Physics-2
15B11PH211

Module 2. Lasers, Optical Fiber and their applications

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Lasers

(acronym)

Light Amplification by Stimulated Emission of Radiation

- The laser is a device that produces coherent (all waves are exactly in phase with one another) nearly monochromatic, Less diverging and extremely intense light beam.

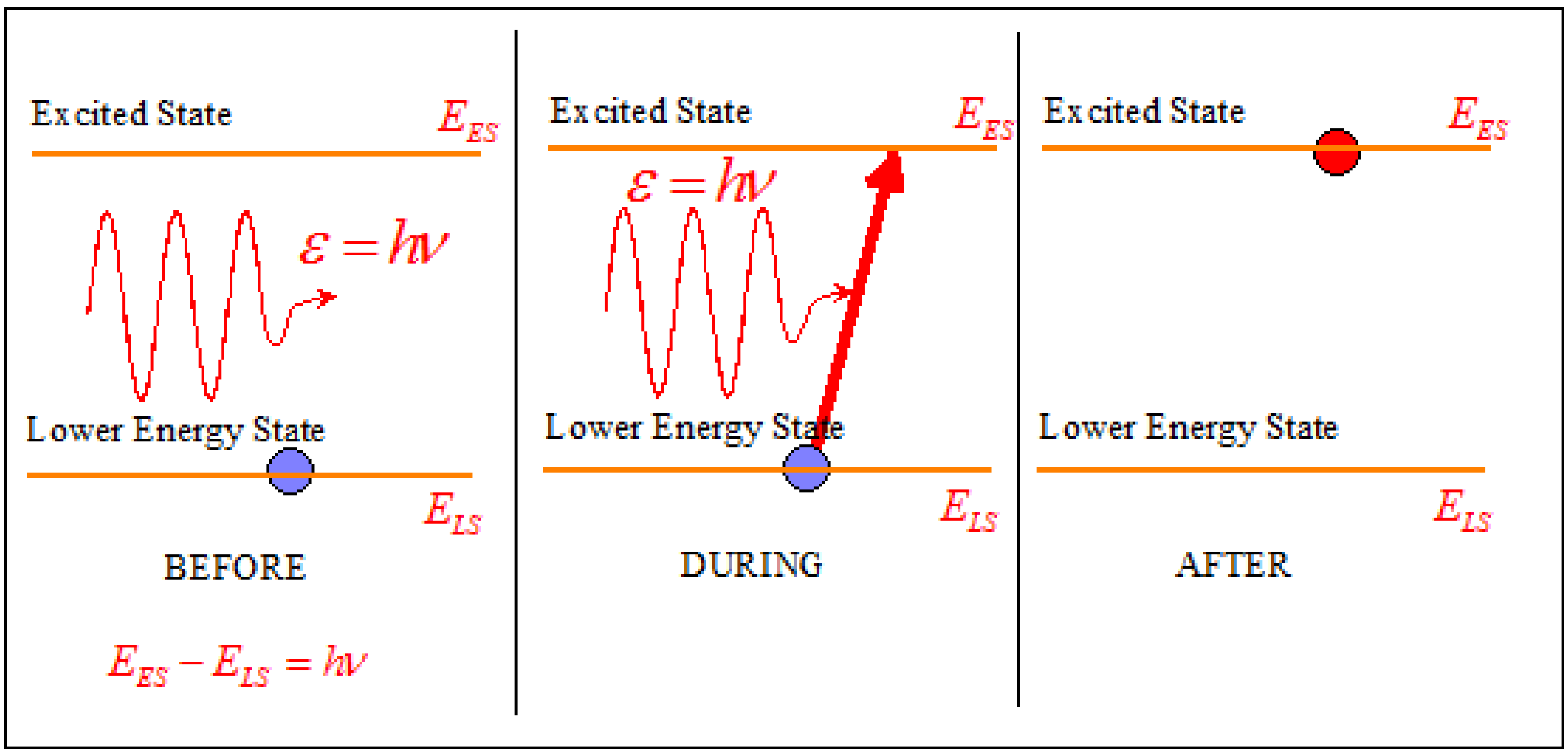
Characteristics of Laser Light

1.Coherent

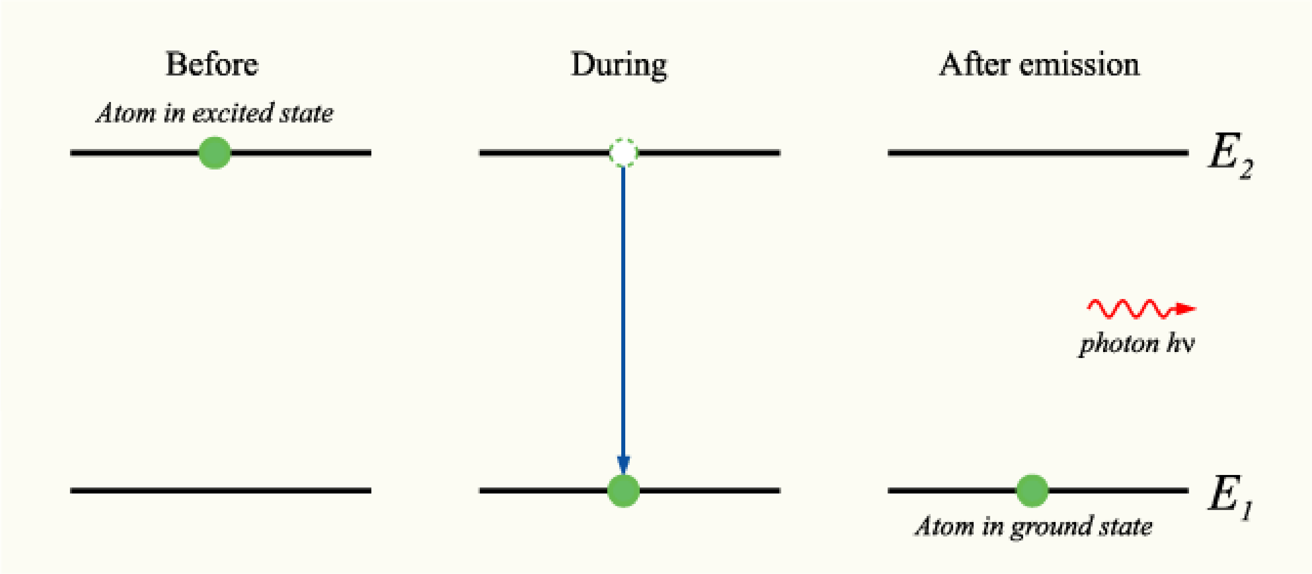
2. Monochromatic.

