports only one mode of of propagation.	1. It supports a large number of modes propagation
2. It has very small core diameter of the order of 5 to 10 mm.	2. It has larger core diameter of the order of 50 to 150 mm.
3. Transmission losses are very small.	3. Transmission losses are more.
4. It has higher bandwidth.	4. It has lower bandwidth.
5. It requires laser diode as source of light.	5. It can work with LED also.
6. It is used for long distance	6. It is used for short distance communication.
7. It is by default step index fibre.	7. It can be step index or graded index fibre.
8. Mostly it is made up of glass.	8. It is made preferably from plastic.

Comparison between Step Index and Graded Index Fibres

Step Index Fibre	Graded Index Fibre
1. Refractive index is uniform fort the core and suddenly charges at core cladding boundary.	1. Refractive index of core is not uniform. It is maximum along the axis of core and decreases towards core cladding boundary.
2. Pulse distortion is present.	2. Pulse distortion is minimum.
3. It can be single mode or multimode.	3. It is only multimode.
4. It can be manufactured easily.	4. Manufacturing is not easy.
5. It has high numerical aperture.	5. It has low numerical aperture.
6. Attenuation is higher.	6. Attenuation is lower.
7. It offers lower bandwidth.	7. It offers higher bandwidth.
8. Reflection losses are present.	8. Reflection losses are absent.

2.4 numerical aperture of a Fibre

A glass fibre consists of a cylindrical central core, clad by a material of slightly lower m. Light rays impinging on the core cladding interface at an angle greater than the critical angle are trapped inside the core of the wave guide rays making larger angle with the axis take longer amount of time to travel the length of the fibre.

For a ray entering the fibre, if the angle of incidence at the core - cladding interface f is greater than the critical angle f_c, then the ray would undergo total internal reflection at that interface. Further because of the cylindrical symmetry in the fibre structure, the ray would suffer total internal reflections at the lower interface also and would therefore get guided through the core by repeated total internal reflections.

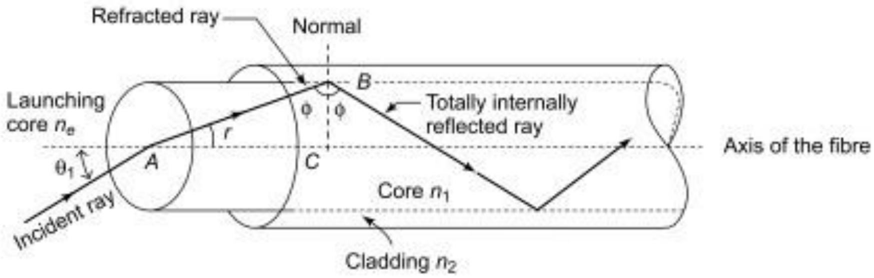


Fig. 2.9

i = angle made by the incident ray in entrance aperture of the fibre. r = angle made by refracted ray with the axis.

$$\therefore \quad \frac{\sin i}{\sin r} = \frac{n_1}{1} = n_1 \qquad (1)$$

The condition for total internal reflection to take place is

$$\sin \phi \geq \frac{n_2}{n_1}$$

$$\sin (90 - r) \geq \frac{n_2}{n_1} \quad \text{as from Fig. 2.9}$$

$$\cos r \geq \frac{n_2}{n_1}$$

$$= \sqrt{1 - \sin^2 r} \geq \frac{n_2}{n_1}$$

$$\sin^2 r \leq 1 - \left(\frac{n_2}{n_1}\right)^2$$

$$\sin r \leq \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2} \qquad (2)$$

But from (1) $\quad \dfrac{\sin i}{n_1} = \sin r.$

Putting in (2), we get

$$\frac{\sin i}{n_1} \leq \sqrt{1 - \frac{n_2^2}{n_1^2}}$$

$$\sin i \leq \sqrt{n_1^2 - n_2^2}$$

If i_{max} is the maximum angle of incidence for which total internal refraction can occur

$$\sin i_m = \sqrt{n_1^2 - n_2^2} \quad \text{for } n_1^2 - n_2^2 < 1$$

$$= 1 \quad \text{for } n_1^2 - n_2^2 \geq 1$$

If a core of light is incident on one end of the fibre, it will be guided through it provided the semi-angle of the core is less than i_m. This angle is a measure of the light gathering power of the fibre and as such one defines the *NA* of the fibre by the following equation.

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

numerical aperture definition

The numerical aperture (*NA*) is defined as the sine of the acceptance angle.

$$\therefore \quad NA = \sin i_m$$

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

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

$$= \left(\frac{n_1 + n_2}{2}\right)\left(\frac{n_1 - n_2}{n_1}\right) 2n_1$$

approximate $\dfrac{n_1 + n_2}{2} \approx n_1$

$$\therefore \quad (n_1^2 - n_2^2) = 2n_1^2 \Delta$$

$$\therefore \quad NA = n_1 \sqrt{2\Delta} \to \Delta = \left(\frac{n_1 - n_2}{n_1}\right)$$

= fractional refractive index change.

Δ has to be + ve as $n_1 > n_2$. In order to guide light rays effectively through a fibre $\Delta \ll 1$.

Typically Δ is of the order of 0.01.

Numerical aperture determines the light gathering ability of the fibre. It is a measure of the amount of light that can be accepted by a fibre.

It is seen that *NA* is dependent only on the refractive indices of the core and cladding material. Its value ranges from 0.13 to 0.50.

A large *NA* implies that a fibre will accept large amount of light from the source.

acceptance angle

We know that the maximum angle of incidence for which the total internal refraction can occur is

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

$$i_m = \sin^{-1}\sqrt{n_1^2 - n_2^2}$$

The angle i_m is called the acceptance angle of the fibre. Acceptance angle may be defined as the maximum angle that a light ray can have relative to the axis of the fibre and propagate down the fibre.

Modes of propagation

Light propagates as an electromagnetic wave through an optical fibre. All the waves having ray directions above the critical angle will be trapped within the fibre due to total internal reflection. But not all rays propagate along the fibre. Only certain ray directions are allowed to propagate. The allowed direction corresponds to the modes of the fibre. Modes can be visualized as the possible number of path of light in an optical fibre. The paths are all zigzag paths except the axial direction. Accordingly, light rays travelling through a fibre are classified as axial rays and zigzag rays.

As the rays get repeatedly reflected at the wall of the fibre, phase shift occurs. Consequently, the waves travelling along certain zigzag path will be in phase and intensified while the waves coursing along certain other paths will be out of phase and diminish due to destructive interference. The light ray path along which the waves are in phase inside its fibre are known as modes.

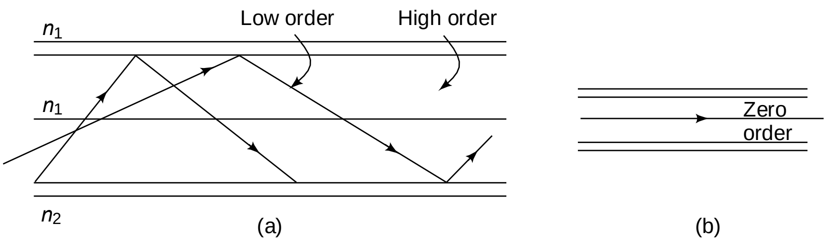


Fig. 2.10

2.5 V-number

An optical fibre is characterized by one more important parameter, known as V-number which is more generally called normalized frequency of the fibre. It is given by the relation

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} \qquad (1)$$

where a is the radius of the core and λ is the free space wavelength. Equation (1) can be written as

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

and

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

2.6 Maximum Possible Modes

The maximum number of modes N_m supported by an SI fibre is determined by

$$\boxed{N_m \cong \frac{1}{2}V^2} \qquad \text{SI fibre}$$

Thus, for $V = 10$, $N_m = 50$.

For $V < 2.405$, the fibre can support only one mode and is classified as an SMF. MMFs have values of $V > 2.405$ and can support many modes simultaneously. The wavelength corresponding to the value of $V = 2.405$ is known as the cut-off wavelength λ_c of the fibre

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

In case of GRIN fibres, for large values of V

$$N_m = \frac{V^2}{4}$$

2.7 losses In optical Fibre

An optical signal propagating through a fibre will get progressively attenuated. The signal attenuation is defined as the ratio of the optical output power from a fibre of length L to the i/p power. It is expressed in decibel per kilometer dB/km.

$$\mu = \frac{10}{L}\log\frac{P_i}{P_0} \qquad (1)$$

where P_i is the power of optical signal launched at one end of the fibre and P_0 is the power of the optical signal emerging from the other end of the fibre. In case of an ideal fibre $p_0 = p_i$ the attenuation is wavelength dependent and therefore the wavelength should also be specified.

dispersion

A light pulse launched into a fibre decreases in the fibre. It also spreads during its travel. The pulse received at the output is wider than input pulse as shown in figure. It means that the pulse becomes distorted as it is propagated through the fibre. Such a distortion arises due to dispersion effects. Dispersion is typically measured in nano seconds per kilometer (ns/km).

