## Module 5 : MODERN PHYSICS
### Lecture 29 : Maser

**Objectives**

In this course you will learn the following

- Population inversion in atomic systems
- Principle of MASER
- Principle of three level and four level Laser
- Different types of Lasers, their properties and applications.

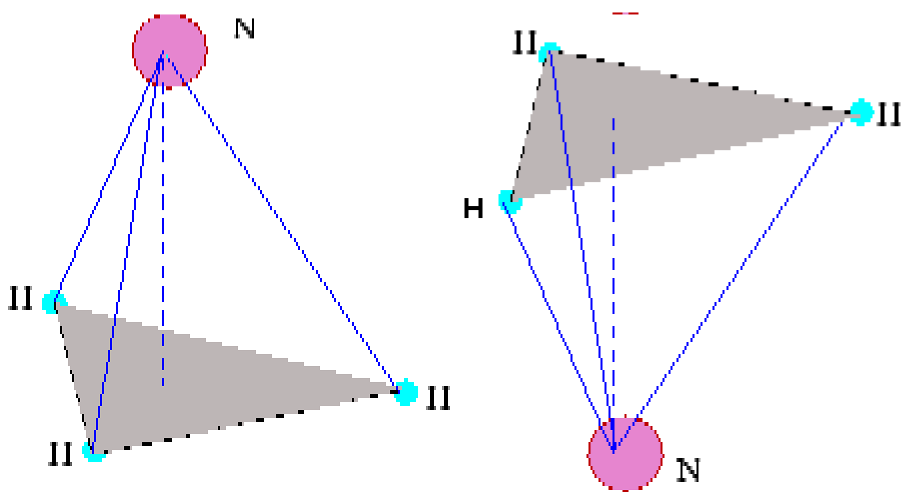
**Population Inversion**

We have seen that when atoms are in equilibrium with the surrounding, the population of atoms in the ground state is more than that in any of the excited states. Population of excited states can be increased by absorption of radiation. However, the life time in the excited states being typically of the order of $10^{-8}$ seconds, atoms which make transitions to the excited states fall back to the ground state soon thereafter. This is also indicated by the ratios of the Einstein coefficients. It is, therefore, not possible to keep the population in the excited states higher than that in the ground state.
The basic principle involved in the operation of laser is **population inversion** , a situation in which the population of the excited state is kept higher than that of the ground state.

**MASER :**

The frequency of microwave photons is $10^{13}$ Hz, corresponding to an energy of the order of 0.01 eV. The energy is of the same order as that of the thermal energy of air molecules. In such a case, the population of the excited states is comparable to that of the ground state at room temperatures. The process of stimulated emission can then be used to amplify microwave signal. MASER is an acronym for **Microwave Amplification by Stimulated Emission of Radiation** .

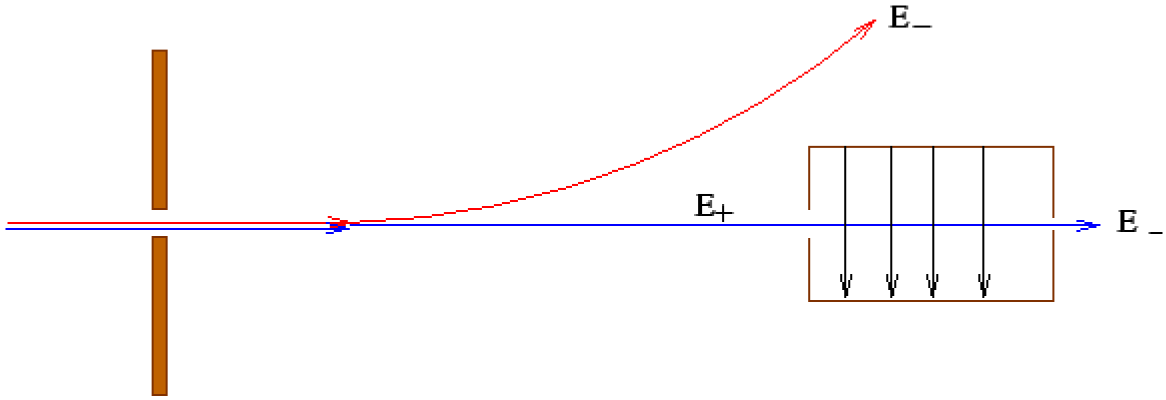
Ammonia Maser is such a device for generating electromagnetic waves. Ammonia molecule has two resonant states with a small energy difference $\sim 0.1$ eV. Geometrically, the two states may be picturised as follows. The three hydrogen atoms are at the vertices of an equilateral triangle which forms the base of a pyramid with the nitrogen atom at the apex of the pyramid. The nitrogen atom may be in two possible positions, either *above* the hydrgen plane or *below* it. (Physically, the two states are distinguished by the direction of their dipole moment in the presence of an electric field.) The molecules make transition from one state to another by absorption or emission of radiation.




