# Photonics and Fibre optics

## Learning objective

1. To learn basics of lasers viz., the fundamental theory, conditions of laser action, few types of lasers, laser application in industries and medicine.
2. Also, to learn the concepts, types and some applications of the optical fibers.

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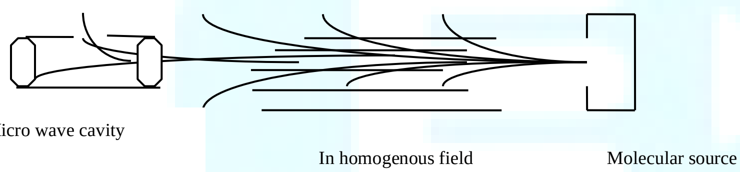
Introduction

In 1950,Lamb and Rutherford's in their papers on fine structure of hydrogen atom quoted the negative absorption what is present day **Population inversion** has made the steping stone to the MASER and later to LASER. From their concepts, it was strongly believed that the electron of each atom, subjected to inhomogeous field under go oscillations and get excitation by observing some energy and releases the same including the losses. The energy observed/liberated may be comparable to the two (ground state, excited state) states of the electron of the atom. This was demonstrated using microwaves in Microwave amplification of stimulated emission (MASER). Later, the Radio waves (RASER), further the light (LASER)




## 1. Basics of Laser

˝LASER˝ is acronym of expansion Light Amplification by Stimulated Emission of Radiation. When light propagates through a medium its intensity reduces due to reflection, refraction and scattering losses. To make the light amplified, the property of the medium on which it propagates should be modified for the following (**conditions for laser action**):

1. There must be population inversion ($N_2>N_1$) in the atoms of medium.
2. The energy density of radiation on the medium should be increased. The $\rho(v)$ is to be increased in optical resonance cavity.
3. The ratio of Einstein's coefficient should be less ($A_{21}/B_{21}<$) so that more stimulated emission to take place than the spontaneous emission.

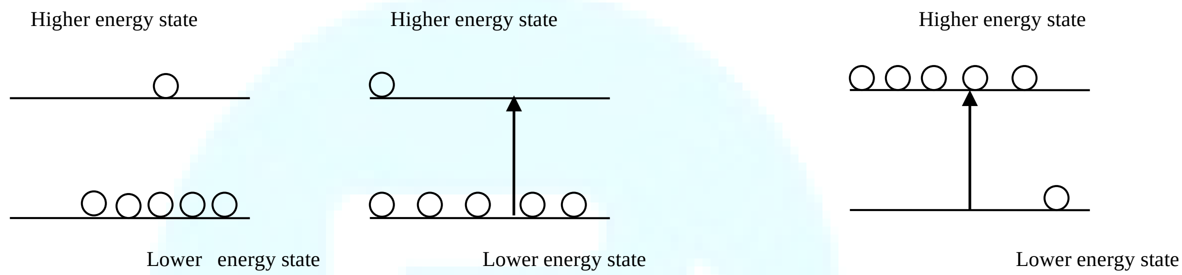
If the above conditions are satisfied on a medium then the laser will be generated .The laser action, which occurs on a medium is called active medium,

## 1.1 Population inversion

In an ideal state of a atoms more of electrons ($N_1$) are available in the lower energy state than the higher energy state Fig.1a.

When the atom is subjected to the electric field/exposed to radiation/ heated in a heat source or kept in a magnetic field, some energy will be supplied to these electrons in lower energy state. These electrons could take up the energy and reaches the higher energy state called excited state and the process is excitation/absorption Fig.1b.

As the result of above, more of electrons ($N_2$) will be present in the higher energy state than the lower energy state after some time. This is contrary to ideal state of a atom, now the atom with more number of electrons at higher energy state is known as “population inversion”Fig.1




1a. Energy states of atom    1b. Excitation ideal    1c. Population Inversion

Fig.1 Ideal, Excitation and Population Inversion of atom

## 1.2 Pumping

The process of obtaining population inversion is called pumping.

The following are the mechanisms used to achieve the population inversion.

1. Optical Pumping

When the medium is exposed to optical radiation for excitation then the mechanism is called optical pumping 2. Electrical discharge pumping

If the active medium is subjected to the electric field for increase of electron velocity which also transfers the energy to near by atoms called electrical discharge pumping.

3. Direct conversion

The electric field will be applied on the direct band gap semiconductor where accelerated electrons and holes mix up in recombination and release the energy by emission of laser radiation.