There are three mechanisms which contribute to the distortion of the light pulse in a fibre. They are known as:

i. Material dispersion
ii. Wave guide dispersion
iii. Intermodal dispersion

(a) *Material Dispersion*

Light waves of different wavelengths travel at different speeds in a medium. The short wavelength waves travel slower than long wavelength waves. Consequently, narrow pulses of light tend to broaden as they travel down the optical fibre. This is known as material dispersion.

Broadening of the signal due to dispersion

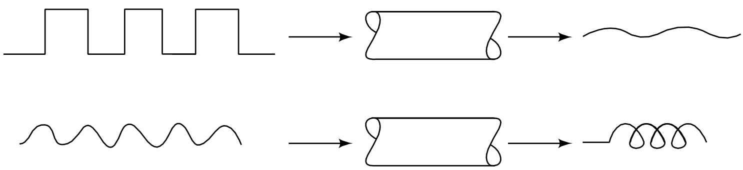


Fig. 2.11

Obviously, the spectral width of the source determines the extent of material dispersion. The material dispersion is given by the equation.

$$D_m = \frac{l(Dl)}{c} L \frac{d^2 n}{dl^2} \qquad (2)$$

where, l = is the peak wavelength
D l = is the spectral width
L = is the length of the core
n = is the refractive index of the core.

To cite an example an LED operating at 820 nm and having a spectral width of 38 nm results in a dispersion about 3 ns/km in a certain fibre. In the same fibre, dispersion can be reduced to 0.3 ns/km using a laser diode operating 1140 nm and having a 3nm spectral width. Thus, material dispersion can be reduced using a more and more monochromatic source.

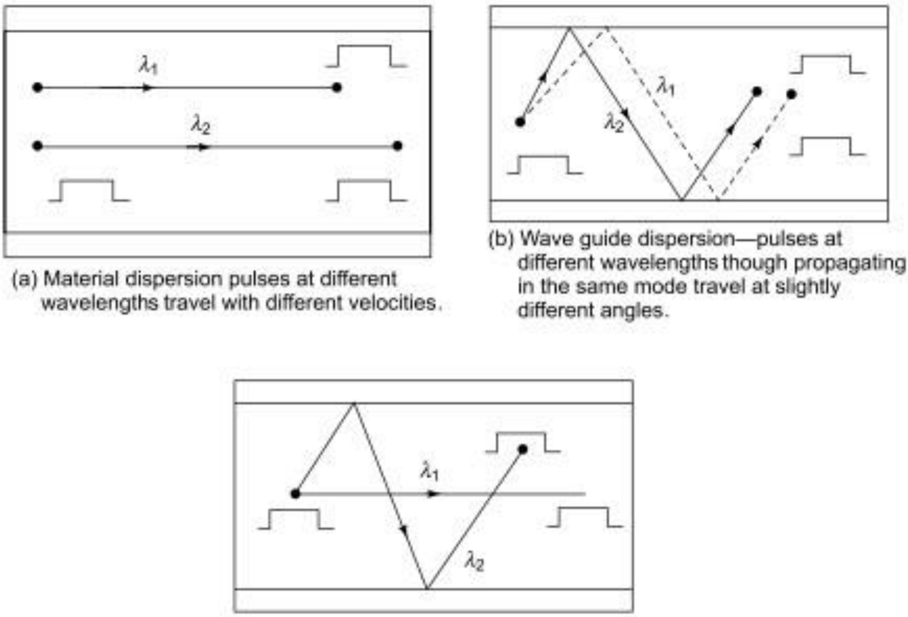
(b) *Wave Guide Dispersion*

Wave guide dispersion arises from the guiding properties of the fibre. The effective refractive index for any mode varies with wavelength, which causes pulse spreading just like the variation in refractive index does. This is known as wave guide dispersion. The amount of wave guide dispersion is governed by an equation similar to (Eq. 2) with the material refractive index being replaced by the effective refractive index.

(c) *Intermodal Dispersion*

A ray of light launched into a fibre follows different zigzag paths. When numerous modes are propagating in a fibre, they travel with different net velocities with respect to fibre axis. Parts of the wave arrive at the output before other parts leading to a spread of the input pulse. This is known as intermodal dispersion. It does not depend on the spectral width of the source. A light pulse from an ideal monochromatic source (D l = 0) would still exhibit spreading.

In a MMF, all three pulse spreading mechanisms exist simultaneously whereas in an SMF, only material and wave guide dispersions exist. Low NA fibres exhibit smaller dispersion. In fibres with large NA there exist more modes leading to larger dispersion. Dispersion may be restricted by a careful selection of low NA fibre and a narrow spectral width source. A solution to the dispersion problem is to use GRIN fibre which produce less distortion than SI fibre. Typically they have pulse spreads of only about a few ns/km which is much smaller than the pulse spreads in SI fibres. However, GRIN fibres are more expensive to manufacture.



(a) Material dispersion pulses at different wavelengths travel with different velocities.

(b) Wave guide dispersion—pulses at different wavelengths though propagating in the same mode travel at slightly different angles.

(c) Modal dispersion—a pulse at a single wavelength divides itself into modes which travel at different axial velocities.

Fig. 2.12. Illustration of signal spreading due to various dispersion processes.

Dispersion limits the bandwidth of a fibre. The information flow i.e., pulse rates must be slow enough that dispersion does not cause adjacent pulses to overlap. If the distortion due to dispersion is large, the pulse may overlap and appear at the output as a single pulse with a number of humps. The detector cannot distinguish between the individual pulses.

other Fibre losses

The losses occurring in optical fibre (glass fibres) may be mainly attributed to three mechanisms, namely, absorption, Rayleigh scattering and geometric effects.

(1) *Absorption*

Even highly pure glass absorbs light in specific wavelength regions. Strong electronic absorption occurs at UV lengths, while vibrational absorption occurs at IR wavelength from 7 to 12 mm. These absorption losses are inherent property of the glass itself and is called intrinsic absorption. However, intrinsic losses are insignificant where fibre systems operate at present.

Impurities are a major source of losses in fibre. Hydroxyl radical ions (OH) and transition metal such as copper, nickel, chromium, vanadium and manganese have electronic absorption in and near visible part of the spectrum. Their presence causes heavy losses. Metal ions must be kept to less than a few parts per billion and OH impurity to less than a few parts per million. The absorption of light either through intrinsic or impurity process constitutes a transmission loss because that much energy is subtracted from the light propagating through the fibre. The absorption losses are found to be a minimum at around 1.3 mm.

(2) *Rayleigh Scattering*

Glass is a disordered structure having local microscopic variations in density which in turn causes local variations in refractive index. Light propagation through such a structure suffers scattering losses. It is known as Rayleigh scattering loss. Because Rayleigh scattering is proportional to l^4 it becomes important at lower wavelength.

Thus, Rayleigh scattering sets a lower limit on the wavelengths that can be transmitted by a glass fibre at 0.8 mm below which the scattering loss is very high

loss µ $\frac{1}{l^4}$

(3) *Geometric effects*

These are fibre losses introduced during manufacturing processes. Irregularities in fibre dimensions may arise in the drawing process, in coating and cabling process or in the installation process. An attenuation combining the losses due to above effects in illustrated is the above figure.

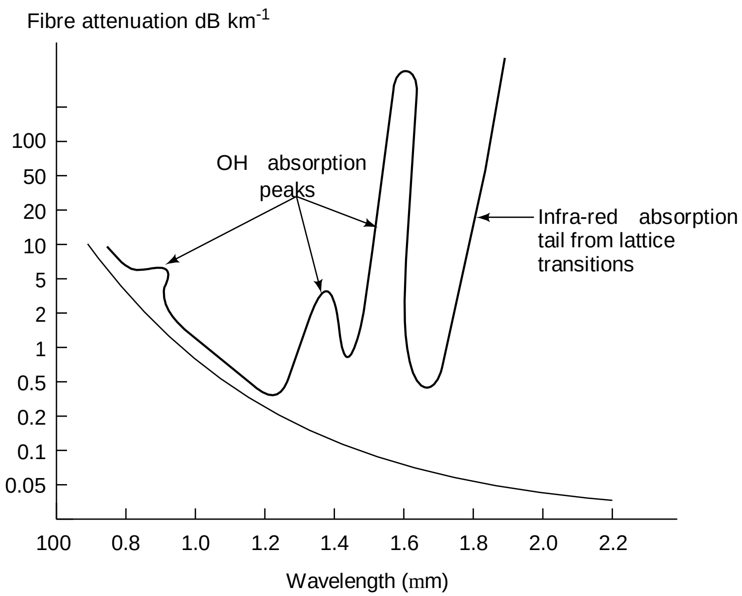


Fig. 2.13 A typical plot of fibre attenuation versus wavelength for a silica based optical fibre.

