2. Laser Pumping Methods/ Methods of Achieving Population Inversion

□ Optical pumping □ Electric discharge or excitation by electrons □ Thermal pumping □ Chemical reactions

Population inversion

Under normal conditions, more electrons are in a lower energy state than in a higher energy state. Population inversion is a process of achieving more electrons in the higher energy state than the lower energy state.

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.

Usually, in an equilibrium system, the number of electrons (N_1) present in the ground state (E_1) is larger than the number of electrons (N_2) present in the higher energy state. The process of making $N_2 > N_1$ is called population inversion. The distribution of the atoms between the levels is given by Boltzmann's Law:

$$\frac{N_2}{N_1} = exp\left[\frac{-(E_2 - E_1)}{KT}\right] \dots \dots .(6)$$

Where K is Boltzmann's constant equal to 1.38064852 × 10-23 m^2 kg s^{-2} K^{-1}, This equation means that at thermal equilibrium, $N_1 > N_2$. To achieve laser operation, one must upset the thermal equilibrium $N_2 > N_1$ in some way so as to produce the nonequilibrium situation of a population inversion.

With three energy levels the energy population ($E_1<E_2<E_3$) and a number of electrons N_1, N_2, and N_3 .respectively (see Fig.7a) initially, the system is at thermal equilibrium, and the majority of electrons stay in the ground state. Then external energy is provided to excite them to level 3, referred to as pumping.

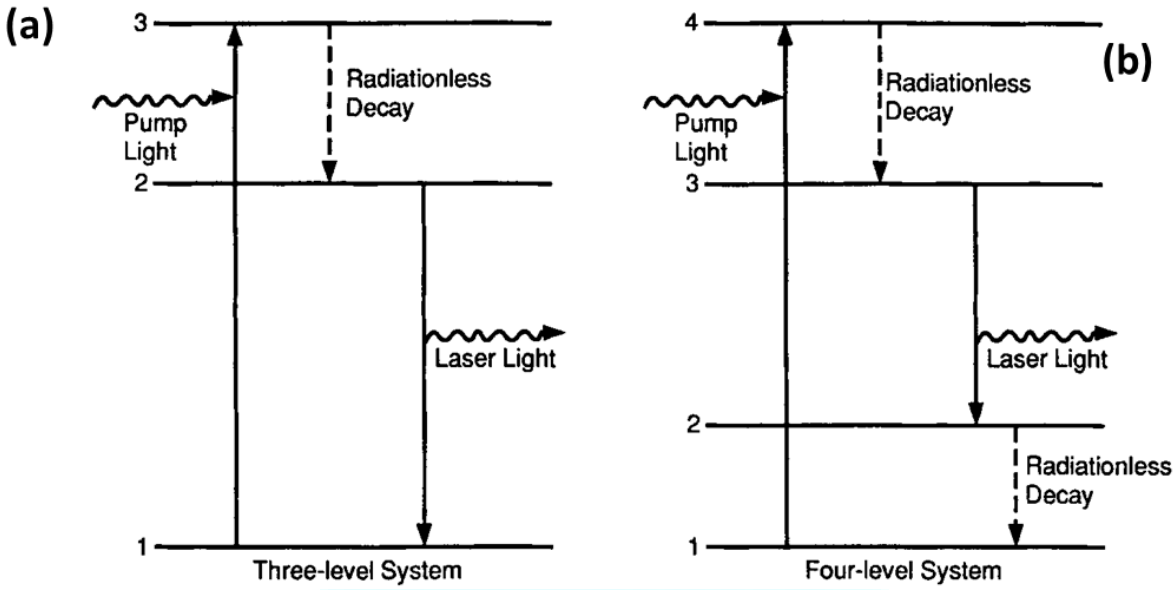

Fig.7: Electron Transitions within (a) 3-level gain medium; and (b) 4-level gain medium

The excited atoms quickly decay to level 2, transferring the energy to the phonons of the lattice of the host material. This wouldn't generate a photon, meaning radiationless. Then electrons on level 2 will decay by spontaneous emission to level 1, meaning laser. When level 2 hosts over half of the total electrons, a population inversion be achieved.