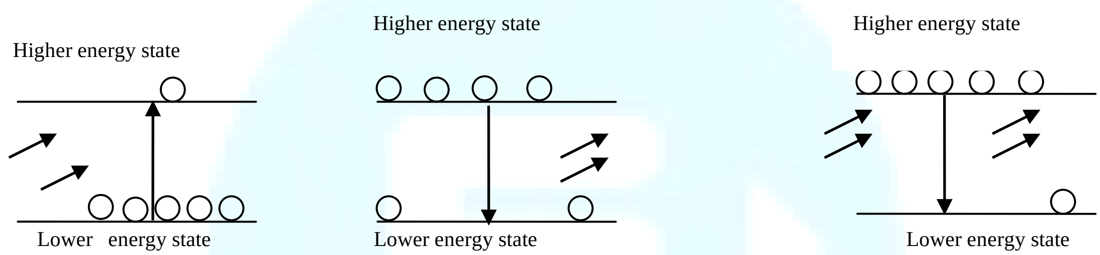
4. Pumping by inelastic collision

In an inelastic collision of atoms with electron, one of atom will be excited. The atom simultaneously releases the energy gained in the collision to its neighbor and make it to become excited known as pumping by in-elastic collision. **1.3 Excitation, spontaneous emission and stimulated emission**

**1.3.1 Excitation**

The Bohr's atom model expresses that the electrons are distributed in the permitted energy levels/orbits. The lowest energy level that occupied by electrons is ground state/lower energy state of the atom.

If the electron belongs to lower energy state absorbs the energy to reach the next higher energy level/state is known as Excitation /absorption (Fig2a)




2a. Excitation

2b. spontaneous emission

2c. Stimulated emission

Fig.2 Excitation, spontaneous and stimulated emission

Then the energy required for excitation of atom is $\Delta E = h\nu = E_2 - E_1$

Where $E_2$ is the energy of excited state of electron in a atom and $E_1$ the energy of ground state of electron in the same atom.

**1.3.2 Spontaneous emission**

Spontaneous emission is a continuous process. Since, the life time of excited electron at higher energy state is less (in the order of nano seconds), the electrons from higher energy could release the energy that gained during excitation by some mechanism and make the whole atom to get de excitation.

The energy released will be $\Delta E = E_2 - E_1$.

If the energy released is continuous in the form of radiation, which does not follow unique wave length then it must be due to spontaneous emission. (Fig2b).

### 1.3.3. Stimulated emission

Stimulated emission is a controlled de excitation. If the energy released in de excitation is controlled in the presence of some energy which is used for the excitation. This situation causes controlled emission of radiation following the unique wave length known as stimulated emission (Fig2c)

### 1.4 Einstein theory and significances

In the present theory the Einstein's coefficients in an equation indicates the electronic/atomic transition between two energy levels as a simple case. Let the energy level be $E_1$(lower) and $E_2$(higher) with arbitrary constant A and B depends on spontaneous emission and stimulated emission respectively.

**The excitation /absorption**

The rate of excitation from lower level $E_1$ to higher level $E_2$ will be

$$\square_{12} \square N_1 \square(\square) B_{12} \qquad (1)$$

Where

$B_{12}$- a constant depends on excitations/absorption.

$N_1$- Number of atoms per unit volume with $E_1$ energy

$\square(\square)$ - Energy density of radiation during the excitation.

**The spontaneous emission**

The rate of spontaneous emission from $E_2$ to $E_1$ (de excitation) is

$$\square_{21} \square N_2 A_{21} \qquad (2)$$

Where

$A_{21}$ – a constant depends on spontaneous emission form $E_2$ to $E_1$.

$N_2$ – Number of atoms per unit vol. with $E_2$ energy level

**The Stimulated emission**

The rate of stimulated emission from $E_2$ to $E_1$ is

$$\square_{21}' \square N_2 \square(\square) B_{21} \qquad (3)$$

Where

$N_2$ – Number of atoms per unit vol. with $E_2$ energy level

$\square(\square)$ - Energy density of radiation during stimulated emission

At thermal equilibrium the rate of excitation = rate of spontaneous emission + rate of stimulated emission, ie.,

$$R_{12} = R_{21} + R_{21}' \qquad (4)$$

Substituting (1), (2) and (3) in (4)

$$N_1 \rho(\nu) B_{12} = N_2 A_{21} + N_2 \rho(\nu) B_{21} \qquad (5)$$

Dividing each term by $N_2$

$$\frac{N_1 \rho(\nu) B_{12}}{N_2} = A_{21} + \rho(\nu) B_{21} \qquad (6)$$

The constant $B_{12}$ depends on excitation which is also depends on stimulated emission because both of them are taking place in a controlled manner.

