LASER

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.

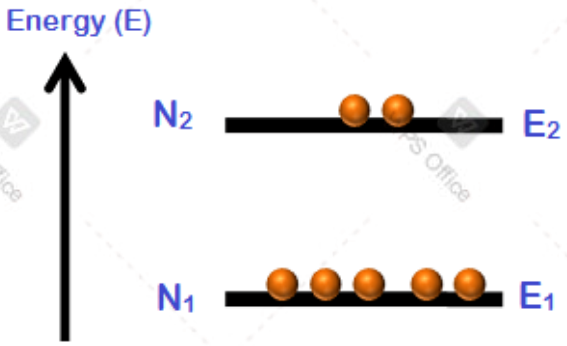
E_1 is the lower energy state and E_2 is the higher energy state.

N_1 is the number of electrons in the energy state E_1.

N_2 is the number of electrons in the energy state E_2.

The number of electrons per unit volume in an energy state is the population of that energy state.

of lasers



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).

$N_1 > N_2$

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.

$N_1 = N_2$

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

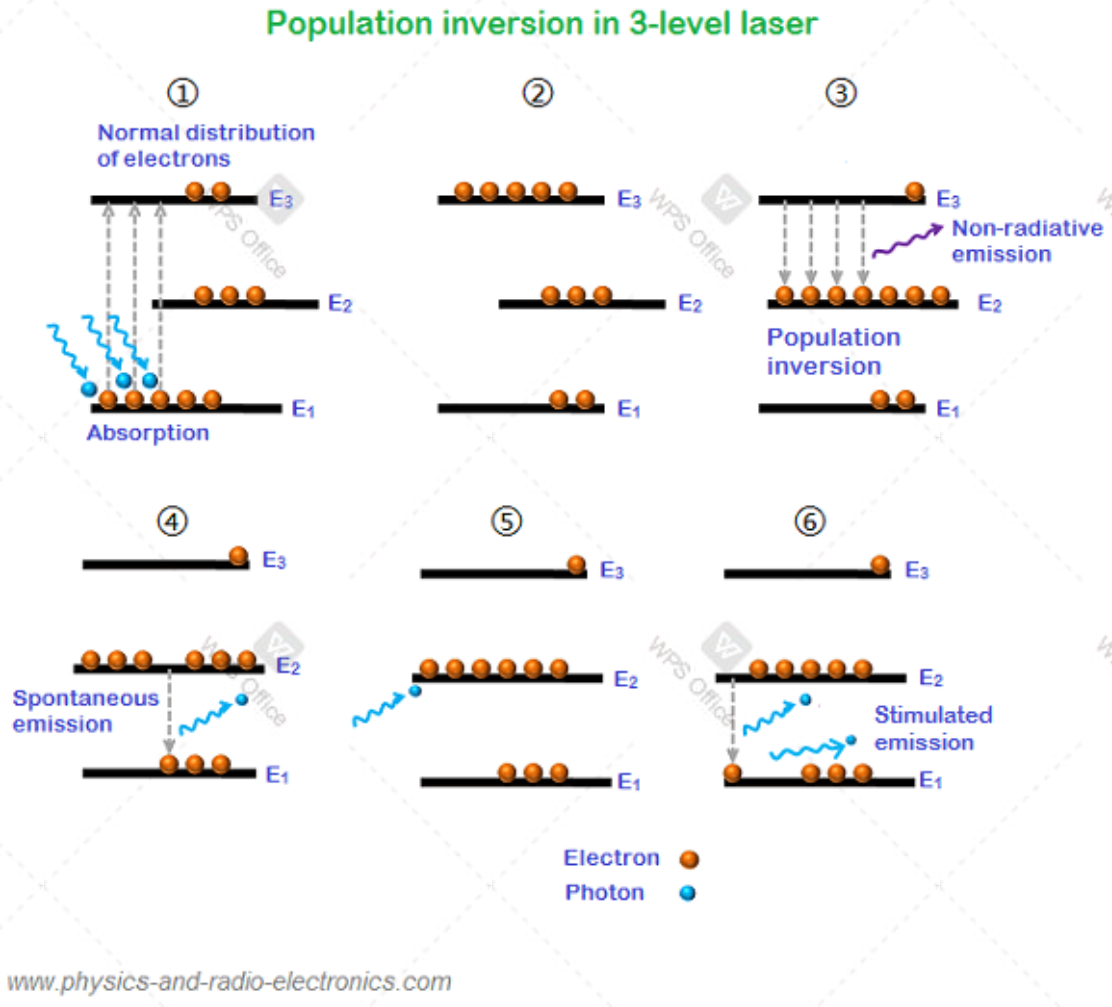
of materials are used to form 3-level laser or 4-level laser.

