



# LASER PRINCIPLES

## Chapter Two

### *Pumping Processes*

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## **CHAPTER TWO: PUMPING PROCESSES**

### **2-1) Pumping**

The amplification process involves transferring atoms of matter from lower energy levels to higher levels. It is a technique for transferring energy from the source to the active medium generating the laser. This method provides the energy needed to convert the material to an inverted distribution state, in addition to replacing the loss systems, especially the loss resulting from the laser output, to maintain the inverted distribution and thus keep the laser operation. The variety of energy sources used for pumping determines the pumping method for the laser system, based on the type of material used (active medium) to generate the laser.

The pumping method depends on the following:

- 1- Type of active medium (solid, liquid, gas).
- 2- Mode of operation (continuous or pulsed).
- 3- Nature of the pumping element (electrical, chemical, optical, thermal).
- 4- Absorption bandwidth (spectrum) of the pumping beam.

Pumping can be pulsed or continuous, depending on:

- High-power excitation source technology.
- The amount of energy appropriate for the active medium to initiate stimulated emission.

Pumping using a pulsed source results in a pulsed laser, while continuous-power pumping produces a continuous laser.

### **2-2) Pumping Types**

To achieve stimulated emission, the reverse distribution of two energy levels must be provided in the active medium to be excited. This is done according to a specific pumping plan from a lower level to a higher one. There are types or pumping techniques that differ according to the energy source needed to generate the reverse distribution of levels. The most important common pumping techniques are the following:

### **1- Optical Pumping:**

This type uses a high-power electromagnetic wave source (light source). This method is used in solid-state and liquid-state lasers. The main sources for this type of pumping can be classified as follows:

- High-power scintillation tubes: As in ruby lasers. High-intensity light from a lamp containing a specific gas (xenon, krypton, nitrogen) is directed at the material to be excited from a lower energy level to a higher energy level. The lamp is positioned around the active material. The type of gas used in the lamp depends on the energy levels.
- A laser source with a spectral width appropriate for the material being pumped: As in dye lasers, where an argon laser is used, meaning that the laser used in the pumping process has a wavelength different from the wavelength of the laser to be produced.
- Concentrated solar energy using a hemispherical mirror.

### **2- Electrical Discharge:**

This method is done using an external electrical voltage, where electrical energy is used in the electrical discharge process in most cases of gas lasers, and it is also used in semiconductor lasers. This type of pumping works by exciting the gas, as the gas is placed between two electrodes and a high electrical voltage is applied to it. When the electrons move from the first electrode to the second electrode, they collide with the atoms or molecules that make up the gas, which leads to exciting these atoms and raising them to higher orbits. An example of lasers that use this method is the carbon dioxide laser.

### **3- Chemical Pumping:**

The chemical reaction between the components of the active medium is the basis for providing energy to excite atoms in chemical laser operation. This method relies on one of two principles:

- Chemical reaction using the heat generated.
- Sporadic chemical explosions that produce a flash of light as they occur inside the tube.

When two chemicals are mixed and reacted, a new substance is formed in an excited state. Examples of this pumping include hydrogen fluoride lasers and deuterium fluoride lasers. Chemical pumping is highly efficient.

**4- Electronic Pumping:**

It occurs through the exchange of energy between high-energy electrons and electrons in a lower energy level in the active material, or through the exchange of energy between atoms in the ground state of the material and excited atoms in another intermediate material. This is accomplished through an electric discharge tube, where the electrons and excited atoms collide with each other. Examples include the helium-neon laser and the argon laser.

**5- Thermal Pumping:**

Both kinetic pressure of gases and temperature changes can excite materials to emit laser radiation, and sometimes radio frequency (RF) sources are used as internal power for the pumping process.

**2-3) Pumping Plans**

The goal of pumping is to achieve inverse distribution and stimulated emission. This goal cannot be achieved using an atomic system with only two energy levels. Using intense electromagnetic radiation of a frequency suitable for the pumping process quickly creates a saturation state. At that point, the qualification of the two relevant levels is equalized and the medium becomes transparent. Therefore, it is possible to work with a laser with three or four energy levels.

