Al-Mustaqbal University

College of Engineering & Technology

Biomedical Engineering Department

Subject Name: Medical Lasers in Engineering

Third Class, Second Semester

Subject Code: [Insert Subject Code Here]

Academic Year: 2024-2025

Lecturer: Assist lect. Hiba Diaa Alrubaie

Email: hiba.diaa.abdulameer@uomus.edu.iq

Lecture No.:-2

Lecture Title: [Basic Elements of Laser]

THE THREE PROCESSES

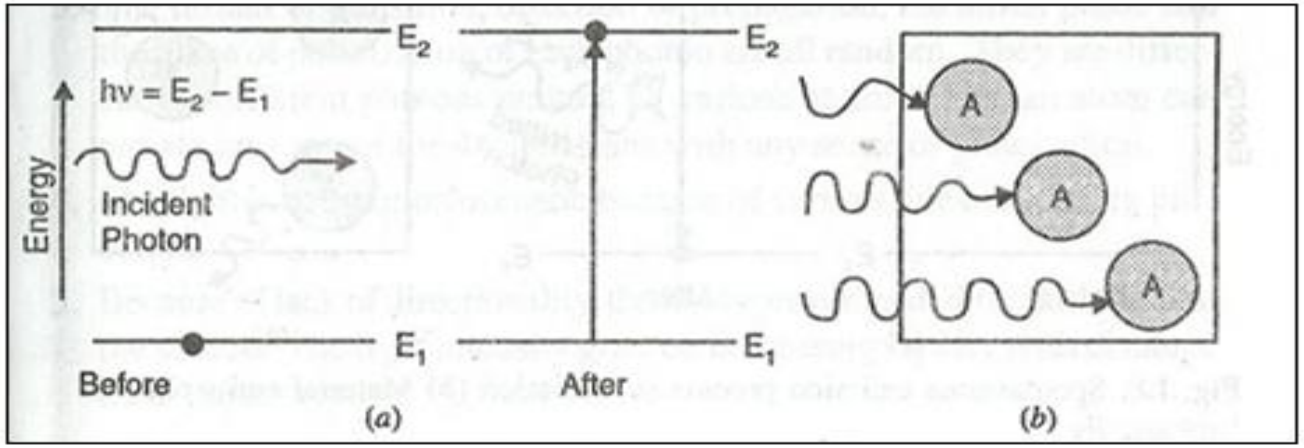
Let us consider a medium consisting of identical atoms capable of being excited from the energy level 1 to the energy level 2 by absorption of photons. Let the levels be denoted by El and E2 and their populations be Nl and N2 respectively. Let the atoms be in thermal equilibrium. In the equilibrium condition, the number of atomic transitions upward must be equal to the number or downward transitions. However, when the atoms are subjected to an external light of frequency v, the following three processes occur in the medium.

(1)Absorption

An atom residing in the lower energy level E1 may absorb the incident photon and jump to the excited state E2 as depicted in figure below. This transition is known as induced or stimulated absorption or simply as absorption. Corresponding to each absorption transition, one photon disappears from the incident light field and one atom adds to the population at the excited energy level E2. This process may be represented as:

$$A + h\nu \rightarrow A*$$

Where A denotes an atom in the lower state and A* an excited atom.

