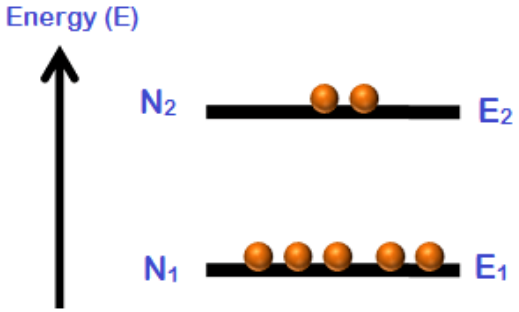
Population Inversion

- Population inversion is the process of achieving greater population of higher energy state as compared to the lower energy state. Population inversion technique is mainly used for light amplification. The population inversion is required for laser operation.
- Consider a group of electrons with two energy levels E_1 and E_2.
- The number of electrons per unit volume in an energy state is the population of that energy state.
- Population inversion cannot be achieved in a two energy level system. Under normal conditions, the number of electrons (N_1) in the lower energy state (E_1) is always greater as compared to the number of electrons (N_2) in the higher energy state (E_2).

  i.e. $N_1 > N_2$

- When temperature increases, the population of higher energy state (N_2) also increases. However, the population of higher energy state (N_2) will never exceeds the population of lower energy state (N_1).
- At best an equal population of the two states can be achieved which results in no optical gain. i.e. $N_1 = N_2$