Merits of optical Fibre

Optical fibres have many advantageous features which are not found in conducting wires.

(i) Optical fibres are cheaper

The optical fibres are made from silica (SiO_2) which is one of the most abundant materials on the earth.

(ii) Optical fibres are small in size, light in weight, flexible and mechanically strong

The cross-section of an optical fibre is about a few hundred micrometers (mm) whereas wires are bigger in size and bulkier in weight. Typically, an RG-19/U coaxical cable weighs about 1100 kg/km wheares a PCS fibre cable weighs 6 kg/km only. Therefore, fibre cables are easier to transport and install than metal cables. Fibres are quite flexible and strong.

(iii) Optical fibres are not hazardous

A wire communication link could, accidentally, short circuit high voltage lines and the sparking occurring thereby could ignite combustible gases in the area leading to a great damage. Such accidents cannot occur with fibre links because of their insulating nature.

(iv) Optical fibres are immune to EMI and RFI

In optical fibres, information is carried by photons. Photons are electrically neutral and cannot be disturbed by high-voltage fields, lightning, etc. external influences so common to wire and wireless transmission. Fibres are therefore immune to externally caused background noise generated through electromagnetic interference (EMI) and radio frequency interference (RFI)

(v) Optical fibres reduce cross-talk possibility

The light waves propagating along the fibres are completely trapped within the fibre and cannot leak out. Similarly, light cannot, couple into the fibre from its sides. Because of this feature, cross-talk susceptibility is greatly reduced.

(vi) Optical fibres have a wider bandwidth

While a telephone cable composed of 900 pairs of wire can handle 10,000 calls, 1 mm fibre cable can transmit 50,000 calls Thus, fibres have ability to carry large amounts of information.

(vii) Optical fibres have low loss per unit length

The transmission loss per unit length of an optical fibre is about 4 dB/km. Therefore, longer cable runs between repeaters are feasible. The spacing of repeaters are about 2 km for copper cables whereas it can range from 30 km to 100 km in case of optical fibres.

A length of optical fibre serves as a transmission line that guides the message-carrying light wave to the receiver. The transmission of the light wave along the fibre suffers transmission dispersion.

2.8 applications

1. Medical applications

One of the important applications of optical fibres is in the field of medicine. A bundle of fibres (MMF) is used to illuminate the areas in human body which are otherwise inaccessible. A second bundle is used to collect the reflected light. An incandescent bulb can be used as the source of light in this application. Such fiberoscopes are employed widely in endoscopic applications.

In ophthalmology, a laser beam guide by the fibres is used to reattach detached retinas and to correct defects in vision.

2. Military applications

Use of fibres in place of copper wires reduces much weight and also maintains true communication silence to the enemy.

Fibre-guided missiles are presented into service during the recent wars. Sensors are mounted on the missile which transmits video information through the fibre to a ground control van and receive commands from the van again. The control van continuously monitors the course of the missile and if necessary corrects it to ensure that the missile precisely hits the target.

3. entertainment applications

A coherent optical fibre bundle is used to enlarge the image displayed on a TV screen. Conventional optional projection system is bulky and expensive.

4. optical Fibre Sensors

If the fibre is subjected to heating, the temperature causes a change in the refractive index of the fibre. As temperature increases, the difference between the refractive indices of core and cladding reduces, leading to the leakage of light into the cladding. Temperatures in the range 80^{o} to 700^{o} are measured using such a thermometer.

A smoke detector and pollution detector can be built using fibres. A beam of light radiating from one end of a fibre can be collected by another fibre. If foreign particles are present, they scatter light and the variation in intensity of the collected light reveals their presence.

A loop of fibre can be used to determine the level of liquid in a container. A part of the cladding is scraped and the loop is suspended above the liquid level. Light is directed to pass through the fibre and its intensity is measured at the output. A bare core loses more light when it is immersed in liquid than when it its exposed to air. A sudden change of outcoming light intensity indicates the liquid level.

5. communications applications

Optical fibre communications systems can be broadly classified into two groups: (i) local and intermediated range systems where the distances involved are small and (ii) long-haul systems whereas cables span large distances.

Smaller systems cover communication networks in a small community, an industry or a bank etc. In many organizations, a LAN distributes information to several stations within the organization. A number of computer terminals are interconnected over a common channel to keep track of the flow of the data and to process the data.

An optical fibre data bus offers a great reduction in cost and enormously increases information handling capacity compared to a parallel multiwire data bus.

2.9 lasers Introduction

Laser is the acronym for "Light amplification by stimulated emission of radiation." Laser is a light source which is highly coherent, i.e., radiation emitted by emitters are all in phase, same direction of emission, same state of polarization and monochromatic.

Due to coherence, the beam has a negligible divergence which makes it different from the conventional source. The theoretical explanation for laser oscillation was given by A.L Schawlow and C.H. Townes in the year 1958. The 1st laser, namely, Ruby Laser, was demonstrated by T.H. Maiman in the year 1960.

2.10 Quantum Processes

The understanding of the working principle of laser requires an appreciation of quantum processes that take place in a material when it is exposed to radiation. A material medium is composed of identical atoms or molecules—each of which is characterised by a set of discrete allowed energy states. An atom when it receives or releases an amount of energy equal to the energy difference between those two states, it is known as a quantum jump or transition.

For the sake of ease in understanding let us restrict our attention to two energy states E_1 and E_2 of an atom. E_1 is the lower energy state while E_2 is the excited state. As the constituent atoms of the medium are identical the energy states E_1 and E_2 will be common to all atoms in the medium.

Let a monochromatic radiation of frequency n be incident on the medium. The radiation may be viewed as a stream of photons, each photon carrying an energy hv. If $hv = E_2 - E_1$ the interaction of radiation with atoms lead to the following three distinct competing processes in the medium.

Process 1 - absorption

An atom residing in the lower energy state E_1 may absorb the incident photon and jump to the excited state as depicted in the figure below. The transition is known as stimulated absorption corresponding to each transition made by an atom one photon disappears from the incident beam. Schematically it may be represented as

$$A + hv \text{ fi } A^*$$

A - atom in the lower state

A^* - atom in the exited state

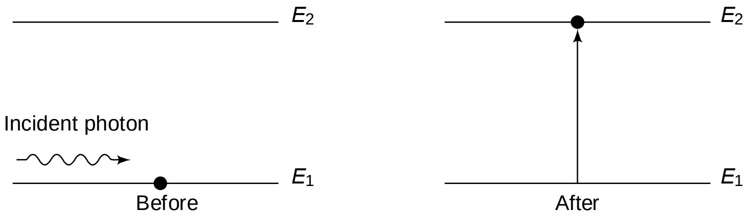


Fig. 2.14

The number of absorption transitions occurring in the material at any instant will be proportional to the number of atoms in the lower state E_1 and the number of photons in the incident beam.

The number of atoms *Nab* excited during the time D*t* is given by

$$Nab = B_{12} N_1 Q\mathrm{D}t \tag{1}$$

where, N_1 is the number of atoms in the state E_1

Q is the energy density of the incident beam

B_{12} is the probability of an absorption transition.

Process 2 - Spontaneous emission

The process in which photon emission occurs without any external source is called spontaneous emission. The process of spontaneous emission is probabilistic i.e., without any control from outside.

The instant of transition, direction of emission of photon, the phase of the photon, the polarization state of the photon are all random quantities.

Hence, the light generated is incoherent containing superposition of many waves of random phases. As a result, the light is not monochromatic.

$$A^* \text{ Æ } A + hv$$

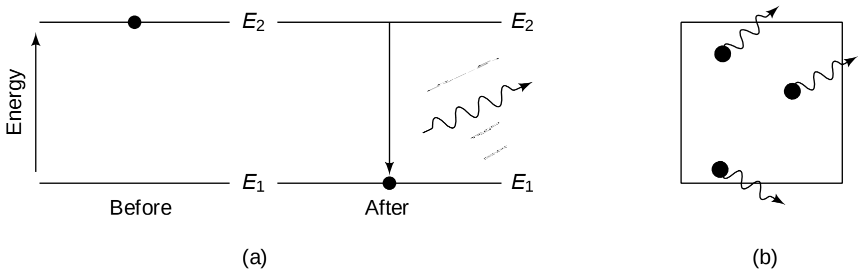


Fig. 2.15 Spontaneous emission (a) emission process (b) material emits haphazardly.