The principle of ammonia maser is to separate the two types of molecules which have different energies and . This is done by subjecting the beam to an inhomogeneous electric field in a transverse

$E_+$ $E_-$

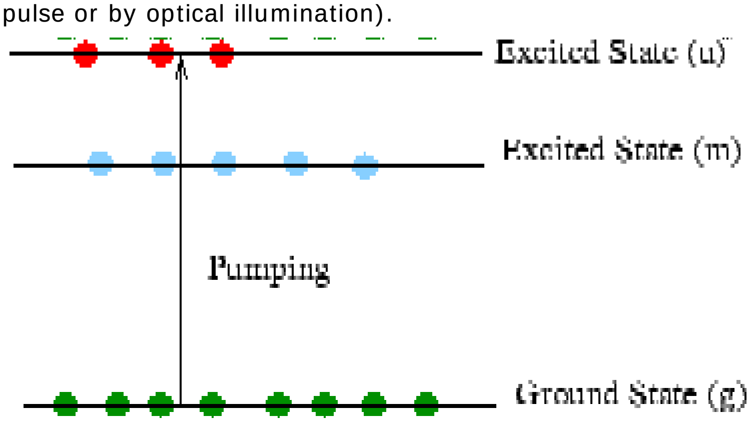
direction.



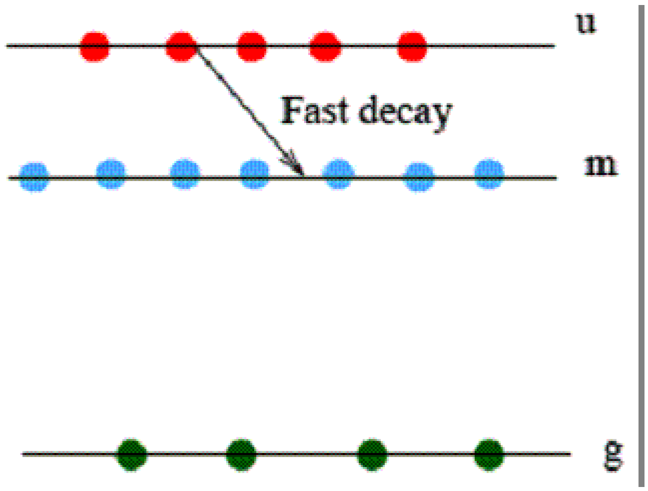

The higher energetic beam is passed through a cavity to which it delivers energy. This is done by having a time varying electric field $E = E_0 \cos \omega t$ in the cavity. If the frequency of the electric field is tuned such that $\omega = 2\pi(E_+ - E_-)/h$, resonance condition is satisfied and the molecules make a radiative transition from states with higher energy to that with lower energy.

**Three Level Laser :**

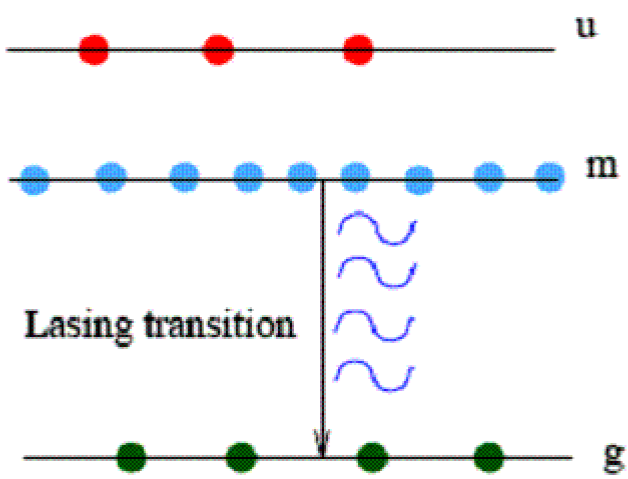
- For optical frequencies, population inversion cannot be achieved in a two level system. In 1956 Bloembergen proposed a mechanism in which atoms are *pumped* into an excited state $u$ by an external source of energy ( such as by an electric pulse or by optical illumination).