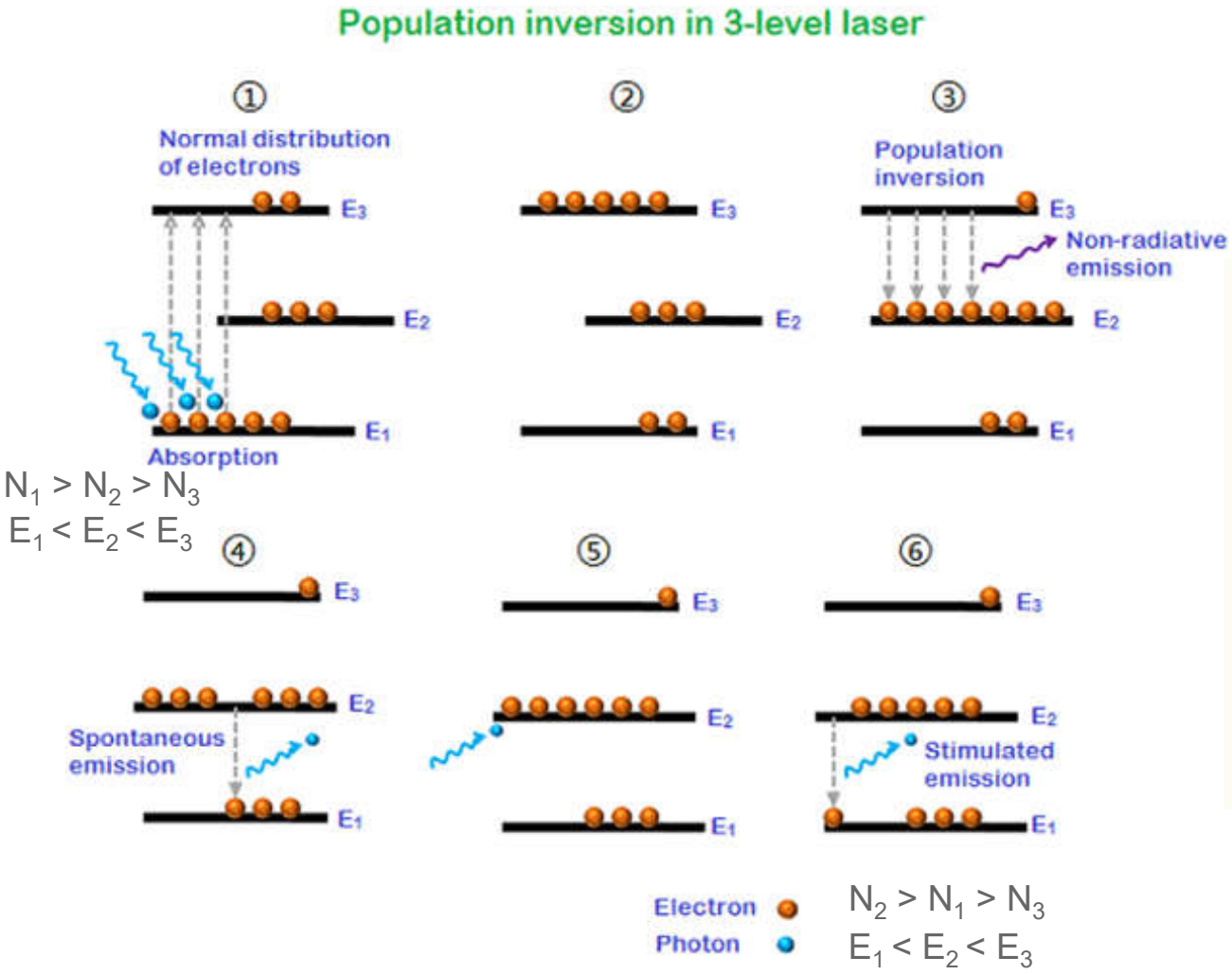


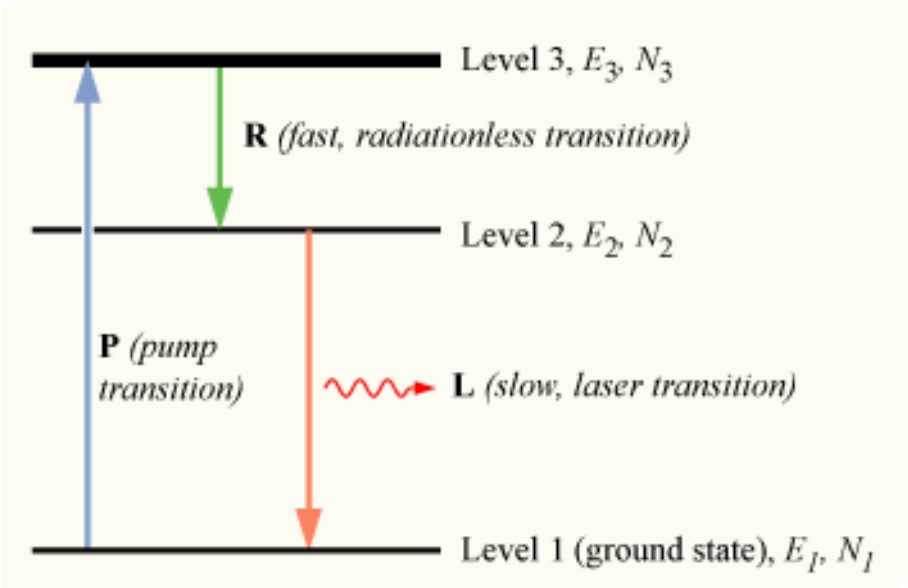
- Therefore, we need 3 or more energy states to achieve population inversion. The greater is the number of energy states the greater is the optical gain.
- There are certain substances in which the electrons once excited; they remain in the higher energy level or excited state for longer period. Such systems are called active systems or active media which are generally mixture of different elements.
- When such mixtures are formed, their electronic energy levels are modified and some of them acquire special properties. Such types of materials are used to form 3-level laser or 4-level laser.

3-level laser:

- Consider a system consisting of three energy levels E_1, E_2, E_3 with N number of electrons. Let N_1 be the number of electrons in the energy state E_1, N_2 be the number of electrons in the energy state E_2 and N_3 be the number of electrons in the energy state E_3.
- We assume that $E_1 < E_2 < E_3$.
- The energy level E_1 is known as the ground state or lower energy state and the energy levels E_2 and E_3 are known as excited states. The energy level E_2 is sometimes referred to as Meta stable state. The energy level E_3 is sometimes referred to as pump state or pump level.
- Under normal conditions, $N_1 > N_2 > N_3$. But to get laser emission or population inversion, N_2 should be greater than N_1.
- Under certain conditions, $N_2 > N_1$ is achieved. Such an arrangement is called population inversion.
- Let us assume that initially the majority of electrons will be in the lower energy state or ground state (E_1) and only a small number of electrons will be in excited states (E_2 and E_3).
- When we supply light energy which is equal to the energy difference of E_3 and E_1, the electrons in the lower energy state (E_1) gains sufficient energy and jumps into the higher energy state (E_3). This process of supplying energy is called pumping.

