range 8000 Å to 40,000 Å (4 μm). The tuning is achieved by using several different colour center crystals in sequence.

A typical colour center laser consists of an alkali halide crystal that contains point defects known as *F centers*. These centers are known as *colour centers* and are produced when the crystal is irradiated with X-rays. The colour centers remain within the crystal for duration ranging from a few days to many years. The colour centers are actually defects in the crystalline lattice and they absorb and emit light as the atoms at the defect site change position. Colour center lasers must be pumped with other lasers and maintained at very low temperatures. The need for a pump laser and cryogenic cooling limits the use of colour center lasers in practical applications.

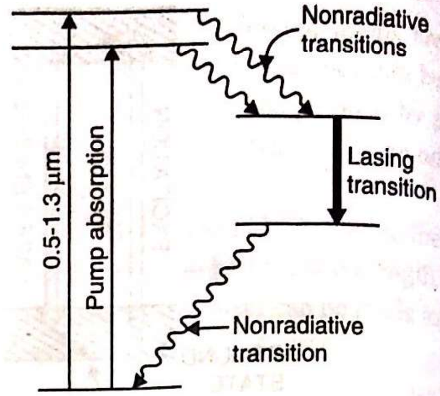


**Fig. 2.9.** Typical energy level diagram of a F-center colour center laser

## 2.3.5 Fiber Lasers

Erbium in a glass host forms a three-level laser with a wavelength range centered around 1.55 μm. Erbium lasers and amplifiers assume importance in fibre-optic communications because optical signals of 1.55 μm travel longer distances through optical fibres with least loss. In long distance fibre-optic communications, amplifiers are required after each specific distance to increase the strength of the signal. They are known as repeaters. Earlier, optical signals are converted into electrical signals and are amplified in each repeater station. It can be alternately done by passing the weak signal through a length of the erbium-doped optical fibre. If the erbium atoms are pumped by a laser diode pump laser at a different wavelength, the weak signal can stimulate the atoms to emit light at the signal wavelength, 1.55 μm, causing an increase in the signal strength. These erbium-amplifiers are highly useful in under-sea communication and long haul communication links.

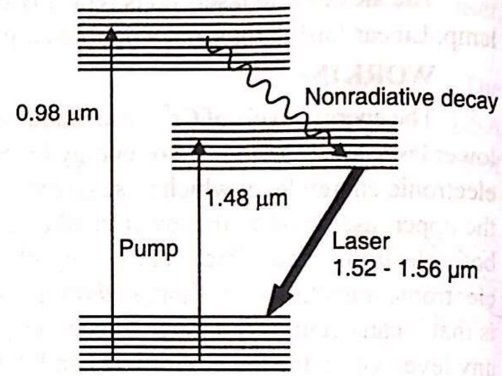


**Fig. 2.10.** Energy level diagram of an erbium-doped fibre laser

## 2.4 GAS LASERS

Gas lasers are the most widely used lasers and the most varied. They range from the low power helium-neon (He-Ne) laser used in college laboratories to very high power carbon dioxide laser used in industrial applications. These lasers operate with rarefied gases as their active media and excited by an electric discharge. There are three different types of gas laser: ion lasers, neutral atom lasers and molecular lasers. In gases, unlike in crystals, the energy levels of atoms involved in the lasing process are well defined and narrow. Broad pump bands do not exist and the pump levels are also narrow. In order to excite atoms, sources with sharp wavelength are required. Finding an appropriate optical source for pumping poses a problem. Therefore, optical pumping is not used in gases. The most common method of exciting gas laser medium is by passing an electric discharge through the gas. Electrons in the discharge transfer energy to atoms in the laser gas by collisions.

Gas lasers, in general can be classified as (*i*) Atomic, (*ii*) Ionic and (*iii*) Molecular lasers.

**(*i*) Atomic lasers:** He-Ne (Helium-Neon) lasers are of this type. In atomic lasers the active medium is noble gas *viz.* Helium, neon, argon, krypton and considered in the neutral state. The atomic lasers are characterised by mixing active gas with other gases which increases the excitation efficiency of the system.

***(ii)* Ionic lasers:** In ionic lasers, ionized gas is used as lasing medium. For this purpose, ionized noble gases like $A_r^+$ (Argon ion) and $K_r^+$ (Krypton ion) are prefered. The most commanly used ionic lasers are $A_r^+$ (Argon) and $K_r^+$ (Krypton) lasers which mostly operate in CW mode. They are operated in Ultra-Violet (UV) Spectral region. Large amount of heat is generated and hence cooling arrangement is essentially needed. These lasers produce a wide range of colours and hence are popularly used in art and entertainment to give visual effects.

