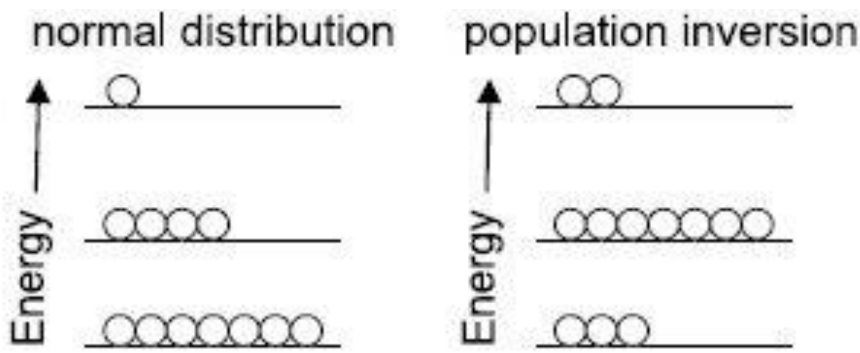
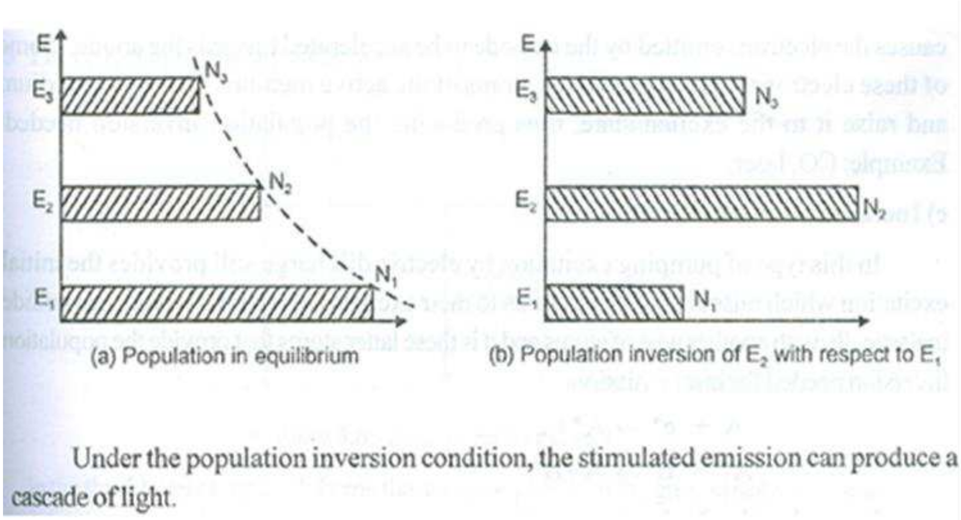
Population Inversion

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.

No. of atoms present in the energy levels is called population. To get laser action more atoms will be present at higher energy level than ground level. At thermal equilibrium more atoms are in ground level than excited level. If E_1 is ground level, E_2 is excited level having populations N_1 and N_2 respectively. Then, $\frac{N_2}{N_1} = \exp\left(\frac{E_2 - E_1}{K_B T}\right)$



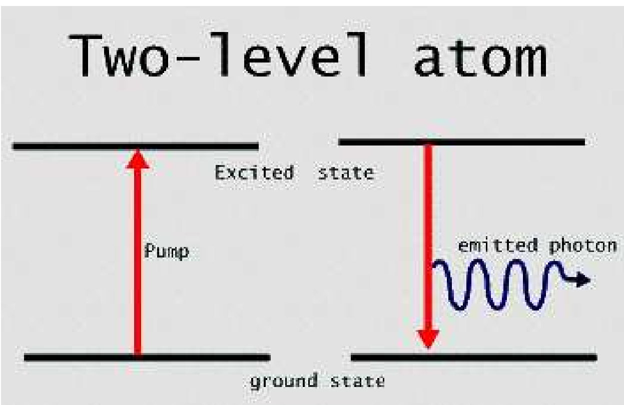
When an atomic system is in equilibrium, absorption and spontaneous emission take place side by side. But, $N_2 < N_1$, absorption dominates. However laser operation requires obtaining stimulated emission exclusively. To achieve a high percentage of stimulated emission, a majority of the atoms should be at the higher energy level than at the lower level. The non equilibrium state in which the population N_2 of the upper energy level exceeds the population N_1 of the lower energy level is known as population inversion.