This process is independent of the external radiation. The number of spontaneous transitions *Nsp* taking place in the material during the time D*t* depends only on the number of atoms N_2 lying in the excited state E_2. It is given by

$$Nsp = A_{21} N_2 \mathrm{D}t \tag{2}$$

N_2 is the number of atoms in the state E_2.

A_{21} represents probability of a spontaneous transition.

Process 3 - Stimulated emission

An atom in the excited state need not wait for spontaneous emission to occur. A photon of energy $hv = E_2 - E_1$ can induce the excited atom to make a downward transition releasing the energy in the form of a photon. Thus, the interaction of a photon with an excited atom triggers the excited atom to drop to the lower energy state giving up a photon. The phenomenon of forced emission of photons is called induced emission or stimulated emission. This process may be represented as

$$A^* + hv = A + hv \tag{3}$$

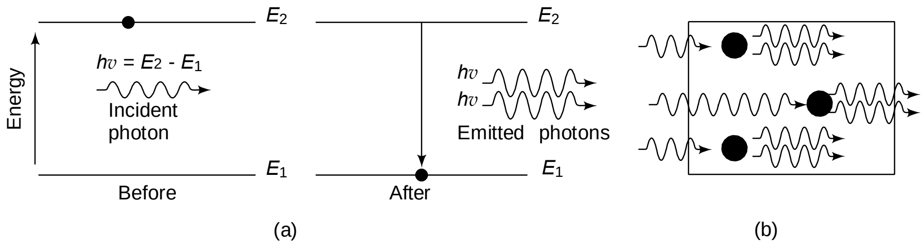


Fig. 2.16 Stimulated emission (a) emission process (b) material emits photons in a coordinated manner.

The number of stimulated transitions N_{st} occurring in the material during time Dt may be written as $N_{st} = B_{21} N_2 Q\text{D}t$, where B_{21} represents the probability of a stimulated emission as depicted in the above figure.

Important points of stimulated emission

(1) The emitted photon is identical to the incident photon in all respects, i.e., both have same frequency, travelling in the same direction with the same state of polarization.

(2) The process is controlled from outside.

(3) The multiplication of photons takes place in the process where one photon deexcites one atom giving in return another photon. Similarly, 2 photons deexcite 2 more and so 4 photons. Soon the multiplication builds up the enormous amplification.

(4) The constructive interference of many waves travelling in the same direction with a common frequency and common phase produces an intense coherent light beam.

Metastable State

The atoms are energised to a higher energy level by absorbing energy from external sources like optical, electrical, etc. They remain in an excited state for a very short period of 10^{-8} second; after that, they spontaneously release their excess energy. For stimulated emission to occur, the atoms shoud remain excited long enough, typically for 10^{-4} second, as atoms are continuously lifted up to the excited state by pumping and a number of them rapidly undergo spontaneous transition to the lower level. Therefore, the state of Population Inversion (PI) is difficult to be achieved. To achieve that state (PI), the excited atoms should remain in the uppermost level till the condition $N_2 > N_1$ gets satisfied. So a metastable state is such a long-lived upper energy level from where the excited atoms do not return to the lower level instantly. In the metastable state, the excited atoms remain for an appreciable time for 10^{-6} s to 10^{-3} s, which is a very long time for an atom in the excited state to create a state of population inversion. The population of atoms in the metastable state is greater than that in the lower state, which leads to population inversion.

2.11. Population Inversion

In a state of thermal equilibrium there are more atoms in lower level than in the upper level. But there must be more atoms in the upper than in the lower level in order to achieve stimulated emission exclusively. Therefore, a non-equilibrium state is to be produced in which the population of the upper energy level exceeds to a large extent the population of the lower energy level.

When this situation occurs, the population distribution between the levels E_1 and E_2 is said to be inverted and the medium is said to have gone into the state of population inversion.

The state of population inversion is sometimes referred to as - ve temp. state. Let us consider the number of atoms N_1 per unit volume that exist in a given energy state E. This number, called population N, is given by Boltzmann's equation.

$$N = N_0 e^{-E/K_B T} \tag{4}$$

where N_0 is the population in the ground state K_B is the Boltzmann's constant. T is the absolute temperature.

It is clear from the above equation that population is maximum in the ground state and decreases exponentially as one goes to higher energy state s. If N_1 and N_2 are the populations in two states a lower state E_1 and a higher state E_2, we have

$$\frac{N_2}{N_1} = \frac{e^{-E_2/k T_B}}{e^{E_1/k T_B}} \tag{5}$$

$$N_2 = N_1 e^{-(E_2 - E_1)/K_B T}. \tag{6}$$

Clearly $N_2 < N_1$ since $E_2 > E_1$

For laser action to take place, it is absolutely necessary that stimulated emission predominates over spontaneous emission. This is possible only if $N_2 > N_1$.

2.12 Pumping

For realizing and maintaining the condition of population inversion, the atoms have to be raised continuously to excited state. It requires energy to be supplied to the system. The process of supplying energy to the medium with a view to transfer it into the state of population inversion is known as pumping.

There are a number of techniques for pumping a collection of atoms to an inverted state.

They are:

1. ***Optical pumping:*** In optical pumping a light source such as a flash discharge tube is used. This method is adopted in solid state laser.
2. ***In electric discharge*** method the electric field causes ionization of the medium and raises it to the excited state. This technique is used in gas lasers.

In this type of excitation the laser medium itself carries the discharge current under suitable conditions of pressure and temperature.

3. *In semiconductor diode lasers*

A direct conversion of electrical energy into light energy takes place.

4. *Inelastic atom-atom collisions*

Here electric discharge method is employed to cause collision and excitation of the atom. In this method, a combination of two types of gases is used say *A* and *B*, both having the same excited state *A** and *B** that coincide or nearly coincide. During electric discharge, A gets excited to *A** (metastable state) due to collisions with electrons. The excited *A** atoms now collide with *B* atoms so that the latter atom gets excited to higher energy *B**. This method is used in He-Ne Laser.

5. *Chemical pumping (excitation by chemical reaction)*

Pumping Schemes

Atoms in general are characterized by a large number of energy levels. Among them only three or four levels will be pertinent to the pumping process.

(a) three-level pumping scheme

Let us assume that an atomic system has three energy levels.

The state E_1 is ground state and E_2, E_3 are excited states. The energy states are such that atoms are readily excited to uppermost state E_3 when light of frequency $\nu = \frac{E_3 - E_1}{h}$ is incident on them. The pump level E_3 is not a stable state. E_2 is a metastable state, the probability of spontaneous transition $E_2 \to E_1$ is extremely small. Now when the atoms are irradiated with a exciting radiation of light frequency $\nu = \frac{E_3 - E_1}{h}$ the atoms are excited to the E_3 state by process of stimulated absorption. Some excited atoms quickly drop to the intermediate level E_2 by spontaneous emission or by a non-radiative process by converting their excess energy into vibrational K.E of the atoms forming the substance. As E_2 is metastable state, atoms remain in this state for longer time = 10^{-3} sec as compared to 10^{-8} sec for short lived state E_3 and for this time the population of the state E_2 is > E_1 thus resulting in population inversion of the collection of atoms. If an atom in state E_2 decays by spontaneous emission or stimulated emission, it emits a radiation of freq. $\nu = \frac{E_2 - E_1}{h}$ producing stimulated emission from other atoms. In this scheme, the terminal state of laser transition is simultaneously the ground state. To achieve population inversion more than half of the ground state atom must be pumped to the upper state.

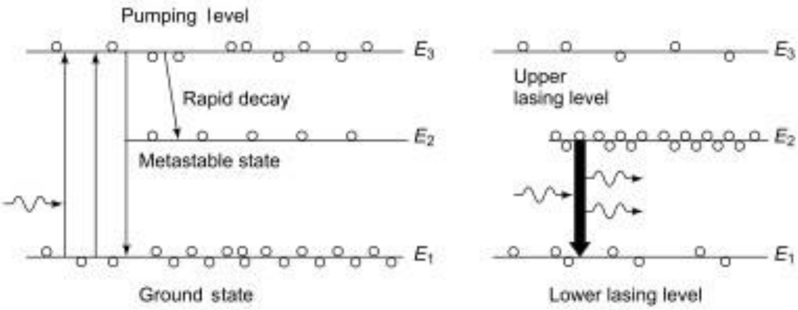


Fig. 2.17 Typical three-level pumping scheme (a) optical pumping (b) lasing action.