**1- Triple-Levels System:**

It consists of three energy levels: the ground level, which represents the lower laser level (LLL), the excited level, which represents the upper laser level (ULL), and the metastable or intermediate level. The energy levels between which the laser action occurs are: the ground level  $E_1$  and the  $E_2$  level. To obtain the laser, half the number of atoms must be pumped from the ground level to the upper level to obtain the inverted distribution. Therefore, we need a very high pumping energy. The metastable level is not chosen for the inverted distribution process because it cannot store a large number of excited atoms or molecules like the upper laser level, which is very wide.

The pumping mechanism in this system is summarized by the fact that pumping leads to raising the atoms from the ground level to the upper level, and the lifetime of the upper excited level is much less than the lifetime of the intermediate level ( $T_3 \ll T_2$ ).

Therefore, when the atoms reach the  $E_3$  level, they quickly fall to Level  $E_2$ ,  $E_2$  is fed from  $E_1$  via  $E_3$ , and the transition from  $E_2$  to  $E_1$  generates the desired laser radiation. An example of this type is the ruby laser.

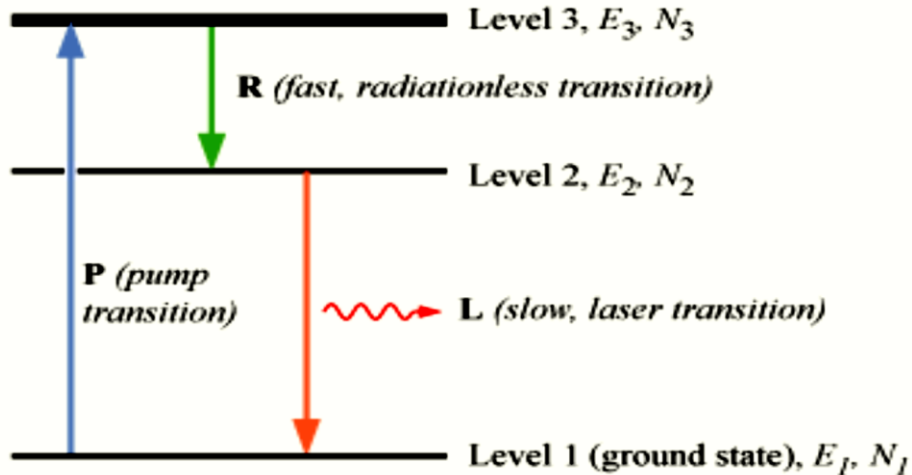


Figure (2-1): A schematic diagram showing a three-level laser system.

The output laser power of a three-level system can be calculated as follows:

$$P_L = hv(w_p \beta N_1 - A_{21} N_2) \dots\dots\dots (2-1)$$

where  $hv$  is the energy of the emitted photon (laser) ( $h$  is Planck's constant,  $v$  is the photon frequency),  $w_p$  is the pumping rate of atoms into the upper level,  $\beta$  is the level efficiency and  $A_{21}$  is the probability of spontaneous emission from the metastable level to the ground level.

**2- Four-Levels System:**

It consists of four energy levels: the ground level, the lower laser level, the excited level, and the upper laser level. The ground level is not the same as the lower laser level, so we do not need a very powerful pumping source to achieve the inverted distribution. Compared to a three-level laser system, there is an additional energy level above the ground level, and this additional level has a very short lifetime. The pumping process in the four-level system is similar to the pumping process in the three-level system.

This is achieved by obtaining the inverted distribution of the E<sub>3</sub> level through the E<sub>4</sub> energy level. Most of the materials used to generate the laser are four-level systems. The most important advantages of the four-level system are that the threshold limit is lower, the efficiency is higher, it requires less pumping energy, and it can operate in continuous mode.

The pumping mechanism in this system can be summarized as pumping leads to the lifting of atoms from the E<sub>1</sub> level to the E<sub>4</sub> level. The active medium is chosen so that the atoms drop to E<sub>3</sub> and also drop rapidly from E<sub>2</sub> to E<sub>1</sub>. This achieves an inverted distribution between the E<sub>3</sub> level as the upper level and the E<sub>2</sub> level as the lower level, where the transition between them generates the required laser radiation. An example of this type is the neodymium laser.