For four-level laser system see Fig.3b. The population of level 2 and 4 are 0 and electrons just accumulate in level 3. Laser transition takes place between level 3 and 2, so the population is easily inverted.

Optical pumping

When light source provides enough energy to the lower energy state E_1 electrons in the laser medium, they jump into the higher energy state E_3. The processes of 3level gain medium start and the population inversion can be achieved. As explained above.

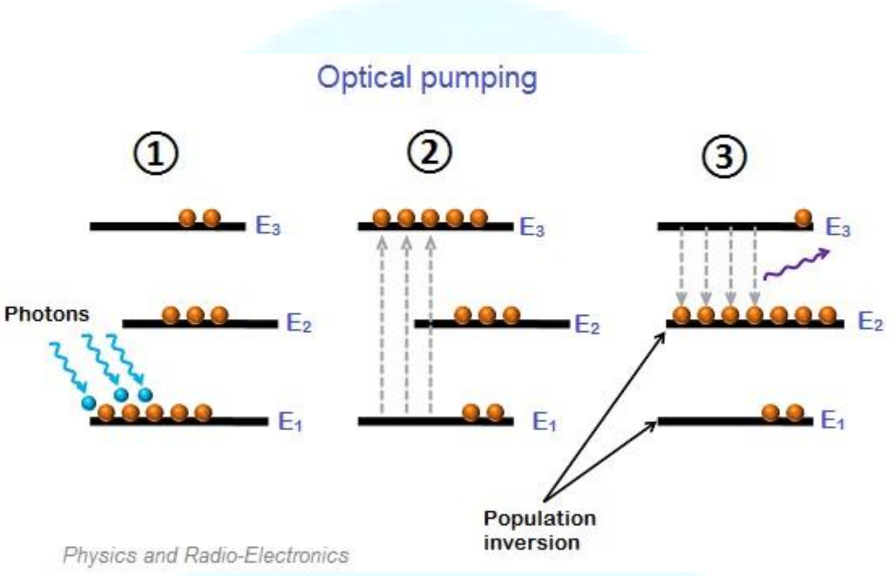

Fig. 8 Optical pumping process

An example of optical pumping is flashlamp configurations for pumping lasers are shown in Figure 9. Figure 9a shows the flashlamp in the form of a helix wrapped around the laser rod. Figures 9b and 9c show the flash lamp inserted into an elliptically-shaped or circularly-shaped elongated laser cavity. In Figure 9b the flashlamp is located at one focus of the ellipse and the laser rod to be pumped at the other focus of the ellipse. Figure 9d shows two flash lamps used in a double elliptical cavity, one of the most favorable arrangements, with the laser rod in the center.