(b) Four-level pumping scheme

In four-level pumping scheme, E_1 is ground state, E_2 another excited state, E_3 is a metastable state and E_4 pumping level. Pump frequency lifts the active centres from ground level E_1 to E_4. From the pump level E_4, atoms fall to excited state E_3. The population at this state grows rapidly, while the level E_2 is virtually empty.

\ Population inversion so achieved is between the states E_2 and E_3.

A photon of energy $hv = E_3 - E_2$ can start a chain of stimulated emissions, bringing the atoms into the state E_2. From there the atom undergoes non-radioactive transitions subsequently to the ground state E_1 and will be available once again to participate in the process.

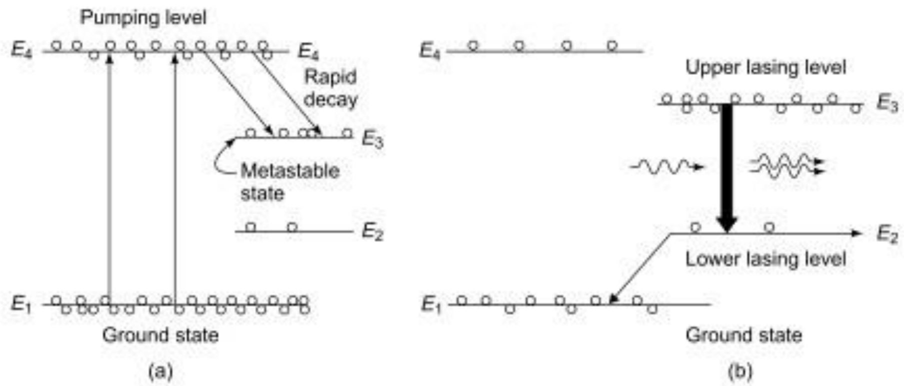


Fig. 2.18 A typical four level pumping scheme (a) pumping (b) lasing action.

1.13 resonant cavity

Light can be amplified by an active medium taken into the state of population inversion. But the spontaneous photons are emitted by atoms independently in various directions which produce stimulated emission in different directions. The resultant effect would be production of incoherent light. An optical resonator is used which generally consists of two mirrors, one of which is semitransparent and the other is 100% reflecting. The mirrors are set normal to the optic axes of the material. This structure is known as Fabry-Perot Resonator.

Fig. 2.19

Febry-Perot optical resonator

Light amplification and oscillations due to the action of optical resonator, follows the process at each step.

Fig. 2.20 (a) Initially active centres in the medium are in ground state.

Fig. 2.20 (b) By pumping mechanism, the material is taken into a state of population inversion.

Fig.2.20 (c) Spontaneous photons are emitted in the initial state in every direction of the stimulated photons as well.

Fig. 2.20 (d) To generate o/p photons with specific direction are selected while others rejected. Also for maximum amplification, stimulated photons are made to pass through the medium a number of times.

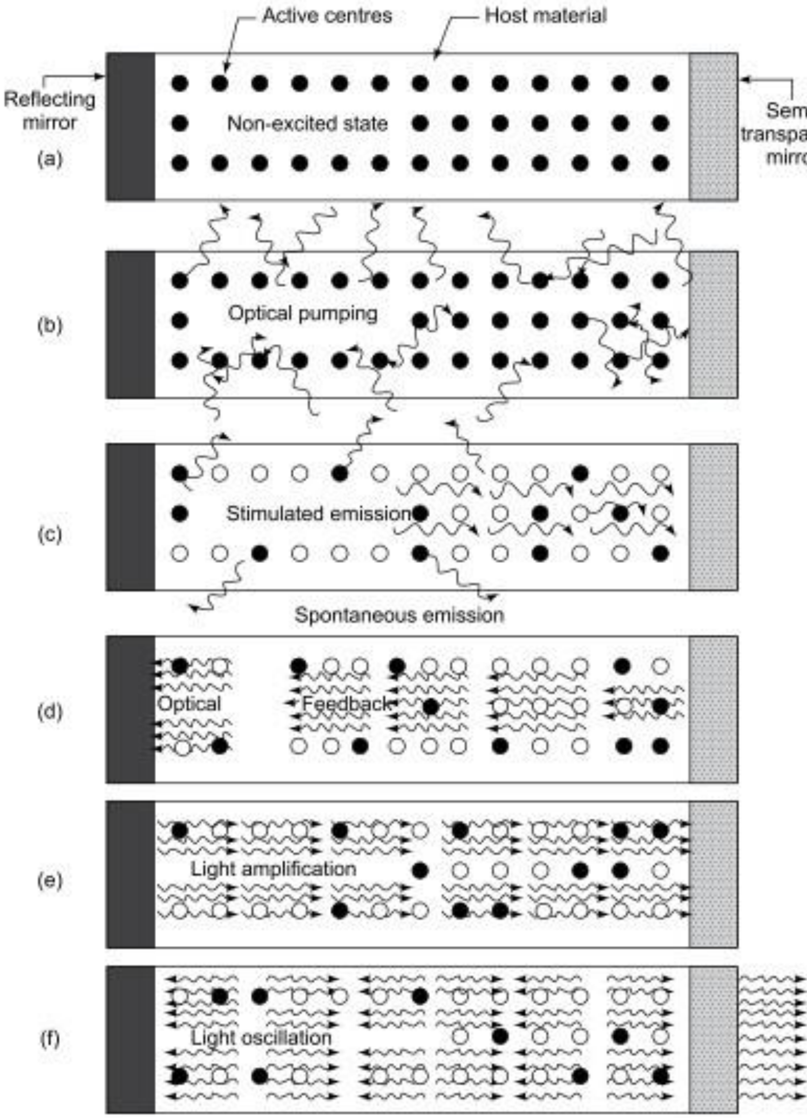


Fig. 1.20 (a) (b) (c) (d) (e) (f)

Now photons emitted in any direction other than parallel to optic axis pass out of side of resonator end are lost. But on reaching semi-transparent mirror sum of the photons are transmitted out and part of them is reflected back. After reflection they build more strength by deexciting more atoms.

(e) The amplified beam will move along the same path as starting photon and undergo multiple reflection at mirrors and build strength.

(f) Laser beam oscillation begins when the amount of amplified light becomes equal to the total amount of light lost through the sides of the resonator, through the mirrors and through absorption by the medium. After enough intensity is built up, a highly collimated intense beam comes out.

Now the wave property of light requires an additional condition to be fulfilled.

The waves propagating within the cavity resonator should take an standing wave pattern. The optical path length travelled by a wave between consecutive reflection should be integral multiple of wavelength.

$$\therefore \qquad 2L = m\,\lambda_m \qquad m = 1, 2, 3\ldots$$

$$L = \left(\frac{m\,\lambda_m}{2}\right)$$

The resonator may support several standing waves of slightly different wavelengths these are called longitudinal modes. Each mode has a distinct frequency given by

$$\nu_m = \frac{mc}{2L}$$ 'm' is called mode number.

laser Beam characteristics

1. **Coherence:** The waves emitted by a laser source will be in phase and are of same frequency. The laser beam is spatially and temporally coherent to all extra-ordinary degree.
2. **Directionality:** Lasers emit light in only one direction as only photons travelling along optical axis of system are selected and augmented.

Any conventional light source like a tubelight emits radiations in all directions unlike a laser source which emits radiation only in one direction. The directionality of the laser beam is usually expressed in terms of full angle beam divergence which is twice the angle that the outer edge of the beam makes with the axis of the beam. The outer edge is defined as a point at which the strength of the beam drops to $\frac{1}{e}$ times its value at centre.

A Gaussian shape of laser beam is shown in Fig. 2.21 and the full angle divergence in terms of minimum spot size is given by

$$\phi = \frac{\lambda}{2\,w_0}$$

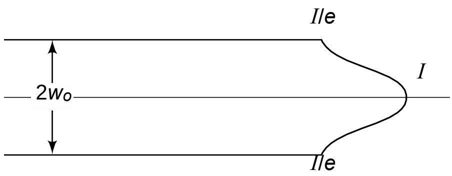


Fig. 2.21 Gaussian beam

where λ is the wavelength of the beam. For a typical planar wavefront emerging from an aperture of diameter d, it propagates as a parallel beam for a distance of $\frac{d^2}{\lambda}$, called the Rayleigh's range, beyond which the beam due to diffraction diverges with an angular spread of $\Delta\theta = \frac{\lambda}{d}$. For a typical laser the beam divergence is less than 0.01 milliradian, i.e., a laser beam spreads less than 0.01 mm for every metre. However, on the other hand, for ordinary light the spread is 1 m for every 1 m of travel.