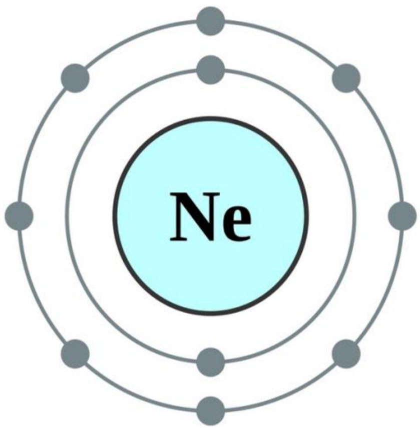


Consider a system that has three energy states E_1, E_2 and E_3. With the system in equilibrium, the uppermost level E_3 is populated least and lowest level E_1 is populated most. The dotted curve shown in figure represents a normal Boltzmann distribution. Since the population in three states is such that $N_3 < N_2 < N_1$, the systems absorbs photons rather than emitting photons. However if the system is supplied with external energy such that N_2 exceeds N_1, we say that the system has reached population inversion. Under the population inversion condition, the stimulated emission can produce a cascade of light.

Pumping schemes

Two level pumping scheme





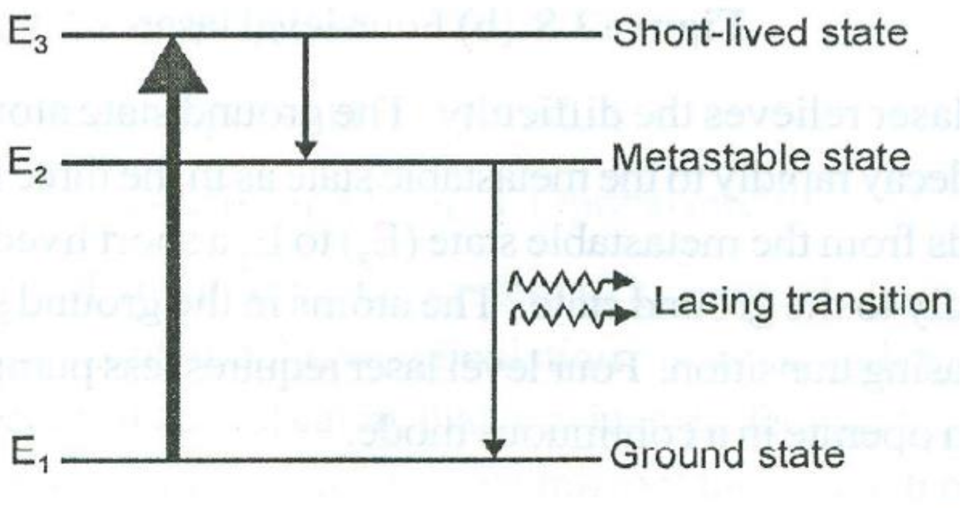
It seems that the simple and straight forward method to achieve population inversion is to pump and maintain excess of atoms into the excited state by applying intense radiation. But basically a two level pumping scheme is not suitable for attaining population inversion.

This is due to two basic reasons.

1. It is difficult to keep a collection of atoms in their excited state until they are stimulated to emit photon.

2. The atoms that happen to be in their ground state will undergo absorption and will thus remove photons from the beam as it builds up.