Therefore, $$B_{12} = B_{21} \qquad (7)$$

From Boltzmann's energy distribution law to the dissimilar particles for a system having energy difference between them as $h\nu = E_2 - E_1$ is

$$\frac{N_1}{N_2} = e^{\left(\frac{E_2 - E_1}{kT}\right)} = e^{\left(\frac{h\nu}{kT}\right)} \qquad (8)$$

Substituting (7) and (8) in (6)

$$\frac{N_1 \rho(\nu) B_{12}}{N_2} = A_{21} + \rho(\nu) B_{21}$$

Therefore, $$\rho(\nu) = \frac{A_{21}}{B_{12}} \frac{1}{e^{\left(\frac{h\nu}{kT}\right)} - 1} \qquad (9)$$

From the Planck's radiation theory the energy density is

$$\rho(\nu) = \frac{8\pi h \nu^3}{c^3} \frac{1}{e^{\left(\frac{h\nu}{kT}\right)} - 1} \qquad (10)$$

Comparing (9) and (10)

$$\rho(\nu) = \frac{A_{21}}{B_{12}}\left(\frac{1}{e^{h\nu/kT} - 1}\right) = \frac{8\pi h\nu^3}{c^3}\left(\frac{1}{e^{h\nu/kT} - 1}\right)$$

$$\therefore$$

and

$$\frac{A_{21}}{B_{12}} = \frac{8\pi h\nu^3}{c^3} \qquad (11)$$

The equation (11) is the ratio of Einstein's coefficients $A_{21}$ and $B_{12}$

**Significance**

The ratio of Einstein coefficients indicated that ($A_{21}$/ $B_{12}$) should be less, as one of the condition for laser action to be satisfied. In this condition $B_{12}$ should be more(stimulated emission ) so that the ratio become minimum Therefore, to obtain the laser action in the active medium one should get the $B_{12}$ value from the ratio contains Einstein's coefficients. If $B_{12}$ is less which results to the ratio become more corresponding to more spontaneous emission **1.5 Some types of lasers.**

In the present section some types of lasers are presented as below

1. Nd-YAG laser
2. $CO_2$-laser
3. Semiconductor lasers

**1.5.1. Nd-YAG laser**

Niodynium-Yttrium Aluminium Garnet is the expansion of Nd-YAG lasers.

**Principle**

The rare earth Nd metal ion is present in the Yttrium Aluminiam Garnet structured mixture which requires minimum energy for excitations. The addition of ($Nd^{3+}$) ions in the Yttrium acts as active centre with Nd-YAG mixture.

**Structure and working**

The laser contains active medium as $Nd^{3+}$ ion doped YAG rod with a resonant optical cavity. The cavity has been formed

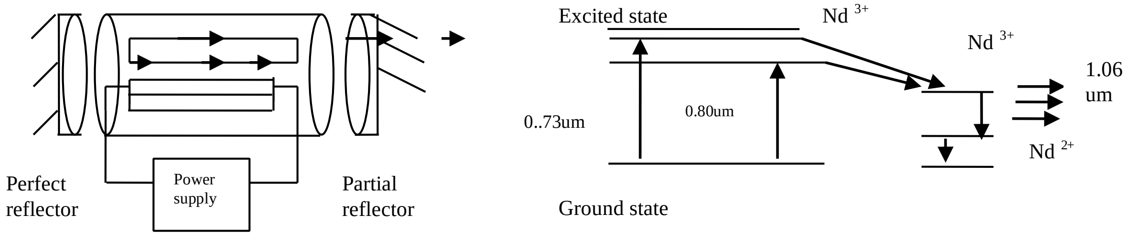



Fig.3 Constructional details and energy level diagram

using perfect reflector and partial reflector one on either sides of the active medium to increase energy density of radiations.

The active medium is kept closed to the flash lamp, where both laser rod and lamp are put closed to each other in an elliptical housing as in Fig3. The flash lamp has been connected to the power supply. As the power supply is switched ON the light comes out from xenon flash lamp interacts with active medium.

All the $Nd^{3+}$ ions form the active medium are excited and deexcited to $Nd^{3+}$ due to their short life time in excited state.

In the above de excitation no radiation will be emitted. Further, de excitation from $Nd^{3+}$ to $Nd^{2+}$takes place in the same mechanism which emits radiation of 1.06μm wavelength. The remaining de excitations are appearing due to radiation less transitions.

The transition from $Nd^{3+}$ to $Nd^{2+}$ gives IR radiations of 1.06μm wavelength using threshold power in 100 W to get several 100W as output power

of radiations.

The Nd-YAG laser has 100 ps duration of pulses and intensity as

$10^{16}W/cm^2$, this has been in the use for industrial applications and laser induced fusion reaction.

### 1.5.2 Carbon di oxide ($CO_2$) laser

**Principle**

A molecule contains few atoms or collections of atoms together and apart from electronic transitions in atom, it may vibrate, rotate and combination of both could also involve in the emission of laser.