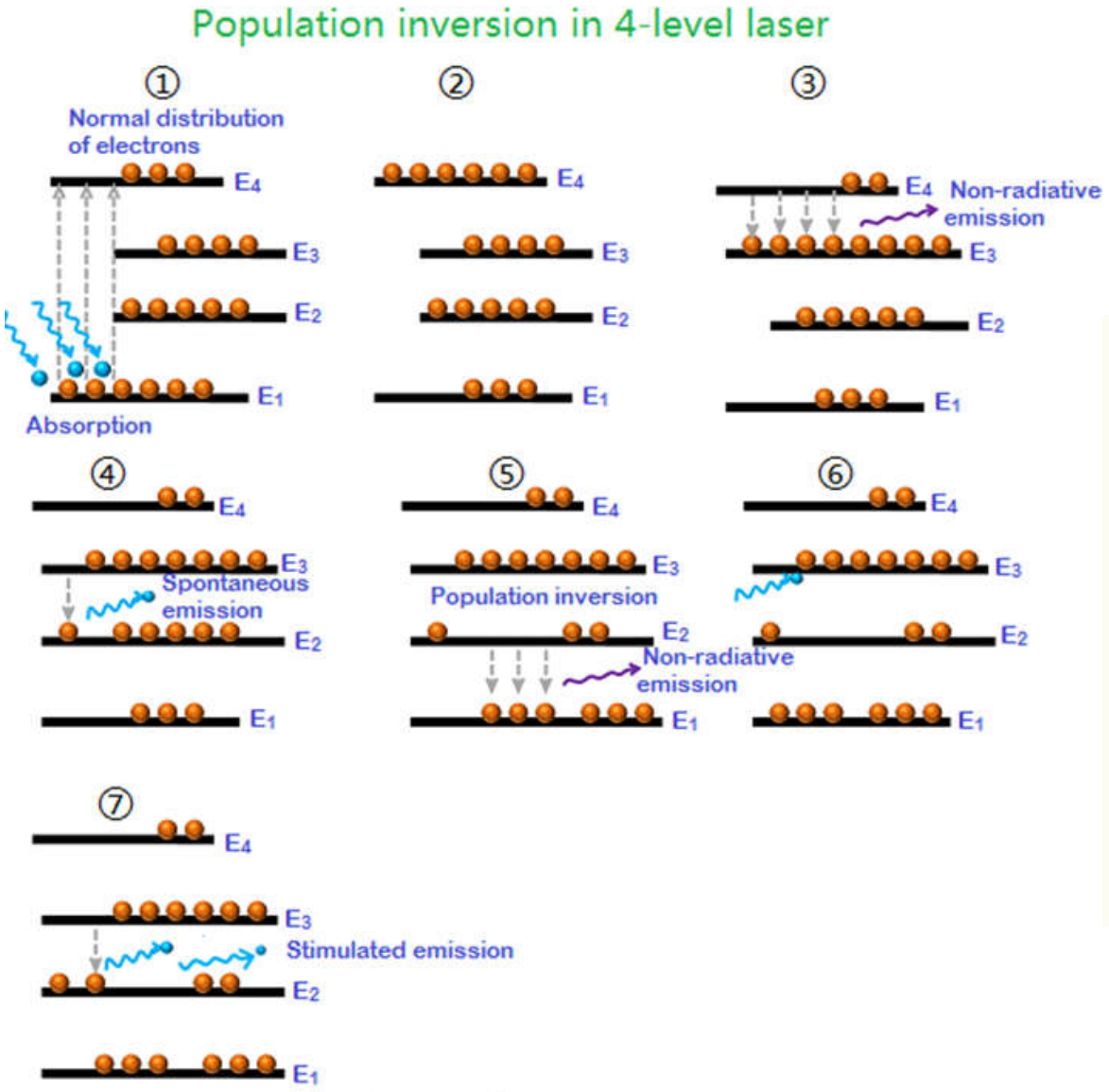
- The lifetime of electrons in the energy state E_3 is very small as compared to the lifetime of electrons in the energy state E_2. Therefore, electrons in the energy level E_3 does not stay for long period. After a short period, they quickly fall to the Meta stable state or energy state E_2 and releases radiation less energy instead of photons. Because of the shorter lifetime(10^{-8} sec), only a small number of electrons accumulate in the energy state E_3.
- The electrons in the Meta stable state E_2 will remain there for longer period because of its longer lifetime(10^{-3} sec). As result, a large number of electrons accumulate in Meta stable state. Thus, we can get $N_2 > N_1 > N_3$. So we can achieve population inversion between energy levels E_1 and E_2.
- After completion of lifetime of electrons in the Meta stable state, they fall back to the lower energy state or ground state E_1 by releasing energy in the form of photons. This process of emission of photons is called spontaneous emission.
- When this emitted photon interacts with the electron in the Meta stable state E_2, it forces that electron to fall back to the ground state. As a result, two photons are emitted. This process of emission of photons is called stimulated emission.
- When these photons again interacted with the electrons in the Meta stable state, they forces two Meta stable state electrons to fall back to the ground state. As a result, four photons are emitted. Likewise, a large number of photons are emitted.
- As a result, millions of photons are emitted by using small number of photons. Thus, light amplification is achieved by using population inversion method. The system which uses three energy levels is known as 3-level laser.
- Drawbacks: In a 3-level laser, at least half the population of electrons must be excited to the higher energy state to achieve population inversion. Therefore, the laser medium must be very strongly pumped. This makes 3-level lasers inefficient to produce photons or light.

