PRINCIPLES OF LASERS

Notes as per Somaiya Vidyavihar University syllabus

Prepared by Divay Galani

BASICS:

- LASER: Light Amplification by Stimulated Emission of Radiation.
- A laser is a device that generates light by a process called STIMULATED EMISSION.
- In 1960, T. H. Maiman built the first laser device (ruby laser).

A short sketch of laser history

1917: Einstein – stimulated absorption and emission of light
1954: Charles Townes and Schawlow – maser, prediction of the optical laser Nobel Prize (1964)
1960: Theodore Maiman – first demonstration of a laser: Ruby laser Rapid progress in the 1960s
1961: first gas laser, first Nd laser
1962: first semiconductor laser
1963: CO2 laser (IR)

CHARACTERISTICS OF LASER:

- **Monochromatic**: The light emitted from a laser is monochromatic, that is, it is of one colour/wavelength. In contrast, ordinary white light is a combination of many colours (or wavelengths) of light.
- **Directional**: Lasers emit light that is highly directional, that is, laser light is emitted as a relatively narrow beam in a specific direction. Ordinary light, such as from a light bulb, is emitted in many directions away from the source.
- **Coherence**: The light from a laser is said to be coherent, which means that the wavelengths of the laser light are in phase in space and time. Ordinary light can be a mixture of many wavelengths.
- **Beam Focus**: The beam is highly focused which means that the angular spread of the beam is very minute as compared to normal sources of light.
- **Beam Intensity**: As compared to ordinary sources of light, the beam is very intense, meaning, a large amount of power is concentrated in a small beam.

DIFFERENCES BETWEEN LASER AND ORDINARY LIGHT:

Beam parameter	Laser sources of light	Ordinary sources of light
Monochromaticity	the spread in wavelength is very small. (< 10 Å)	wide wavelength range (few thousands of Å)
Coherence	coherent length is few metres to few kilometres	coherent length is few millimetres to centimetres
Directionality	emitted only in one direction	emitted in all directions
Beam focus	small angular spread with distance (down to $\frac{1}{10^6}$ times the ordinary sources)	high angular spread with distance
Beam intensity	large power is concentrated in a small part of beam. Can be up to few kW/cm^2 at 1 meter	Intensity decreases rapidly with distance. Usually few mW to W/cm^2 at 1 meter
Examples	He-Ne laser, CO_2 laser, Ar-laser, Nd-YAG laser	LED, CFL, Halogen, Candle

CONCEPTS OF LASER:

- **Population**: The number of atoms in a particular energy level is called population.

- **Absorption**: When energy is supplied to an atom in the ground state, the atom absorbs energy and makes a transition into an excited state. This is called absorption. It will absorb energy that is equal to

  $$\mathbf{h\nu = E_2 - E_1}$$

  The number of atoms excited during time Δt is,

  $$\mathbf{N_{ab} = B_{12} N_1 Q \Delta t}$$

  Where: B_{12} is Einstein coeff.
  N1 is Number atoms in ground state
  Q is Energy Density
  Δt is time from start to end

- **Spontaneous Emission**: An atom in the excited state returns to the ground state thereby emitting a photon of energy hv=E2-E1 without any external inducement. This is called Spontaneous Emission.
  The number of atoms de-excited during time t by spontaneous emission is,

  $$\mathbf{N_{sp} = A_{21} N_2 t}$$

- **Stimulated Emission**: An atom in an excited state is induced to return to the ground state as it de-excites. This leads to two photons having the same energy and frequency. This is called stimulated Emission. The energy of the atom is $hv = E_2 - E_1$
The number of atoms de-excited during time t by stimulated emission is,
$$\mathbf{N_{st} = B_{21}N_2Q\ \Delta t}$$

- **Population inversion**: When the number of excited electrons residing in upper levels are more as compared to the electrons in the lower level, the condition is called a "population inversion".