Therefore, the emission of laser is not only through electronic transitions but also in other types of transitions viz., vibration and rotation

Each electronic level is split into various vibrational sublevels and each vibrational level could sub divided into rotational sub levels.

Thus, energy difference between various electronic levels corresponding to visible and Ultra violet (UV) region. Similarly, energy difference between various vibrational levels corresponds to IR region. The energy difference between various rotational levels corresponds to far IR region of the spectrum.

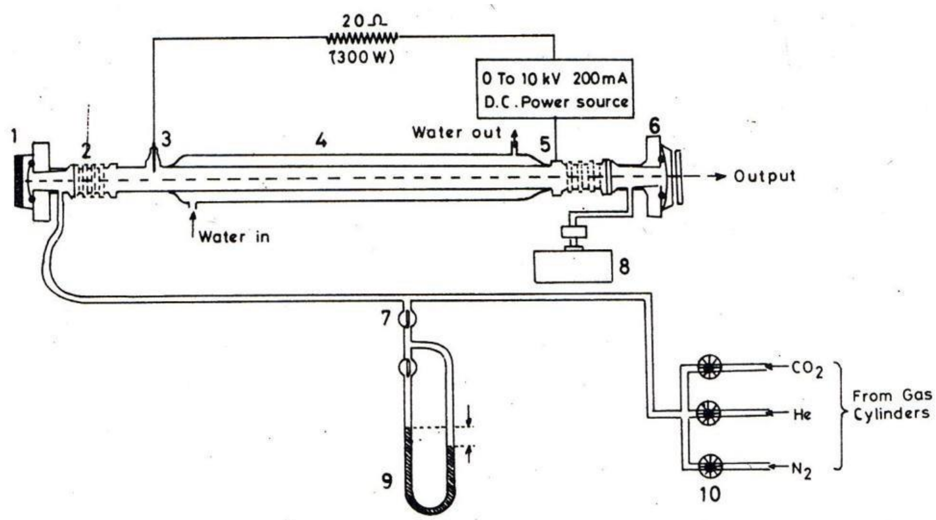
**Structure and Working**

A typical $CO_2$ laser structure is shown in the Fig 4. The mixture of $CO_2$, $N_2$ and He in 0.33:1.2:7 ratios with few tens Torr. pressure is taken in water cooled discharge tube. The above gaseous mixture is excited by dc voltage/RF voltage.

The resonator reflectors are kept one on either side of the discharge tube connected through metallic bellow. The length of discharge tube can be adjusted depending on operating voltage.

The discharge tube consists of 1.6cm inner diameter and 1.5 m length borosilicate glass tube with water circulation tube. The discharge tube has tungsten anode and copper cathode with perfect reflector of 90% ZnS on one side and partial reflector on other side.

The power supply for the discharge tube has 60 mA 8KV DC supply. The Brewster's angle windows are provided for polarized laser beams.




1-Perfect reflector,2-Metal bellow,3-tungstant anode,4glass jacket,5-copper cathode,6-output relector,7-glass stop cock,8-mechanical pump,9-oil monometer,10-Needle valve Fig.4 $CO_2$ Laser structure

The functioning of laser could be expressed using symmentric stretching and asymmentric stretching and bending modes as below.

**Symmentric stretching**

In symmentric stretching of $CO_2$ molecule, the carbon atoms are stationary and oxygen atom oscillates simultaneously along the $CO_2$ axis represented as (100) mode.

**ASymmentric stretching**

In asymmentric stretching of $CO_2$ molecule the carbon atom are stationary and oxygen atom oscillates irregularly representing (010) mode.

**Bending mode**

In bending mode the carbon and oxygen atoms are moving in perpendicular direction to molecular axis representing (001) as in fig 5.

When electric discharge takes place in the mixtures of gases, first $N_2$ and $O_2$ atom absorbs the energy and excited to higher energy level.