3. Collimated.

Stimulated Absorption: In this process a photon with an energy equals to the difference in energy between two of the atomic levels interacts with the atom. The electron of the atom is in the lower energy state, absorbs the photon, and jumps to the higher energy state (excited state). The photon is completely absorbed by the atom. The final state of the atom is excited.

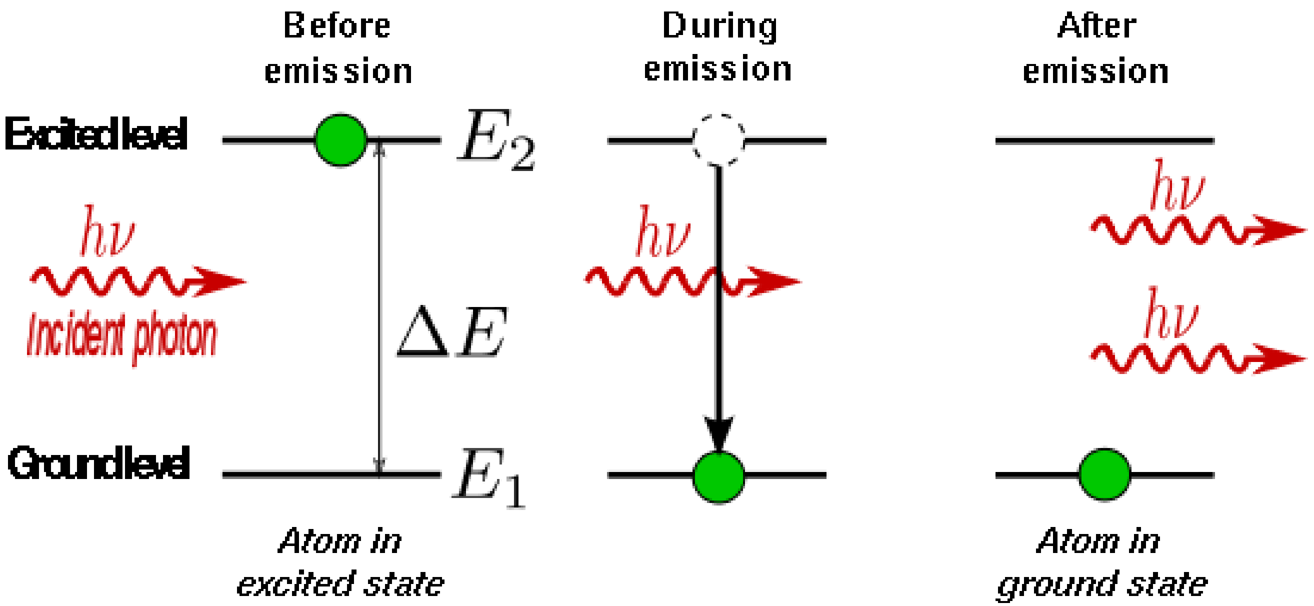


Spontaneous (self) emission:



In this case, the atom de-excites itself and emits a photon with an energy equals to (E_2-E_1). The direction and phase of emitted photon is completely random. Therefore this emission does not favor lasing action.

Stimulated (induced) emission



$$E_2 - E_1 = \Delta E = h\nu$$

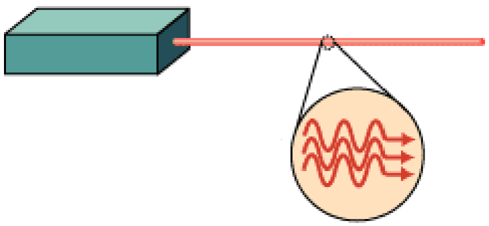
When a photon with the energy $\Delta E = (E_2 - E_1)$ *interacts with the excited electron at* E_2 *, the electron jumps down to the lower energy state* E_1 *emitting an* ***additional photon which has same phase, direction and energy as the incident photon.***

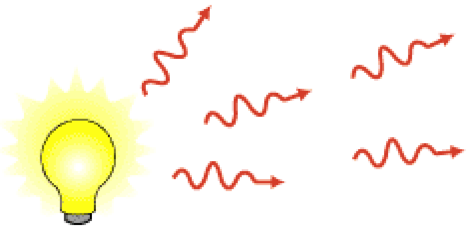
Spontaneous Emission	Stimulated Emission
1. In this emission process the photons emitted from various atoms have no phase relationship between them.	1. In this emission process the emitted photons have same frequency and are in phase with incident photons.
2. Achieved radiations are incoherence.	2. Achieved radiations are coherent and unidirectional .
3. Emitted photon can have any direction.	3. For every incident photon, there are two outgoing photons moving in the same direction.
4. Spontaneous emission disfavors laser action.	4. Stimulated emission favors laser action.

