Lasers

- LASER stands for "Light Amplification by Stimulated Emission of Radiation".
- Directional, focused, monochromatic, coherent and bright source of light

Laser Sources	Ordinary Sources
Single value of wavelength: **monochromatic**	Wide wavelength range: **non monochromatic**
highly coherent (waves in phase with one another)	**Incoherent:** no definite phase relation.
Travels as a **concentrated parallel beam**	Doesn't travel as a concentrated parallel beam
Very intense	Intensity rapidly reduces with increase in distance
Unidirectional (travels in one direction)	**Multidirectional** (travels in all directions)
Examples of laser sources: He-Ne laser, Ruby laser, Nd:**YAG laser, CO2 laser, diode laser**	Examples of ordinary sources: CFL, **halogen lamp**, Na-vapour lamp, incandescent bulb, LED

Parameters: (All light waves and radiations are of laser source)

- **Beam intensity:**
  - Optical power output per unit area
  - W/m^{23}
  - I = P/A
- **Monochromaticity:**
  - Measure of linewidth of radiation
  - Linewidth is the frequency range of a light source.
- **Coherence:**
  - Measure of coherence length
  - Time and distance up to which the light waves are either in phase or bear a fixed phase difference with each other.
  - $I = \frac{\lambda^2}{2\Delta\lambda}$ where $\Delta\lambda$ is the spread in wavelengths (linewidth), λ is the central wavelength.
- **Directionality**
  - Ordinary light is emitted in all directions.
  - Laser light is emitted only **along the axis** of the laser source in the form of a **cylindrical cavity**.
- **Divergence:**
  - Measure of angular spread of the laser beam

- $\phi = \frac{d1-d2}{z1-z2}$; Z1 and Z2 are the perpendicular distance of the detector from the laser source. d1 and d2 are diameters of laser beam at distance Z1, Z2 respectively.
- [take any two beams. Calculate their diameters and their perpendicular distance from the source. Take their differences and ratio them.

Interaction with matter

- Interaction of radiation with matter means interaction of photons with atoms and molecules.
- Light absorbed and light emitted by a material are both interactions of light with matter

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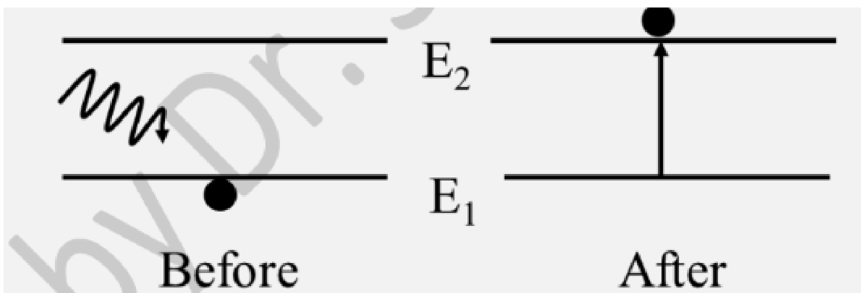
A. Stimulated Absorption of light

a. An atom in the lower energy state absorbs the incoming photon of light and jumps to the next higher energy state. This is known as stimulated absorption or induced absorption. (because we had to supply energy externally)

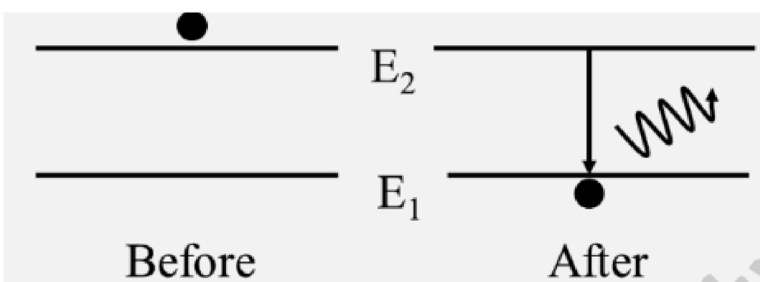
b. 

c. Probability rate of transition: $\frac{dN}{dt}|ab = B_{12}N_1Q$

d. B12: probability of absorption process (constant)
N1: number of atoms in lower energy level E1
Q: energy density of incident radiation per frequency

B. Spontaneous Emission

a. When the earlier excited electron returns to its lower energy state, due to its tendency to attain minimum potential energy, excess energy is released as a photon of energy $h\nu = E2 - E1$.

b. 