- The system, in addition to the state $u$, has an excited state $m$ which is a *metastable* state, i.e. a state inwhich the atom has a long life time. Atoms from the upperlevel $u$ decays spontaneously to this metastable state $m$. Life time in the level $m$ is such that the rate of spontaneous decay from level $m$ to the ground level $g$ is slower than the rate at which atoms decay from $u$ to $m$. This results in a population inversion between the metastable level and the ground state.



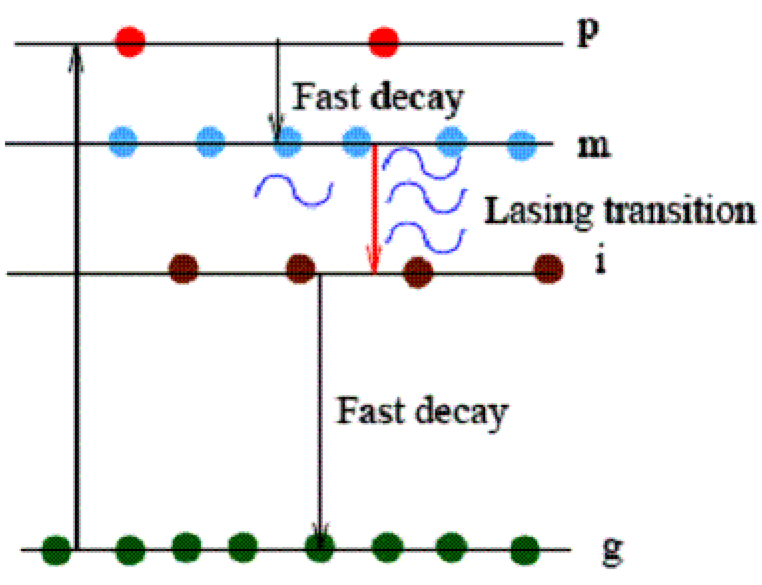

- The emitted photons are confined to a laser cavity to stimulate further emission from the excited atoms. Ruby laser works on the principle of a three level system. The pumping power required for such a system is very high because more than half of the ground state atoms have to be pumped into the upper level to achieve population inversion.




**Four Level Laser :**

One of the most popular and low cost lasers is helium-neon laser, which works on the basis of a four level system with two levels intermediate between the ground state $g$ and the pumpng level $p$.

The ground state atoms are electrically pumped to a short lived state $p$. Atoms from this state undergo fast decay to a metastable state $m$. Between $m$ and $g$, yet another short lived excited state $i$ exists. A population inversion takes place between this intermediate state $i$ and the metastable state $m$, between which the lasing transition occurs.




**Properties of Laser Beam :**

Laser beams are characterized by the following special properties :

- **Coherence :** Laser beam is highly coherent, i.e, different parts of the beam maintain a phase relationship for a long time. this results in interference effect. When a laser beam reflects off a surface, the reflected light can be seen to have bright regions separated by dark regions.
- **Monochromaticity:** Laser beam is highly monochromatic with the spread of wavelength being very small.
- **Directionality :** Laser beam is highly collimated and can travel long distances without significant spread in the beam cross section.