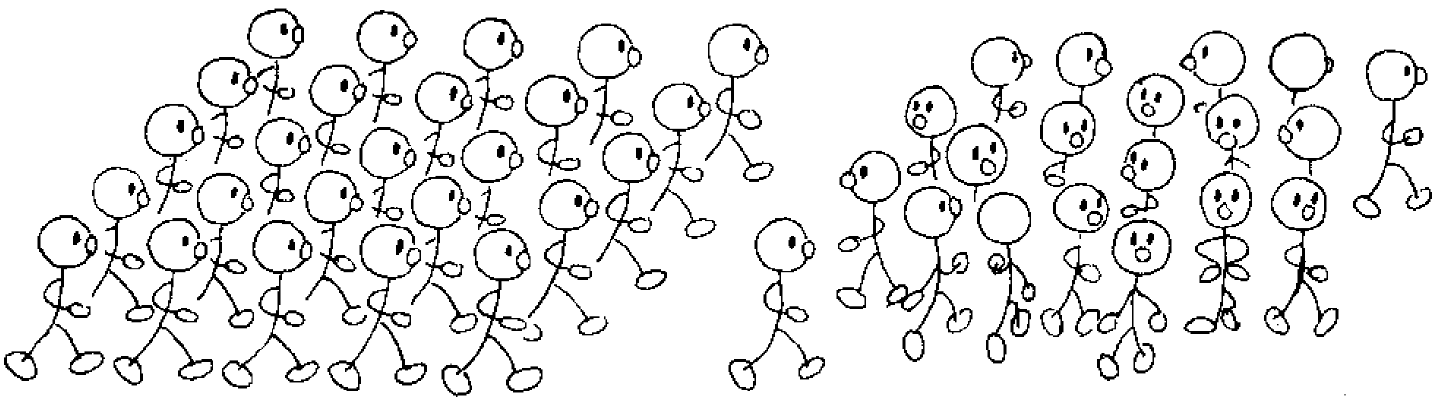
Light Amplification by Stimulated Emission of Radiation

Stimulated emission

Spontaneous emission







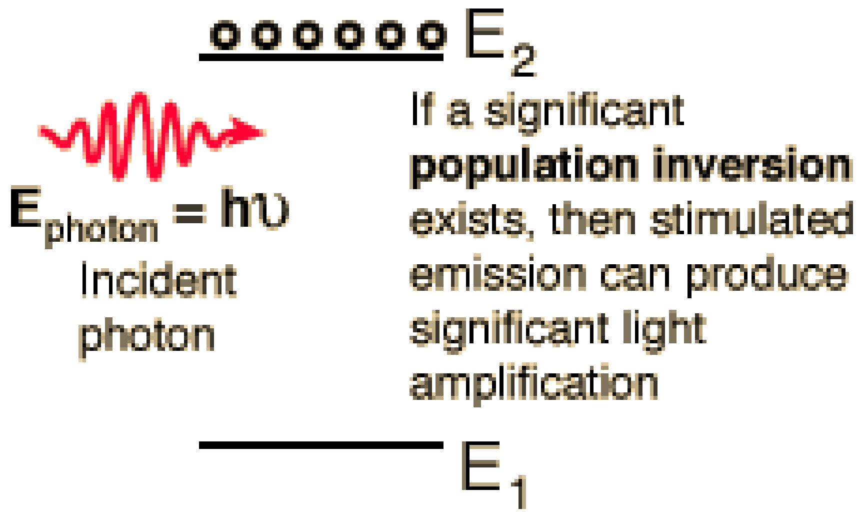
Coherent

Incoherent

- ***Population inversion**:* *If situation is such that more atoms are in an excited state than in the ground state, a net emission of photons can result. Such condition is called population inversion.*

This fact is the fundamental principle involved in the operation of a laser.

Light Amplification by Stimulated Emission of Radiation.



*Precondition for laser action is **population inversion**. Electrons will normally reside in the lowest available energy state.*