Three level pumping scheme



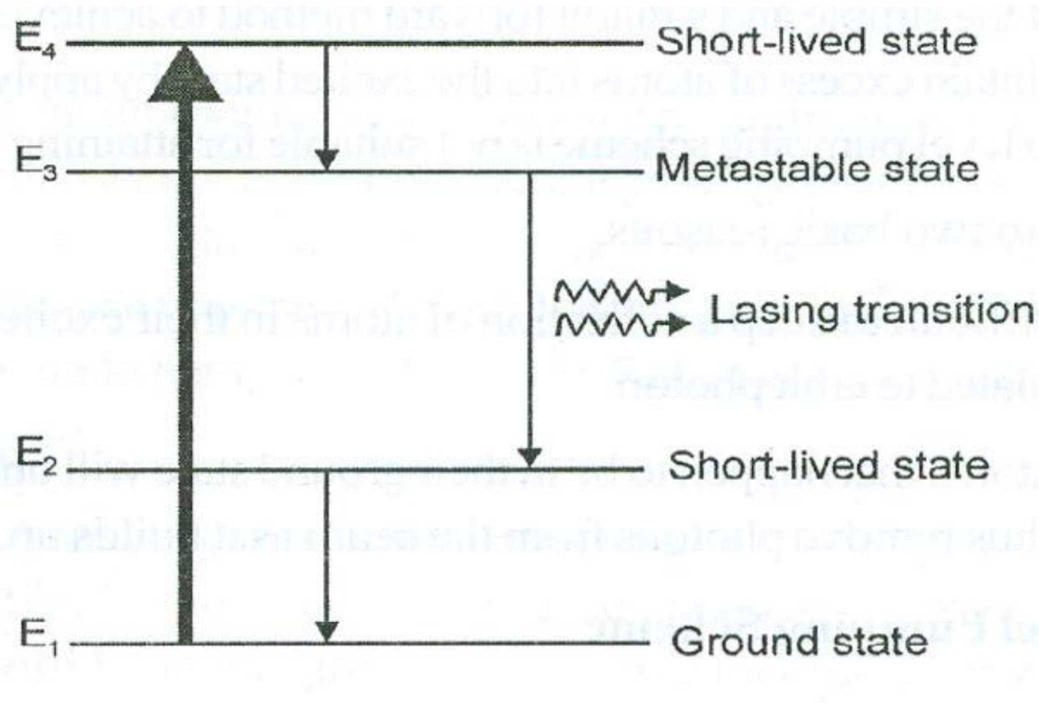
A three-level laser

In the three level pumping scheme the atoms originally in the ground state are pumped into the excited state by some external source of energy (an electric pulse or a flash of light). The pump is assumed to lift atoms from level 1 to level 3 from which they decay rapidly to level 2 through non-radiative decay. The excited atoms decay by spontaneous emission very rapidly into a lower excited which is a metastable state.

Atoms stay in metastable state for about 10^{-6} to 10^{-3} sec. Therefore it is possible for a large number of atoms to accumulate at a metastable sate. In the metastable state, population can exceed the population of a lower level and lead to the state of population inversion. If the metastable state does not exist, there could be no population inversion, no stimulated emission and hence no laser operation. This system solves the first problem arose with the two level laser i.e., placing the collection of atoms in their excited states. But it does not solve the second problem i.e. any atom in the ground state will absorb the lasing transition and remove photons from the beam. Three level scheme requires high pump powers and can produce the light only in pulses.