**Types of Lasers and Applications :**

Lasers have found wide applications in areas as diverse as optical communications, medical surgery, welding technology, entertainment electronics etc. What makes such veritable use of lasers possible is the highly collimated nature of the laser beams and the consequent possibility of delivering a very high energy density in a limited region of space. Depending on the material used for the *active medium* , lasers are broadly classified as

(i) conventional or gas lasers

(ii) solid state lasers

(iii) liquid lasers and

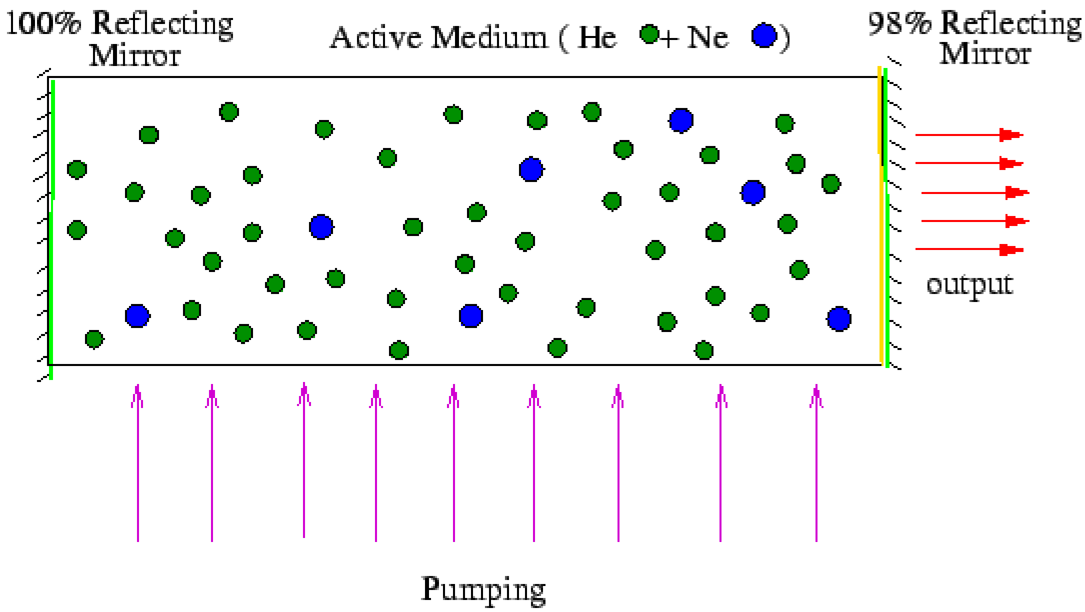
(iv) semiconductor lasers.

Among the gas lasers, some of the most commonly used ones are Helium - Neon laser, Carbon dioxide laser and Argon- ion laser.