  <u>In order to obtain the coherent light from stimulated emission, two conditions must be satisfied:</u>
  1. *The atoms must be excited to the higher state. That is, an inverted population is needed, one in which more atoms are in the upper state than in the lower one, so that emission of photons will dominate over absorption.*
  2. *The higher state must be a metastable state - a state in which the electrons remain longer than usual so that the transition to the lower state occurs by stimulated emission rather than spontaneously.*

- **Pumping**: The process of supplying energy to transfer atoms from lower energy state to higher energy state is called pumping.

- **Active Medium**: The medium in which population inversion is possible is called active medium. The active medium can be solid, liquid or gas. The atoms of the active medium are called active atoms or active centres.

- **Resonance Cavity**: Light emitted in the active medium of a laser source initially consists of mostly spontaneously emitted photons. These photons do trigger stimulated emission but since the inducing photons were randomly directed, the stimulated photons are also scattered in all directions.
Moreover, they may be incoherent and have random phases. Thus, there is a requirement of tuning all or most of the stimulated radiation. This is achieved by means of a resonant cavity.

- **Meta-stable state**: Excited atoms have a natural tendency to rapidly de-excite and return to their ground-state. This process usually takes 10^{-8} secs. But, in some energy levels, this process takes as long as 10^{-3} secs which is very long as compared to normal energy levels. These energy levels in which the atom can stay in the excited state for a longer period of time as compared to normal, are called Meta-stable state

DIFFERENCES BETWEEN SPONTANEOUS AND STIMULATED EMISSION:

S. No.	Stimulated Emission	Spontaneous emission
1.	An atom in the excited state is induced to return to the ground state , thereby resulting in two photons of same frequency and energy is called Stimulated emission	The atom in the excited state returns to the ground state thereby emitting a photon, without any external inducement is called Spontaneous emission.
2	The emitted photons move in the same direction and is highly directional	The emitted photons move in all directions and are random
3	The radiation is highly intense, monochromatic and coherent	The radiation is less intense and is incoherent
4	The photons are in phase, there is a constant phase difference	The photons are not in phase (i.e.) there is no phase relationship between them.
5	The rate of transition is given by $R_{12}(Sp) = A_{21}\ N_2$	The rate of transition is given by $R_{12}(Sp) = A_{21}\ N_2$

PUMPING & PUMPING SCHEMES:

There are three types of pumping:

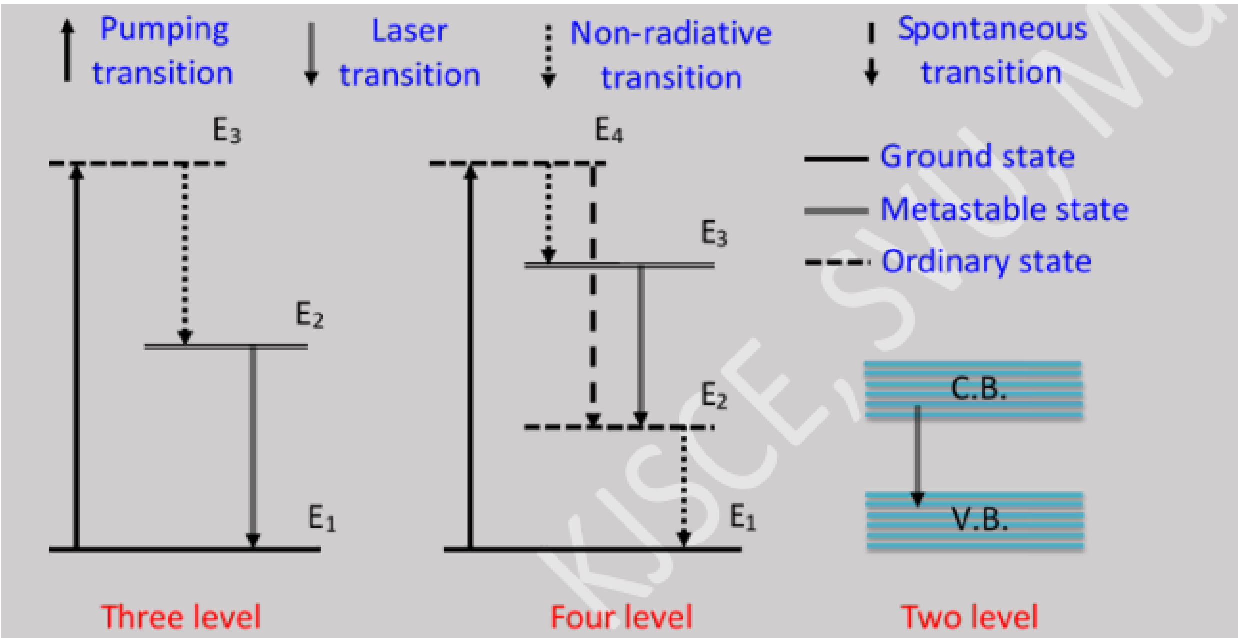
1. **Optical Pumping**: A source of light (photons) is used to supply energy. For example, in the Ruby laser, the Ruby crystal is surrounded by a Xenon flash lamp. The material absorbs the incident radiation and a number of $Cr3+$ ions are excited to higher states. Stimulated emission results if necessary population inversion is achieved properly.