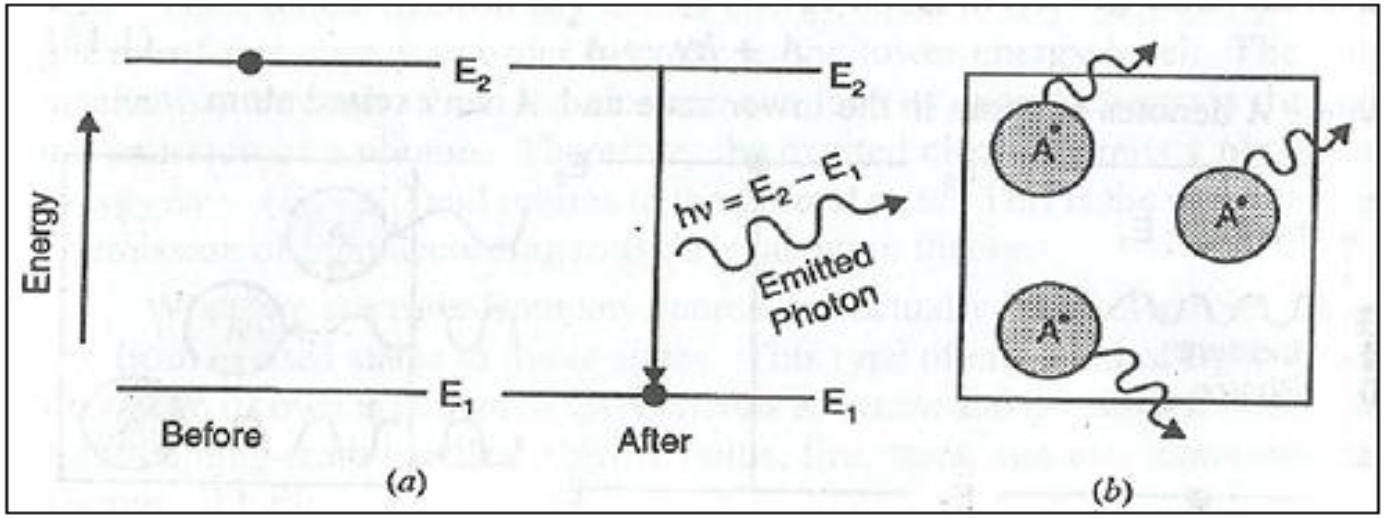


Absorption process (a) induced absorption (b) Material absorbs photons.

(2) Spontaneous Emission

An excited atom can stay at the excited level for an average lifetime τsp. If it is not stimulated by any other agent during its short lifetime, the excited atom undergoes a transition to the lower energy level on its own. During the transition, it gives up the excess energy in the form of a photon, as shown in figure below. This process in which an excited atom emits a photon all by itself and without any external impetus is known as spontaneous emission. The process is represented as:

$$A* \rightarrow A + h\nu$$



Spontaneous emission process (a) Emission (b) Material emits photons.

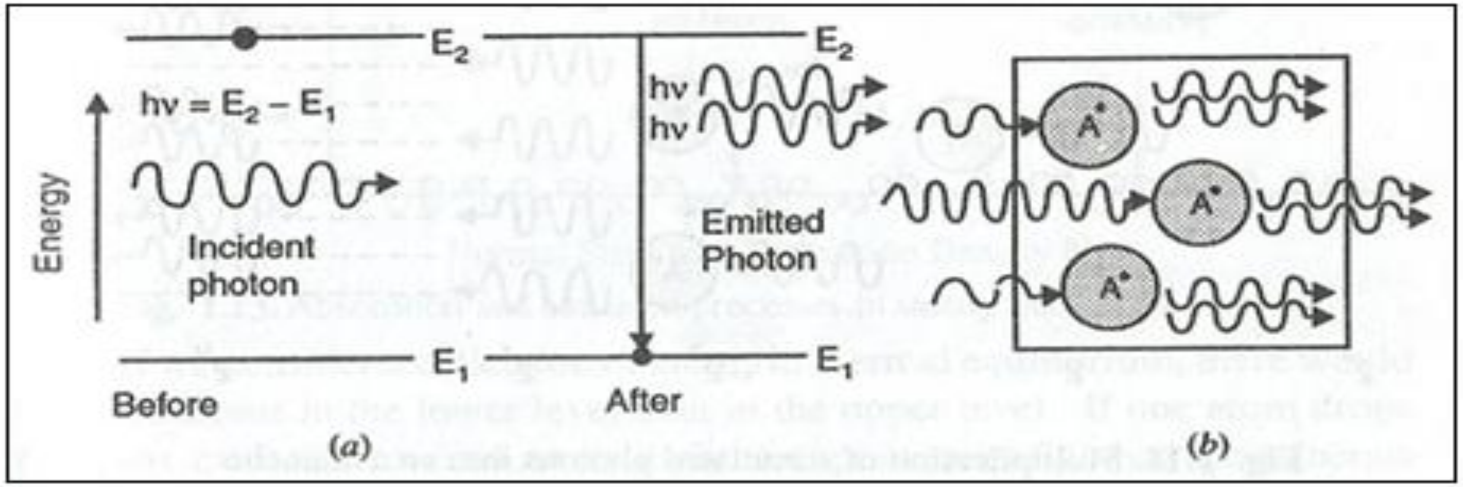
Important Features:

1. The process of spontaneous emission is not amenable for control from outside.
2. It is essentially probabilistic in nature.
3. The instant of transition, direction of propagation, the initial phase and the plane of polarization of each photon are all random. They are different for different photons emitted by various atoms.
4. The light is not monochromatic.
5. Because of lack of directionality, the light spreads in all directions around the source. The light intensity goes on decreasing rapidly with distance from the source.
6. The light is incoherent.