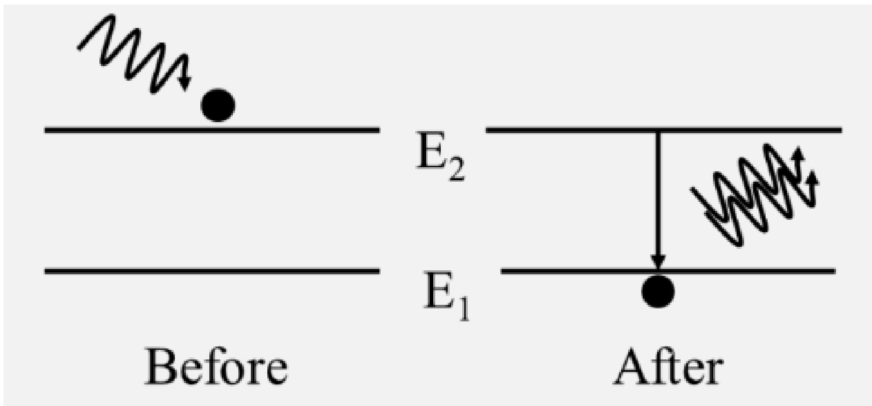
c. There is no external radiation, hence this is called spontaneous emission.

d. $\frac{dN}{dt}|sp = A_{21}N_2$

e. A21: probability of spontaneous emission process
N2: number of atoms in higher energy level E2

f. The number of spontaneous emission events taking place at any instant is **proportional to the number of atoms** present in the higher energy state. The process of spontaneous emission is **completely probabilistic**.
g. Spontaneously emitted light is incoherent, divergent, diffused and undirected since there is no control over spontaneously emitted radiation because it involves transitions from varied energy levels with all possible directions and random phase factors.

C. Stimulated Emission

a. 

b. The electron in the excited state does not necessarily need to wait for spontaneous emission to take it back to E1. If an incoming photon is introduced whose energy is equal to the energy difference between the two energy levels, the electron in E2 can prematurely move to E1 by releasing energy as another photon. This phenomenon is called stimulated emission.
c. The emitted photon is identical to the incident photon absolutely. Both travel in the same direction.
d. This type of process exists along with the above two processes but at room temperature, spontaneous emission dominates over stimulated emission and the latter is generally negligible.
e. $\frac{dN}{dt}|st = B_{21}N_2Q$: symbol meanings similar to spontaneous emission
f. The number of stimulated emission events taking place at any instant is primarily proportional to the number of atoms in the higher energy state.

Advantages of Stimulated Emission

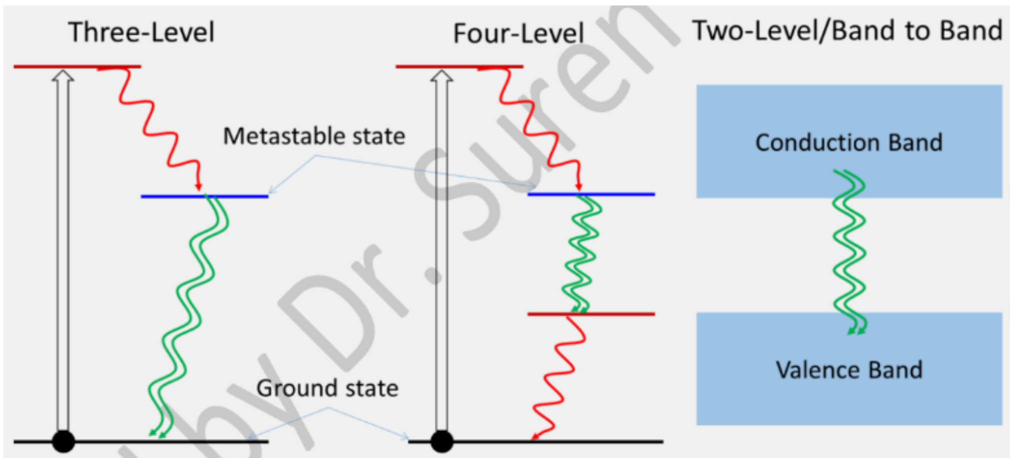
- The process is **controllable** from outside.
- The induced radiation is **identical** to the incident radiation in every respect.
- By selecting proper active medium and resonance conditions, **multiplication of photons** is achieved.
- As a result, we get highly monochromatic, coherent, directional, focused and intense light. Thus, to obtain laser light means to **obtain light amplification** by stimulated emission of radiation at a desired wavelength.

