Lasers

Basic terms

We have learnt that the energy levels in atom, ions and molecules are discrete. The lowest possible energy level is known as the ground state and higher energy levels are called the excited states. As the energy of the excited states increase, the separation between the adjacent energy levels become smaller and smaller until the separation becomes so small that the energy levels appear continuous. Such continuous spread of energy is called the continuum.

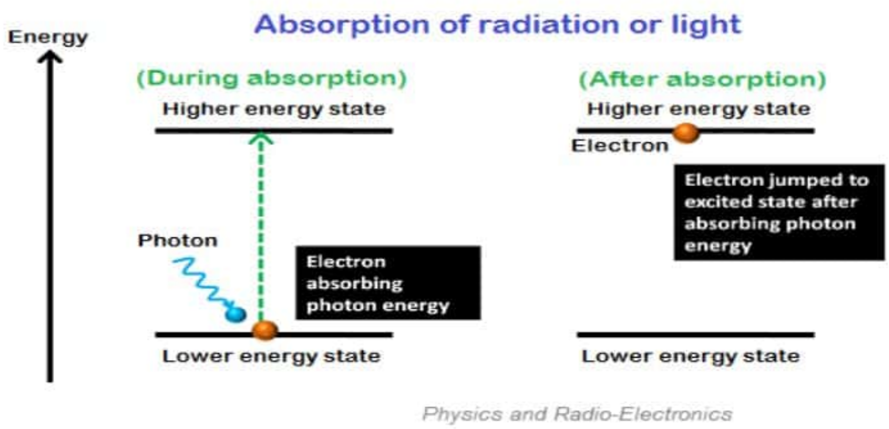
There are three ways in which an incident radiation can interact with the energy levels of atoms.

Absorption

An electron in one of the lower level (ground state or a lower lying excited state) with energy E_i can make a transition to a higher level having energy E_f by absorbing an incident photon. Absorption can occur only when the frequency of the incident radiation ν is given by

$$\nu = (E_f - E_i)/h$$

If this condition is not satisfied, the matter becomes transparent to incident radiation.



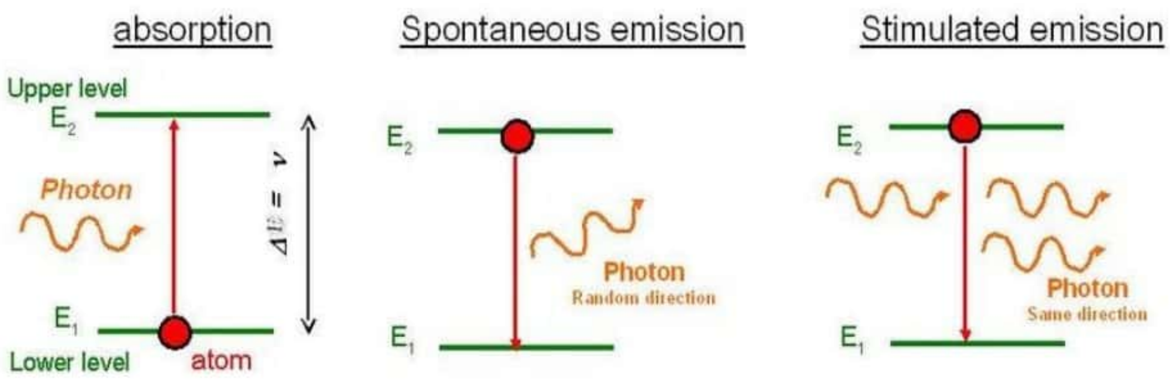
Spontaneous Emission

Atoms which are in excited states are not in thermal equilibrium with their surroundings. Such atoms will eventually return to their ground state by emission of a photon. If E* is the energy in the excited state and E the energy of a lower lying state (which could be the ground state), the frequency of the emitted photon is given by

$$\nu = (E^* - E)/h$$

Stimulated Emission

In 1917, Einstein showed that under certain conditions, emission of light may be stimulated by radiation incident on an excited atom. This happens when an electron is in an excited state E* and a photon whose energy is equal to the difference E* between and the energy E of a lower lying level (could be the ground state) is incident on the atom. The incident photon induces the electron in the excited state to make a transition to the lower level by emission of a photon. The emitted photon travels in the same direction as the incident photon. Significantly, the new photon has the same energy as that of the incident photon and is perfectly in phase with it. When two waves travel in the same direction with a constant phase relationship, they are said to be coherent .