(3) Stimulated Emission

- An atom in the excited state need not "wait" for spontaneous emission to occur. If a photon with appropriate energy hν = (E2 - E1) interacts with the excited atom, it can trigger the atom to undergo transition to the lower level and to emit another photon, as shown in figure below. The process of emission of photons by an excited atom through a forced transition occurring under the influence of an external agent is called induced or stimulated emission. The process may be represented as:

$$A* + h\nu \rightarrow A + 2h\nu$$

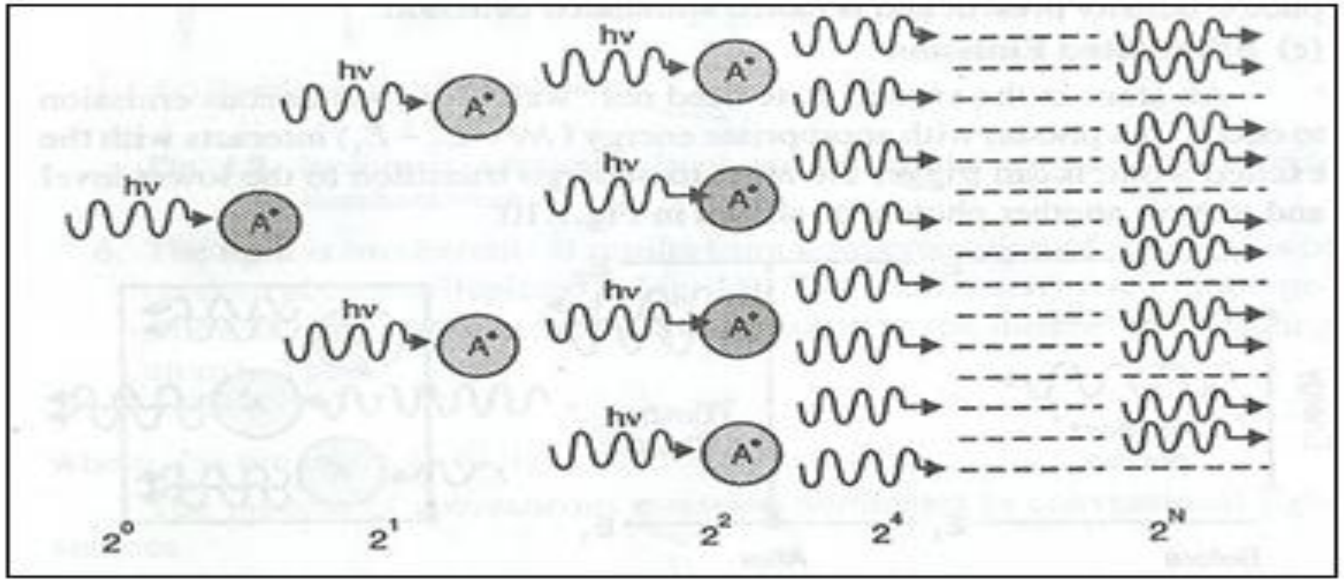


Stimulated emission process (a) Emission (b) Material emits photons in a coordinated manner.

Important Features:

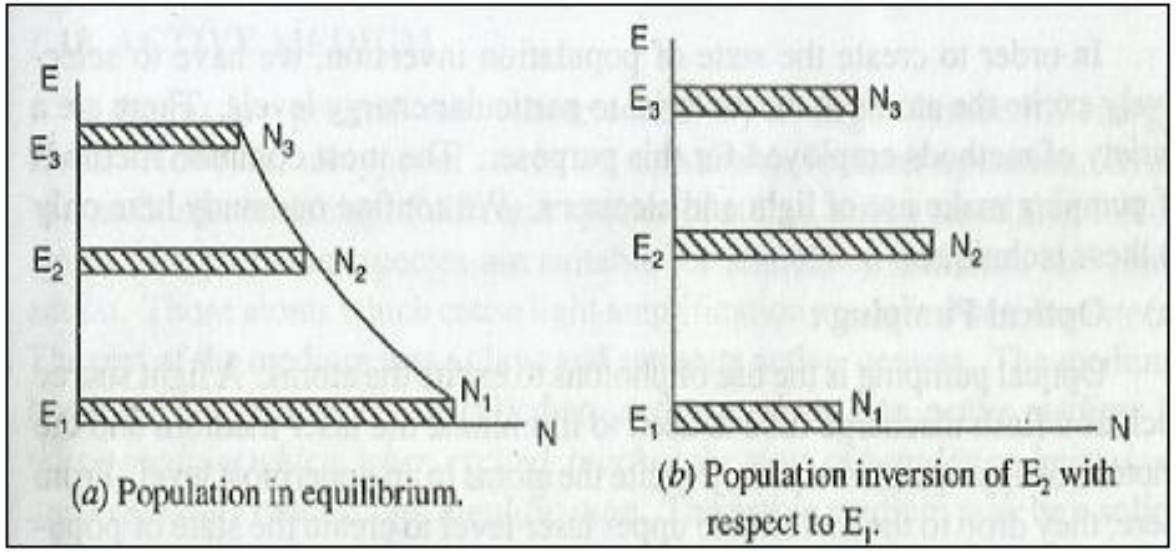
1. The process of stimulated emission is controllable from outside.
2. The photon emitted in this process propagates in the same direction as of the stimulating photon.
3. The emitted photon has exactly the same frequency, phase and plane of polarization as those of the incident photon.
4. The light produced in this process is directional, coherent and monochromatic.
5. High Intensity.