2. **Electrical pumping**: An electric field is set up by a pair of oppositely charged electrodes. For example, in the He-Ne laser, the molecules of helium are ionized and accelerated by the electric field. They gain kinetic energy in this process making many molecules to get transferred into the excited states. Stimulated emission results when population inversion is achieved.

3) **Direct conversion**: Electrical current itself achieves pumping. This is achieved in diode lasers. The energy levels used are conduction band and valence band. The forward bias enhances diffusion currents of holes and electrons to flow into either side, getting many electrons in the conduction band and holes in the valence band. The population inversion is established between these energy bands.

PUMPING SCHEMES:

Generally, three or more energy levels are involved in the event of laser output. The systems in which three energy levels are involved are said to have a three-level pumping scheme. The energy levels, which are actually involved in laser transitions, are called upper and lower lasing levels and the transition between these states is called laser transition.



1) **Three level pumping**: In three-level pumping, the lower level is normally the ground state energy level. The atoms are first raised from the ground state to an excited state E_3. These atoms normally de-excite to an intermediate energy state E_2 by a non-radiative process like emission of heat energy. E_2 being a metastable state, the atoms have a lasting transition from there to the ground state(E_1).
The atoms have to be constantly raised from the ground state to an excited state. It is very difficult to alter the population of the ground state since it is the most stable energy level. High pumping power is required to achieve population inversion.

2) **Four-level pumping**: In four-level pumping, lower as well as upper energy levels are some intermediate excited energy states. Atoms are first pumped to an excited state E_4. From there, they quickly return to level E3 by some non-radiative process like emission of heat. E3 being a metastable state, the atoms have a lasting transition to state E_2. From E_2 again they de-excite to ground state by transferring energy during non-radiative process like collision.
It is easier to achieve population inversion between two excited states rather than pumping atoms continuously from the ground state. Population inversion is achieved faster. Further, Lesser pumping power is required to keep lasing transitions going once the atoms are raised to higher

energy levels from the ground state. Therefore four-level pumping schemes are more efficient than three-level schemes.

3) **Two level pumping**: This word is quite misleading because the levels are not singular energy states but they are rather energy bands. Such type of pumping is achieved in diode lasers. The electrons are transferred from the valence band to the conduction band and they come back to the valence band by giving laser radiation. Some of the input energy is of course, lost but the diode lasers can give maximum output efficiency even better that 70% at times.

TYPES OF LASER SOURCES:

Laser sources are normally divided into six types depending upon the phase of laser source material. They are as follows:

1. **Solid state lasers**: Here, the material used as a laser source is a solid and mostly, crystalline solid. Many times, it is doped with some foreign atoms and these foreign atoms actually give rise to laser light while the host acts as a supporting bulk or heat sink. Common examples of solid state lasers are Ruby laser which is Al_2O_3 crystal doped with Cr and Nd:YAG laser which is Yttrium aluminium garnet ($Y_3Al_5O_{12}$) doped with neodymium.