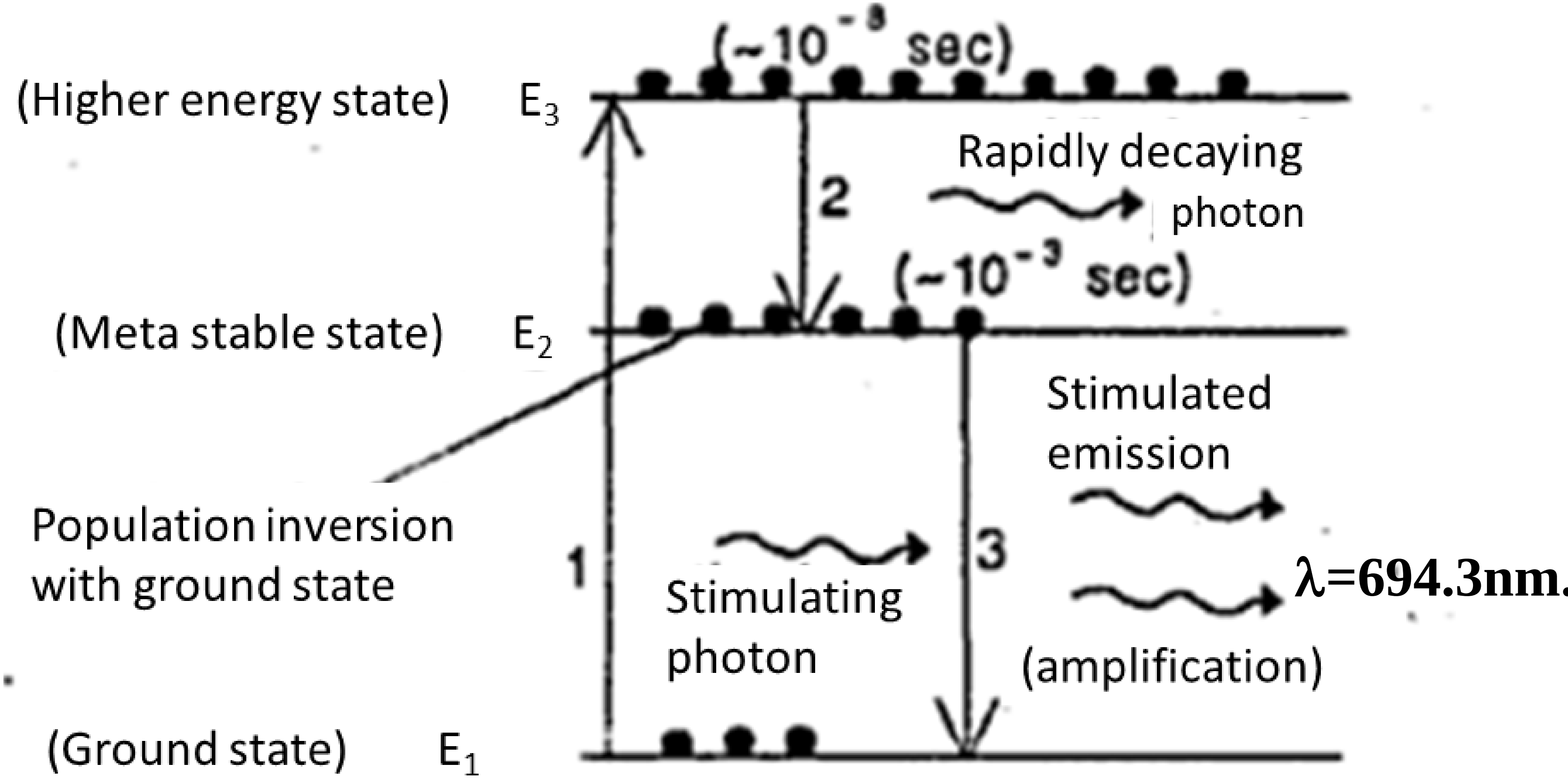
A population inversion cannot be achieved with just two levels because the probability for absorption and for spontaneous emission is exactly the same.

What is population inversion? Explain why laser action can't occur without population inversion between atomic levels.

$N(E_2)>>N(E_1)$, non equilibrium condition.

Probability of stimulated emission is proportional to $N(E_2)/N(E_1)$

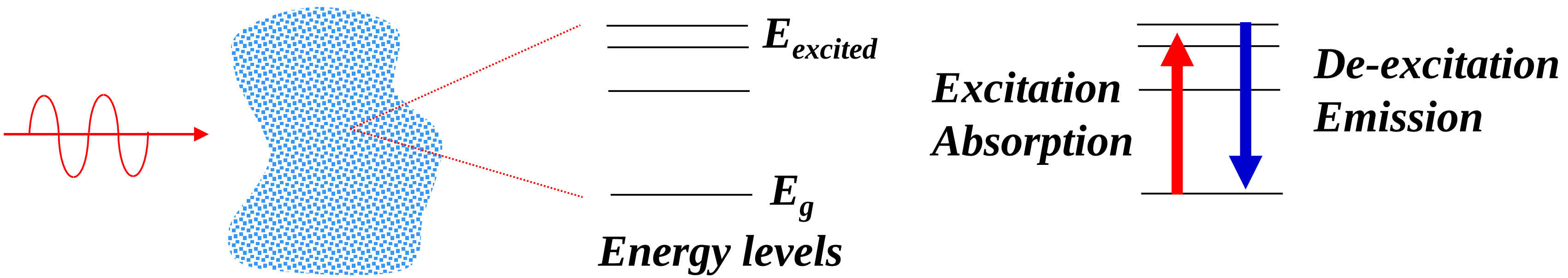
Three Level Laser



- Population Inversion: $N(E_2) > N(E_1)$, no of atoms in metastable state is greater than the ground state.
- This is very difficult, a lot of pumping is required.
- The output is pulsed e.g. Ruby laser

Interaction of light with excited media

Excited media: *Matter which has energy in excited energy levels*
Process of excitations



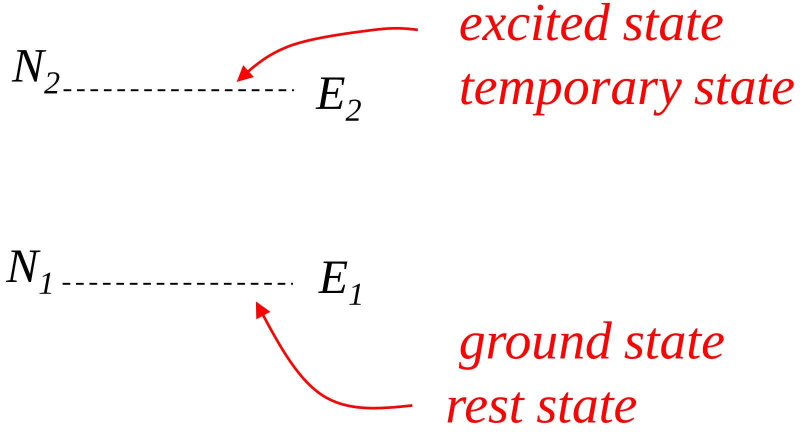
Assumptions *- quantized energy levels - electronic, vibrational rotational*