- **6. Light Amplification:** The outstanding feature of this process is the multiplication of photons. For one photon hitting an excited atom there are two photons emerging. The two photons are in phase and travel along the same direction. These two photons stimulate two excited atoms in their path and produce a total four photons which are in phase and travel along the same direction. These four photons can in turn stimulate four excited atoms and generate eight photons and so on. The number of photons builds up in an avalanche like manner, as illustrated in figure below.



POPULATION INVERSION

When an atomic system is in thermal equilibrium, photon absorption and emission processes take place side by side, but because N1 > N2, absorption dominates. However, laser operation requires obtaining stimulated emission exclusively. To achieve a high percentage of stimulated emission, a majority of atoms should be at the higher energy level than at the lower level. The non equilibrium state in which the population N2 of upper energy level exceeds to a large extent the population N1 of the lower energy level is known as the state of population inversion.



(a) Population in equilibrium.
(b) Population inversion of E_2 with respect to E_1.

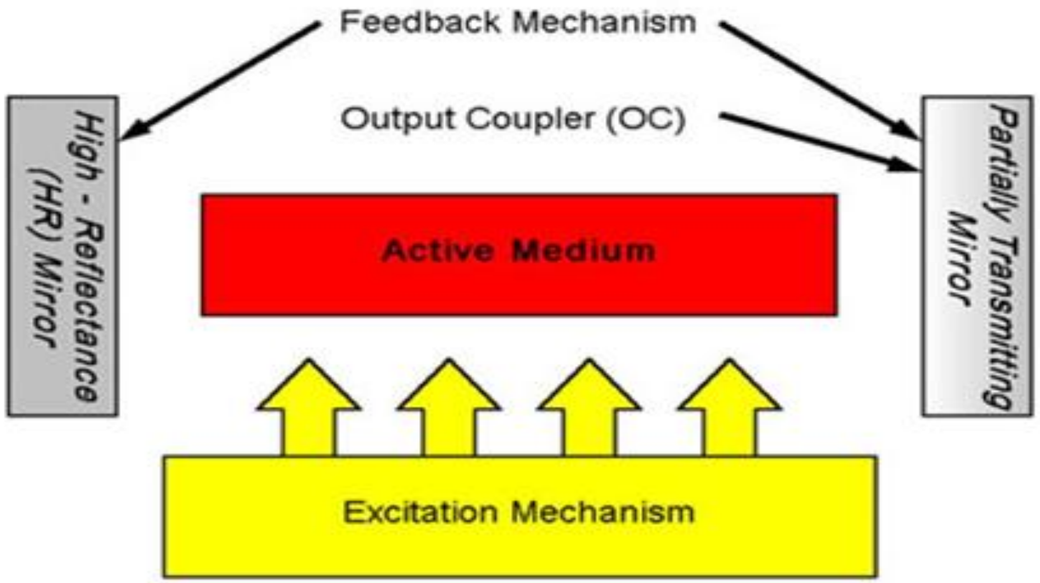
Why does this make stimulated emission difficult?

Because the best way to stimulate emission from an excited atom is with spontaneous emission from an identical excited atom. That would seem easy if you had a lot of atoms in the excited state, but in equilibrium more atoms would be in the low-energy state than in the excited state. A population inversion exists whenever more atoms are in an excited atomic state than in some lower energy state. The lower state may be the ground state, but in most cases, it is an excited state of lower energy. Lasers can produce coherent light by stimulated emission only if a population inversion is present. And a population inversion can be achieved only through external excitation of the atomic population.

Basic Elements of Laser

Three functional elements are necessary in lasers to produce coherent light by stimulated emission of radiation as shown in Figure.

1. Active medium or laser (gain) medium
2. An energy source (referred to as the pump or pump source)
3. An optical resonator consisting of a mirror or system of mirrors



Elements of Laser

1. Active Medium

The active medium is a collection of atoms or molecules that can be excited to a state of inverted population; that is, where more atoms or molecules are in an excited state than in some lower energy state.

How a laser works?

The two states chosen for the lasing transition must possess certain characteristics. First, atoms must remain in the upper lasing level for a relatively long time to provide more emitted photons by stimulated emission than by spontaneous emission.

Second, there must be an effective method of "pumping" atoms from the highly-populated ground state into the upper lasing state in order to increase the population of the higher energy level over the population in the lower energy level. An increase in population of the lower energy level to a number above that in the high energy level will decline the population inversion and thereby prevent the amplifications of emitted light by stimulated. The gain medium may be solid crystals such as ruby or Nd:YAG, liquid dyes, gases like CO2 or Helium/Neon, or semiconductors such as GaAs.

2. Pumping Mechanism The pump source is the part that provides energy to the laser system. Examples of pump sources include electrical discharges, flash lamps, arc lamps, light from another laser, chemical reactions and even explosive devices. The type of pump source used principally depends on the gain medium.