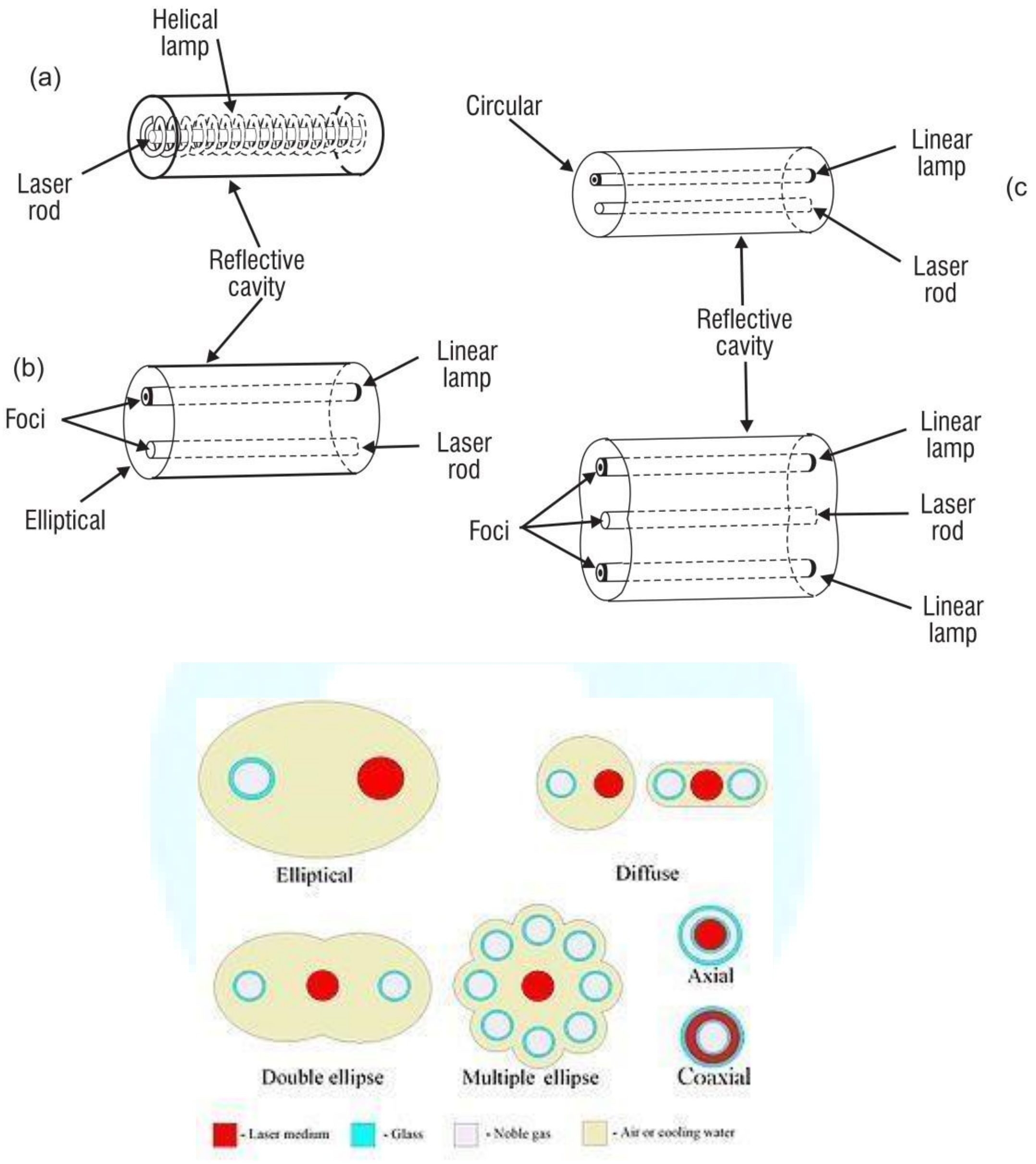

Figure 9: Flash lamp configurations for pumping lasers

To calculate the pumping efficiency, the pump process can be divided into four steps: (i) the emission of radiation by the lamp; (ii) the transfer of this radiation to the active medium; (iii) the absorption in the medium; (iv) the transfer of the absorbed radiation to the upper laser level. Consequently, the pumping efficiency can be written as the product of four terms, namely,

$$\eta_p = \frac{P_r}{P_p} \cdot \frac{P_t}{P_r} \cdot \frac{P_a}{P_t} \cdot \frac{P_m}{P_a} = \eta_r \cdot \eta_t \cdot \eta_a \cdot \eta_{pq}$$

P_m here is minimum pump power,

where (i) $\eta_r = P_r / P_p$ is the ratio between the radiated power of the lamp in the wavelength range to the actual electrical pump power entering the lamp, P_p, here η_r is referred to as the lamp radiative efficiency

(ii) $\eta_t = P_t / P_r$ is the ratio between the power actually transmitted to the medium by the pumping system and the radiated power, P_r. Here η_t is referred to as the transfer efficiency.

(iii) $\eta_a = P_a / P_t$ is the ratio between the power actually absorbed by the medium, P_a, and the power transmitted into it, P_t. Here η_a is referred to as the absorption efficiency.

(iv) $\eta_{pq} = P_m / P_a$ is the ratio between the minimum pump power need to start the process of lasing and the absorbed power P_a. Here η_{pq} is referred to as the power quantum efficiency.

Electric discharge or excitation by electrons

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.

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.

Chemical reactions

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. An example is hydrogen fluoride molecules:

$$F + H_2 \rightarrow HF^* + H$$

$$H + F_2 \rightarrow HF^* + F$$

$$HF^* \rightarrow HF + h\upsilon$$