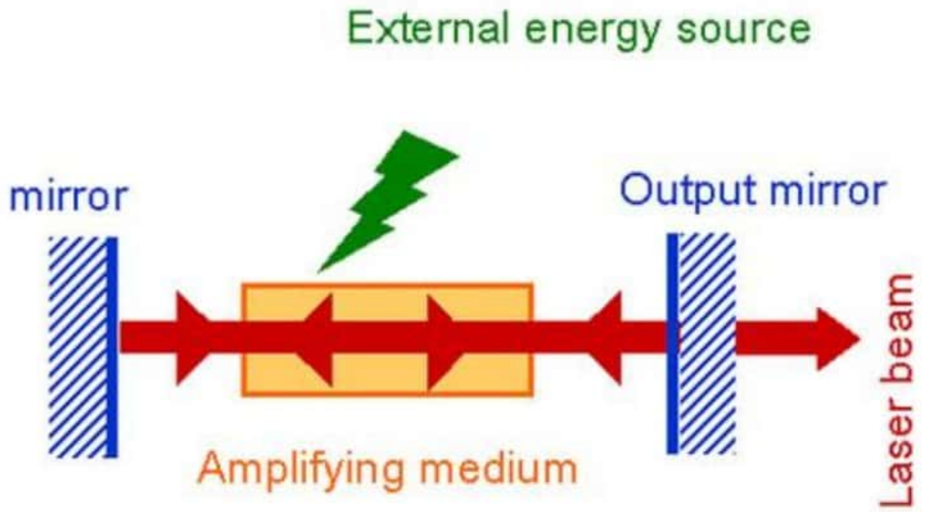
LASER - Light Amplification by Stimulated Emission of Radiation : In 1958, Charles H. Townes and Arthur L. Schawlow showed that the effect of stimulated emission can be amplified to produce a practical source of light, which is coherent and can travel long distances without appreciable spread of the beam width. Such a light source is called LASER, an acronym for Light Amplification by Stimulated Emission of Radiation.

Lasers are devices that produce intense beams of light which are monochromatic, coherent, and highly collimated. The wavelength (color) of laser light is extremely pure (**monochromatic**) when compared to other sources of light, and all of the photons (energy) that make up the laser beam have a fixed phase relationship (**coherence**) with respect to one another. Light from a laser typically has very low divergence (**highly directional**). It can travel over great distances or can be focused to a very small spot with a brightness which exceeds that of the sun. Because of these properties, lasers are used in a wide variety of applications in all walks of life.

A laser consists of two fundamental elements:

- An amplifying or gain medium (this can be a solid, a liquid or a gas). This medium is composed of atoms, molecules, ions or electrons whose energy levels are used to increase the power of a light wave during its propagation. The physical principle involved is called stimulated emission.
- A system to excite the amplifying medium (also called a pumping system). This creates the conditions for light amplification by supplying the necessary energy. There are different kinds of pumping system: optical (the sun, flash lamps, continuous arc lamps or tungsten-filament lamps, diode or other lasers), electrical (gas discharge tubes, electric current in semi-conductors) or even chemical.

These two components are sufficient to amplify an existing light source. This is known as a laser amplifier. However, most lasers also incorporate an optical resonator (or cavity) in order to produce a very special radiation. Technically, the whole device is known as a laser oscillator, but this term is often shortened to simply "laser". The laser oscillator uses reflecting mirrors to amplify the light source considerably by bouncing it back and forth within the cavity. It also has an output beam mirror that enables part of the light wave in the cavity to be removed and its radiation used.