Laser-Physics Terms and Concepts

1. Population:
    a. The number of active atoms occupying a particular energy state is called the population of that energy state.
    b. If N1 and N2 are the population of states E1 and E2 respectively. $N_1 = g_1e^{-E1/kT}$ and $N2 = g_2e^{-E2/kT}$ where g1 and g2 are called "degeneracy" of levels E1 and E2 respectively.
    c. An energy level is said to be degenerate if it has different quantum states with identical energy. //bla bla bla ignore this point
    d. $\frac{N1}{N2}=\frac{g1}{g2}e^{(E2-E1)/kT}$ Let both the energy levels E1 and E2 be non-degenerate and are singly occupied so that g1 = g2. Thus, $\frac{N1}{N2}=e^{(E2-E1)/kT}$
2. Equilibrium conditions and Einstein's coefficients
    a. At equilibrium, the number of upward transitions is equal to the number of downward transitions so that the ratio N1/N2 remains constant.
    b. Thus,
    $$\left.\frac{dN}{dt}\right]_{ab} = \left.\frac{dN}{dt}\right]_{sp} + \left.\frac{dN}{dt}\right]_{st}$$
    $$\therefore B_{12}N_1Q = A_{21}N_2 + B_{21}N_2Q$$
    c. **Derivation** in notebook.
3. Laser emission is a non-equilibrium process
    a. The stimulated emission is negligible with other two processes at room temperature.
    b. At room temperatures and at thermal equilibrium, absorption and spontaneous emission processes nearly balance each other.
    c. At equilibrium, N1 >> N2 and also, A21 > B21.
    d. Therefore, we do not observe laser light in normal conditions and the light due to all ordinary sources is a result of spontaneous emission processes.
    e. Since we have to disturb the equilibrium condition, lasers are often called **non-equilibrium processes.**
4. Population inversion
    a. Stimulated emission occurs when population inversion is achieved, meaning more atoms occupy the higher energy level (E_2) than the lower one (E_1).
    b. The fact that E2 has more electrons than E1 is population inversion.
5. Pumping
    a. The process of supplying energy to the system in order to keep population inversion intact is called pumping. Since population inversion needs more electrons in E2, we need to supply external energy to continue exciting electrons. This ensures that electrons from E1 keep exciting to E2.
        i. **Optical Pumping** : Source of light is used to supply energy.

ii. **Electrical Pumping**: Used in gaseous ion lasers. A slowing electric field is set up by oppositely charged electrodes. Accelerated electrons collide with atoms. Atoms are ionised and excitation is produced.
iii. Direct conversion: Excites electrons using current using LEDs. Used in semiconductor lasers.

b. //derivation of relation between A and B in notebook <der no 2>

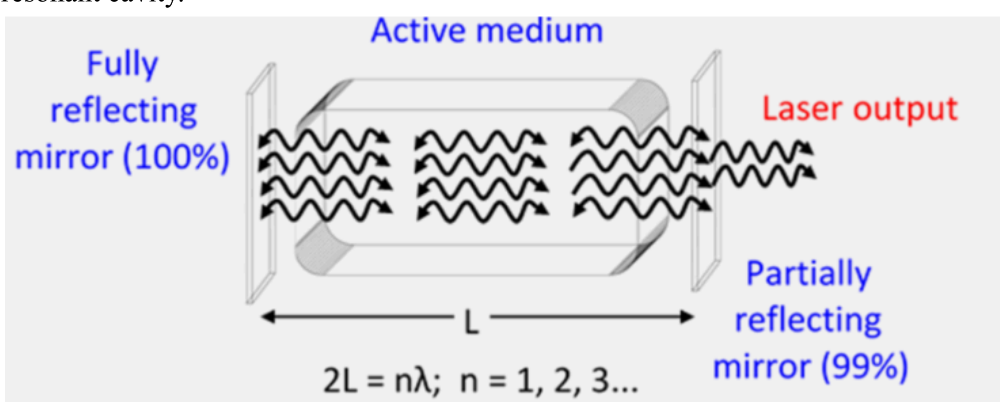
6. Pumping Schemes
   a. Laser systems use three or four energy levels for operation. Three-level systems (e.g., Ruby laser) and four-level systems (e.g., He-Ne, Nd:YAG) enable lasing. The transition between upper and lower lasing levels (energy levels involved in laser transitions) produces laser output. Transition between lasing levels is called laser transition.
   b. 

      i. Three level pumping
         1. Atoms are first raised to an excited state(in red).
         2. These deexcite to an intermediate state, in blue by some non radiative processes like emission of heat energy.
         3. The metastable states have a lasing transition from there to ground state, indicated in green.
         4. These atoms have to be raised from the ground state to excited state. It’s difficult to alter the population of the ground state since it is very stable. High pumping power is needed to achieve population inversion.
      ii. Four level pumping
         1. Atoms are first pumped to an excited state shown in red
         2. They quickly return to level E3 in blue, by some non radiative process.
         3. E3 is a metastable state, and atoms have a lasing transition from state E2 in green.
         4. From E2, they deexcite to ground state by transfer of energy thru non radiative processes like collisions etc.
         5. It’s easier to achieve population inversion between two excited states, like here, than pumping atoms continuously from the ground state.
         6. Population inversion is achieved faster.
         7. Less pumping power is required.
         8. This is more efficient than three level pumping