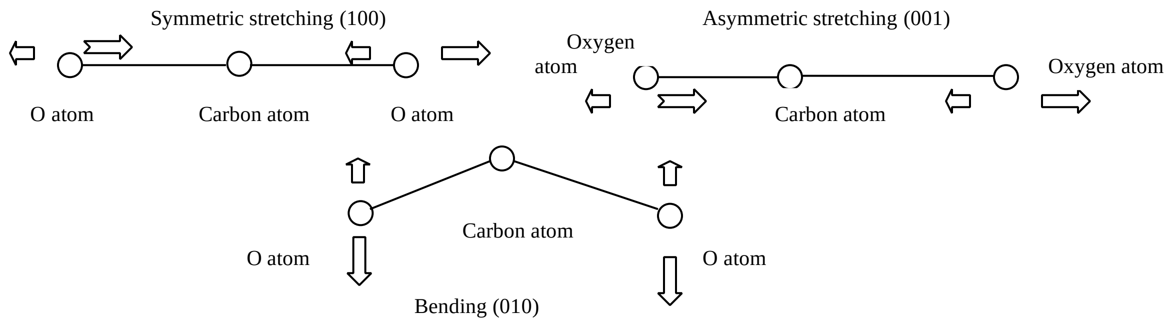



Fig.5 Carbon and oxygen atomic vibrations in $CO_2$ laser

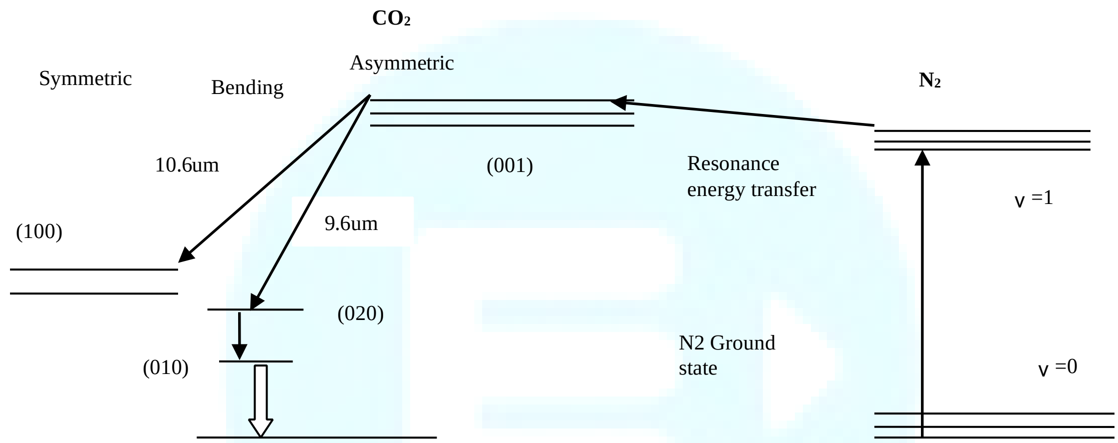



Fig.6 Energy level diagram for $CO_2$ laser

In the collision between them, that causes excitation of $CO_2$ by $N_2$ atoms. Consequently, there is efficient transfer of energy from $N_2$ to $CO_2$ called resonant energy transfer. In excited state the population inversion has been obtained at energy levels K5 and K4. Similarly, K5 and K3. The de excitation from K5 to K4 gives emission of radiation with wavelength 10.6 μm(IR). K5 to K3 de excitation produces 9.6 μm wavelength of IR. Remaining de excitations from K3 to K2 and K2 to K1 produces radiation less transition and heat developed will be taken by the presence of He gas in the mixture.

**Features and application.**

The laser radiation is highly intense in both continuous and pulsed modes with high energy per unit area. $CO_2$ laser found wide application in material processing and medical applications followed by communication purpose.

### 1.5.3. Semiconductor laser

Semiconductors are used to prepare solid state diodes. There are two types of impure semiconductors as p-type and n-type. The p-type can be put to n-type where pn junction would be formed using same semiconductors. These diodes are "homo junction" diodes for both the rectifier as well as laser emission. Other than same material, ie., semiconductors with metal are used to form pn junction diodes to the same purpose called "hetero junction " diodes.

**The band structures and semiconductor lasers**

In atomic model, the lower energy levels are equivalent to valence states of electrons from the atoms of semi conductors. Similarly, the higher energy level of a atom equivalent to conduction states of electrons from semiconductor atoms, where electron could occupy more in number during population inversion by direct conversion. The electrons are majority charge carrier in N-type or donor semiconductor and holes are majority charge carrier in P-type as acceptor semiconductor. When p-type fused over ntype, the p-n junction will be formed. Applying electric field on the junction causes acceleration of charges and mixing of one over the other called "recombination" in semiconductors.

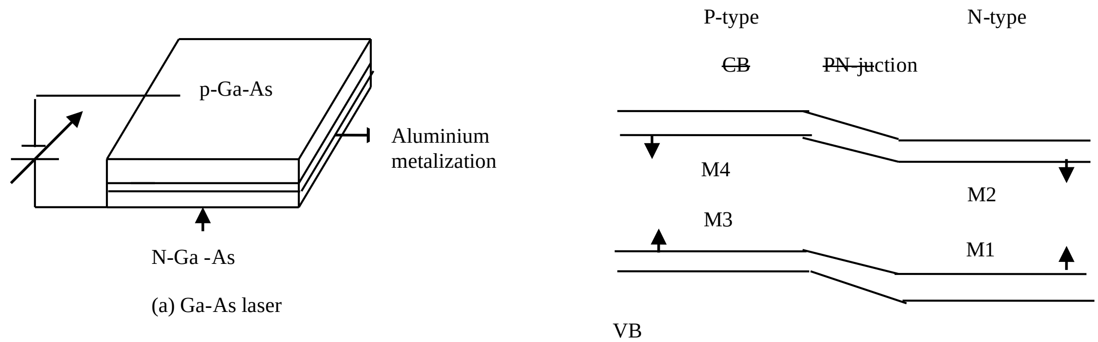
The energy from recombination has been used for driving of electrons in pn junction to P-type and holes in pn junction to N-type, where the p-n junction diode functions in forward bias is called rectifier action.