***(iii)* Molecular lasers :** All the gas lasers are based on *electronioc levels* however in molecular lasers other energy levels are also taken into account. The atoms comprising the molecular vibrate about their mean position giving rise to *vibrational energy levels* and also can rotate as a whole. The gives rise to *rotational energy levels.*

The first gas laser was He-Ne laser which was demonstrated in 1961 at Bell Telephone Laboratories, U.S.A. by Ali Javan, William R. Bennett, Jr., and Donald R. Herriott. The generic gas laser is shown in Fig. 2.11.

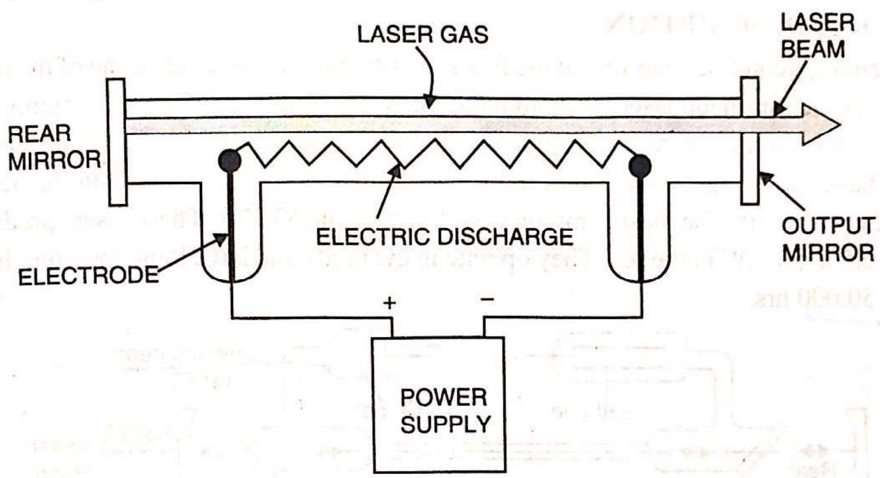


**Fig. 2.11.** Schematic arrangement of a gas laser.

The laser gas is contained in a tube with cavity mirrors attached at each end, one totally reflecting and one transmitting light to form the output beam. The laser is excited by an electric discharge. First, a high dc voltage ionizes the gas so that it will conduct electricity. The electrons accelerated through the electric field transfer their kinetic energy to the gas atoms by inelastic collisions. In practice, for optimum operation, the laser medium contains a mixture of two gases, say $A$ and $B$, at low pressure. Atoms of kind $A$ are initially excited by electron impact and they in turn transfer their energy to atoms of kind $B$ which are the actual active centers.

The cavity mirrors can be either inside the gas container or outside. If they are inside, than the output light is generally unpolarized. For the outside case, to minimize reflection loss, discharge tube edges are cut at the Brewster angle. The Brewster angle is given by

$$\theta_B = \tan^{-1}\sqrt{\frac{\mu_2}{\mu_1}}$$

where $\mu_2$ and $\mu_1$ are the refractive indices of glass and the gas mixture respectively. It is known that light incident at Brewster angle is polarized parallel to the plane of incidence and has a transmission coefficient of 1. The passage of light through a glass container at Brewster angle does not involve any transmission losses and thus parallel polarization component has a higher effective gain. Therefore, for the outside mirror arrangement, light is plane polarized in general.

Gas lasers vary widely in their characteristics. Their output wavelengths range from near UV to far IR . Some of them operate in pulsed mode and others in CW mode. The output power varies from less than a milliwatt (mW) to over 10 kW.

**Important feature of gas lasers.** The gas lasers having following important features :

1. The line width of the spectral transition is relatively smaller as compared to solid state lasers.
2. The laser emission is narrower.
3. No optical inhomogeneties. Hence, yields the good quality laser.
4. The conerence properties are also superior.
5. The monochromaticity is very high.
6. The quality factor (Q) of the modes are high we shall describe them in detail.

### 2.4.1 Helium-Neon Laser

**GENERAL DESCRIPTION**

The Helium-Neon laser was one of the first lasers ever developed and is one of the most widely used lasers. The helium-neon laser is an atomic laser which employs a four-level pumping scheme. The active medium is a mixture of 10 parts of helium to 1 part of neon. Neon atoms are the active centers and have the energy levels suitable for laser transitions while helium atoms help efficient excitation of neon atoms. The most common wavelength is the 6328 Å. These lasers produce powers in the range 0.5 to 50 mW in the red. They operate in cw mode and have long operating life times of the order of 50,000 hrs.