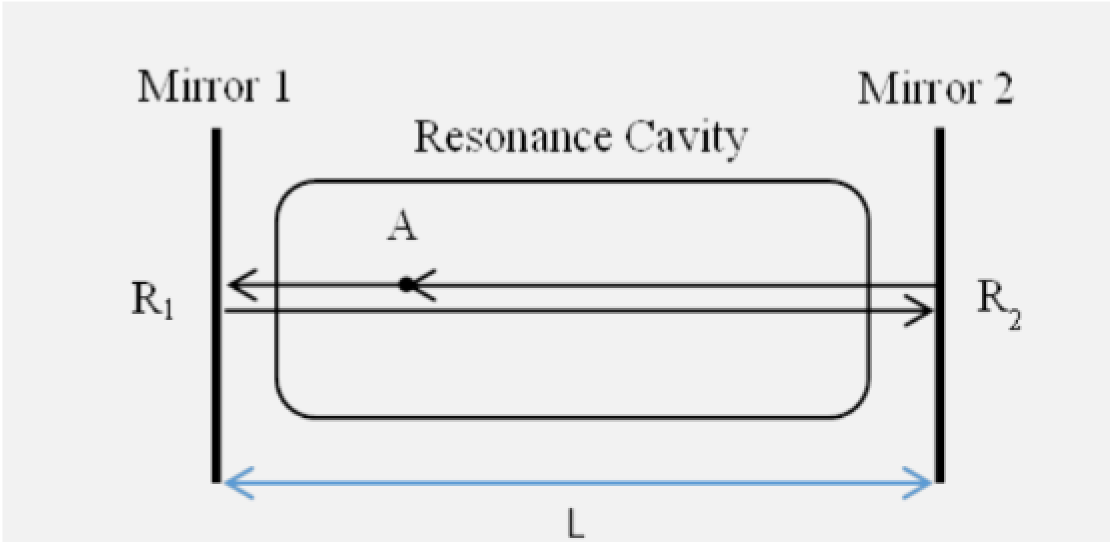
iii. Two level pumping
    1. Achieved in diode laser
    2. The electrons are transferred from the VB to CB and they return to the valence band by giving laser radiation in green.
    3. Some energy input is lost but diode lasers give max output efficiency.

c. Metastable states
    i. There are certain energy states in which excited atoms can reside for longer than usual. These states are called metastable states.
    ii. Metastable states delay de-excitation, allowing population inversion to last longer.
    iii. Otherwise the population of the excited states would rapidly decrease and there would be no laser transitions.
    iv. Without metastable states, lasers would not work.

d. Active system
    i. The region in which population inversion is achieved
    ii. Actual laser light is emitted yahan se
    iii. The whole system may not participate in population inversion, only a fraction is responsible.

e. Resonant cavity / optical resonator
    i. Light emitted in the active medium initially consists of spontaneously emitted photons.
    ii. These photons do trigger stimulated emission. But since the inducing photons were randomly directed, the stimulated photons are also scattered in all directions.
    iii. They may be also incoherent.
    iv. Thus, we need to tune all of our stimulated radiation. This is achieved via resonant cavity.
    v. 

7. Threshold condition for lasing



L is the length of the resonance cavity.
R1 and R2 are the reflectivity of the two mirrors.
γ is the overall gain coefficient
α is the overall loss coefficient of the active medium

- The pumping radiation triggered at an arbitrary point "A" will lead to a stimulated emission. Point A is within the active medium.
- For convenience, let the emitted radiation be directed towards mirror 1. It gets reflected and traverses through the active medium, gets reflected from mirror 2 and comes back at point A, where it started thus completing a round trip.

I_0 is the initial intensity of pumping radiation.
$I_{(x)} = I_0 \, e^{(\gamma - \alpha)x}$

When the radiation reflects at mirror 1, the intensity becomes $R_1 I_0 e^{(\gamma-\alpha)x}$ and after reflection at mirror 2, it becomes = $R_1 R_2 I_0 e^{(\gamma-\alpha)x}$. After one complete round, the intensity becomes
$I = R_1 R_2 I_0 e^{(\gamma-\alpha)2L}$

$$\frac{I}{I0} = R1R2e^{(\gamma-\alpha)2L}$$

When $I/I_0 < 1$, net attenuation; laser radiation dies
$I/I_0 > 1$, net amplification
$I/I_0 = 1$, sustained oscillations.

Net amplification and sustained oscillations together correspond to light amplification. The last condition sets the gain (gamma) needed for stimulated emission to dominate spontaneous emission.
Derivation in notebook.