Ministry of Higher Education and Scientific Research
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Laser Physics

Boltzmann distribution

First stage

Lecture3

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Energy States (Levels):

Every atom or molecule in nature has a specific structure for its energy levels. The lowest energy level is called the ground state, which is the naturally preferred energy state. As long as no energy is added to the atom, the electron will remain in the ground state. When the atom receives energy (electrical energy, optical energy, or any form of energy), this energy is transferred to the electron, and raises it to a higher energy level (in our model further away from the nucleus).The atom is then considered to be in an excited state. The electron can "**jump**" from one energy level to another, while receiving or emitting specific amounts of energy. These specific amounts of energy are equal to the difference between energy levels within the atom.

Energy transfer to and from the atom :

Energy transfer to and from the atom can be performed in **two different ways**:

1. Collisions with other atoms, and the transfer of kinetic energy as a result of the collision. This kinetic energy is transferred into internal energy of the atom.

2. Absorption and emission of electromagnetic radiation.

Since we are now interested in the lasing process, we shall concentrate on the second mechanism of energy transfer to and from the atom (The first excitation mechanism is used in certain lasers, like Helium- Neon, as a way to put energy into the laser.

Population Inversion

Laser theory is dealing with a system that contains a large number of active atoms or molecules that **interact** with electromagnetic radiation.
Normally, the system (substance or **active medium**) absorbs **electromagnetic radiation incident on it**. While in the process of obtaining the laser beam must make the medium as an amplifier to electromagnetic radiation incident on it. This can be done by obtaining the state of population inversion (reverse distribution) by disrupting the natural state of the distribution of atoms or molecule **resulting from the state of thermal equilibrium.** By population inversion we mean getting the **highest number of excited atoms at a high energy level**.

Boltzmann Distribution :

If we suppose an isolated system consisting of a number of N atoms or molecules are distributed over a number of energy levels at a certain temperature. We assume that **N1** of these atoms or molecules occupy the **first energy level** with amount of energy **E1**, and the number of **N2** in the energy level **E2**. The **Boltzmann equation** gives us the relative distribution (**N2 / N1**) of all atoms or molecules of two energy levels E2 compared with E1:

N2/N1 = exp (-(E2-E1)/kT--------------------(1)

k = **Boltzmann constant=** **1.38×10^{-23} Joule / K**.

T= **temperature** in **Kelvin** degrees. (**0 K**)) absolute temperature

Boltzmann's distribution in the perspective of physics and mathematics is a function of the probability of the distribution of a system of particle atoms or molecules) at energy levels, that is, it gives the probability of a certain number of atoms or molecules at any level energy ($i = 1,2,3$) .

Boltzmann equation shows the dependence of the number of atoms or molecules (**N_i**) on the energy level (**E_i**) at the temperature T, and from this equation we see that:

1. **The higher the temperature**, the greater the distribution of atoms or molecules.

2. **The higher the level of energy**, the lower the distribution number. The relationship between the relative distribution number (**N2 / N1**) does not depend on the values of E1 and E2 energy levels, but only on the difference between them.

E2 - E1 The figure below shows the distribution of atoms or molecules at each energy level in the case thermal equilibrium condition. **Figure (1**) shows an illustrative diagram of the energy state of natural distribution of the atoms or molecules of a given material in a range of different energy levels in the case of a thermal equilibrium