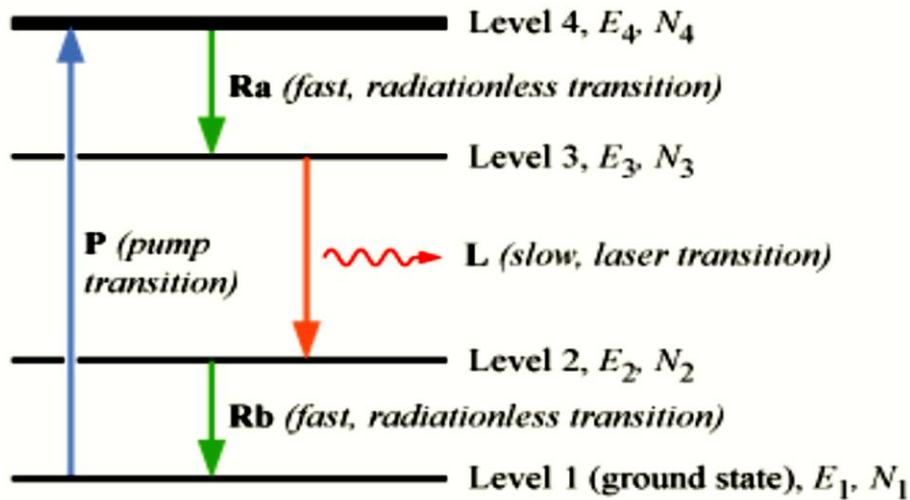


Figure (2-2): A schematic diagram showing a four-level laser system.

Although the three-level system can achieve inverse distribution, it is preferable to use a four-level pumping scheme. This is because implementing this distribution in a four-level system is easier, as the required pumping power in a four-level system is less than in a three-level system. The laser power output from a four-level system can be calculated as follows:

$$P_L = h\nu\Delta N_c w_L = h\nu\Delta N_c \left( \frac{P_2}{\Delta N_c} - w_{21} \right) \dots\dots\dots (2-2)$$

Where  $\Delta N_c$  represents the value of the inverse distribution,  $w_L$  represents the rate of descent of atoms from the upper laser level to the lower laser level, and  $P_2$  is the effective pumping power and is calculated as follows:

$$\dot{P}_2 = P_2 \left[ 1 - \left( \frac{w_2}{w_{10}} \right) \left( 1 + \frac{P_1}{P_2} \right) \right] \dots\dots\dots (2-3)$$

If the number of atoms  $N_2$  is greater than  $N_1$  by (1), this means that the inverse distribution has occurred between the levels  $E_3$  and  $E_2$ .

The three-level system and the four-level system can be compared as follows:

No.	Three-Levels System	Four-Levels System
1	It consists of three levels.	It consists of four levels.
2	It requires pumping half the number of atoms from the ground level to the excited level to achieve the inverted distribution.	It requires pumping a small number of atoms from the ground level to the excited level to achieve the inverted distribution.
3	The ground level is the same as the lower laser level.	The ground level is not the lower laser level.
4	Lasing action occurs between $E_2$ and $E_1$ .	Lasing action occurs between $E_3$ and $E_2$ .
5	It requires a high pumping power source.	It does not require a high-energy pumping source.
6	The lifetime of the $E_3$ level is very short.	The lifetime of the $E_4$ level is very short.
7	A rapid transition occurs between $E_3$ and $E_2$ .	A rapid transition occurs between $E_4$ and $E_3$ .
8	Less efficient than the four-level system.	Higher efficiency than the three-level system.
9	The output laser power can be calculated from the equation:  $P_L = h\nu(w_p\beta N_1 - A_{21}N_2)$	The output laser power can be calculated from the equation:  $P_L = h\nu\Delta N_c \left( \frac{\dot{P}_2}{\Delta N_c} - w_{21} \right)$