If a_1 and a_2 are the diameters of laser radiation at distances d_1 and d_2 from a laser source respectively, then the angle of beam divergence in degrees is given by

$$\phi = \frac{a_2 - a_1}{2(d_2 - d_1)}$$

3. **Divergence:** The divergence of or angular spread of the laser beam is extremely small.

$$\Delta\theta = 10^{-5} \text{ to } 10^{-6} \text{ radians}$$

4. **Intensity:** Intensity of conventional source decreases with distance as it spreads in the form of spherical waves so not harmful to eyes.

   A laser emits light in the form of narrow beam propagating as plane waves. As energy is concentrated in a narrow region its intensity is tremendously high. For example, light from 1mW laser is 10,000 times brighter than the light from the sun at earth's surface. The intensity of laser beam stays nearly constant with distance.

5. **Monochromatic:** A normal monochromatic source has a wavelength spread of 100Å to 1000Å. The laser light is highly monochromatic. Spread is of the order of a few angstrom (< 10Å) only. The monochromaticity is related to the wavelength spread of radiation given by $\Delta\lambda = \left(\frac{-c}{\nu^2}\right)\Delta\nu$.

1.14 Einstein equation

Einstein theory of Spontaneous Stimulated emission

In 1917, Einstein predicted the existence of two different kinds of processes by which an atom emits radiation. They are spontaneous emission and stimulated emission.

Let us assume that only the spontaneous emission is present and there is no stimulated emission of light. At thermal equilibrium condition, the rate of absorption = the rate of emission of light.

∴ From equations (1) and (2)

$$B_{12} N_1 Q = A_{21} N_2 \tag{7}$$

$$Q = \frac{A_{21} N_2}{B_{12} N_1} \tag{8}$$

According to Boltzmann distribution function, the population of atoms in the upper and lower energy levels is related by

$$\frac{N_2}{N_1} = \frac{e^{-E_2/kt}}{e^{-E_1/kt}} \tag{9}$$

Substituting $\frac{N_2}{N_1}$ in equation (8), we get

$$Q = \frac{A_{21}}{B_{12}} e^{-(E_2 - E_1)/kT} \tag{10}$$

According to black body radiation, the energy density

$$Q = \left(\frac{8\pi h\nu^3}{c^3}\right)\left(\frac{1}{e^{h\nu/KT} - 1}\right) \tag{11}$$

where h is the Planck's constant and 'c' is the velocity of light. Comparing the above two equations eqs. (10) and (11), we observe that they are not in agreement.

To rectify the discrepancy, Einstein proposed another kind of emission known as stimulated emission of radiation. Therefore, the total emission is the sum of the spontaneous and stimulated emissions of radiation. At thermal equilibrium,

The rate of absorption = the rate of emission

From equation

$$N_{ab} = N_1 B_{12} Q\Delta t$$

$$N_{sp} = A_{21} N_2 \Delta t$$

$$N_{st} = B_{21} N_2 Q\Delta t$$

We can write

$$A_{21} N_2 + B_{21} N_2 Q = B_{12} N_1 Q \tag{12}$$

From this, we get

$$Q = \frac{A_{21} N_2}{B_{12} N_1 - B_{21} N_2} \tag{13}$$

By dividing $B_{21} N_2$ in all terms, we have

$$Q = \frac{A_{21}}{B_{21}} \times \frac{1}{\frac{B_{12} N_1}{B_{21} N_2} - 1}$$

Substituting $\frac{N_1}{N_2}$ as $\exp\left(\frac{E_1 - E_2}{KT}\right)$,

We have

$$Q = \frac{A_{21}}{B_{21}} \times \frac{1}{\left[\left(\frac{B_{12}}{B_{21}}\right)\exp\left(\frac{hv}{KT}\right) - 1\right]} \quad (14)$$

The above equation must agree with Planck's energy distribution radiation formula

$$Q = \frac{8\pi hv^3}{C^3} \times \left(\frac{1}{\frac{hv}{KT} - 1}\right) \quad (15)$$

Comparing the two equations (14) and (15), we get

$$B_{12} = B_{21}$$

$$\frac{A_{21}}{B_{21}} = \frac{8\pi hv^3}{C^3} \quad (16)$$

The coefficients A_{21}, B_{12} and B_{21} are known as "Einstein's coefficients."

types of lasers

Lasers are classified into five major categories based on the type of active medium. They are:

(i) Solid state lasers
(ii) Gas lasers
(iii) Liquid dye lasers
(iv) Solid state diode lasers (semiconductor laser): Usually laser light falls in Red or IR region.
(v) Dye and chemical lasers.

2.15 Semiconductor laser

The most compact of all the lasers is semiconductor diode laser in its simplest form. The diode laser consists of a p-n junction doped in a single crystal of a suitable semiconductor such as Gallium Arsenide.

Principle

When a forward bias is applied to the diode the holes are injected into the *p*-side of the junction and electrons are injected into the *n*-side. The recombination of holes and electrons within the junction region result in recombination radiation. If the junction current density is large enough a population inversion can be obtained between the electron levels and hole levels. Stimulated emission can be obtained for laser action when the optical gain exceeds the loss in the junction layer. In diode laser, this layer is very thin, typically in the order of few microns and the end faces of the crystal are made partially reflecting to form an optical resonator.

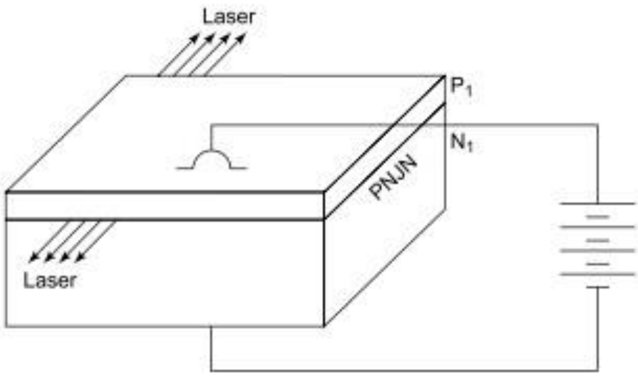


Fig. 2.22 Semiconductor laser.

To produce laser action the following conditions should be satisfied:

i. Population inversion
ii. Stimulated emission
iii. Cavity resonator.

Ga-As Laser

It is a *p*-*n* junction diode with the *p*-type and *n*-type regions heavily doped. Under large applied forward bias, electrons and holes are injected into and across the transition region in considerable concentration. As a result the region around the junction contains a large number of electrons within the conduction band and a large number of holes within the valence band. When the population density is high enough, a condition of population inversion is achieved and recombination may be stimulated resulting in laser action. If the emission is not stimulated the device is called a light emitting diode. To convert an LED into a laser diode, a high current is required to achieve population inversion. In the case of semiconductor lasers there is no need of external mirrors the edges are cleaved and polished to act as optical resonators.

A typical semiconductor laser is shown in fig. 2.22. In the case of gallium arsenide, we get a light radiation in the infrared region. Thus, a Ga-As converts electricity into light. The efficiency can go up to 100%. When the temperature is reduced to 100° K the operating current is supplied from a pulse generator up to 5-20 m*s*. The energy separation between the conduction band and valence band is 1.4ev and hence the wavelength of light emitted is 8400 Å.

The efficiency is more than 10% and it can be increased by decreasing the temperature alone. It can have a continuous wave output or pulsed output. The modulator of the output is possible. It is highly economical and further the arrangement is compact.

Merits

1. Simple
2. Compact
3. Highly efficient

4. Requires very little power
5. Requires very little auxiliary equipment
6. Output can be controlled by controlling the junction current.

demerits

1. Compared to He-Ne laser, diode laser gives more divergent beam having an angular spread of the order a 5° to 15°.
2. Less monochromatic
3. Highly temperature sensitive.

applications

1. Used in satellites
2. Optical communication (as light sources)
3. Laser printers, copiers
4. CD player, optical floppy disc
5. Measuring instruments like strain gauges, velocity meters, etc.

tunable laser

A **tunable laser** is a laser whose wavelength of operation can be altered in a controlled manner. While all laser gain media allow small shifts in output wavelength, only a few types of lasers allow continuous tuning over a significant wavelength range.