3. Optical Resonator The optical resonator or optical cavity, in its simplest form is two parallel mirrors placed around the gain medium which provide feedback of the light. Light from the medium produced by the spontaneous emission is reflected by the mirrors back into the medium where it may be amplified by stimulated emission. One of the mirrors reflects essentially 100% of the laser light while the other reflects partially of the laser light and transmits the remainder.

The Einstein Relations The three processes of stimulated absorption, stimulated emission and spontaneous emission are related mathematically through the requirement that; for a system of atoms in thermal equilibrium with its own radiation the rate of upward transitions (from E1 to E2) must equal the rate of downward transitions (from E2 to E1).

If there are N_1 atoms in the assembly with energy E_1, then the upward transition rate is proportional to both N_1 and to the number of photons present with the appropriate frequency v.

The energy density ρ_v of such photon is simply;

$$\rho_v = N\,hv \qquad (1)$$

where N is the number of photons per unit volume.

The upward transition rate can then be written as:

$$\text{Stimulated absorption rate} = N_1\,\rho_v\,B_{12} \qquad (2)$$

Where B_{12} is a constant for a given pair of energy levels (the "12 " indicates the energy levels involved).

Similarly, if there are N_2 atoms per volume in the assembly with energy E_2, then:

$$\text{Stimulated emission rate} = N_2\,\rho_v\,B_{21} \qquad (3)$$

Where again B_{21} is a constant for the pair of energy levels involved.

The spontaneous transition rate depends on the average lifetime, τ_{21}, of the atoms in the excited state.

The probability that a particular atom will undergo a spontaneous transition in a time dt is; dt / τ_{21} which equals A_{21}.Where, A_{21} is a constant.

Thus as there are N_2 atoms in the upper level, then

$$\text{Spontaneous emission rate} = N_2 A_{21} \tag{4}$$

The constants A_{21}, B_{12} and B_{21} are called the **Einstein coefficients.**

The relationships between them can be established by considering the condition for the assembly of atoms to be in *thermal equilibrium*.

$$N_1 \rho_v B_{12} = N_2 \rho_v B_{21} + N_2 A_{21} \tag{5}$$

From this equation:

$$\rho_v = \frac{A_{21}/B_{21}}{(B_{12}N_1/B_{21}N_2) - 1} \tag{6}$$

The number N_j of atoms in the *jth* level (or populations) of the various energy levels E_j of a system in *thermal equilibrium* is given by *Boltzmann statistics* to be;

$$N_j = N_0 \frac{\exp(-E_j/kT)}{\sum_i \exp(-E_i/kT)} \quad (7)$$

Where; N_0 is the total number of atoms and E_j is the energy of the *jth* level. $\sum_i \exp(-E_i/kT)$ is the summation for all energy levels. k is Boltzmann constant (1.380649×10^{-23} m^2 kg s^{-2} K^{-1}) and T is the temperature of the system.

From (7), the ratio of the population N_1 and N_2 in the levels E_1 and E_2 is:

$$\frac{N_1}{N_2} = \exp((E_2 - E_1)/kT)) \quad (8)$$

N_2 can approach, but never exceed N_1 if thermal equilibrium is maintained.

Substituting (8) in (6):

$$\rho_v = \frac{A_{21}/B_{21}}{\frac{B_{12}}{B_{21}} \exp(hv/kT) - 1} \quad (9)$$

$$\rho_v = \frac{8\pi h v^3}{C^3 \left(\exp(hv/kT) - 1\right)} \quad (10)$$

comparing (9) and (10) for ρ_v ;

$$\boldsymbol{B_{12} = B_{21}} \quad (11)$$

and,

$$A_{21} = B_{21} \frac{8\pi h v^3}{C^3} \quad (12)$$

These equations are known as the ***Einstein relation***.

Equation (11) enables to evaluate the ratio of the rates of spontaneous and stimulated emission for a given pair of energy levels in thermal equilibrium with the radiation.

The ratio R is;

$$R = \frac{N_2 A_{21}}{N_2 B_{21} \rho_v} = \frac{8\pi h v^3}{\rho_v C^3} \qquad (13)$$

Substituting for ρ_v from (8), gives:

$$R = \exp\left(\frac{hv}{kT}\right) - 1 \qquad (14)$$

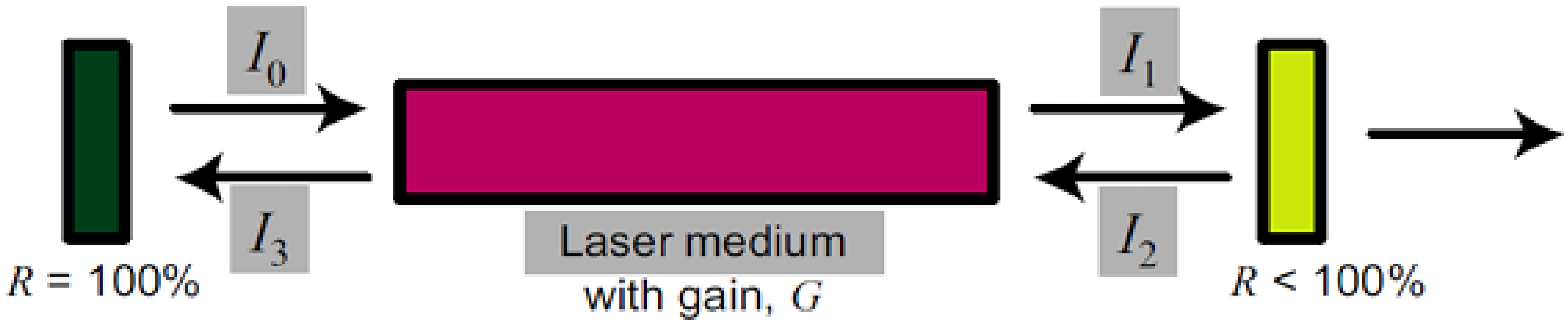
- The above calculation confirms that under conditions of thermal equilibrium stimulated emission is most unlikely. Hence, laser action is possible only when depart from thermal equilibrium. To amplify a beam of light by stimulated emission, the rate of this process must be increased relative to the other two. Consideration of the expression for stimulated emission given above indicates that to achieve this for a given pair of energy levels both the population density of the upper level and the radiation density should be increased because of the Einstein relation (B12 = B21), then (N2 > N1) must be ensured even though (E2 > E1), which means creating a population inversion.

- **Threshold Condition**

A laser action will be achieved if the beam increases in intensity during a round trip: that is, if I3 >I0.Usually, additional losses in intensity occur, such as absorption, scattering, and reflections. In general, the laser will lase if, in a round trip

Gain>Loss

This is called achieving Threshold



Excitation Mechanisms

1. **Two level system**

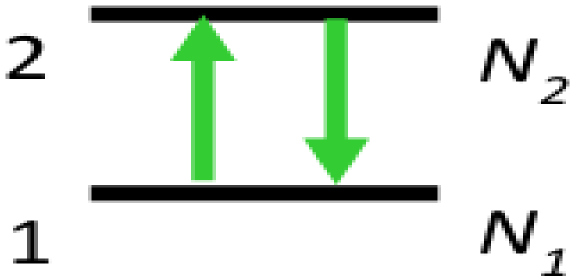
Lasing activity cannot be made to occur with just two energy levels because a population inversion cannot be achieved in a two-level scheme of operation. In a state of thermal equilibrium, the population of the upper of the two levels is less than that of the lower one by virtue of the Boltzmann distribution. Away from equilibrium, the population of the upper level can at most be equal to that of the lower level when the transitions from the upper to the lower level occur at an equal rate, and no further net transfer of the population can occur (saturation). By Writing the rate equations for the densities of the two states.

$$\frac{dN_2}{dt} = BI(N_1 - N_2) - AN_2$$

Absorption

Stimulated emission

Spontaneous emission



$$\frac{dN_1}{dt} = BI(N_2 - N_1) + AN_2$$

$$\frac{d\Delta N}{dt} = -2BI\Delta N + 2AN_2$$

$$\frac{d\Delta N}{dt} = -2BI\Delta N + AN - A\Delta N$$

The total number of atoms N is:

$$N \equiv N_1 + N_2$$

$$\Delta N \equiv N_1 - N_2$$

$$
\begin{aligned}
2N_2 &= (N_1 + N_2) - (N_1 - N_2) \\
&= N - \Delta N
\end{aligned}
$$