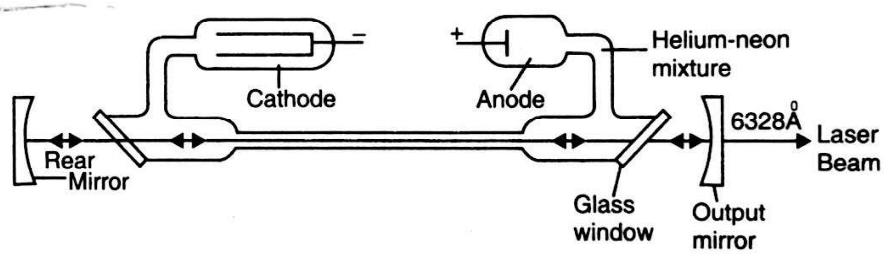


**Fig. 2.12.** Schematic of a He-Ne laser with external mirrors.

**STRUCTURE**

The construction of a typical He-Ne laser is shown in Fig. 2.12. It consists of a glass discharge tube of about typically 30 cm long and 1.5 cm diameter. The discharge tubes in general may have lengths of 10 cms to 50 cms and vary in diameter from 1.5 cm to 5 cms. The tube is filled with a mixture of helium and neon gases in the ratio 10:1. Electrodes are provided in the tube to produce a discharge in the gas. They are connected to a high voltage power supply. The tube is hermetically sealed with glass windows orientated at the Brewster angle to the axis of the tube. The cavity mirrors are arranged externally.

**WORKING**

The energy level schemes of helium and neon are shown in Fig. 2.13.

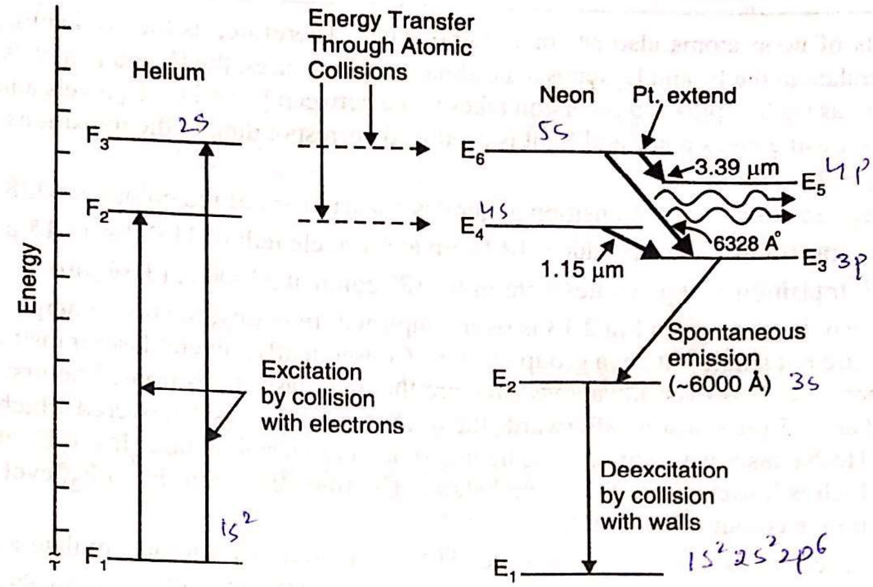


**Fig. 2.13.** Energy levels of helium and neon atoms and transitions between the levels.

When the power is switched on, a high voltage of about 10 kV is applied across the gas. It is sufficient to ionize the gas. The electrons and ions produced in the process of discharge are accelerated towards the anode and cathode respectively, as shown in Fig. 2.14.

