Module 1 Unit 3

PRINCIPLES OF LASERS

(As per SVU-R2020 Scheme & Syllabus)

- **Introduction**

LASER stands for "Light Amplification by Stimulated Emission of Radiation". Laser is a highly directional, focused, monochromatic, coherent and bright source of light. The difference of laser light from ordinary light is contained in the name itself - the process of *stimulated or forced emission*. Ordinary light, on the contrary, is a result of *spontaneous or natural emission*. Stimulated emission cannot occur at normal conditions. The first successful laser source was the Ruby laser developed by T. H. Maiman in 1960.

- **Laser beam parameters**

Laser light enjoys at least five advantages over ordinary light. They can be listed as the laser beam parameters. Following table gives a summery of laser beam parameters:

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

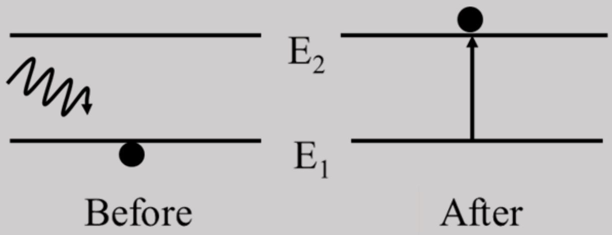
- **Interaction of radiation with matter**

Radiation consists of photons and matter consists of atoms and molecules. Obviously, interaction of radiation with matter means interaction of photons with atoms and molecules. The interaction can be as simple as light absorbed by a material or light emitted from a material. There are three processes, which coexist at all temperatures whenever there is an interaction between radiation and matter. Their proportion may change depending upon the material and its temperature. They are *Absorption, spontaneous and stimulated emission*.

  - **Absorption**

  Consider an atom residing in the lower energy state E_1 and a radiation of certain energy is incident. The atom may absorb the incident energy (if sufficient) and jump to the next energy state E_2. This process is called as *induced or stimulated absorption* because we have to externally supply energy.

The atoms will not automatically jump into the excited states. It means there is no spontaneous absorption as such.



Corresponding to each transition from E_1 to E_2, one photon of energy $h\nu = E_2 - E_1$ disappears and the atom is excited. The number of atoms excited during time Δt is,

$N_{ab} = B_{12}N_1Q\Delta t$ Where,

B_{12}: probability of absorption process

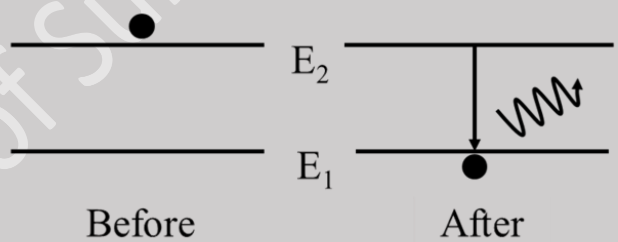
N_1: number of atoms in lower energy level E_1

Q: energy density of incident radiation (given in J-s/m^3)

The number of absorption events taking place at any instant is proportional to number of atoms present in the lower energy states. Since atoms tend to stay in the lowest possible energy states, most of the photons are absorbed as radiation penetrates the matter i.e. it is attenuated.

- **Spontaneous emission**

  An atom raised to its excited state does not stay there for long time because the excited state is inherently unstable. Excited atoms rapidly de-excite due to the natural tendency of atoms to seek for the lowest energy state. This type of process in which, atom on its own releases a photon is called as *natural or spontaneous emission.*



Corresponding to each transition E_2 to E_1, one photon of energy $h\nu = E_2 - E_1$ appears. The number of atoms de-excited during time Δt by spontaneous emission is,

$N_{sp} = A_{21}N_2\Delta t$ Where,

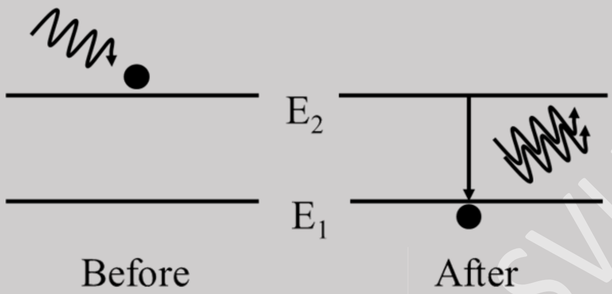
A_{21}: probability of spontaneous emission process

N_2: number of atoms in higher energy level E_2

The number of spontaneous emission events taking place at any instant is proportional to number of atoms present in the higher energy state. The process of spontaneous emission is completely probabilistic.