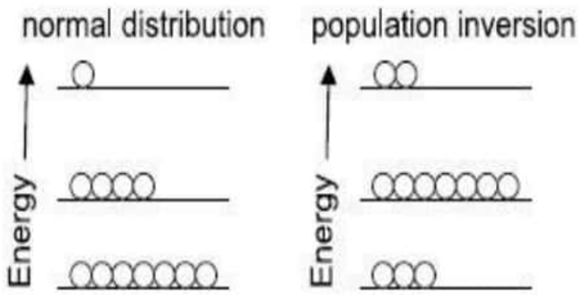


The principle behind such amplification is simple. Suppose we start with one photon which strikes an atom in an excited state and releases a photon, we would have two photons and an atom in the ground state. These two photons, in turn, may be incident on two more atoms and give rise to four photons, and so on.

The time for which an electron remains in an excited state is approximately seconds. Thus it is difficult to keep atoms in excited states till they are stimulated to radiate a photon. The excited atom is more likely to de-excite spontaneously. Photons released through spontaneous processes are emitted in random directions and are not coherent with the incident photon. The photons that are incident and those which are generated may be absorbed by atoms in ground states, leading to depletion in the number of photons.

Population inversion

In science, specifically statistical mechanics, a **population inversion** occurs while a system (such as a group of atoms or molecules) exists in a state in which more members of the system are in higher, excited states than in lower, unexcited energy states. Under normal circumstances, the higher an energy level is, the less it is populated by thermal energy. Under some circumstances (for example, the presence of an upper energy level that has a relatively long lifetime), a system can be constructed so that there are more atoms/molecules in an upper energy level than is allowed under conditions of normal thermodynamic equilibrium. Such an arrangement is called a population inversion. It is called an "inversion" because in many familiar and commonly encountered physical systems, this is not possible. This concept is of fundamental importance in laser science because the production of a population inversion is a necessary step in the workings of a standard laser.



When a population inversion exists, an upper-state system will eventually give off a photon of the proper wavelength and drop to the ground state. This photon, however, can stimulate the production of other photons of exactly the same wavelength because of stimulated emission of radiation. Thus, many photons of the same wavelength (and phase, and other similar characteristics) can be generated in a short time. This is light amplification by stimulated emission of radiation, or LASER—usually seen in lowercase as laser. Lasers typically have a very narrow wavelength range of emission.

Pumping

In order to achieve population inversion, we need to supply energy to the laser medium. The process of supplying energy to the laser medium is called pumping. The source that supplies energy to the laser medium is called pump source. The type of pump source used is depends on the laser medium. Different pump sources are used for different laser mediums to achieve population inversion. Some of the most commonly used pump sources are as follows:

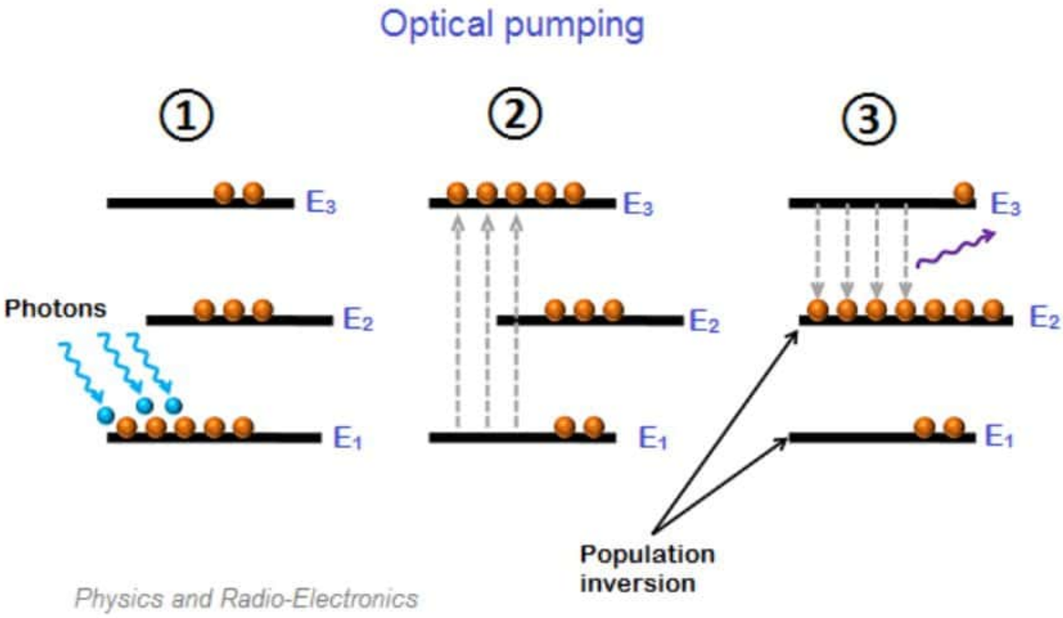
- Optical pumping
- Electric discharge or excitation by electrons
- Inelastic atom-atom collisions
- Thermal pumping
- Chemical reactions

Population inversion is easily achieved when the system of molecules or atoms have the energy levels with favorable properties. For example, the upper energy level has a long lifetime and the lower energy level has a short lifetime.

Optical Pumping

As the name suggests, in this method, light is used to supply energy to the laser medium. An external light source like xenon flash lamp is used to produce more electrons (a high population) in the higher energy level of the laser medium.

When light source provides enough energy to the lower energy state electrons in the laser medium, they jump into the higher energy state E_3. The electrons in the higher energy state do not stay for long period. After a very short period, they fall back to the next lower energy state or meta stable state E_2 by releasing radiation less energy.

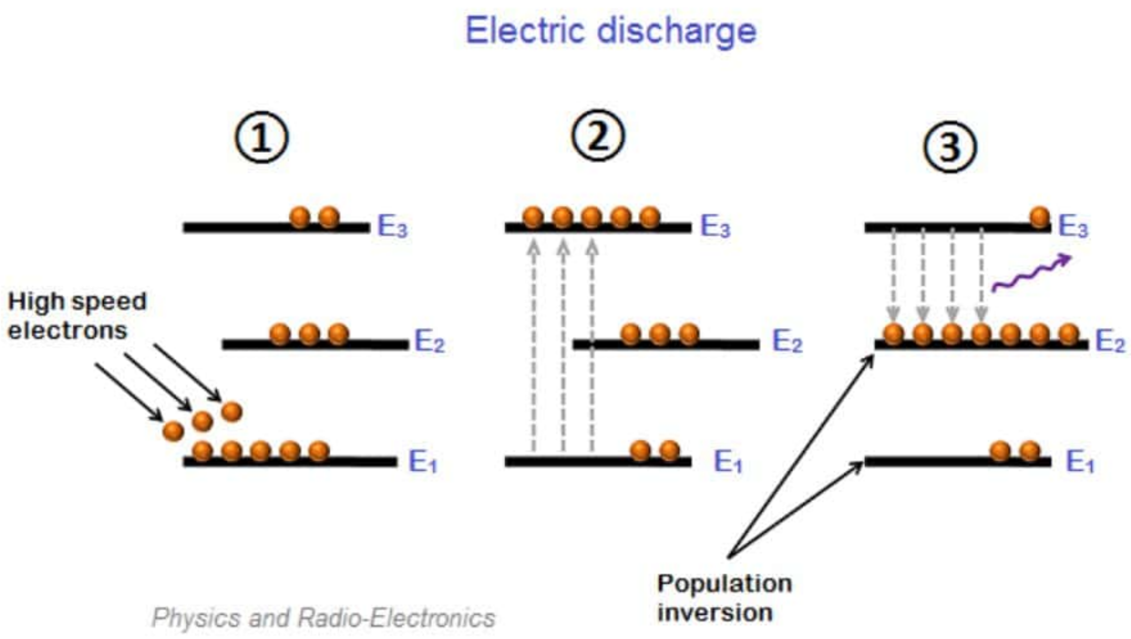


The metastable state E_2 has greater lifetime than the lower energy state or ground state E_1. Hence, more electrons are accumulated in the energy state E_2 than the lower energy state E_1. Thus, population inversion is achieved. Optical pumping is used in solid-state lasers such as ruby lasers.