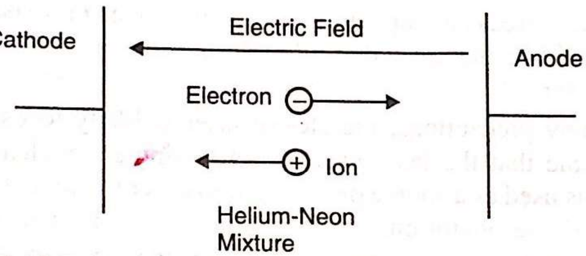


**Fig. 2.14.** Migration of electrons and positive ions in a discharge tube.

Since the electrons have a smaller mass, they acquire a higher velocity. They transfer their kinetic energy to helium atoms through inelastic collisions. Helium atoms are much more readily excited by electron impact because they are fairly light. Thus, the initial excitation affects only the helium atoms, with the result that these atoms are excited to the levels $F_2$ and $F_3$ which lie at 19.81 eV and 20.16 eV respectively above the ground sate. These two levels are metastable levels and the excited helium atoms cannot return to the ground state through spontaneous emission. Though a radiative transition is not possible, the excited helium atoms can return to the normal state by transferring their energy to neon atoms through collision. Such an energy transfer can take place when the two colliding atoms have identical energy states. It is called *resonant transfer* of energy. The neon energy levels, namely $E_6$ level at 20.66 eV and $E_4$ level at 18.7 eV nearly coincide with the $F_3$ and $F_2$ levels respectively of helium atom. Therefore, the resonant transfer of energy can occur readily. The additional 0.05 eV energy required is provided by the kinetic energy of helium atoms. When a helium atom in the metastable state collides with a neon atom in the ground state, the neon atom is excited to $E_4$ or $E_6$ level and the helium atom drops back to the ground state. This is the pumping mechanism in He-Ne laser. The neon atoms which are much heavier could not be pumped up efficiently without the helium atoms. The role of helium atoms is thus to excite neon atoms and cause population inversion. The probability of energy transfer from helium atoms to neon atoms is more as there are 10 atoms of helium per 1 neon atom in the gas mixture. For this reason, the probability of reverse transfer of energy from neon to helium atom is extremely small. The $E_4$

and $E_6$ levels of neon atoms also are metastable states. Therefore, as the collisions go on, neon atoms accumulate in the $E_4$ and $E_6$ states. At ordinary temperatures, the $E_5$ and $E_3$ levels are sparsely populated and as such population inversion takes place between $E_6$ and $E_5$, $E_3$ levels and between $E_4$ and $E_3$ levels. Lasing takes place and light is produced corresponding to the transitions, $E_6 \rightarrow E_5$, $E_6 \rightarrow E_3$ and $E_4 \rightarrow E_3$.

(*i*) $E_6 \rightarrow E_3$ transition : This transition generates a laser beam of red colour at 6328 Å.

(*ii*) $E_4 \rightarrow E_3$ transition : This produces IR beam at a wavelength of 11500 Å (1.15 μm).

(*iii*) $E_6 \rightarrow E_5$ transition : It generates light in for IR region at 33900 Å (3.39 μm)

The energy level diagram Fig 2.13 is over simplified. In reality, the neon energy levels $E_6$, $E_5$, $E_4$, $E_3$ and $E_2$ are not single but are a group of lines. Consequently, several laser transitions, as many as 150, are possible. However, the above three are the main laser transitions. The first He-Ne laser was operated at 1.15 μm but soon afterwards the 6328 Å red line was discovered which has become the standard He-Ne laser wavelength. The neon atoms in the terminal laser level, $E_3$, decay rapidly to $E_2$ level which is however, not the ground state. (The transition from $E_3$ to $E_2$ level gives rise to the familiar orange colour of neon lights.)

The $E_2$ level is again a metastable state. The neon atoms tend to accumulate at this level if they are not somehow removed from the level. The $E_2 \rightarrow E_1$ transition can be induced by collisions with the walls of the discharge tube. To enhance the probability of atomic collisions with the walls, the discharge tube is made as narrow as possible. Once the atoms reach the ground state, they will be again available for pumping. $E_2$ level is more likely to be populated by the electric discharge itself. It may be recalled here that electric discharge is used to produce neon lighting. An increase in population at $E_2$ leads to a decrease in population inversion and lasing ceases. Therefore, the current in the discharge tube should be maintained at a low level. For this reason, high powers cannot be obtained from a He-Ne laser.

In the absence of any precautions, the He-Ne laser is likely to oscillate at the three main wavelengths. It is desirable that the laser oscillates at a single wavelength only. In most of the applications He-Ne laser is used as a source of red light. In order to prevent the laser from oscillating at the other wavelengths, the resonator mirrors are coated with multi-layer dielectric coatings which are highly reflective at 6328 Å and absorptive at the other two wavelengths. The laser oscillates at the wavelength which is reflected more by cavity mirrors.

Without the Brewster windows, the light output is unpolarized. The Brewster windows cause the laser output to be linearly polarized.

Although, 6328 Å is the standard wavelength of He-Ne laser, other visible wavelengths 5430 Å (green), 5940 Å (yellow-orange), 6120 Å (red-orange) can also be produced.

The He-Ne laser operates in CW mode and the over all gain is very low and is typically about 0.01% to 0.1%. However, the laser is simple, practical and less expensive. The laser beam is highly collimated, coherent and monochromatic.

He-Ne lasers are widely used in laboratories as a monochromatic source, in interferometry, laser printing, bar code reading etc. These lasers provide a very stable single transverse mode reference beam to identify optical properties of materials such as surface smoothness. Most supermarket and other types of stores now use these lasers as scanners to read the digitally encoded bar codes located on products. They are also used as a reference beam in surveying, for alignment in pipe laying etc works.

## 2.4.2 Ion Gas Lasers

Helium, neon, argon, xenon and krypton are noble gases and they have electronic states capable of laser transitions. However, except for neon, noble gases are difficult to pump and thus are not of practical interest. However, if these noble gases are first ionized by electron collisions then they are easy to pump.