There are many types and categories of tunable lasers. They exist in the gas, liquid, and solid state. Among the types of tunable lasers are excimer lasers, CO_2 lasers, dye lasers (liquid and solid state), transition metal solid-state lasers, semiconductor diode lasers, and free electron laser. Tunable lasers find applications in spectroscopy, photochemistry and optical communications.

1 Types of tunability

(i) Single-line tuning

(ii) Multi-line tuning

(iii) Broadband tuning

Single-line tuning

Since no real laser is truly monochromatic, all lasers can emit light over some range of frequencies, known as the line width of the laser transition. In most lasers, this line width is quite narrow (for example, the 1064 mm wavelength transition of a Nd:YAG laser has a line width of approximately 120 GHz, corresponding to a 0.45 nm wavelength range). Tuning of the laser output across this range can be achieved by placing wavelength-selective optical elements (such as an etalon) into the laser's optical cavity, to provide selection of a particular longitudinal mode of the cavity.

Multi-line tuning

Most laser gain media have a number of transition wavelengths on which laser operation can be achieved. For example, as well as the principal 1064 nm output line, Nd:YAG has weaker transitions at wavelengths of 1052 nm, 1074 nm, 1112 nm, 1319 nm, and a number of other lines. Usually, these lines do not operate unless the gain of the strongest transition is suppressed, e.g., by use of wavelength selective dielectric mirrors. If a dispersive element, such as a prism, is introduced into the optical cavity, tilting of the cavity's mirrors can cause tuning of the laser as it "hops" between different laser lines. Such schemes are common in argon-ion lasers, allowing tuning of the laser to a number of lines from the ultraviolet and blue through to green wavelengths.

Broadband tuning

Some types of lasers have an inherently large line width, and thus can be continuously tuned over a significant wavelength range by modification of the laser's cavity.

Distributed feedback (DFB) semiconductor lasers and vertical cavity surface emitting lasers (VCSELs) use periodic distributed Bragg reflector (DBR) structures to form the mirrors of the optical cavity. If the temperature of the laser is changed, thermal expansion of the DBR structure causes a shift in its peak reflective wavelength and thus the wavelength of the laser. The tuning range of such lasers is typically a few nanometers, up to a maximum of approximately 8 nm, as the laser temperature is changed over ~ 50 K. Such lasers are commonly used in optical communications applications such as DWDM-systems to allow adjustment of the signal wavelength.

The first true broadly tunable laser was the dye laser. Dye lasers and some vibronic solid-state lasers have extremely large line widths, allowing tuning over a range of tens to hundreds of nanometers. Titanium-doped sapphire is the most common tunable solid-state laser, capable of laser operation from 670 nm to 1100 nm wavelength. Typically these laser systems incorporate a Lyot filter into the laser cavity, which is rotated to tune the laser. Other tuning techniques involve diffraction gratings, prisms, etalons, and combinations of these.

Helium-neon laser

The first gas laser to be operated successfully was the He-Ne laser. In the case of solid state laser such as ruby, the pumping is done using flash lamp. Such a technique is efficient if the lasing system has broad absorption bands. In gas laser such as Helium-Neon the atoms are characterized by sharp energy levels as compared to those in solids. Hence, one generally uses an electric discharge to pump the atoms.

Construction: The discharge tube is of length 50 cm and diameter 1 cm filled with a mixture of Helium and Neon gases in ratio 10 : 1 with a partial pressure of 1 mm of Hg. A discharge is produced in gas by electrodes connected to high voltage power supply. The tube is then sealed with inclined windows at its edge. Two reflections from Febry-Perot resonator are fixed on the axis of the tube. The distance between the mirrors is adjusted to support standing wave (Fig. 2.23).

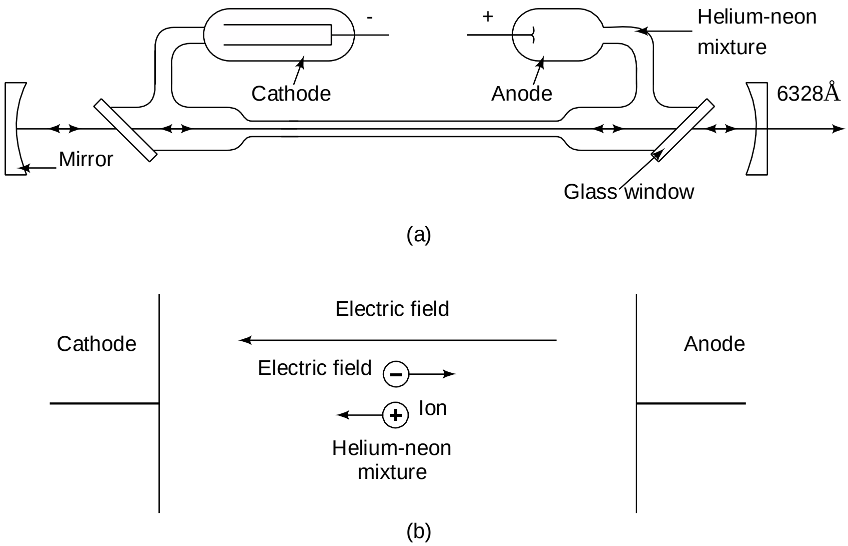


Fig. 2.23

Working: He-Ne laser employs a four-level pumping scheme. The gas mixture is ionized due to electric field using high voltage power supply. Due to electric field the electrons and ions are accelerated towards anode and cathode respectively. Since the electrons have a small mass, they acquire a higher velocity.

Helium atoms are more readily excitable than neon atoms therefore they are lighter. Helium atoms are excited to levels F_2 and F_3 at 19.81 eV and 20.16 eV due to collisions with electrons. F_2 and F_3 are metastable states and as current is passed more in discharge tube, more Helium atoms accumulate in excited states. Since a radioactive transition is forbidden. Helium atoms return to ground state by transferring their energy to Neon atoms through collisions.

Neon atoms acquire energy and go to excited states E_6 level and E_4 level of 20.66 eV and 18.7 eV respectively of neon atom which nearly coincide with F_3 and F_2 levels of Helium atoms. Neon atoms are active centres and the role of Helium is to excite the neon atoms and cause population inversion. Probability of energy transfer from He atoms to Ne atoms are more as 10 Helium atoms to 1 Neon atom is in mixture. Now E_6 and E_4 levels of Neon atoms being metastable states achieve population inversion compared to E_5 and E_3 state.

But random photon emitted spontaneously set on stimulated emission from following transition.

1. E_6 - E_3 transition - laser beam of red colour l = 6328 Å
2. E_4 - E_3 transition - laser beam of l = 11500 Å
3. E_6 - E_5 transition - laser beam of l = 33900 Å

E_5 and E_3 being terminal levels, neon atoms make a downward transition to E_2 level. E_2 level being a metastable state, accumulate neon atoms again. But neon atoms drift towards surrounding walls and collide with it, give up energy and return to ground state. He-Ne laser operates in continuous wave mode.

Merits

a. He-Ne laser is operated continuously.
b. Highly monochromatic
c. Highly stable
d. The output of the laser can be turned to certain available wavelength.
e. No separate cooling arrangement is necessary.

Demerits

Very low power in milli watts while ruby laser has power about 10,000 watts.

Applications

a. In holograms
b. Industries
c. Communication

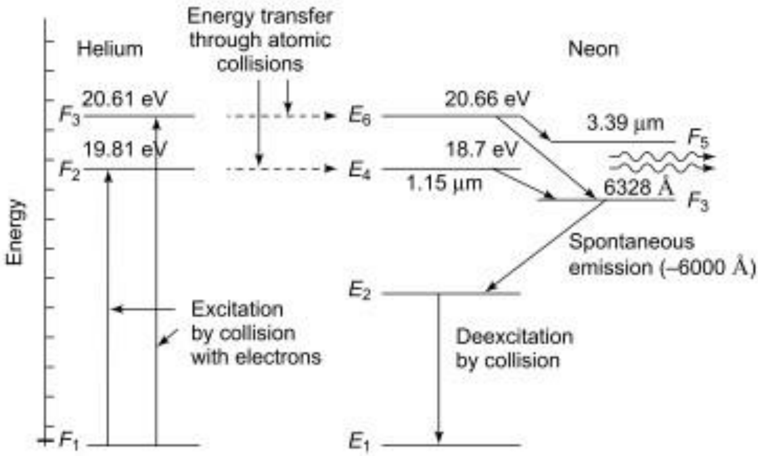


Fig. 2.24 Energy levels of helium and neon atoms and transitions between the levels.

distinction between ruby laser and He-ne laser

Ruby Laser	He-Ne Laser
1. The output beam is in pulses.	The output beam is continuous.
2. The laser beam is very intense.	The laser beam is not very intense.
3. Chromium ions are used as active material.	Vapours of metals are used as active media.
4. It has moderate monochromaticity.	It has exceptionally high monochromaticity.
5. It does not have a pure and continuous spectrum	It has extremely pure and continuous spectrum.
6. It does not have high stability of frequency.	It is having a high stability of frequency.