Electric Discharge or Excitation by Electrons

Electric discharge refers to flow of electrons or electric current through a gas, liquid or solid.

In this method of pumping, electric discharge acts as the pump source or energy source. A high voltage electric discharge (flow of electrons, electric charge, or electric current) is passed through the laser medium or gas. The intense electric field accelerates the electrons to high speeds and they collide with neutral atoms in the gas. As a result, the electrons in the lower energy state gains sufficient energy from external electrons and jumps into the higher energy state. This method of pumping is used in gas lasers such as argon lasers.



The process of achieving population inversion in the gas laser is almost similar to the solid laser. The only difference is the pump source used for supplying energy and the type of material or medium (solid or gas) used as a laser medium. In solid lasers, an external light source like xenon flash lamp is used as pump source whereas, in gas lasers, a high voltage electric discharge is used as a pump source.

Types of lasers

Lasers are classified into 4 types based on the type of laser medium used:

- Solid-state laser
- Gas laser
- Liquid laser
- Semiconductor laser

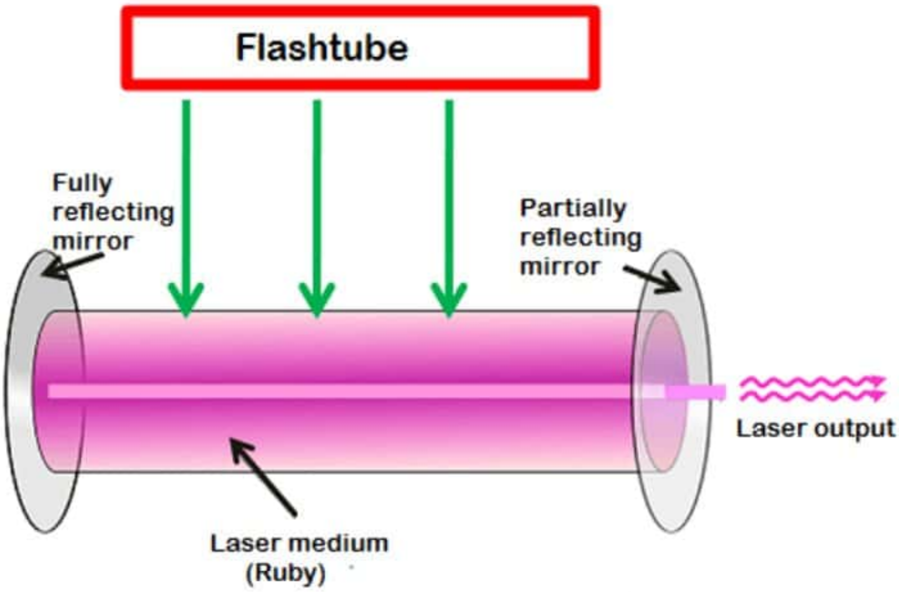
Solid-state laser

A solid-state laser is a laser that uses solid as a laser medium. In these lasers, glass or crystalline materials are used.

Ions are introduced as impurities into host material which can be a glass or crystalline. The process of adding impurities to the substance is called doping. Rare earth elements such as cerium (Ce), erbium (Eu), terbium (Tb) etc are most commonly used as dopants.

Materials such as sapphire (Al_2O_3), neodymium-doped yttrium aluminum garnet (Nd:YAG), Neodymium-doped glass (Nd:glass) and ytterbium-doped glass are used as host materials for laser medium. Out of these, neodymium-doped yttrium aluminum garnet (Nd:YAG) is most commonly used.