### 2.4.2.1 Argon Laser

**GENERAL DESCRIPTION**

The argon laser belongs to the group of ion lasers. It is a four-level laser which operates in visible region over a wavelength range from 3510 Å to 5200 Å. It is the most powerful CW laser operating in visible region. The importance of argon and krypton lasers is that they are extensively used in laser light shows. The argon ion laser can provide approximately 25 visible wavelengths ranging from 4089 Å to 6861 Å and more than 10 ultraviolet wavelengths ranging from 2750 Å to 3638 Å. In the visible region, CW powers of about 100 W are available. The discharge tubes have an operating life of 2000 to 5000 hrs.

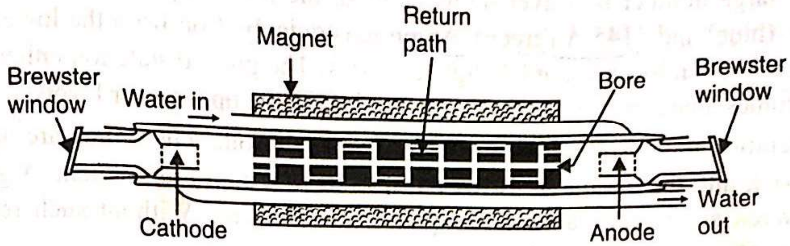


**Fig. 2.15.** Schematic of a typical ion laser tube

**STRUCTURE**

In argon lasers, the active medium is argon gas and the active centres are ionized argon atoms. A typical design of the discharge tube is shown in Fig 2.15. It consists of a narrow water-cooled ceramic tube in which an arc discharge takes place. The electrodes are arranged at the ends of the capillary tube. The anode and cathode spaces communicate through a return gas path which ensures free circulation of the gas. A magnet surrounds the discharge tube. Its function is to constrict the discharge area and increase the concentration of ions along the axis of the tube. This increases the output power and efficiency.

**WORKING**

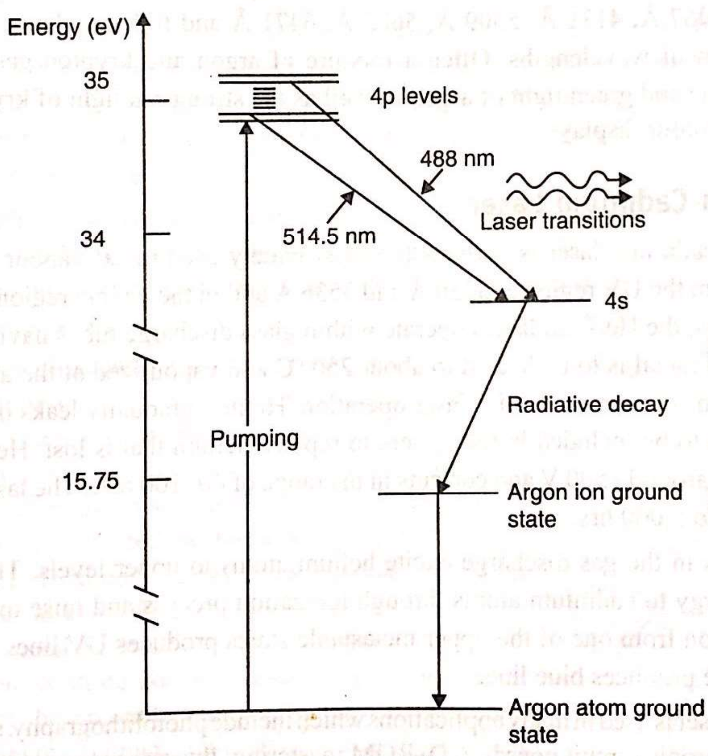


**Fig. 2.16.** Energy level scheme for an argon atom.

As in He-Ne laser, an initial high voltage pulse ionizes the gas so that it conducts current. Electrons in the current transfer energy directly to argon atoms, ionizes them and raises the ions to a group of high energy levels, shown in Fig 2.16, which are about 35 eV above the ground state of neutral argon atom. Different processes populate the metastable upper laser level. Three possible processes are : (*a*) electron collisions with Ar+ ions in the ground state, (*b*) collision with ions in metastable states and (*c*) radiative transitions from higher states. The life time of upper laser level is $10^{-8}$s while that of the lower laser level is of the order of $10^{-9}$s. Therefore, the condition for population inversion is satisfied. Transitions can occur between many pairs of upper and lower lasing levels and therefore many laser wavelengths are emitted.

Out of the large number of wavelengths emitted, the most important and the most intense lines are 4881 Å (blue) and 5145 Å (green). Argon ions quickly drop from the lower laser level to the ground state of the ion by emitting UV light at 740 Å. The ground state ion either recaptures an electron and becomes a neutral atom or it is again excited to the upper laser levels.