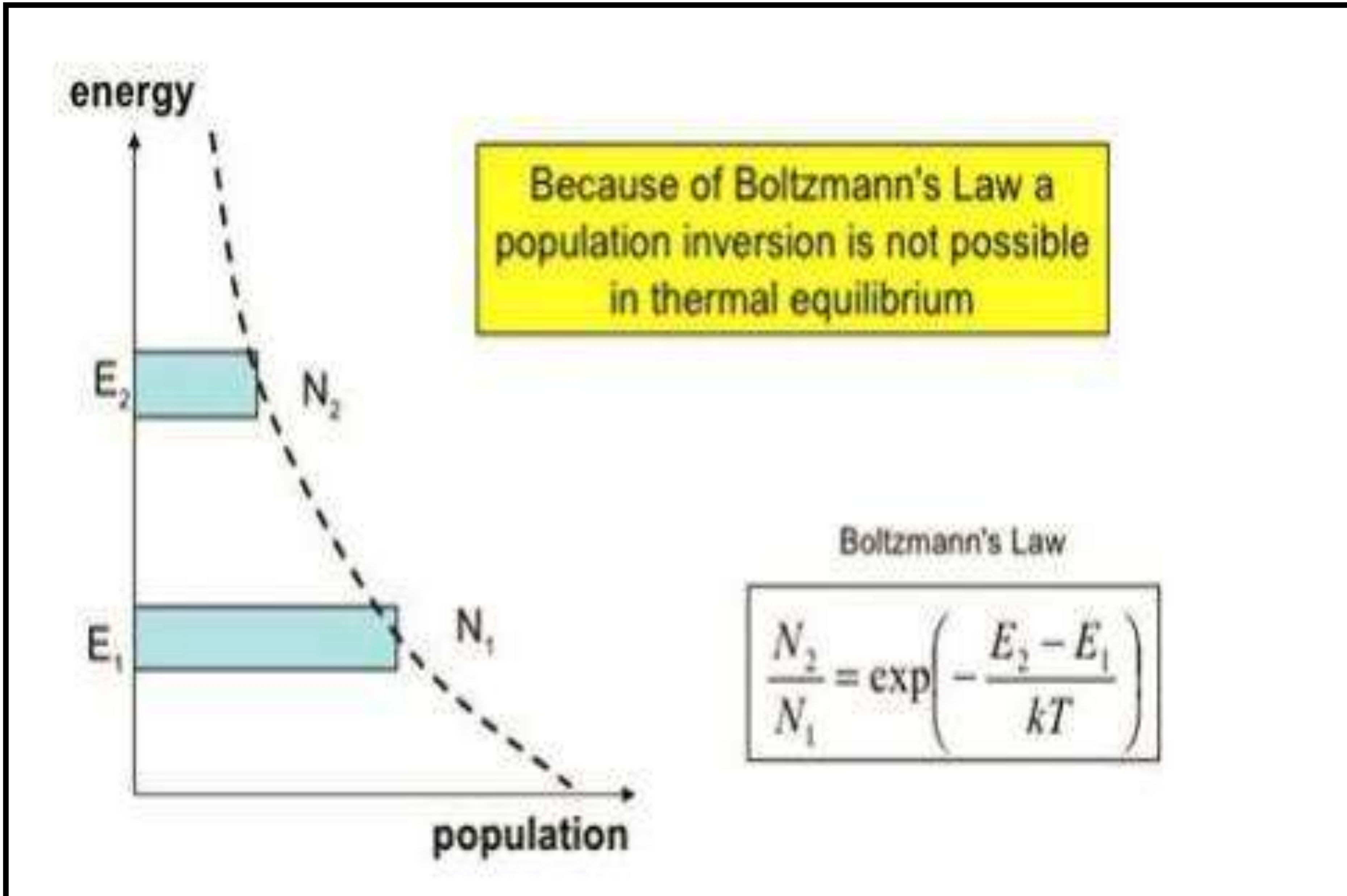


Figure : Normal population distribution.

Example:

Calculate the ratio of the population numbers (N1, N2) for the two energy levels E2 and E1 when the material is at room temperature (300°K), and the difference between the energy levels is 0.5 [eV]. What is the wavelength (λ) of a photon which will be emitted in the transition from E2 to E1? where $k_B = 1.38x10^{-23}$ J/K

Solution:

When substituting the numbers in the equation, we get:

$$\frac{N_2}{N_1} = \exp\left(-\frac{E_2 - E_1}{k_B \cdot T}\right) = \exp\left[-\frac{(0.5 \cdot eV) \cdot \left(1.6 \cdot 10^{-19} \cdot \frac{J}{eV}\right)}{\left(1.38 \cdot 10^{-23} \cdot \frac{J}{K}\right) \cdot (300K)}\right] = 4 * 10^{-9}$$

This means that at room temperature, for every 1,000,000,000 atoms at the ground level (E1), there are 4 atoms in the excited state (E2) !!!