Limitations *– Optical processes only*

Emission and Absorption – Basic ideas

Restrict ourselves to two level system

$$E_2 - E_1 = h\nu = hc/\lambda$$

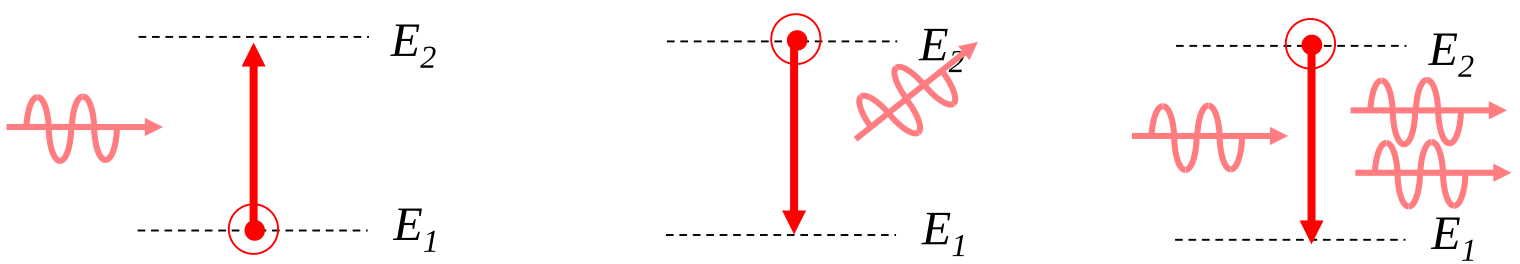


Number of atoms (or molecules) / unit volume

N = number density $N = N_1 + N_2$

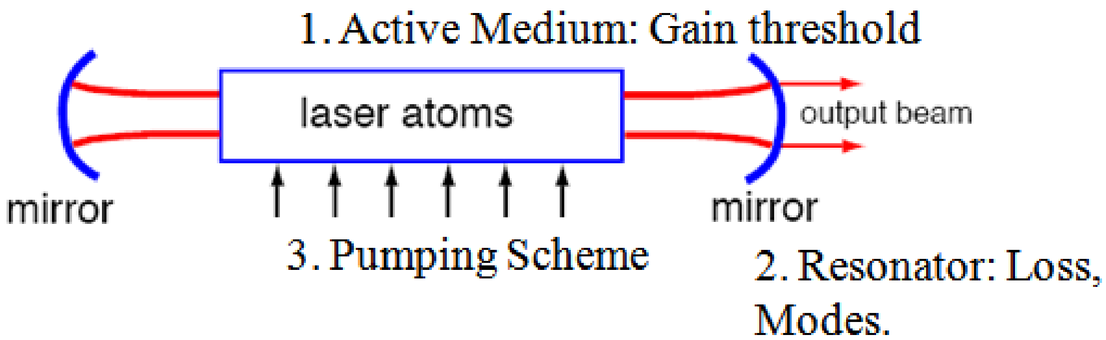
$N_{1,2}$ *= population of levels 1 & 2*

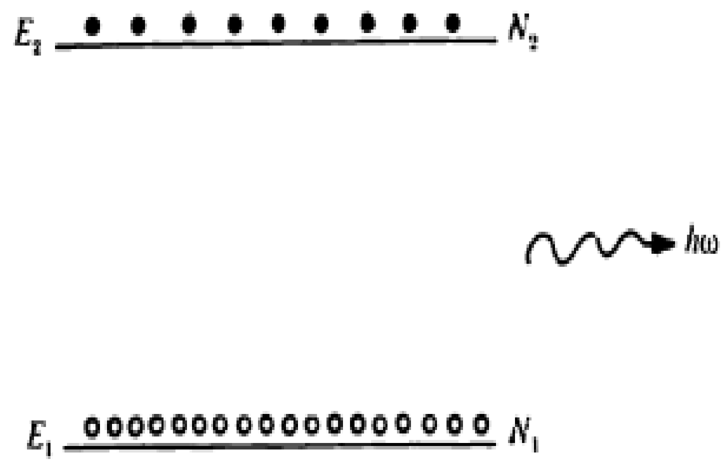
Three basic processes



Absorption ***Spontaneous Emission*** ***Stimulated Emission***

How laser works





The three main components of any laser are

1. ***The amplifying medium:*** The amplifying medium consists of a collection of atoms, molecules or ions which act as an amplifier for light waves.

2. ***The pump:*** The pump is the source of energy which maintains the medium in this population inverted state.

3. ***The optical resonator:*** The optical resonator which consists of a pair of mirrors facing each other provides optical feedback to the amplifier so that it can act as

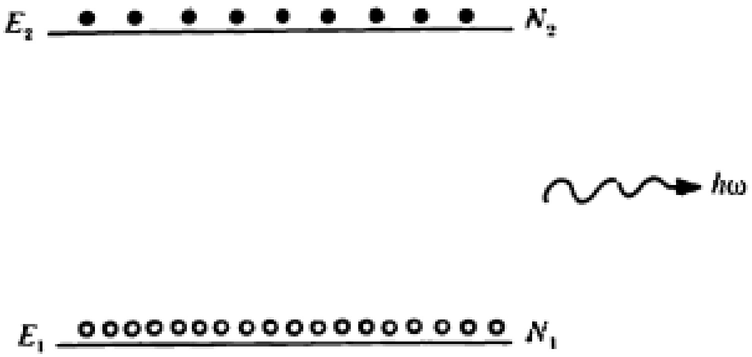
   a source of radiation.