2. **Gas lasers**: In this, the material used is in gaseous form or they are gases under normal condition. Occasionally they may be metallic vapours. Normally the gas or their mixture is enclosed in a quartz tube which is sealed at both ends. Sometimes, the gases are pumped into the tube. Normally, an electric field is established to excite the gas molecules. Here, one particular gas provides the actual laser light while the other gas or gases are mixed for various reasons like improved efficiency, heat carrier, uniform distribution of pumping power etc. Common examples of gas lasers are He-Ne laser which is a mixture of helium and neon in 10:1 proportion and Argon laser using energy states of Ar^+ ions excited using electric field.

3. **Molecular lasers**: The main laser source under this category is CO_2 laser which is also treated as a gas laser. It is a mixture of carbon dioxide, nitrogen and helium in 1:2:3 proportions. The name is so because the energy levels involved in laser transitions belong to molecular vibrational and rotational energy levels of CO_2 molecules instead of atomic levels of carbon or oxygen. The working of molecular lasers is quite involved.

4. **Tuneable lasers/ Dye lasers**: These are also called as liquid dye lasers as they consists of organic dyes like rhodamine 6G dissolved in solvents like ethanol, benzene or even water.

They have a broad absorption spectrum in the range from near ultraviolet to near infrared. Most importantly, they can be easily tuned to any wavelength in the above region with a little effort so that the same material can emit laser light of different wavelengths. Furthermore, they are highly efficient and economical. There are over 200 different dye lasers being worked out.

5. **Diode lasers**: They form the widest class of laser sources. There are over hundreds of different semiconducting compounds used for diode lasers. They are mainly composed of binary compounds like GaAs, GaP, InAs, InSb, ternary compounds like AlGaAs, InGaAs or quaternary compounds like InGaAsP, InGaAsSb. There are also heterojunction lasers (quantum well lasers) consisting of several layers of semiconducting materials in thin film form. Most of them emit laser light from infrared to red region. Currently people are working on diode lasers emitting light in the blue to ultraviolet region.

6. **Chemical lasers**: These are based on chemical reactions and the energies of chemical reactions of molecules. Some of the energy levels happen to be metastable. An example of this sort is a laser source involving hydrogen and fluorine passed into containers which quickly form the compound hydrogen fluoride. The excitation energy can be used as laser output when the compound comes to ground state.

RELATIONSHIP BETWEEN EINSTEIN'S COEFFICIENTS A-B

* Relation b/w Einstein's coeff A & B :-

abs. - $N_{ab} = B_{12} N_1 Q \Delta t$ upward transitn

spont. $N_{sp} = A_{21} N_2 Q \Delta t$ downward "

stim. $N_{st} = B_{21} N_2 Q \Delta t$ downward "

$$N_1 = N_0 e^{-E_1/KT} \quad \text{--- (1)} \qquad N_2 = N_0 e^{-E_2/KT} \quad \text{--- (2)}$$

$$\boxed{\frac{N_1}{N_2} = e^{\frac{1}{KT}(E_2 - E_1)}}$$

$\because [E_2 - E_1 = h\nu]$

$$\boxed{\frac{N_1}{N_2} = e^{h\nu/KT}} \quad \text{(3)}$$

At eq^{m} $N_{ab} = N_{sp} + N_{st}$

$$B_{12} N_1 Q \Delta t = A_{21} N_2 \Delta t + B_{21} N_2 Q \Delta t$$

$$Q (B_{12} N_1 - B_{21} N_2) = A_{21} N_2$$

$$\therefore Q = \frac{A_{21} N_2}{B_{12} N_1 - B_{21} N_2}$$

$$Q = \frac{A_{21} N_2 / B_{21} N_2}{\frac{B_{12} N_1}{B_{21} N_2} - \frac{B_{21} N_2}{B_{21} N_2}}$$

$$Q = \left(\frac{A_{21}}{B_{21}}\right) \frac{1}{\left[\frac{B_{12}}{B_{21}}\left(\frac{N_1}{N_2}\right) - 1\right]} \quad \text{- (3)}$$

From 1 & 2 & 3

$$Q = \frac{A_{21}}{B_{21}} \frac{1}{\left[\left(\frac{B_{12}}{B_{21}}\right)\left(e^{h\nu/KT}\right) - 1\right]} \quad \text{--- (4)}$$