Alternatively, the energy from recombination get enhanced and in turn generates light radiation from p-n junction diode functions in forward bias is called laser action. If the semiconductor of p-type and n-type are fused together to get p-n junction, then it is homo junction laser diode. If metal with semiconductors of p-type and n-type are fused together to get p-n junction, with third material at the junction forms the diode called hetero junction laser diode.

**Homo junction laser diode**

Ga-As homo junction laser diode can be formed by doping Ga p-type semiconductor on one side and n-type As on other, so that p-n junction could be formed. The p-n junction is the active medium and the junction has been metallized on outer surface using aluminium mirror for resonance cavity where the energy density of radiation enhances by back and forth reflection. The structure of homo junction diode laser is as shown in fig.7

In the fig, the M1M2 represents the energy band gap of n type semiconductor and M3M4




(a) Ga-As laser (b) Band structure

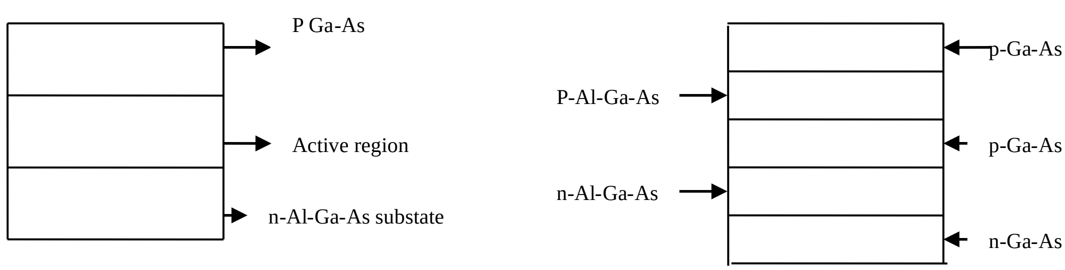
Fig.7 Ga-As laser and its band structure

to corresponding energy band gap in p-type. The band gap as been reduced at the pnjunction due to fusion, which helps in recombination to get light (mixing of holes to electron called appears as exciton which disappear as photons and electrons). In this way, the light will be produced continuously from the diode. This light reflects back and forth at the junction to increase the energy density forms laser radiations.

**Hetero junction laser diode**

The Ga-As n-type semiconductor can be used as base material on which n-type Al –GaAs has been formed followed by p-type Ga-As and p-AlGaAs. These layers are formed as show in the fig. The junction of Al-Ga-As p-type and AlGaAs n-type forms 2 junctions of differing semiconductors. The junction on suitable biasing potential emits laser radiation from hetero junction.

The diodes can be edge emitting laser diodes and bulk emitting laser diodes. If the laser emitted direction is parallel to the surface then it this edge emitting laser diodes, where as the laser emitted direction is perpendicular to the surface then it is bulk emitting laser diodes.




(a) Hetero junction laser (b) Double hetero junction

Laser diode

Fig.8 Hetero junction Semi conductor laser diode

## 1.6 Applications of lasers

### Industrial applications

The laser can be used in Material processing viz., welding, hole drilling, laser cutting vaporizing and deposition.

### Welding

In welding the material is added to join the two surfaces. Therefore, laser power should not be high to evaporate material, in the same time removal of metal should not be encouraged. Thus, laser for welding should have high average power than high peak power. The high peak power has been focused on to the surface for suitable heating as in fig. The laser welding found significant application in the field of electronics and mico electronics which requires precise welding.