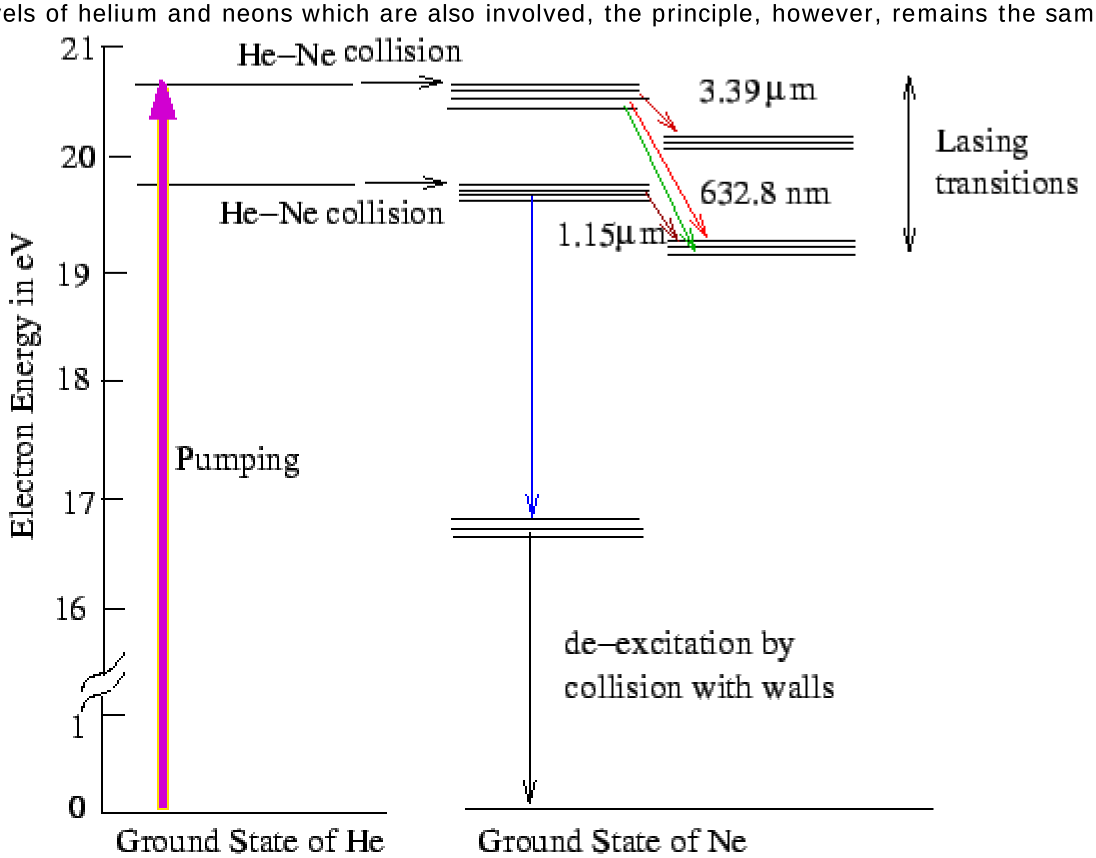
**Helium-Neon Laser :**

Helium-neon laser consists of an active medium of a gas mixture with about 80% He and 20% Ne, kept in a glass chamber at at low pressure. The ends of the chamber are silvered with one end having a perfectly reflecting mirror while the other end has a mirror which reflects 98%.

Pumping helium atoms to their excited states is provided by electrical discharge at about 1 keV. The mirrors reflect light back and forth extending the path travelled by light which increases the probability of stimulated emission. The emergent laser light is primarily in the red region of spectrum at $\lambda = 632.8$ nm. The principle of lasing is as follows.




Among many excited states of helium, one of the states is a metastable (long lived) state with an energy which is 20.6 eV above the ground level. (An electron in this level is not permitted to return to the ground state by emission of a photon as it would violate conservation of angular momentum.) The ground state of neon has an electronic configuration of $2p^6$. Neon atoms have various excited levels of which there is a set of levels corresponding to a configuration $2p^5 5s$ which are coincidentally removed from the ground state of neon by 20.6 eV with a small spread of 0.04 eV. Helium atoms which are pumped into the excited state may collide with the neon atoms in their ground states and transfer their energy to the neon atoms, taking the latter to their excited levels. The small energy spread of 0.04 eV can be accounted for by the kinetic energy of colliding atoms. The following figure shows the transitions that takes place. (The figure shows additional energy levels of helium and neons which are also involved, the principle, however, remains the same.)




Neon has lower lying energy levels at about 18.7 eV above its ground state corresponding to the atomic configuration . At any instant there are more atoms in the than in any of the lower levels,

$2p^5 3p$ $2p^5 5s$

resulting in a population inversion. Lasing transition takes place between the $2p^5 5s$ level and the $2p^5 3p$ level which emits in the red at a wavelength of 632.8 nm. Lasing also occurs in infrared and far infrared with emissions at 3.39 $\mu$m and 1.15 $\mu$m as shown in the figure. Less prominent emissions in the green part of the spectrum (543 nm) also takes place.

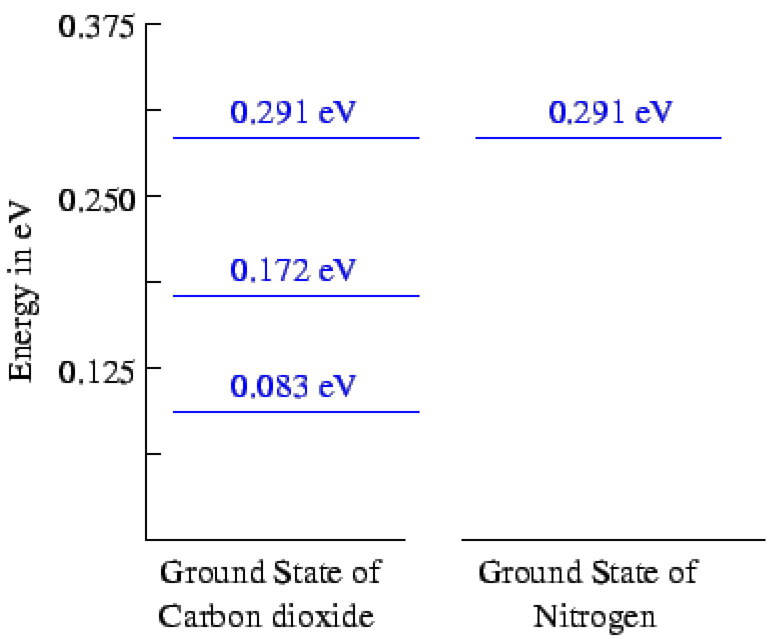
Helium-neon laser, which is a low cost device is not particularly an energy efficient device, its energy output being a few milliwatts whereas the pumping power is between 10 to 100 watts. However, its primary utility lies in the coherence and directionality of the beam as well as the energy that can be delivered over a small area because the power, though small, is concentrated over a small beam diameter giving a power density between 0.1 to 1 kW/m $^2$. Coherence of the beam is useful in interferometric and holographic applications. Collimation and the ability to traverse traverse long distances is used in measuring and sensing devices, as barcode scanners etc. As the emission is in the red - green region of the visible region, He-Ne lasers are used as tools in advertising in light shows and in entertainment electronics.