2.16 nd:yag laSer

The Nd:YAG laser consists of yttrium aluminium garent ($Y_3 Al_5 O_{12}$) crystal in which 1.5% neodymium ions (Nd^{3+} ions) are doped as impurities. These Nd^{3+} ions occupy yttrium ion sites and provide lasing transition. Figure 2.25 shows the schematic diagram of an Nd:YAG laser. This laser consists of three essential parts:

(i) Yttrium aluminium garnet in which 1.5% of Nd^{3+} is doped as impurities. Nd^{3+} is the lasing ion.

(ii) Two end mirrors M_1 and M_2 which will act as resonant cavity. While mirror M_1 is a totally reflecting one, mirror M_2 is partially reflecting.

(iii) Krypton flash lamp which acts as a pump.

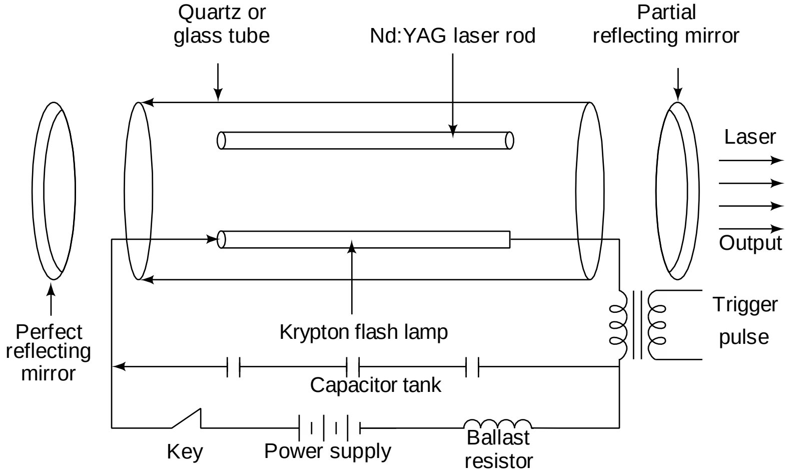


Fig. 2.25 Schematic diagram of Nd:YAG laser.

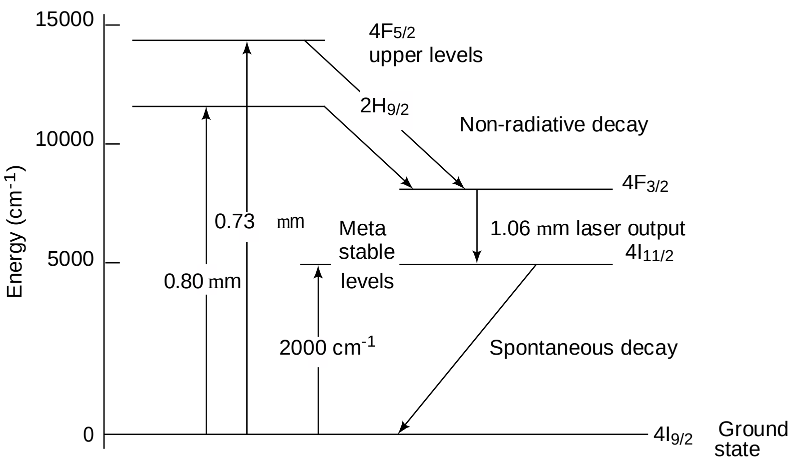


Fig. 2.26 Energy levels of neodymium ions.

The Nd:YAG laser rod has a length of about 5 to 10 mm with a diameter 6 to 9 mm. It is kept at one foci of an elliptical glass tube. A krypton flash lamp, the optical pump source, is placed at the other foci of the glass tube. As shown in Fig. 2.25, on the left side there is a perfect reflecting mirror while on the right a partially reflecting mirror is kept. These two mirrors act as resonant cavity to produce a stimulated and amplification process. The krypton flash lamp is provided with the necessary power supply arrangement.

Figure 2.26 shows the energy levels involved of Nd^{3+} ions (neodymium) in lasing action.

When the krypton flash lamp is energized it gives out radiations, and the Nd^{3+} ions, by absorbing 0.73 mm and 0.80 mm from the input radiations, get excited to the higher energy levels $2H_{9/2}$ and $4F_{5/2}$. These are energy levels where Nd^{3+} ions can stay for a duration of about 10^{-8} *s*. Therefore, these ions undergo a non-radiative decay process to reach the metastable level $4F_{3/2}$. Therefore, such a system will produce a population inversion process. If by chance a spontaneous transition takes place from the metastable level $4F_{3/2}$ to still a lower energy level $4I_{11/2}$, it will lead to a photon which on oscillating between the end mirrors will lead to a stimulated process to yield the laser output of wavelength 1.06 mm. Some important features of Nd:YAG laser are:

(i) It is a four-level laser.

(ii) Uses a rare earth ion like neodymium. Erbium and dysprosium may also be used instead of neodymium ions.

(iii) Energy levels of Nd^{3+} with the inner 4*F* shell is shown in Fig. 2.28.

(iv) Nd^{3+} ion concentration corresponds to ground state population of 6 ¥ 10^{19} ions/cc.

(v) The metastable level $4F_{3/2}$ has a lifetime of 0.23 ¥ 10^{-3} *s*.

(vi) The Nd:YAG laser is quasi-continuous wave laser.

(vii) In some cases YAG is doped with Cr^{3+} ions in addition to Nd^{3+} ions. In this case the xenon flash lamp can be used as a pumping source.

(viii) Gives output in the infrared region.

applications of lasers

Laser applications are numerous and diverse. In fact they range over a different disciplines such as physics, chemistry, biology, medicine and engineering.

Laser offers a wonderful opportunity to investigate the basic laws of interaction of atom and molecules with electromagnetic waves with high intensity.

Medical applications of lasers

Presently lasers are predominantly used in medicine for non-invasive observations and in surgery. Some of the important applications of laser in medicine are:

1. Low intensity lasers interacting with tissue can result in a characteristic luminescence which supplies information regarding the tissue, such as blood flow, pH and oxygen content. It can also indicate pathological alteration in the tissue caused by cancer.

2. **Photochemotherapy:** The laser light triggers chemical reactions in the body which are utilized for therapeutic applications.
3. **Heating-Laser coagulation and welding:** Blood in coagulated by the heat that the laser energy generates. This is useful to control bleeding during laser surgery.
4. **Laser Surgery:** Lasers can be used to cut through tissue by vaporization in general surgery, gynecology, orthopaedic surgery and hemosurgery. The focussed laser beam proved to be an unique scalpel, capable of bloodless surgery, since the beam not only cuts but also “welds” blood vessels being cut.
5. Laser beam transmitted through the fibre was successfully used to disintegrate urinary stone

6. Laser radiation is efficient in hemorrhage control. Therefore, lasers are used for reduction of hematic losses, which is especially important for patients with poor blood coagulation. Most common sources for these applications are CO_2 and argon ion lasers.
7. A separate medical field for laser surgery is ophthalmology where the laser (usually Ar+) has already been in use for several years to treat the detachment of the retina. Lasers are also used to treat cataract, varied tumours, and glaucoma.
8. Lasers are now finding increasing use in therapy. The He-Ne laser has produced curing effect on tropic ulcers, poorly healing wounds, and bone fractures.
9. Stomatology is another field in medicine where the laser has also been found useful. Laser can replace dental drills. In this function it has demonstrated a much higher performance and operated without pain.

defence applications of lasers

High intensity, good spectral brightness and low divergence of lasers have given rise to many defence applications.

1. **Laser Range Finding (LRF) Systems:** Distance measurement by laser radiation is one of the earliest uses of lasers. The shorter wavelength of the laser radiations makes it possible to range different specific targets, a few meters in size, at distances up to 20 km. The laser range finder used in defence are called pulse optical radar. Multiple echo discrimination is one essential feature of LRF which can detect and discriminate individual structures at longer distances.
2. **Laser Communication:** In another important defence application. Recent advances include the laser guided communication between submarines and satellites/aircraft offer emergency action messages to be relayed efficiently and quickly.
3. **Laser Weaponry:** Being a highly intense beam, laser finds wide range of application in weaponry. Laser guided missiles, laser guns and laser induced bombs are used in defence.