Four level pumping scheme

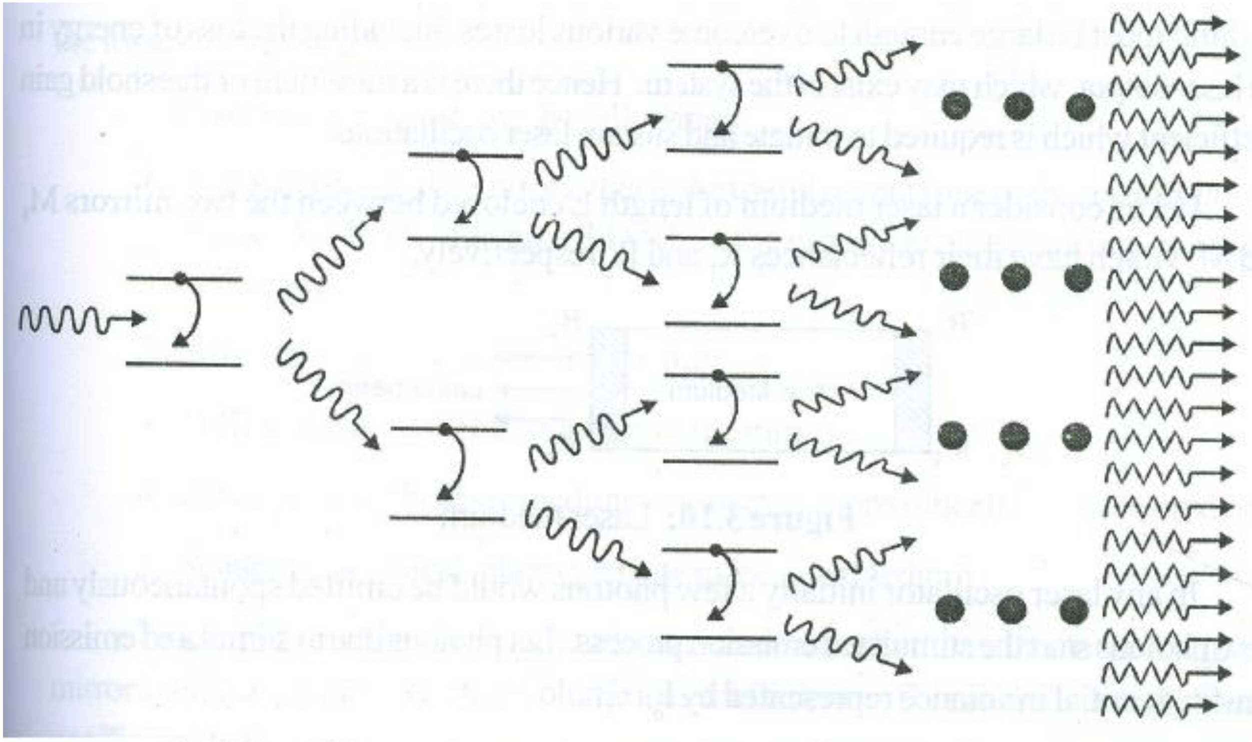
Four level laser relieves the difficulty. The ground state atoms are pumped to the excited state and decay rapidly to the metastable state as in the three level laser. The lasing transition proceeds from the metastable state (E_3) to E_2 a short lived state from where the atoms decay rapidly to the ground state. The atoms in the ground state cannot absorb at the energy of the lasing transition. Four level laser requires less pumping energy than three level laser and can operate in a continuous mode.



Four-level laser

Principle of Laser

The outstanding feature of this process is the multiplication of photons. For one photon hitting an excited atom, there are two photons emerging. The two photons are in phase and travel along the same direction. These two photons stimulate two excited atoms in their path and produce four photons which are in phase and travel along the same direction. These four photons can in turn stimulate four excited atoms and generate eight photons and so on.



Buildup of intense beam in a laser. Each emitted photon interacts with an excited atom and produce two photons. Multiplication of stimulated photons.

Components required for laser action

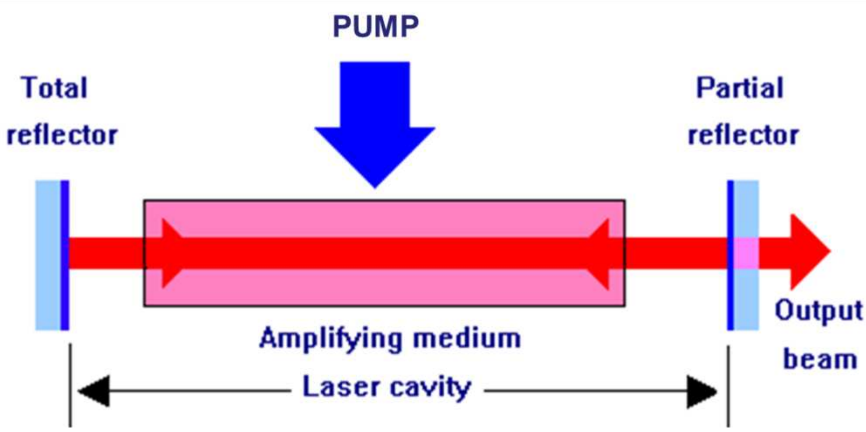
A laser requires three components for operation

1. Energy source 2. Active medium 3. Optical cavity

The energy source that will raise the system to an excited state. Next there is an active medium that, when excited, achieves population inversion and subsequently lasers. The active medium may be solid, a liquid or a gas. Third in most cases there is an optical cavity that provides the feedback necessary for laser oscillation. The optical cavity is formed by two mirrors facing each other.