**Carbon dioxide Laser :**

Carbon dioxide laser was invented by C. K. N. Patel of Bell Laboratories in 1964. It is basically a three level system, though a fourth level is also involved in the transition. It contains a mixture of gases of $CO_2$, $N_2$ and He, approximately in the ratio 1:1:8. Note that inspite of the name, the primary constituent is helium. In case of $CO_2$ laser, in addition to the quantized electronic levels of the atoms, the vibrational and the rotational states of the molecules are also involved in the transition. Electrical discharge is used to excite the nitrogen molecules to higher excited states, which are long lived and cannot decay by emission of photons. The excited nitrogen molecules collide with carbon dioxide molecules which happen to have a second excited level (the pumping level) precisely at the excitation energy of the nitrogen molecules. A population inversion occurs and lasing transition takes place in far infrared ( $\sim 10.6\mu$ m) and also at $9.4\mu$m. Helium has an important role to play in the laser operation. Carbon dioxide molecules to return to the ground state by collision with helium atoms. In addition, helium improves the thermal conductivity of the gas mixture without which the gas would become hotter and would have an increased population in the excited levels negating the effect of population inversion.

**Exercise 1**

The adjacent figure shows the energy levels of nitrogen and carbon dioxide molecules. Using this, explain laser action in $CO_2$ lasers.