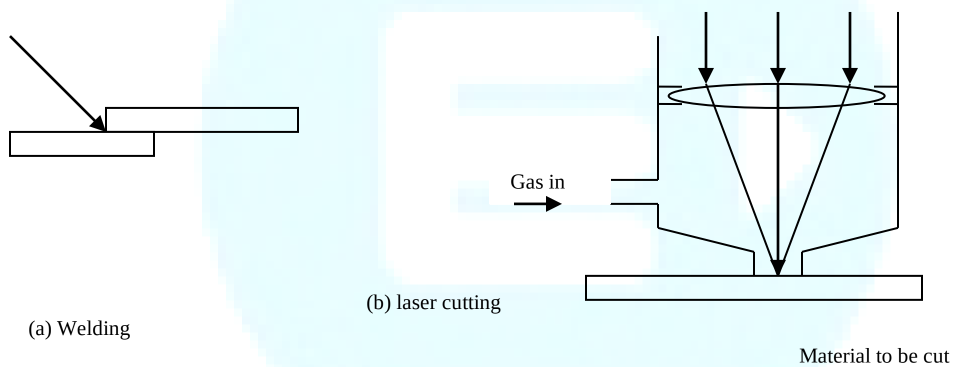



Fig.9 Laser in material processing

### Hole drilling

Drilling of holes in various substances is another application of laser. Removal of some materials from the substance causes hole drilling. For example 100um of diameter of hole on hard substance can be done using laser.

### Laser cutting

Laser also find application in cutting, $CO_2$ laser is the common laser used for the cutting process. In cutting process the removal of metal along the cut direction should be performed. If cuts are obtained using pulsed lasers, then the repetition frequency of the pulse and the motion of the laser across the material is to be adjusted so that series of partially overlapping holes could be avoided. The caution should be taken in the cut which should be with the allowance to avoid any re welding of the cut materials. The efficiency of the laser can be improved by keeping gas jet co axially with laser. In certain cases Oxygen can be used so that when the laser heats the material it interacts with gas and gets bunts. The structure of the face is also helps to drive molten material to improve the efficiency. The N2 like gas can also be used to improve the efficiency.

**Vaporizing and deposition**

Laser can be used to vaporizing of materials and also used for deposition on substrate. Some pre selected area of material may be evaporated or evaporatrant may be located closed to the substance. Brittle material like rock marble etc., can be fractured using laser beams. Such technique finds application in rock crushing and boring.

**1.7 Laser in Medicine**

The laser is used in the medicine for treatment and diagnosis.

**Laser in therapy**

Retinal repair

The human eye is roughly spherical and consists of an outer transparent wall called Cornea. This is followed by the Iris (a control slit to allow light in to eye) and lens. On the part of Cornea and the lens at the back of the eye the light sensitive elements are present called Retina. When the light falls on a lens and retina, the photosensitive cells present on retina converts light in to electrical signal and the optical nerve carries the signal to brain. The resulting is the mechanism of visuals

Due to some diseases or impact, the retina could detach and created partial blindness. Before the application of laser therapy, the Xenon lamp was in use to attach the retina. The unique application of laser is to attach the retina, where laser can be used to focus the small spot of light precisely. The time involved is also extremely small in the order of 300usec. at 1J of energy.

**Laser for cancer**

Lasers are used extensively in the cancer treatment. In laboratories the *Amelanotic melanoma* was given to the lab animals and ruby laser radiation was administered for complete tumor treatment which disappeared in 30days.

## Holography

A Photography is two dimensional recording of three dimensional scenes. Since, the photo sensitive material is coated on to photo film which could record intensity variations and does not respond to phase distribution. Since the intensity variations are alone recorded the 3dimesion features is lost.

## Recording

In principle the phase distribution was introduced during the record i,e one wave from the object (object wave ) superimposed on to a reference wave. The two waves interfere in the plane of recording medium and produce interference fringes. This called recording process. These fringes are depending on object and recording medium which records the intensity distribution with phase distribution, hence three dimensional images are formed as in Fig.10.