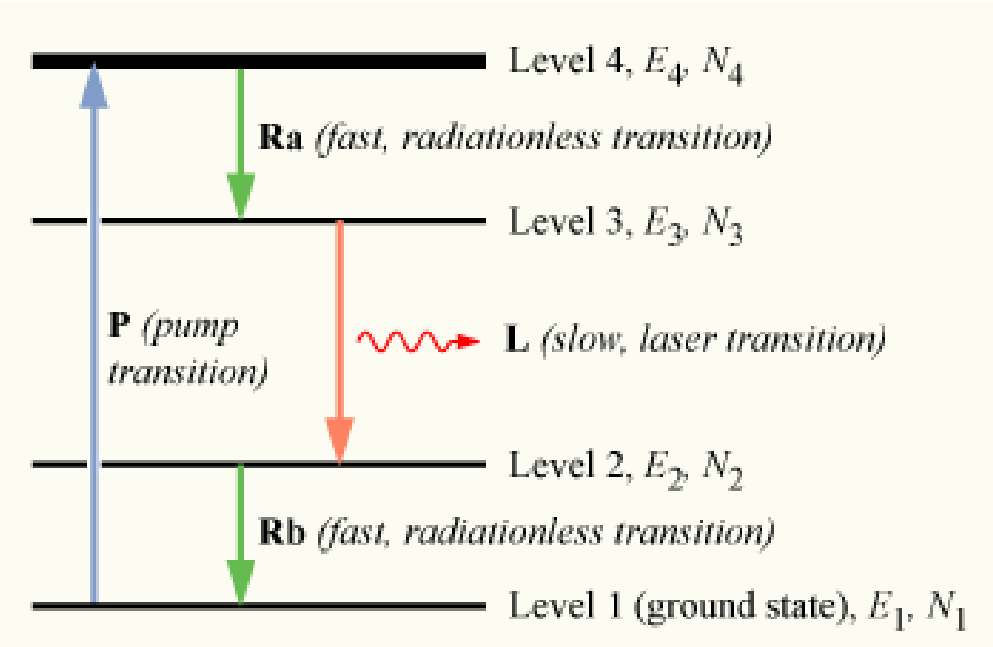

Population inversion in 3-level laser
①
Normal distribution of electrons
E3
E2
E1
Absorption
②
E3
E2
E1
③
Population inversion
E3
Non-radiative emission
E2
E1
N1 > N2 > N3
E1 < E2 < E3
④
E3
E2
Spontaneous emission
E1
⑤
E3
E2
E1
⑥
E3
E2
Stimulated emission
E1
Electron
Photon
N2 > N1 > N3
E1 < E2 < E3


Level 3, E_3, N_3
R (fast, radiationless transition)
Level 2, E_2, N_2
P (pump transition)
L (slow, laser transition)
Level 1 (ground state), E_1, N_1

4-level laser:

- Consider a group of electrons with four energy levels E_1, E_2, E_3, E_4 with $E_1 < E_2 < E_3 < E_4$.
- The number of electrons in the lower energy state or ground state is given by N_1, the number of electrons in the energy state E_2 is given by N_2, the number of electrons in the energy state E_3 is given by N_3 and the number of electrons in the energy state E_4 is given by N_4.
- The lifetime of electrons in the energy state E_4 and energy state E_2 is very less. Therefore, electrons in these states will only stay for very short period (10^{-8} sec.)
- When we supply light energy which is equal to the energy difference of E_4 and E_1, the electrons in the lower energy state E_1 gains sufficient energy and jumps into the higher energy state E_4.
- The lifetime of electrons in the energy state E_4 is very small. Therefore, after a short period they fall back into the next lower energy state E_3 by releasing non-radiation energy.
- The lifetime of electrons in the energy state E_3 is very large as compared to E_4 and E_2. As a result, a large number of electrons accumulate in the energy level E_3. After completion of their lifetime, the electrons in the energy state E_3 will fall back into the next lower energy state E_2 by releasing energy in the form of photons……Spontaneous emission happens
- Like the energy state E_4, the lifetime of electrons in the energy state E_2 is also very small. Therefore, the electrons in the energy state E_2 will quickly fall into the next lower energy state or ground state E_1 by releasing non-radiation energy.
- Thus, population inversion is achieved between energy states E_3 and E_2.
- In a 4-level laser, only a few electrons are excited to achieve population inversion. Therefore, a 4-level laser produces light efficiently than a 3-level laser. In practical, more than four energy levels may be involved in the laser process.