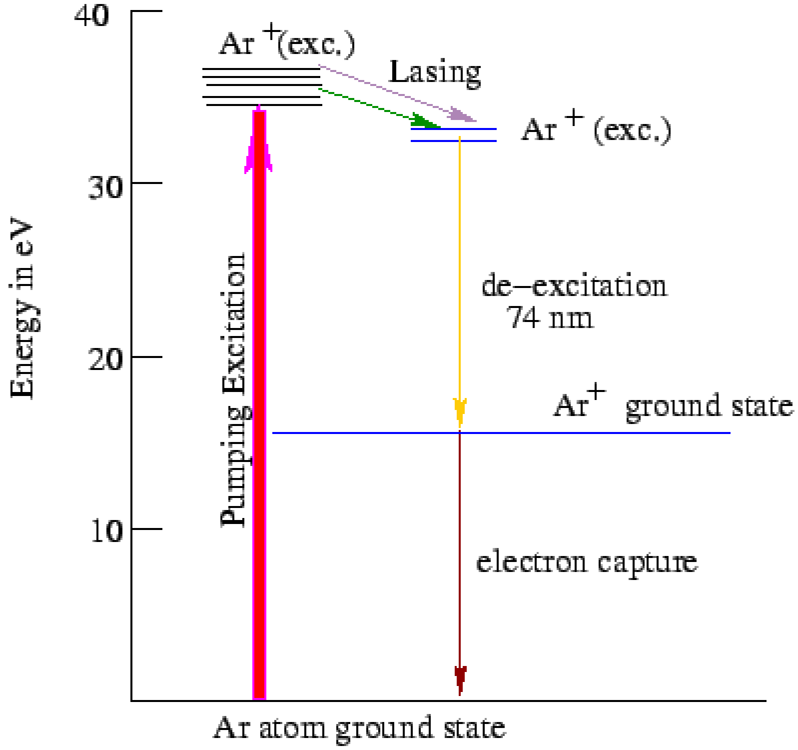



Nitrogen-carbon dioxide laseer system is the most efficient and powerful among all the lasers, the output efficiency being about 12%. Because of such high power, $CO_2$ lasers are used in industrial applications like cutting and welding. It has been used extensively in military applications for rangefinding through a technology called LIDAR (Light Detection and Ranging), which is very similar to RADAR which uses radio waves in that the distance of an approaching aircraft may be determined by measuring time delay in arrival of a laser pulse at its source after reflection. $CO_2$ lasers have been used in medical applications in thoracic and retinal surgery.

**Argon-ion Laser**

Argon-ion laser is an example of a **continuous wave (CW)** laser, which is a type of laser in which a coherent beam is generated continuously as an output. Because of this it has applications in communication technology. It can be operated in CW mode at about 25 different wavelengths from 350 nm in the ultraviolet to 520 nm in the blue green, but the strongest lines are 488 nm and 514 nm. Because of such prominent lines in the visible region, the laser is used in light shows.

The energy levels of neutral argon as well as that of a singly ionized argon ($Ar^+$) is shown alongside. The neutral atom is pumped into its excited state. As we are dealing with noble gases, the excitation energy is very high. Ionization of neutral Ar atoms requires a voltage pulse of about 10 kV. The process of ionization creates argon ions in their ground as well as excited states. The ground state of $Ar^+$, which has a configuration of $3s^2 3p^5$, is about 15.75 eV above the ground level of neutral Ar. Stimulated emission occurs between the $3s^2 3p^4 4p^1$ excited state of the ion and the $3s^2 4p^4 4s^1$ excited of the ion. The ion in the latter excited state drops to the ground state of the ion by a spontaneous emission at 74 nm. From this state electron capture returns the ion to the ground state of the neutral atom.




[See the Animation]

High energy required for ionizaton makes the laser rather energy inefiicient. However, high energy outputs up to about 20 W can be obtained in CW mode. Because of this, argon ion lasers have applications in scientific studies where high power is required. In addition, the laser is used extensively in opthalmic and general surgery.

**Solid State Lasers :**

Typical examples of solid state lasers are Ruby lasers, Nd-glass laser etc. Ruby laser consists of rods of ruby, which are $Al_2O_3$ with about 0.05% Cr with a highly polished mirror at one end and a semi-transparent mirror at the other. A xenon flash bulb is used to excite chomium atoms to their excited states. Lasing transition at 694.3 nm takes place between states of chromium. Pulsed beam with bursts lasting

$1.2 \times 10^{-14}$ seconds can be generated with such a laser. Power output of solid state lasers are high and they have wide variety of applications like cutting, welding, printing and xeroxing, medical and surgical applications etc.

**Semiconductor Lasers :**

Semiconductor lasers make use of junction between different semiconductors as the active medium. Laser action is achieved by heavily doping the junction which ensures availability of a large concentration of electron hole pairs for recombination. Ends of the device are polished so that spontaneously emitted light travels back and forth enabling stimulated emission. Emission wavelengths span a wide range from near red into far infrared. Power output of semiconductor lasers can be from a few milliwatts to several watts under cw conditions while pulsed power of several hundreds of watts may be made available. Semiconductor lasers have wide range of applications. These include their use in communication systems, environmental sensing, audio compact discs, laser printing etc.

**Recap**

In this course you have learnt the following

- The basic principle of laser operation is to create conditions so that the population at a higher level is more than that in the ground state. This is known as population inversion.
- Maser works on the principle of stimulated emission of atoms from an excited state to the ground state. When microwave is incident on a cavity containing excited atoms, it triggers the atoms or molecules to radiate energy with the same wavelength as that of the incident wave. The wavelength produced is so stable that it can be used as a clock standard.
- It is not possible to achieve population inversion in a two level system. It is, however, possible to achieve population inversion between a metastable state which lies between the ground state and an upper excited state. Electrons pumped into the upper level decay fast to the metastable level which undergoes lasing transition to the ground state.
- Laser beams are highly monochromatic, have directionality and phase coherence. Lasers are now used in a wide variety of applications such as welding and cutting retinal surgery, compact discs, optical communications etc.