During operation the positive ions tend to collect at cathode where they are neutralized and diffuse slowly back into the discharge. However, it leads to a pressure gradient. A gas return path is provided between anode and cathode to equalize the pressure. Without such return path, the discharge may eventually be extinguished.

The laser needs active cooling. Any desired wavelength can be selected through proper cavity optics. For example, a small prism may be inserted into the optical cavity and the position of the end mirror is rotated such that it comes into a position normal to the path of the light of desired wavelength. Then, only the desired wavelength is sustained in to and fro reflections while other wavelengths are lost from the cavity after a few reflections.

### 2.4.2.2 Krypton Ion Laser

The krypton ion laser resembles the argon ion laser in energy level arrangement and in operation. Krypton laser provides different laser wavelengths than the argon laser. The dominant output occurs at 4067 Å, 4131 Å, 5309 Å, 5682 Å, 6471 Å and 6764 Å. Thus, these lasers offer a broader spectrum of wavelengths. Often a mixture of argon and krypton gases is used which provides strong blue and green light of argon as well as the strong red light of krypton. Such lasers are used for multicolour displays.

### 2.4.2.3 Helium-Cadmium Laser

The helium-cadmium laser is perhaps the most widely used metal vapour laser. It produces continuous output in the UV region at 3250 Å and 3536 Å and in the visible region at 4416 Å (blue). Like He – Ne lasers, the He – Cd lasers operate within glass discharge tubes having a bore of 1 – 2 mm. The cadmium metal is to be heated to about 250 °C and vapourized at the anode end in order to produce cadmium vapour needed for laser operation. Helium gradually leaks out and therefore a helium reservoir is to be included in the system to replace helium that is lost. He – Cd lasers need discharge voltages around 1500 V and currents in the range of 60- 100 mA. The lasers typically have lifetimes of 4,000 to 5,000 hrs.

The electrons in the gas discharge excite helium atoms to upper levels. The excited helium atoms transfer energy to cadmium atoms through ionization process and raise them to upper laser levels. The transition from one of the upper metastable states produces UV lines and the transition from the other state produces blue line.

The He–Cd laser is used in many applications which include photolithography, stereolithography, inspections of electronic circuit boards, CD–ROM mastering, fluorescence analysis etc.

### 2.4.2.4 Copper-Vapour Laser

Copper – vapour laser is one of the important metal vapour lasers. It operates only in pulsed mode and produces pulsed energies of the order of 1mJ leading to average powers of 10 – 100W for pulse repetition rates of 10 – 100 kHz. Copper vapour laser produces light at 5105 Å (green) and 5782 Å (yellow). The metallic vapour is contained within a cylindrical discharge tube filled with helium or neon as a buffer gas. The optimum pressure for the laser is of the order of 1 torr of metal vapour which requires the metallic copper to be heated upto 1500 $^0$C. However, the copper metal will last typically for 500 – 100 hrs of operation, after which it is to be reloaded.

When an electric discharge passes through copper vapour, copper atoms are excited to one of the two upper laser levels. If the vapour pressure is optimum, the atoms stay long enough at the upper laser level to produce stimulated emission. With the onset of stimulated emissions, the atoms quickly drop to lower laser levels. The lower laser levels are metastable levels and as atoms accumulate at these levels, the laser operation ceases. All this takes less than 100 ns. Depopulation of lower laser level takes place by collision of atoms with the walls of discharge tube. Again the laser gets ready for producing next pulse of light.

Copper vapour lasers have high gain and can operate without resonant mirrors.

### 2.4.2.5 Gold-Vapour Laser

The gold vapour laser operates in a similar way to that of the upper vapour laser. It produces orange beam at a wavelength of 6278 Å.

Copper vapour lasers are used to pump tunable dye lasers, in high – speed flash photography and material processing. The gold vapour laser is used in photodynamic therapy for destroying the cancerous tissue.

### 2.4.3 Carbon Dioxide ($CO_2$) Laser

**GENERAL DESCRIPTION**

The carbon dioxide laser is one of the most powerful and efficient lasers. It is a four-level molecular laser and operates on a set of vibrational-rotational transitions. The laser output is in the middle infrared at 10.6 μm and 9.4 μm wavelength region. Both cw and pulsed output occurs. The laser produces CW powers of greater than 100 kW and pulsed energies of as much as 10 kJ.

*Energy levels of $CO_2$ molecule :*

In case of isolated atoms, the electron energy levels are discrete and narrow. On the other hand, the energy spectrum of molecules is complex and includes many additional features. Each electron level is associated with a number of equispaced vibrational levels and each vibrational level in turn has a number of rotational levels.