We know $\Rightarrow$ $Q = \left[\frac{8\pi h\nu^3}{C^3}\right] \frac{1}{\left[e^{h\nu/KT} - 1\right]}$ --- (5)

From 4 & 5

$$\boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{C^3}} \quad \& \quad \boxed{\frac{B_{12}}{B_{21}} = 1}$$

$$\Rightarrow \boxed{B_{12} = B_{21}}$$

EQUILIBRIUM CONDITIONS AND EINSTEIN'S COEFFICIENTS

At equilibrium (no exchange of energy in any form except light), the number of upward transitions is equal to the number of downward transition so that the ratio N_1/N_2 remains constant. This gives

$$N_{abs} = N_{sp} + N_{st}$$

$$\therefore B_{12}N_1Q\Delta t = A_{21}N_2\Delta t + B_{21}N_2Q\Delta t$$

According to Einstein, the probabilities of stimulated events i.e. absorption and emission are the same i.e. is $B_{12} = B_{21}$. Therefore we get $\frac{N_1}{N_2} = 1 + \frac{A_{21}}{B_{21Q}}$.

According to Boltzmann's statistics, the ratio of population of two levels at temperature T is given by $\frac{N_1}{N_2} = e^{h\nu/kT}$. Therefore, we get $1 + \frac{A_{21}}{B_{21Q}} = e^{h\nu/kT} \Rightarrow Q = \frac{A_{21}}{B_{21}}\left(\frac{1}{e^{h\nu/kT} - 1}\right)$.

Comparing the above expression for Q with the Planck's formula for incident radiation energy density namely $Q = \frac{8\pi h\nu^3}{c^3}\left(\frac{1}{e^{h\nu/kT} - 1}\right)$, we get $\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$.

Above equation gives the ratio of Einstein's A and B coefficients and the unit is J-s/m^3.

Further, let us compare the stimulated emission with other two processes:

$$\frac{\text{stimulated emission}}{\text{spontaneous emission}} = \frac{B_{21}}{A_{21}}Q; \qquad \frac{\text{stimulated emission}}{\text{absorption}} = \frac{N_2}{N_1}$$

- At room temperatures and at thermal equilibrium, absorption and spontaneous emission processes nearly balance each other. At equilibrium, $N_1 >> N_2$ and also, $A_{21} > B_{21}$. RHS of both terms are less than unity and the stimulated emission is negligible with other two processes. Therefore, we do not observe laser light in normal conditions and the light due to all ordinary sources are a result of spontaneous emission processes.

- Q must be made large enough so that the product on the RHS of the first term becomes greater than unity. Further, we have to make $N_2 > N_1$. Since this cannot happen naturally, we have to supply energy to the atoms and maintain them in higher energy levels.

- Note: To achieve stimulated emission we have to make N2 > N1. But this is the reserve condition of what is observed at equilibrium condition. Since we have to disturb the equilibrium condition, lasers are often called as non-equilibrium processes.

THRESHOLD CONDITION FOR LASERS:

- When the small-signal gain just equals the resonator losses, then it is called the threshold condition of a LASER.
- When operation is well above the threshold, then power output is significant, power efficiency is good and stable, noise is low.
- A low threshold power requires low resonator losses and a high gain efficiency.
- It is achieved using a small laser mode area in an efficient gain medium with limited emission bandwidth.
- The optimization of the laser output power for a given pump power usually involves a compromise between high slope efficiency and low laser threshold.

LASER BEAM PARAMETERS:

- **Beam Diameter (Radius, Width)**: The beam diameter (generally defined as twice the beam radius, is the most important propagation-related attribute of a laser beam.
- **Spatial Intensity Distribution (Beam Profile)**: It incorporates all the mechanical, thermal and electromagnetic variables that created the beam.
- **Divergence**: The beam divergence of a laser beam is a measure for how fast the beam expands as it propagates in space.
- **Beam Quality Factor M^2 (Beam Parameter Product)**: It describes the propagation of an arbitrary beam and derived from the uncertainty principle. M^2 is a measurable quantity in order to characterise real mixed-mode beams.