$$\frac{d\Delta N}{dt} = -2BI\Delta N + AN - A\Delta N$$

In steady state: $0 = -2BI\Delta N + AN - A\Delta N$

$$\Rightarrow (A + 2BI)\Delta N = AN$$

$$\Rightarrow \Delta N = AN/(A + 2BI)$$

$$\Rightarrow \Delta N = N/(1 + 2BI/A)$$

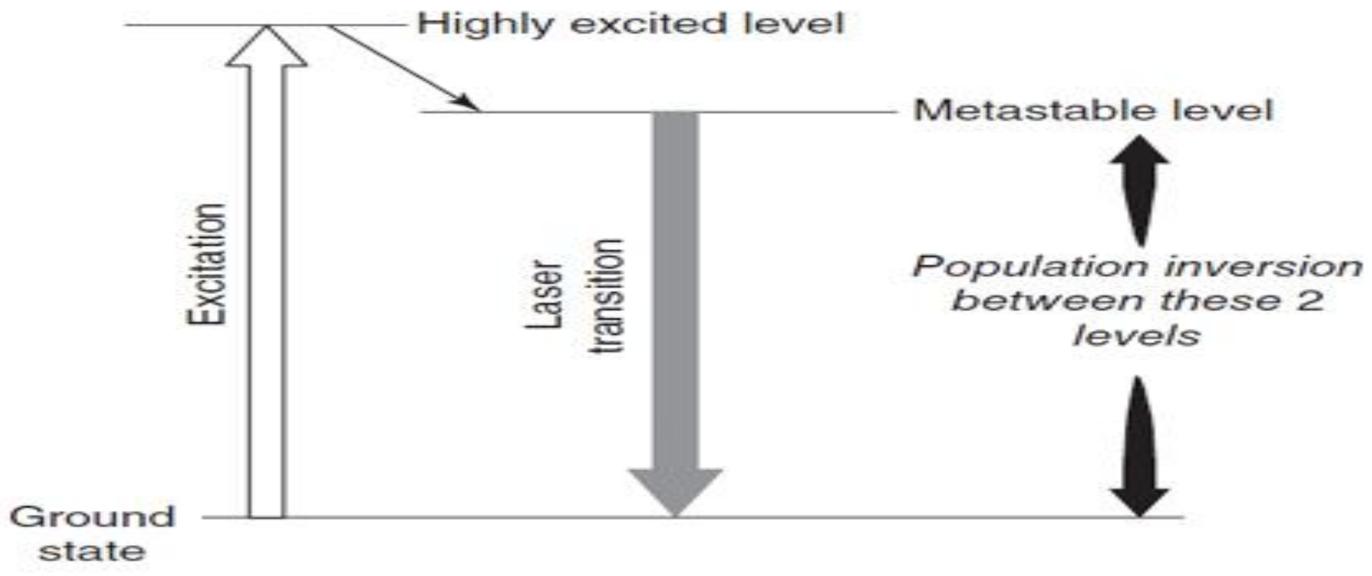
Let the saturation intensity $I_{sat} = \frac{A}{2B}$

$$\Delta N = \frac{N}{1 + I/I_{sat}}$$

ΔN is always positive, no matter how high I is. It is impossible to achieve an inversion in a two-level system.

2. Three Level System

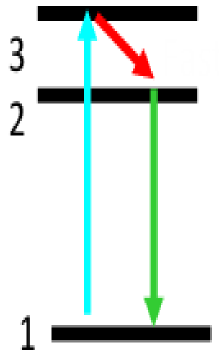
Consider the three-level laser system shown in Figure. Atoms start in the ground state, which is also the lower laser level. Energy from an external source excites ground-state atoms to a short-lived energy level slightly above the metastable level. Then, the atoms quickly drop down to the metastable upper laser level, where they remain a longer than in the higher level. The atoms collect in the metastable level, creating a population inversion between it and the lower laser level. A few photons spontaneously emitted by atoms in the metastable state then stimulate a cascade of laser emission from atoms remaining in the metastable state.



Assume we pump to a state 3 that rapidly decays to level 2.

$$\frac{dN_2}{dt} = BIN_1 - AN_2$$

$$\frac{dN_1}{dt} = -BIN_1 + AN_2$$



$$\frac{d\Delta N}{dt} = -2BIN_1 + 2AN_2$$

$$\frac{d\Delta N}{dt} = -BIN - BI\Delta N + AN - A\Delta N$$

Note that BIN_1 represents the absorption and AN_2 represents the spontaneous emission.

The total number of atoms N is:

$$N \equiv N_1 + N_2$$
$$\Delta N \equiv N_1 - N_2$$

$$2N_2 = N - \Delta N$$
$$2N_1 = N + \Delta N$$

Noting that N_3 =0 because Level 3 decays fast and so is zero.