3-level Laser

Consider a system consisting of three energy levels E_1, E_2, E_3 with N number of electrons.

We assume that the energy level of E_1 is less than than E_2 and E_3, the energy level of E_2 is greater than E_1 and less than E_3, and the energy level of E_3 is greater than E_1 and E_2.

It can be simply written as $E_1 < E_2 < E_3$. That means the energy level of E_2 lies in between E_1 and 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.

The N number of electrons in the system occupies these three energy levels. 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.

To get laser emission or population inversion, the population of higher energy state (E_2) should be greater than the population of the lower energy state (E_1).

Under normal conditions, the higher an energy level is, the lesser it is populated. For example, in a three level energy system, the lower energy state E_1 is highly populated as compared to the excited energy states E_2 and E_3. On the other hand, the excited energy state E_2 is highly populated as compared to the excited energy state E_3. It can be simply written as $N_1 > N_2 > N_3$.

Under certain conditions, the greater population of higher energy state (E_2) as compared to the lower energy state (E_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.

We also use other methods to excite ground state electrons such as electric discharge and chemical reactions. The flow of electrons from E_1 to E_3 is called pump transition.

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, 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. As result, a large number of electrons accumulate in Meta stable state. Thus, the population of metal stable state will become greater than the population of energy states E_3 and E_1.
It can be simply written as $N_2 > N_1 > N_3$.

In a three level energy system, we 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.

We may get a doubt, in order to excite an electron we hit the electron with a photon. This excited electron again emits photon when fall back to the ground state. Then how could light amplification or extra photons is achieved.

We may also use other types of energy sources such as electrical energy to excite electrons. In such case, a single photon will generates large 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.

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. The three level lasers are the first type of lasers discovered.

4-level Laser

Consider a group of electrons with four energy levels E_1, E_2, E_3, E_4.