The $CO_2$ molecule is basically a linear molecule consisting of a central carbon atom with two oxygen atoms linked one on either side. It can undergo three independent vibrational oscillations (Fig. 2.17) known as the *vibrational modes*. The modes are termed as stretching mode, the bending mode and the asymmetric stretching mode. Each mode is quantized, so the molecule can have 0, 1, 2, or more units of vibrational energy in each mode. At any one time, a $CO_2$ molecule can vibrate in any linear combination of these three fundamental modes. The energy states of the molecule is then represented by three quantum numbers (m n q ). These numbers represent the amount of energy associated with each mode. For example, the number (020) indicates that the molecule

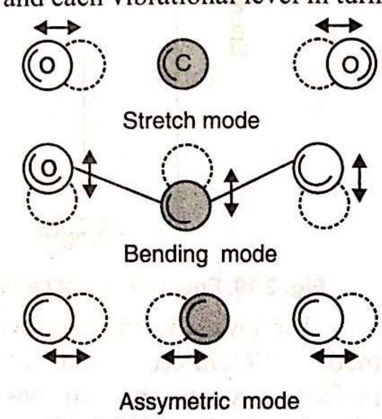


**Fig. 2.17.** Vibrational modes of $CO_2$ molecule.

in this energy state is in the pure bending mode and has two units of energy. Each vibrational state is associated with rotational states corresponding to the rotation of the molecule about its centre of mass. The separations between vibrational – rotational states are much smaller on the energy scale compared to the separations between electron energy levels.

**STRUCTURE**

The schematic of a typical $CO_2$ laser is shown in Fig 2.18. It is basically a discharge tube having a bore of cross-section of 1.5 $cm^2$ and a length of about 26 cm. The discharge tube is filled with a mixture of carbon dioxide, nitrogen and helium gases in 1:4:5 proportions respectively.

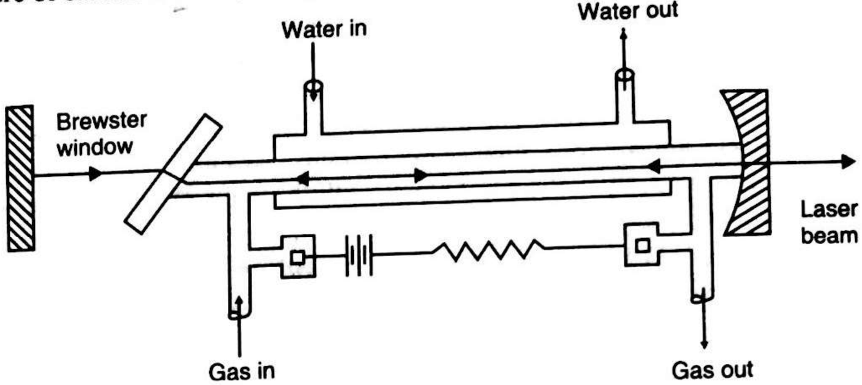


**Fig. 2.18.** A schematic of a typical $CO_2$ laser.

Typically, a high dc voltage causes an electric discharge to pass through the tube. The discharge breaks down $CO_2$ molecules to form oxygen and carbon monoxide. Therefore, a small amount of water vapour is added to the gaseous mixture which regenerates $CO_2$.

**WORKING**

Fig. 2.19 shows the lowest vibrational levels of the ground electron energy state of $CO_2$ molecules and an $N_2$ molecule also. In the $CO_2$ laser, nitrogen plays a similar role to that of helium in the He-Ne laser. Both nitrogen and $CO_2$ absorb energy from electrons in the discharge.