$$\frac{d\Delta N}{dt} = -BIN - BI\Delta N + AN - A\Delta N$$

In steady state: $0 = -BIN - BI\Delta N + AN - A\Delta N$

$$\Rightarrow (A + BI)\Delta N = (A - BI)N$$

$$\Rightarrow \Delta N = N(A - BI)/(A + BI)$$

Let the saturation intensity $I_{sat} = \frac{A}{B}$

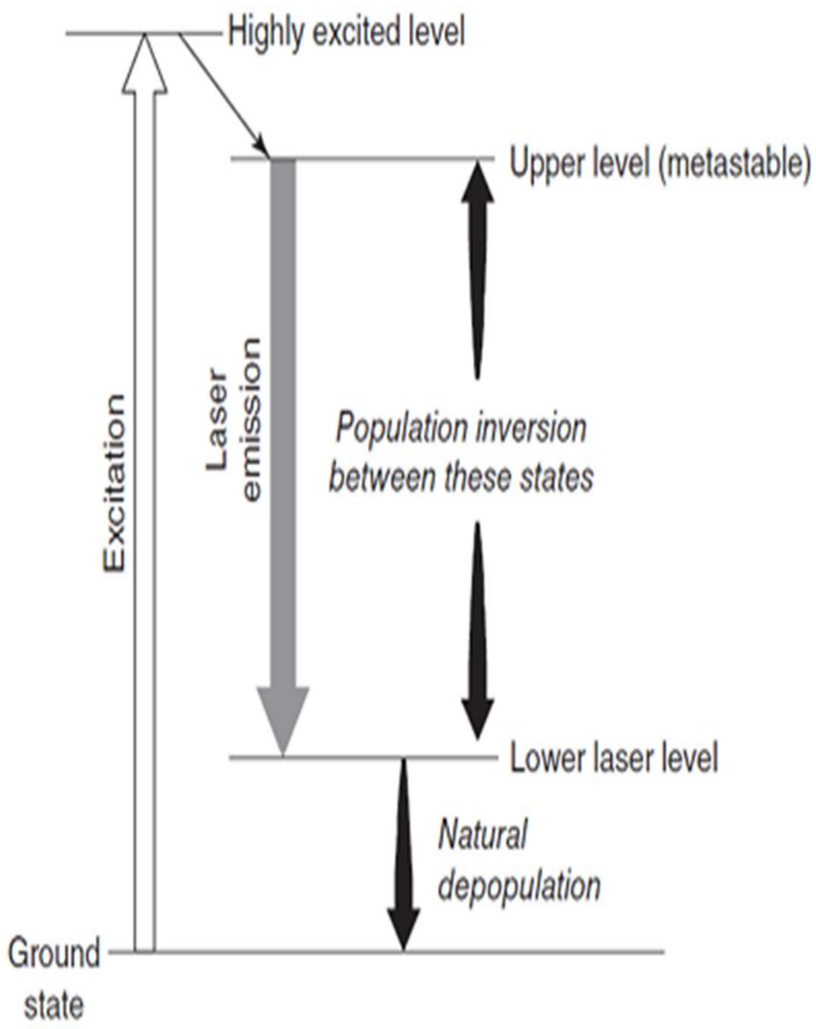
$$\Delta N = N\frac{1 - I/I_{sat}}{1 + I/I_{sat}}$$

Now if $I > I_{sat}$, then; ΔN is negative.

3. Four Level System

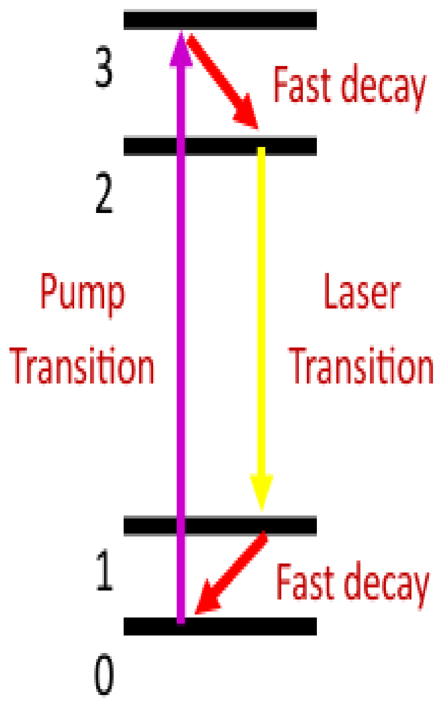
The atom is excited from the ground state to a short-lived, highly excited level, then drops quickly to a metastable upper laser level. Stimulated emission on the laser transition drops atoms to the lower laser level, which in a four-level laser is above the ground level, as shown in Figure (2.5). The atoms then drop from the lower laser level to the ground state, releasing energy by spontaneous emission or other processes.

The key difference is that the lower level of a four-level laser is not the ground state. This is important because it means the population of the upper laser level only must exceed that of the lower laser level, not the ground state. That avoids the need to excite most atoms out of the ground state, opening the door to continuous output.



Now assume the lower laser level 1 rapidly decays to the ground level 0.

$$\frac{dN_2}{dt} = BIN_0 - AN_2$$



The total number of the atoms N is:

$$N \equiv N_0 + N_2$$

$$N_0 = N - N_2$$

$$\frac{dN_2}{dt} = BI(N - N_2) - AN_2$$

Because $N_1 \approx 0, \quad \Delta N \approx -N_2$

$$-\frac{d\Delta N}{dt} = BIN + BI\Delta N + A\Delta N$$

At steady state: $0 = BIN + BI\Delta N + A\Delta N$

$$0 = BIN + BI\Delta N + A\Delta N$$

$$\Rightarrow \quad (A + BI)\Delta N = -BIN$$

$$\Rightarrow \quad \Delta N = -BIN/(A + BI)$$

$$\Rightarrow \quad \Delta N = -(BIN/A)/(1 + BI/A)$$

Let the saturation intensity $I_{sat} = \frac{A}{B}$

$$\Delta N = -N\frac{I/I_{sat}}{1 + I/I_{sat}}$$

Now ΔN is negative always.

Two-, three-, and four-level systems

Four-level systems are best.