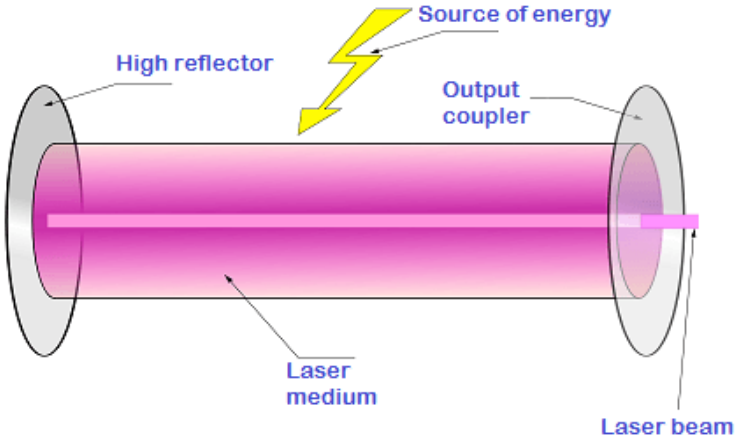

Population inversion in 4-level laser
①
Normal distribution of electrons
E4
E3
E2
E1
Absorption
②
③
Non-radiative emission
④
Spontaneous emission
⑤
Population inversion
Non-radiative emission
⑥
⑦
Stimulated emission


Level 4, E_4, N_4
Ra (fast, radiationless transition)
Level 3, E_3, N_3
P (pump transition)
L (slow, laser transition)
Level 2, E_2, N_2
Rb (fast, radiationless transition)
Level 1 (ground state), E_1, N_1

Components of Laser

A laser or laser system consists of three important components:

- Active medium
- Optical Resonator
- Pump source



Active medium:

- The active medium is a medium in which laser action is made to take place. The laser medium will determine the characteristics of the laser light emitted.
- The laser medium can be solid, liquid, or gaseous where atoms/ions are lying in excited state to facilitate stimulated emission. It should capable of population inversion
- This is also called gain medium or laser medium

Example:

✓Ruby laser is an example for solid-state laser. In this, a ruby crystal is used as an active medium. In this laser, xenon discharge tube which provides a flash light acts as pump source.

✓Helium – Neon laser is an example for gaseous laser. In this, neon is used as an active medium. In this laser, radio frequency (RF) generator acts as pump source.

Optical Resonator:

- The laser medium is surrounded by two parallel mirrors which provides feedback of the light. One mirror is fully reflective (100 % reflective) whereas another one is partially reflective (~ 95-98 % reflective). These two mirrors as a whole is called optical resonator. Optical resonator is also known as optical cavity or resonating cavity.
- The completely reflective mirror is called high reflector whereas the partially reflective mirror is called output coupler. The output coupler will allows amplified light to leave the optical cavity to produce the laser's output beam.
- This condition is must: $l = \frac{n\lambda}{2}$

Where,
l = length of cavity,
λ = wavelength of laser
n= 1,2,3..

Pump source:

- The process of supplying energy to the laser medium to achieve population inversion is called as pumping. The external source that supplies energy to the laser medium is called pump source.
- The type of pump source used is depends on the laser medium.

✓Optical pumping

✓Electric discharge or excitation by electrons

✓Inelastic atom-atom collisions

✓Direct conversion

✓Chemical reactions

➢ Optical pumping:

- ✓ In this method, light is used to supply energy to the laser medium. For example xenon flash lamp
- ✓ This method of pumping is used in solid state lasers such as ruby laser.

➢ Electric discharge or excitation by electrons:

- ✓ 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.

➢ Inelastic atom-atom collisions

- ✓ In this method, pumping by electrical discharge provides the initial excitation which raises ONE type of atoms to their excited states. These atoms collide inelastically with another type of atoms and provide them sufficient energy to excite them to higher state and thus population inversion achieved
- ✓ This method of pumping is used in gas lasers such as He-Ne laser.

➢ Direct Conversion:

- ✓ In this method, the electrons combine with holes producing laser light. This it is direct conversion of electrical to light.
- ✓ This method of pumping is used in gas lasers such as Semiconductor lasers.

➢ Chemical Reaction:

- ✓ In this method, Radiation come out of a chemical reaction, without any need of other energy source. For example when hydrogen combine with fluorine, heat energy is produced
- ✓ This method of pumping is used in gas lasers such as CO_2 lasers.