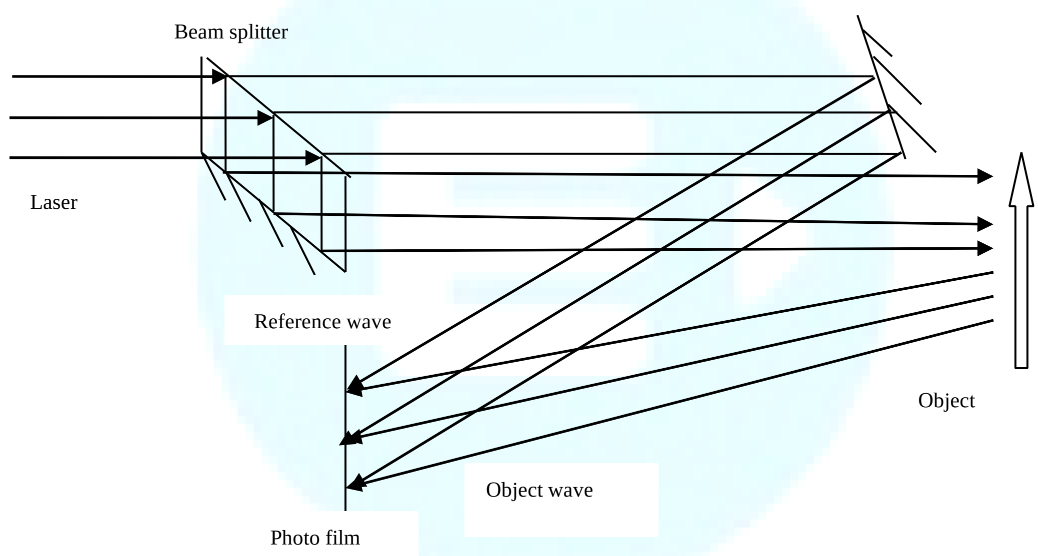



Fig.10. Recording of Hologram

## Reconstruction

## The line holography

Before the use of laser in the mixing of reference wave to object wave both of them should be almost parallel and the traversed path should be equal called line holograph. This is one of the basic requirements, due to the source as discharge lamps which had small coherent length. Since, the interference wave forms virtual and real images along the same direction it causes unfocussed real image wile occurrence of the virtual image.

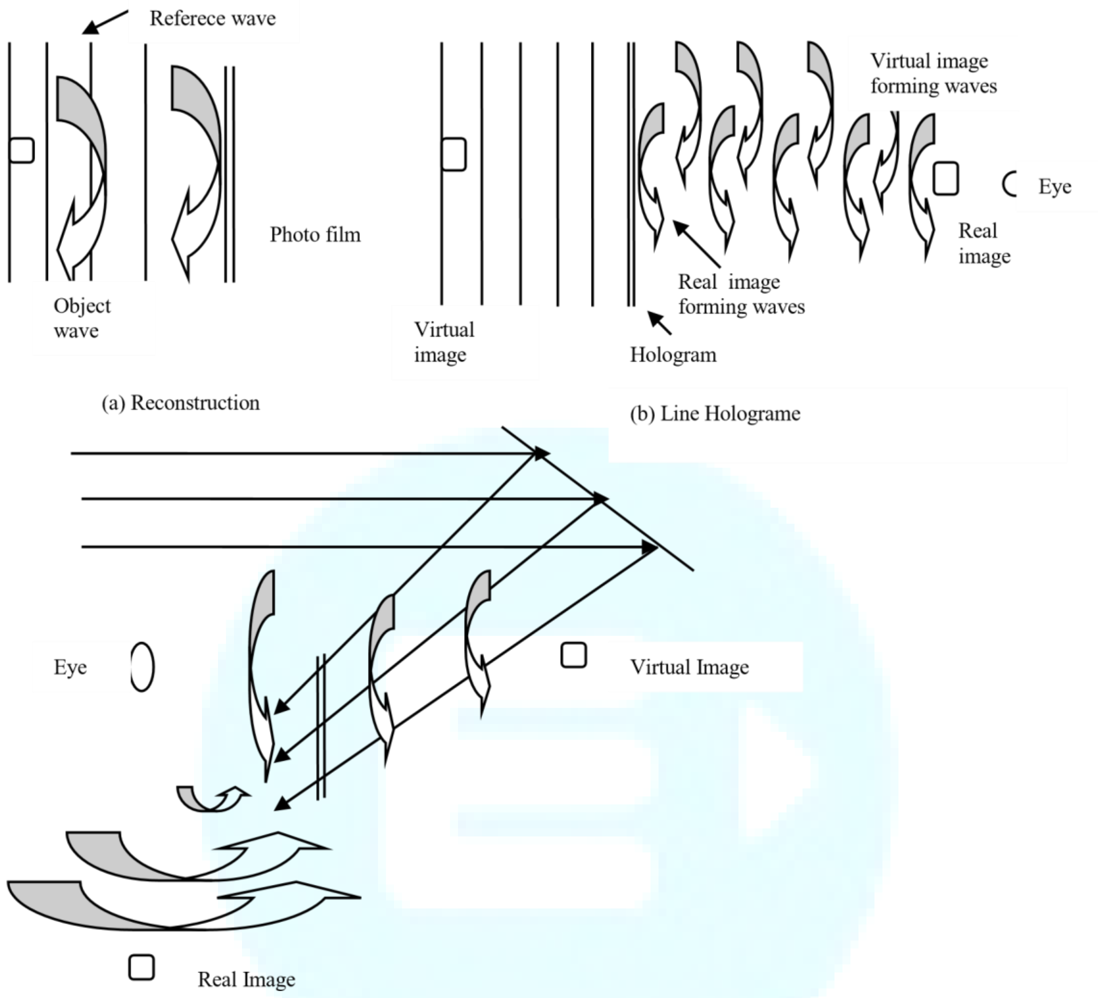



Fig.11 Reconstruction and line hologram

**Off axis holography using laser**

To over come the defect in line holograph an off axis holograph was introduced followed by present day laser based holography.