The first solid-state laser was a ruby laser. It is still used in some applications. In this laser, a ruby crystal is used as a laser medium.

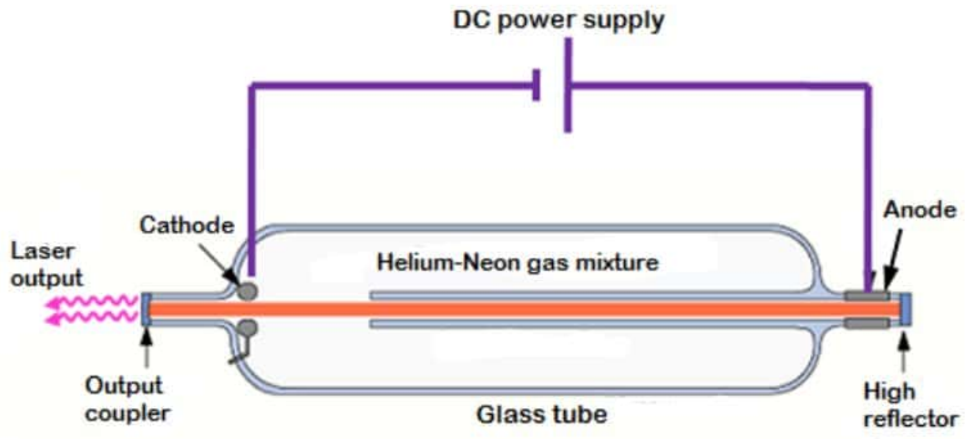


In solid-state lasers, light energy is used as pumping source. Light sources such as flashtube, flash lamps, arc lamps, or laser diodes are used to achieve pumping.

Semiconductor lasers do not belong to this category because these lasers are usually electrically pumped and involve different physical processes.

Gas laser

A gas laser is a laser in which an electric current is discharged through a gas inside the laser medium to produce laser light. In gas lasers, the laser medium is in the gaseous state.



Gas lasers are used in applications that require laser light with very high beam quality and long coherence lengths.

In gas laser, the laser medium or gain medium is made up of the mixture of gases. This mixture is packed up into a glass tube. The glass tube filled with the mixture of gases acts as an active medium or laser medium.

A gas laser is the first laser that works on the principle of converting electrical energy into light energy. It produces a laser light beam in the infrared region of the spectrum at 1.15 μm.

Gas lasers are of different types: they are, Helium (He) – Neon (Ne) lasers, argon ion lasers, carbon dioxide lasers (CO_2 lasers), carbon monoxide lasers (CO lasers), excimer lasers, nitrogen lasers, hydrogen lasers, etc. The type of gas used to construct the laser medium can determine the lasers wavelength or efficiency.

Liquid laser

A liquid laser is a laser that uses the liquid as laser medium. In liquid lasers, light supplies energy to the laser medium.

A dye laser is an example of the liquid laser. A dye laser is a laser that uses an organic dye (liquid solution) as the laser medium.

A dye laser is made up of an organic dye mixed with a solvent. These lasers generate laser light from the excited energy states of organic dyes dissolved in liquid solvents. It produces laser light beam in the near ultraviolet (UV) to the near infrared (IR) region of the spectrum.

Semiconductor laser

Semiconductor lasers play an important role in our everyday life. These lasers are very cheap, compact size and consume low power. Semiconductor lasers are also known as laser diodes.

Semiconductor lasers are different from solid-state lasers. In solid-state lasers, light energy is used as the pump source whereas, in semiconductor lasers, electrical energy is used as the pump source.

In semiconductor lasers, a p-n junction of a semiconductor diode forms the active medium or laser medium. The optical gain is produced within the semiconductor material.

By mode of operation

- CW
- Pulsed

By pumping and laser levels

- 3- level laser
- 4- level laser