To calculate the **wavelength:**

$$\lambda = \frac{h \cdot c}{\Delta E} = \frac{(6.626 \cdot 10^{-34} \cdot J \cdot sec) \cdot \left(3.10^{8} \cdot \frac{m}{sec}\right)}{(0.5 \cdot eV) \cdot \left(1.6 \cdot 10^{-19} \cdot \frac{J}{eV}\right)} = 2.48 \cdot \mu m$$

This wavelength is in the Near Infra-Red (NIR) spectrum.

Pumping sources

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 **types** of pumping:

1 . Optical pumping :

When light source provides enough energy to the lower energy state E1 electrons in the laser medium, they **jump** into the higher energy state E3.

The processes of **3-level gain medium** start and the population inversion can be achieved.

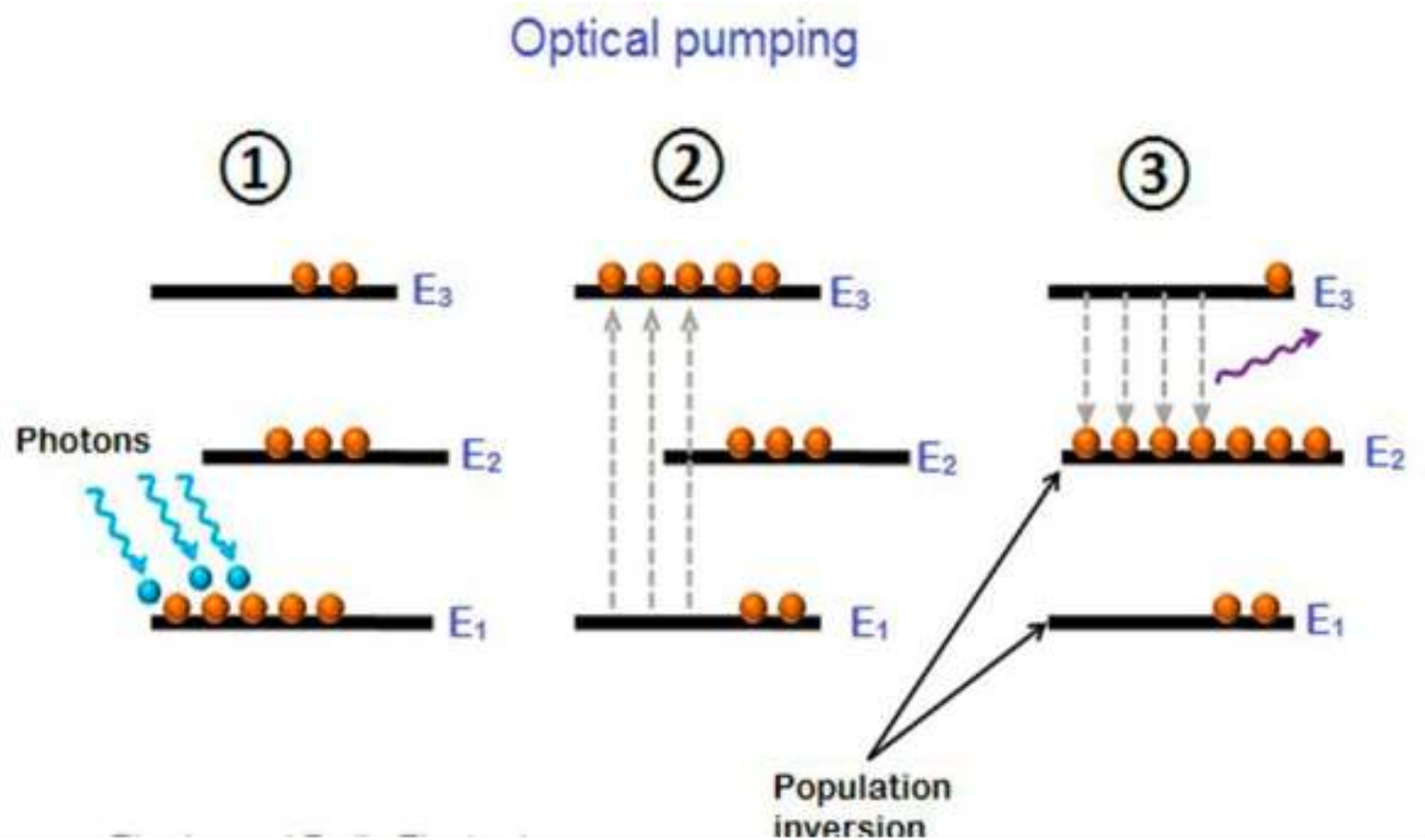


Figure: The optical pumping.

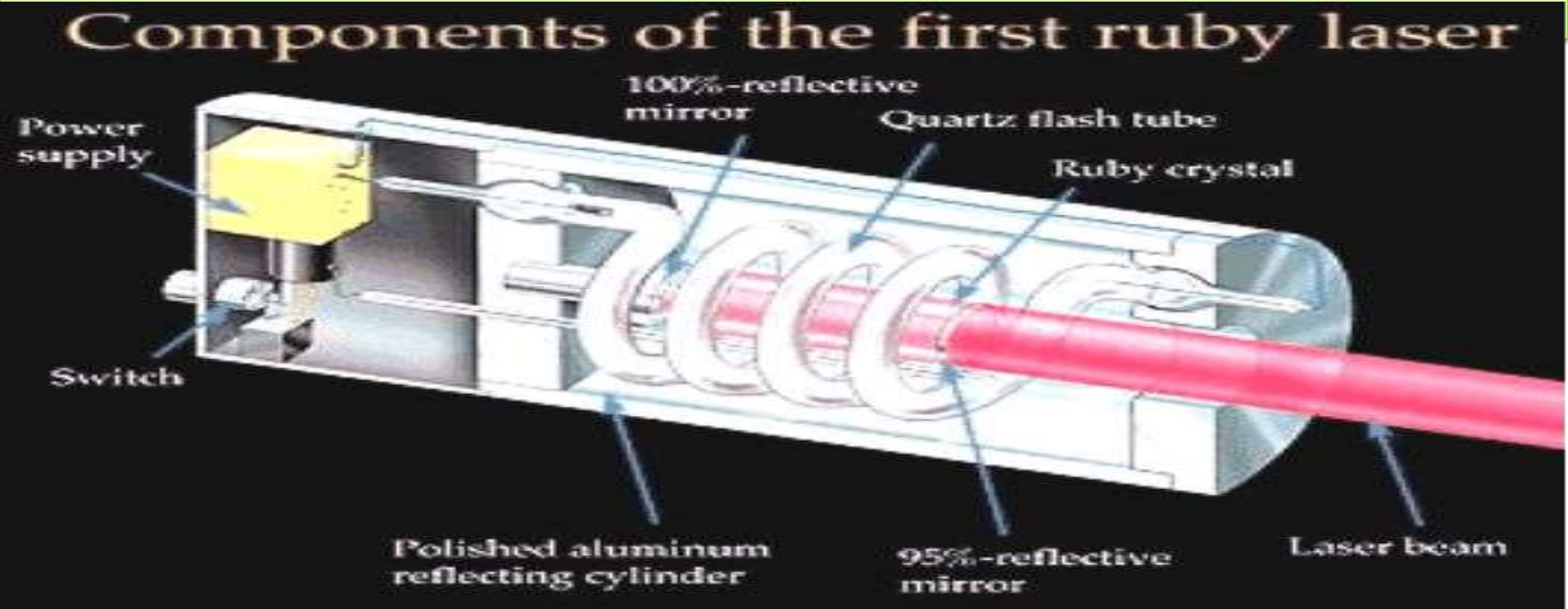
Optical pumping can be implemented by :

a) Using Special lamps:

1. Pulsed laser – Xe-lamps or Kr-lamps (pressure value of 450 up to 1500 Torr).

2. C.W laser - Kr-lamps (pressure value of 4000 -8000 Torr). Or Tungsten .

b) Another laser for pumping – as in Dye lasers, where Ar+

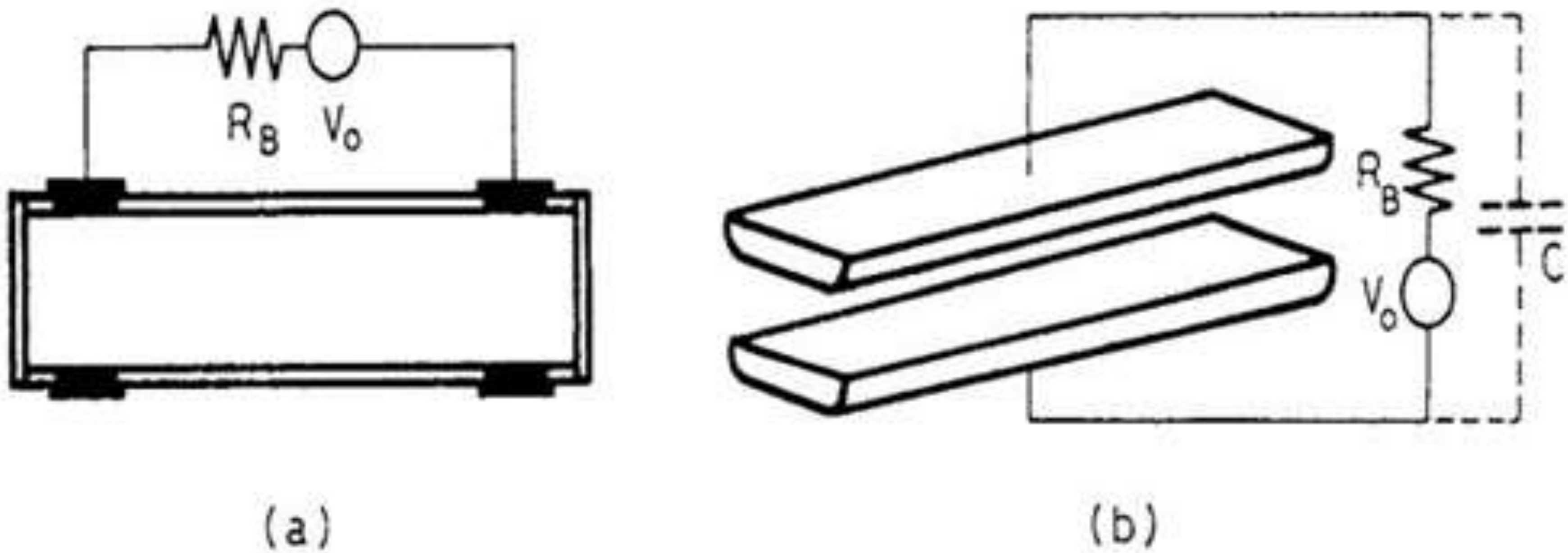


2. Electrical pumping :

In this method, 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 which can achieve the population inversion conditions. This method of pumping is used in gas lasers such as ***argon lasers***.

Used in : Gas laser – electrical discharge.

Excitation in the **laser gas**: For gas laser in order to excite the gas, **high voltage** is **needed** in order to get a **discharge** in the **gas medium**, so generating **ions and/or fast electrons gaining** extra energy from the electric field while colliding with gas atoms causing excitation.



Most frequently used pumping configurations for gas-discharge lasers: (a) Longitudinal discharge. (b) Transverse discharge.

3. Chemical pumping :

If an atom or a molecule is produced through some chemical reaction and remains in an excited state at the time of production, then it can be used for pumping. Does not need external source of energy, where the
output of the chemical reaction represents the active medium and the reaction-generated energy can be used to excite the active medium and getting the population inversion.

Ex: Hydrogen fluoride laser

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4. Thermal pumping :

Sometimes we can achieve population inversion by ***heating*** the laser medium. In **thermal pumping**, heat acts as the **pump source or energy source**. In this method, population inversion is achieved by supplying heat into the laser medium. When heat energy is supplied to the laser
medium, the **lower energy state electrons gain** sufficient energy and
jumps into the **higher energy level**