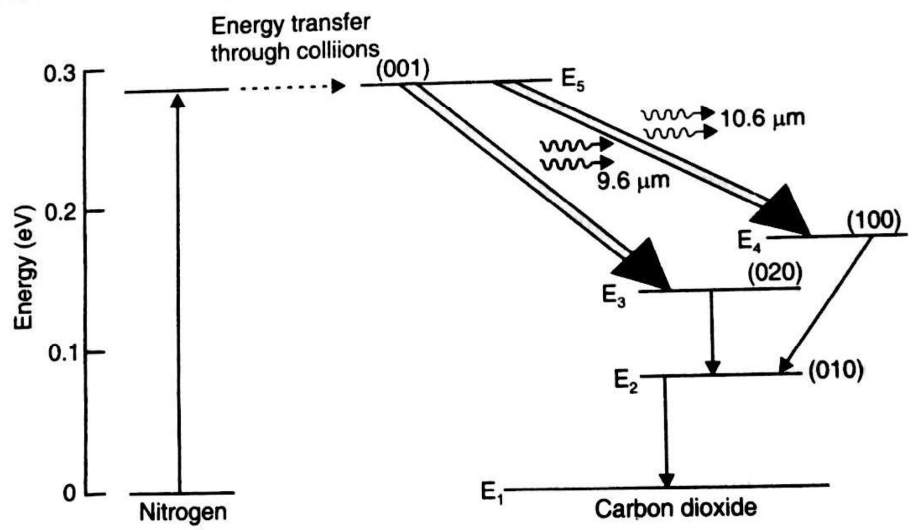


**Fig. 2.19.** Energy levels of carbon dioxide and nitrogen molecules and transitions between the levels.

The lowest vibrational level of $N_2$ has nearly as much energy as the asymmetric stretching mode of $CO_2$ molecule and so the excited nitrogen molecules readily transfer energy to the $CO_2$ molecules in resonant collisions. As a result, $CO_2$ molecules are excited to (001) level ($E_5$). The (100) $CO_2$ level ($E_4$) has a lower energy and cannot be populated in this way. So population inversion is established between the (001) level, ($E_5$) and the (100) level, ($E_4$). Simultaneously, in the same manner population inversion is created between (001) level, $E_5$, and (020) level $E_3$. The lasing transitions $E_5 \rightarrow E_4$ and $E_5 \rightarrow E_3$ produce IR radiation at wavelength 10.6 μm and 9.6 μm respectively. The $E_3$ and $E_4$ levels are metastable states. The $CO_2$ molecules at these levels fall to the lower bending level $E_2$, through inelastic collisions with helium atoms. The decay from the $E_2$ level to the ground state should be very fast. Otherwise there would be accumulation of molecules in this level which leads to decrease in population inversion. The helium atoms deplete the level $E_2$ through collisions. There is yet another function of helium. The $E_2$ level is very close to the ground state $E_1$ and tends to be populated through thermal excitations. It becomes therefore necessary to keep the temperature of $CO_2$ low. Helium has a high thermal conductivity and conducts heat away to the walls and keeps $CO_2$ cold. Thus, while nitrogen helps to increase the population of the upper laser level, helium depopulates the lower laser level.

Some of the other structures used for $CO_2$ lasers are briefly described here.

**Wave-guide laser**

This structure is the most efficient way to produce a compact CW $CO_2$ laser. It consists of two transverse RF electrodes separated by insulating sections that form the bore region. The lateral dimensions of the bore are up to a few mm. An rf power supply is connected to the electrodes to provide a h.f. field across the electrodes within the bore region. This type of laser produces cw powers of about 100 W.

**Gas-dynamic laser**

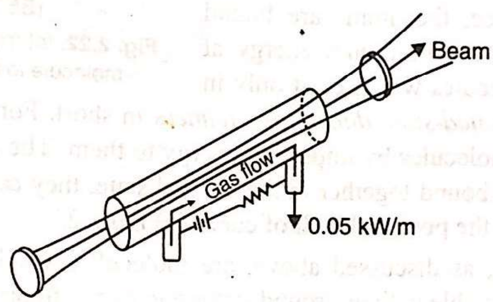


**Fig. 2.20.** Schematic of an axial flow $CO_2$ laser.

An electric discharge is not the only way to produce population inversion in carbon dioxide. Rapidly flowing hot, high pressure $CO_2$ is allowed to expand supersonically through an expansion nozzle into a low pressure region. The expansion causes the gas to supercool. In the process as all the molecules do not drop to lower levels, a population inversion condition is attained. Lasers of this design produce cw outputs greater than 100 kW.

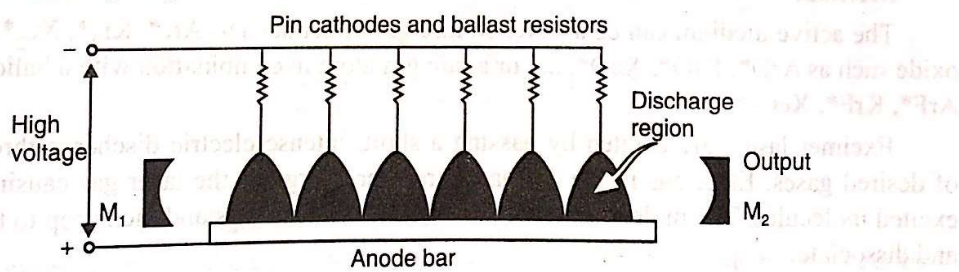


**Fig. 2.21.** Illustration of discharge in a TEA laser.

**TEA $CO_2$ Lasers**

This laser operates at gas pressure of around one atmosphere with a pulsed electric discharge passing through the gas. It works better if the electric discharge is transverse to the laser axis. Such lasers are called TEA lasers (Fig. 2.21).