The Einstein coefficients

We consider two levels of an atomic system and let N_1 and N_2 be the number of atoms per unit volume present in the energy levels E_1 and E_2 respectively. If radiation at a frequency corresponding to the energy difference (E_2 - E_1) falls on the atomic system, it can interact in three distinct ways:

(a) Absorption: An atom in the lower energy level E_1 can absorb the incident radiation and be excited to E_2. This excitation process requires the presence of radiation. The rate at which absorption takes place from level 1 to level 2 will be proportional to the number of atoms present in the level E_1 and also to the energy density of the radiation at the frequency (E_2-E_1). Thus if $u(\omega)d\omega$ represents the radiation energy per unit volume between ω and $\omega+d\omega$ then we may write the number of atoms undergoing absorptions per unit time per unit volume from level 1 to level 2 as

$$\Gamma_{12} = B_{12} u(\omega) N_1$$



where B_{12} is a constant of ***Absorption*** (proportionality) and depends on the energy levels.

(b) De-excitation: Einstein postulated that an atom can make a transition from E_2 to E_1 through two distinct processes, namely stimulated emission and spontaneous emission.

In the case of ***stimulated emission***, the radiation which is incident on the atom stimulates it to emit radiation and the rate of transition to the lower energy level is proportional to the energy density of radiation at the frequency ω. Thus, the number of stimulated emissions per unit time per unit volume will be

$$\Gamma_{21} = B_{21} u(\omega) N_2$$

where B_{21} is the coefficient of ***stimulated emission (***proportionality) and depends on the energy Levels.

(c) An atom which is in the upper energy level E_2 can also make a spontaneous emission; this rate will be proportional to N_2 only and thus, the number of atoms making spontaneous emissions per unit time per unit volume

$$U_{21} = A_{21} N_2$$

At thermal equilibrium between the atomic system and the radiation field, the number of upward transitions must be equal to the number of downward transitions. Hence, at thermal equilibrium

$$N_1 B_{12} u(\omega) = N_2 A_{21} + N_2 B_{21} u(\omega)$$

or

$$u(\omega) = \frac{A_{21}}{(N_1/N_2) B_{12} - B_{21}}$$

Using Boltzmann's law, the ratio of the equilibrium populations of levels 1 and 2 at temperature T is

$$N_1/N_2 = e^{(E_2 - E_1)/k_B T} = e^{\hbar\omega/k_B T}$$

where k_B ($= 1.38 \times 10^{-23}$ J/K) is the Boltzmann's constant. Hence

$$u(\omega) = \frac{A_{21}}{B_{12} e^{\hbar\omega/k_B T} - B_{21}}$$

Now according to Planck's law, the radiation energy density per unit frequency interval is given by

$$u(\omega) = \frac{A_{21} / B_{21}}{B_{12} / B_{21} \exp(h\nu / kT) - 1} = \frac{8\pi h\nu^3 / c^3}{\exp(h\nu / kT) - 1}$$

$$A_{21} / B_{21} = 8\pi h\nu^3 / c^3$$

$$B_{12} / B_{21} = 1$$

At thermal equilibrium, **the ratio of the number of spontaneous to stimulated emissions (R)** is given by:

$$R = \frac{A_{21}}{B_{21} u(\omega)} = \exp(h\nu / kT) - 1$$

Thus, at thermal equilibrium at a temperature T, for frequencies

***ω* >> *k_BT/ħ*, the number of spontaneous emissions far exceeds the number of stimulated emissions.**

Example: Let us consider an optical source at T= l000K. At this temperature:

$$\frac{k_B T}{\hbar} = \frac{1.38 \times 10^{-23}(\mathrm{J/K}) \times 10^3(\mathrm{K})}{1.054 \times 10^{-34}(\mathrm{J\ s})} \approx 1.3 \times 10^{14}\ \mathrm{Hz}$$

Thus for $\boldsymbol{\nu} >> 1.3 \times 10^{14}$ Hz, the radiation would be mostly due to spontaneous emissions.

For example for $\lambda \approx 5000$Å, $\boldsymbol{\nu} \approx 3.8 \times 10^{15}$ Hz and hence,

$$R \approx e^{29.2} \approx 5.0\times10^{12}$$

So, at visible light frequencies the emission is predominantly due to spontaneous transitions and hence, the light from usual light sources is incoherent at T around 1000 K (i.e. 700 C temp.).

Interesting Conclusions:

$$R = \frac{A_{2-1}}{B_{2-1}\rho(\nu)} = \exp(h\nu / kT) - 1$$

Visible light photons, energy: 1.6eV – 3.1eV.

kT at 300K ~ 0.025eV. **hν /kT >>1, so in general Spontaneous emission dominates for visible light at around room temperature.**

Around room temperature, Stimulated emission could dominate only when hν /kT <<1, so one way is to have ν smaller than the ν of visible light and one such option is microwaves as **$\nu_{microwave}$ << $\nu_{visible\ light}$.** Or we can say that for microwaves: hν <0.0015eV, **So this was the reason for the firstly development of MASER before LASER for room temp.** **This is answer of thequestion that why MASER were developed before LASER?**

Numerical Examples

Example 1.29. *The wavelength of emission is 6000 Å and the lifetime τ_{sp} is 10^{-6} s. Determinie the coefficient for the stimulated emission.*

Example 1.30. *(a) At what temperature are the rates of spontaneous and stimulated emission equal ? Assume $\lambda = 5000$ Å.*

(b) At what wavelength are they equal at 300 K ?