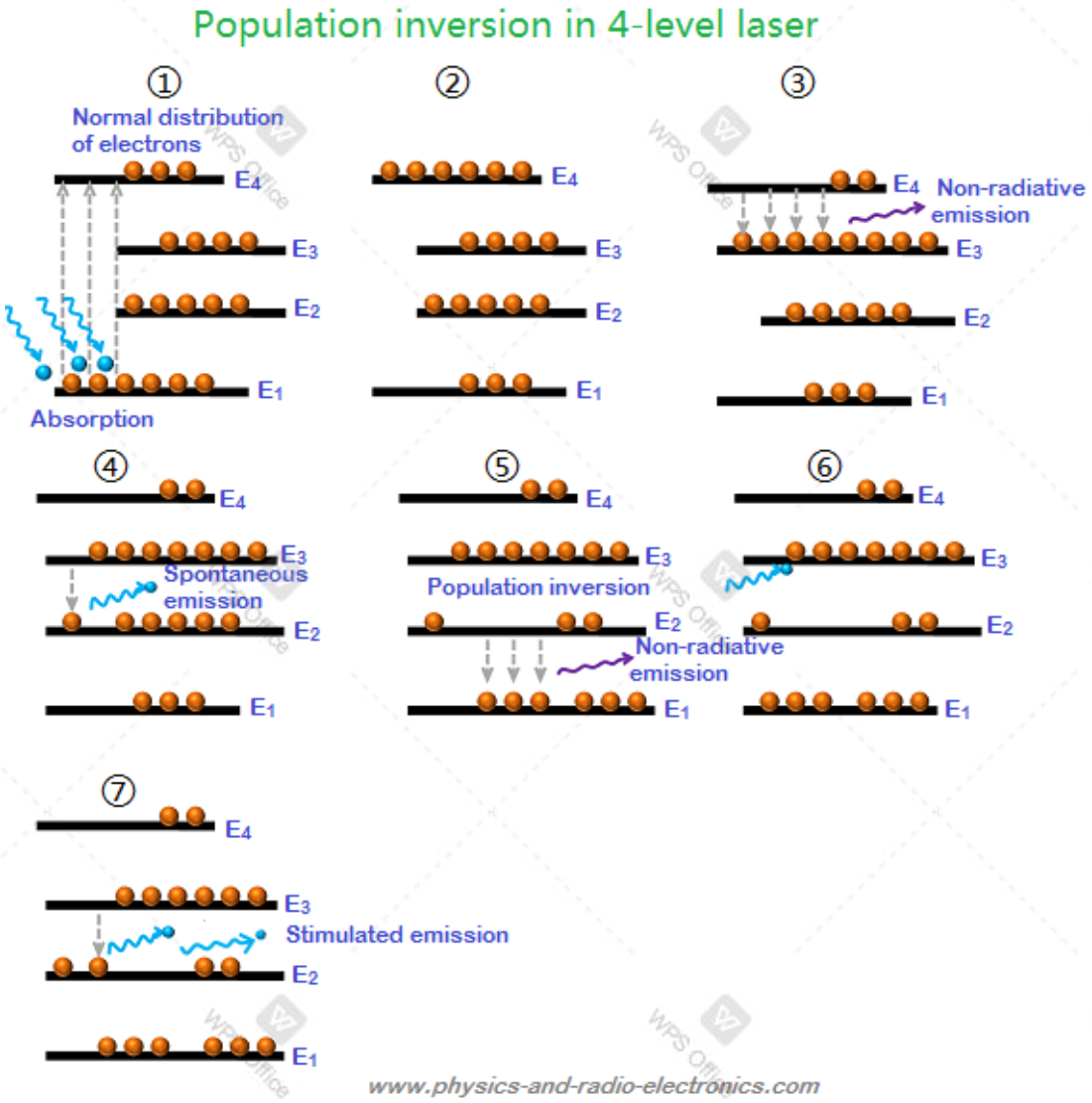
E_1 is the lowest energy state, E_2 is the next higher energy, E_3 is the next higher energy state after E_2, E_4 is the next higher energy state after E_3.

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.

We assume that $E_1 < E_2 < E_3 < E_4$. 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.

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.

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.

In 3-level and 4-level lasers, the frequency or energy of the pumping photons must be greater than the emitted photons.

PREV NEXT

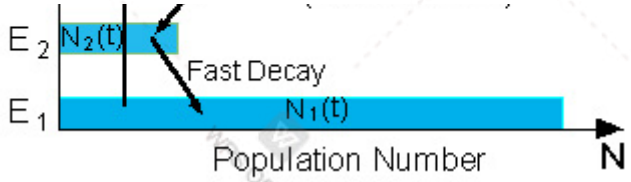


Figure 2.7: Energy level diagram in a four level laser

The pumping operation of a four level laser is similar to the pumping of a three level laser. This is done by a rapid population of the upper laser level (E_3), through the higher energy level (E_4).

The **advantage of the four level laser** is the **low population of the lower laser energy level (E_2)**. To create population inversion, there is no need to pump more than 50% of the atoms to the upper laser level.
The population of the lower laser level ($N_2(t)$) is decaying rapidly to the ground state, so practically it is empty. Thus, a continuous operation of the four level laser is possible even if 99% of the atoms remain in the ground state (!)