One of the mirrors is coated to 100% reflectance; the other mirror is partially transparent to let some of the radiation pass through.

COMPONENTS OF LASER



- **<u>ACTIVE MEDIUM</u>**
  Medium, which when excited, reaches the state of population inversion and eventually causes light amplification. Based on active medium, Lasers are classified as Solid state, liquid ans gaseous lasers.
- **<u>PUMPING :</u>** The Process of providing external energy to the medium to create the condition of population inversion is called Pumping. Depending on the type of laser, there are different ways of pumping.

  <u>PUMPING METHODS</u>: The commonly used methods for pumping action are

  (i) Optical pumping

  (ii) Electrical discharge method

  (iii) Direct conversion

  (iv) Inelastic atom – atom collision and

  (v) Chemical reaction

(i) Optical Pumping (by photons): In this type, the atoms are excited with the help of photons emitted by an external optical source. The atoms absorb energy from the photons and reach the excited state. This method is called optical pumping.

Examples: This method is used in Ruby – laser and Nd – YAG laser (Solid state laser).

(ii) Electrical discharge method (by electrons): The electrons are accelerated to very high velocities due to strong electrical field. These accelerated electrons collide with gas atom and the gas atoms are raised to excited states. This method is called electrical discharge method.

Examples: This method is used in Argon laser and CO_2 laser (Gas lasers).

(iii) Direct Conversion: The combination of electrons and holes takes place in semiconductors due to supply of electrical energy. The electrical energy is directly converted into light energy. This method is called direct conversion.

Example: Gallium arsenide [GaAs] semiconductor laser.

(iv) Chemical reactions: Due to some chemical reactions, the atoms in the ground state move to the excited state.

Example: Dye laser.

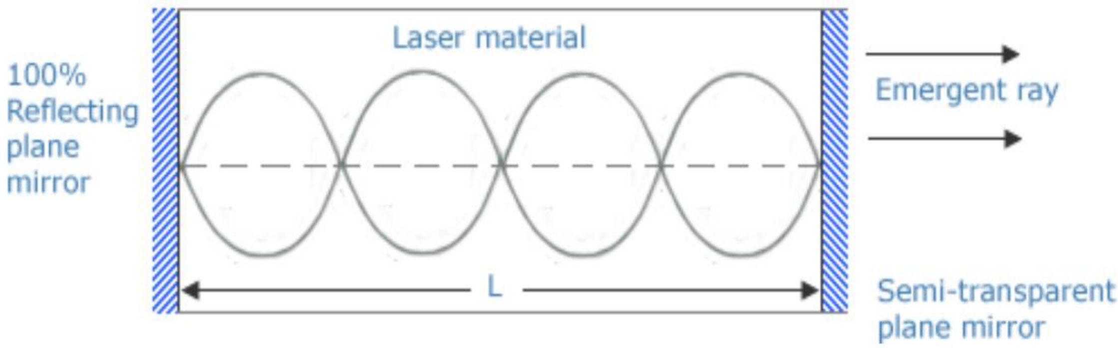
(v) Inelastic atom – atom collisions: In this type of pumping, a combination of two types of gases say A and B are used. Both are having same or nearly excited states. During the first step, A-atoms get excited due to collision with accelerated electrons. This excited A* atoms now collide with B-atoms. Now B atoms reach excited B* due to gain of energy by B-atoms. This method is called inelastic atom-atom collision.

$$e^- + A \rightarrow A^* ; A^* + B \rightarrow B^* + A$$

Examples: He – Ne laser and CO_2 laser.

➢ OPTICAL RESONATOR

An optical resonator is needed to build up the light energy in the beam. The resonator is formed by placing a pair of mirrors facing each other so that light emitted along the line between the mirrors is reflected back and forth.



When a population inversion is created in the medium, light reflected back and forth increases in intensity with each pass through the laser medium. Other light leaks around the mirrors without being amplified. In an actual laser cavity, one or both mirrors transmit a fraction of the incident light.