Example 1.31. *Find the ratio of spontaneous emission to stimulated emission for a cavity of temperature 50K and wavelength* 10^{-5} *m.*

Example 1.33. *The half-width of the gain profile of a He-Ne laser material is about 2×10^{-3} nm. What should be the maximum length of the cavity in order to have a single longitudinal mode oscillation ?*

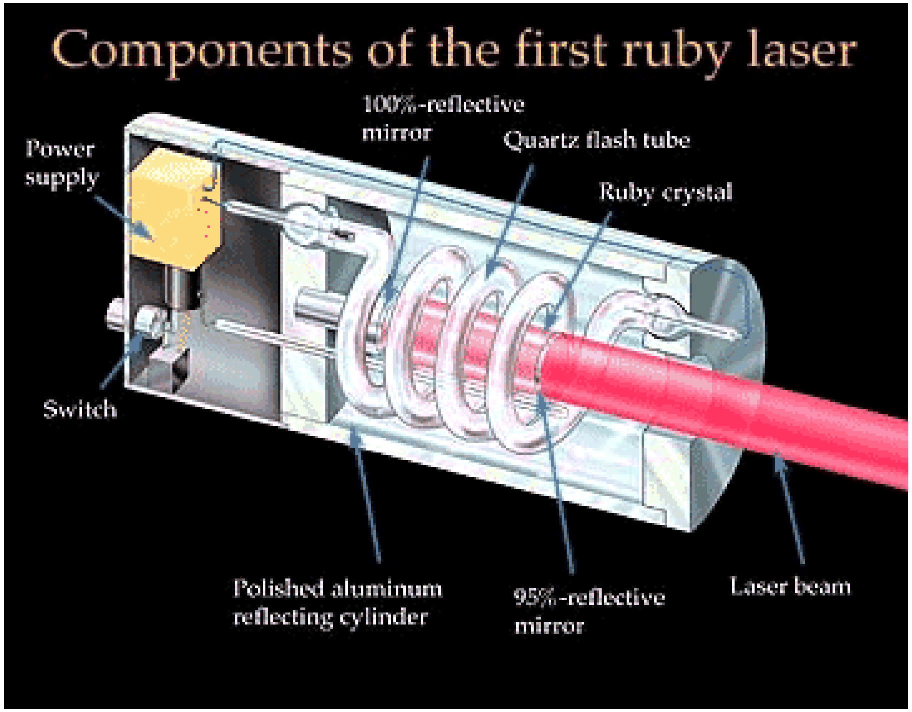
Example 1.34. *The half-width of the gain profile of a He-Ni laser material is about 2×10^{-3} nm. If the length of the cavity is 30 cm, how many longitudinal modes can be excited ? The emission wavelength of He-Ne laser is 6328 Å.*

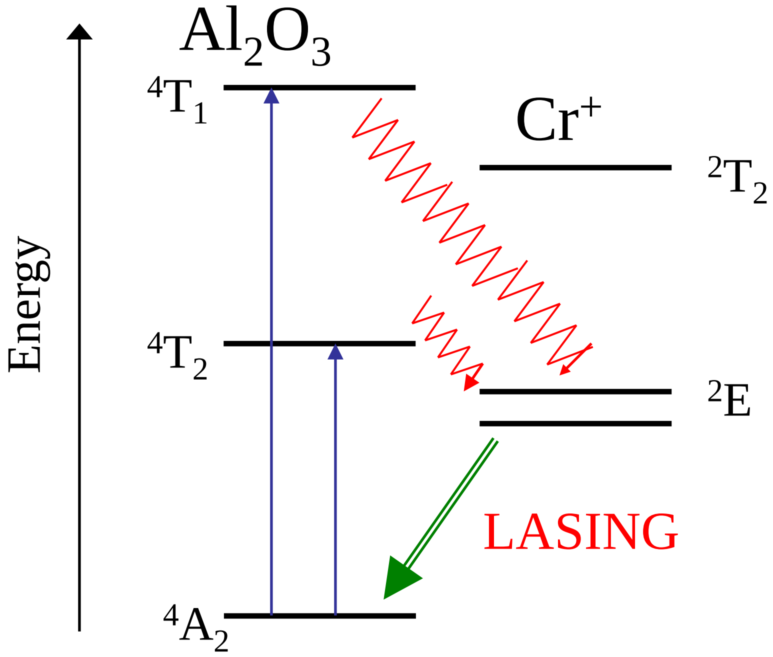
Example 1.35 *Calculate threshold pumping power per unit volume in case of Ruby laser. Given : $N = 1.6 \times 10^{25}$ atoms/m^3, frequency $\nu_p = 6.25 \times 10^{14}$ and $t_{sp} = 3 \times 10^{-3}$ sec.*

Solution. In three level laser scheme, as in the case of Ruby laser, let N_2 be the number of atoms in the upper laser level E_2 (metastable state) and t_{sp} the spontaneous time at this level, then

Ruby laser

- discovered in 1960 by T. H. Maiman.
- ruby (Al_2O_3) monocrystal, Cr doped.





1. **Optical pumping: 510-600nm and 360-450nm.(Green and Blue light)**
2. **Fast transition on ^2E.**
3. **Lasing: ^2E on $^4A_2$,**

- ✓ **Lasing from the Cr^{3+}.**
- ✓ **three level laser**

- **694nm (Red Color)**

Not in Syllabus: You may skip it

Temporal Coherence (longitudinal coherence)is the relative phase or the coherence of the two waves at two separate locations along the propagation direction of the two beams.If we assume that the two waves are exactly in phase at the first location, then they will still be at least partially in phase at the second location up to a distance lc, where lc is defined as the th. The coherence length can be determined to be

$$l_c = \lambda\left(\frac{\lambda}{\Delta\lambda}\right) = \frac{\lambda^2}{\Delta\lambda},$$

Where $\Delta\lambda$ represents the difference in wavelength between the two waves and λ is their average wavelength. lc has a significant value only when $\Delta\lambda \ll \lambda$, that is, when the wavelengths of both waves are nearly identical.

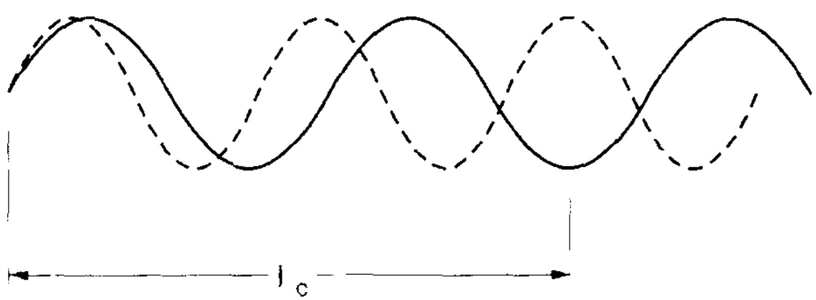


Figure 2-11(a) Temporal coherence length l_c

What is the temporal coherence length l_c of (1) a mercury vapor lamp emitting in the green portion of the spectrum at a wavelength of 546.1 nm with an emission bandwidth of $\Delta\nu = 6 \times 10^8$ Hz, and (2) a helium–neon laser operating at a wavelength of 632.8 nm with an emission width of $\Delta\nu = 10^6$ Hz?

$$|\Delta\lambda| = \frac{\lambda^2 \Delta\nu}{c}.$$

Using this expression, we can determine $\Delta\lambda$ for the mercury lamp to be

$$\Delta\lambda = \frac{(546.1 \times 10^{-9}\ \text{m})^2 (6 \times 10^8\ \text{s}^{-1})}{3 \times 10^8\ \text{m/s}} = 5.96 \times 10^{-13}\ \text{m} = 5.96 \times 10^{-4}\ \text{nm},$$

and thus the temporal (longitudinal) coherence length can be determined to be

$$l_c = \frac{\lambda^2}{\Delta\lambda} = \frac{(546.1 \times 10^{-9}\ \text{m})^2}{5.96 \times 10^{-13}\ \text{m}} = 0.50\ \text{m}.$$

For the helium–neon laser we find that $\Delta\lambda$ is given by

$$\Delta\lambda = \frac{\lambda^2 \Delta\nu}{c} = \frac{(632.8 \times 10^{-9}\ \text{m})^2 (1 \times 10^6\ \text{s}^{-1})}{3 \times 10^8\ \text{m/s}} = 1.33 \times 10^{-15}\ \text{m} = 1.33 \times 10^{-6}\ \text{nm}.$$

The temporal coherence length is thus

$$l_c = \frac{\lambda^2}{\Delta\lambda} = \frac{(632.8 \times 10^{-9}\ \text{m})^2}{1.33 \times 10^{-15}\ \text{m}} = 301\ \text{m}.$$

Hence the laser beam in this case has a significantly longer coherence length than that of the mercury lamp.

Spatial Coherence/transverse coherence/ lateral coherence: describes how far apart two sources, or two portions of the same source, can be located in a direction transverse to the direction of observation and still exhibit coherent properties over a range of observation points. More specifically, by what distance lt can two points be separated in the transverse direction at the region of observation and still have interference effects from the source region over a specific lateral direction of the source.

$$l_t = \frac{r\lambda}{s} = \frac{\lambda}{\theta_s} \qquad \text{where } \theta \cong s/r.$$

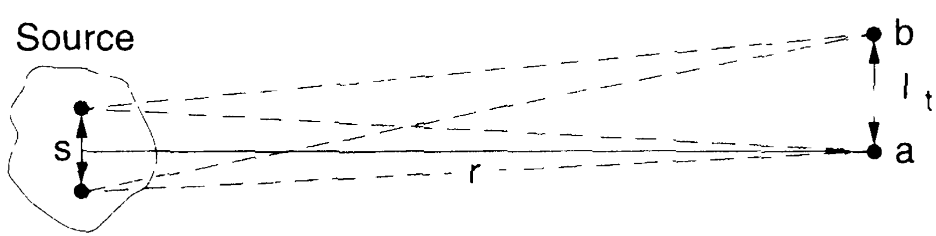


Figure 2-11(b) Transverse coherence length l_t

A laser-produced plasma consisting of a 100-μm–diameter ball radiates very strongly at a wavelength of 10 nm. At a distance of 0.5 m from the source, what is the spatial coherence resulting from light emitted from opposite sides of the plasma?

$$l_t = \frac{r\lambda}{s} = \frac{(0.5\text{ m})(1 \times 10^{-8}\text{ m})}{1 \times 10^{-4}\text{ m}} = 5 \times 10^{-5}\text{ m}.$$

Hence, at any location within 50 μm in any transverse direction from a specific point P that is 0.5 m from the source, the flux will be incoherent with respect to the radiation arriving at the point P.