- **Stimulated emission**

This type of process also exists along with the above two processes but at room temperature, spontaneous emission dominates stimulated emission and the latter is generally negligible. The idea behind stimulated emission is that the process of emission need not be always probabilistic but we can make some transitions to occur. A photon of energy $h\nu = E_2 - E_1$ or greater can induce the excited atom to de-excite to release energy in the form of another photon. The released photon is identical to the incident photon in every respect. This is called *induced or stimulated emission*.



Corresponding to every induced transition E_2 to E_1 due to a single photon, two identical photons of energy $h\nu = E_2 - E_1$ appear. The number of atoms de-excited during time Δt by stimulated emission is,

$N_{st} = B_{21}N_2Q\Delta t$ Where,

B_{21}: probability of stimulated emission process

N_2: number of atoms in higher energy level E_2

Q: energy density of incident radiation

The number of stimulated emission events taking place at any instant is primarily proportional to number of atoms in the higher energy state.

The spontaneous emission events are completely probabilistic meaning there is no control to which and how many atoms will de-excite at a given time and which energy levels are involved. Therefore spontaneously emitted light is incoherent, divergent, diffused and undirected. It may or may not be monochromatic. Light from ordinary sources (e.g. bulb, tube light, LED, Na – light, candle, burner etc) is a result of spontaneous emission.

The process of stimulated emission has following advantages over spontaneous emission:

1) The process is controllable from outside. We can control the intensity and energy density of inducing radiation.
2) The induced radiation is identical to the incident radiation in every respect: energy, frequency or wavelength, phase, state of polarization, direction of propagation etc.
3) By selecting proper active medium and resonance conditions, multiplication of photons is achieved. This leads to oscillations of radiation within a specially prepared region called as optical resonance cavity.

As a result, we get a highly monochromatic, coherent, directional, focused and intense. Thus, to obtain laser light means to obtain light amplification (rather oscillations) by stimulated emission of radiation at a desired wavelength.

- Note: When an atom absorbs a photon/s, the energy is actually shared by its orbital electrons. The electrons are either transferred to higher energy states or they even be dislodged from the atom. It is normally a practice to say that the atom is excited instead of calling electrons being exited. Following this, it is also a practice of showing an atom itself, transferred from one energy state to the other.

- **Important laser physics terms**

When studying lasers, we come across to a number of important terms and concepts. Some of them are listed below to get a brief idea about principles of lasers.

1) Population

The number of *active* atoms occupying a particular energy state is called population of that energy state. Active atoms mean atoms, which are likely to be excited by incident radiation or atoms, which are already excited by absorbing photon/s and are about to de-excite. Thus, N_1 and N_2 is population of state E_1 and E_2 respectively.
At equilibrium, we have,

$$N_1 = N_2 e^{(E_2 - E_1)/kT}$$

Since $E_2 > E_1$, at equilibrium, $N_1 >> N_2$ that is, the lower state E_1 is said to be *populated* as compared to the excited state E_2 which seems obvious.

2) 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

$$N_{abs} = N_{sp} + N_{st}$$
$$\therefore B_{12} N_1 Q \Delta t = A_{21} N_2 \Delta t + B_{21} N_2 Q \Delta t$$

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 that 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 is a result of spontaneous emission processes.
- Q must be made large enough so that product on RHS of 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 $N_2 > N_1$. But this is 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***.**

3) Population inversion

There must be more atoms in the higher energy level E_2 than in the lower energy level E_1 in order to achieve stimulated emission exclusively. This is a non-equilibrium process as noted above in which the higher energy state is pore populated than the lower energy state. When this situation is achieved, the population between the energy levels E_1 and E_2 is said to be *inverted* and the medium or region in which this is achieved is said to be transferred in the state of *population inversion*.

4) Active system or active medium

The region in which the state of population inversion is achieved is called as the *active medium or active system*. The actual laser light is emitted from this region. The system can be a solid, liquid or gas. Further, the whole system may not take part in population inversion; only a fraction of it is responsible. For example, in semiconductor diode laser, it is the depletion region which goes in the state of population inversion and not the entire diode. In Ruby laser, the lattice sites occupied by Cr^{3+} ions act as active centres and the Al_2O_3 crystal (Ruby) just acts as host and heat sink.

5) Pumping

For maintaining the state of population inversion, the atoms have to be continuously raised to excited states. It requires energy to be supplied to the system from outside. The process of supplying energy to the system with an objective of keeping it into the state of population inversion is called as pumping. Various methods used for pumping are:

1) **Optical pumping:** A source of light (photons) is used to supply energy. For example, in Ruby laser, the Ruby crystal is surrounded by Xenon flash lamp. The material absorbs the incident radiation and a number of Cr^{3+} ions are excited to higher states. Stimulated emission results if necessary population inversion is achieved properly.

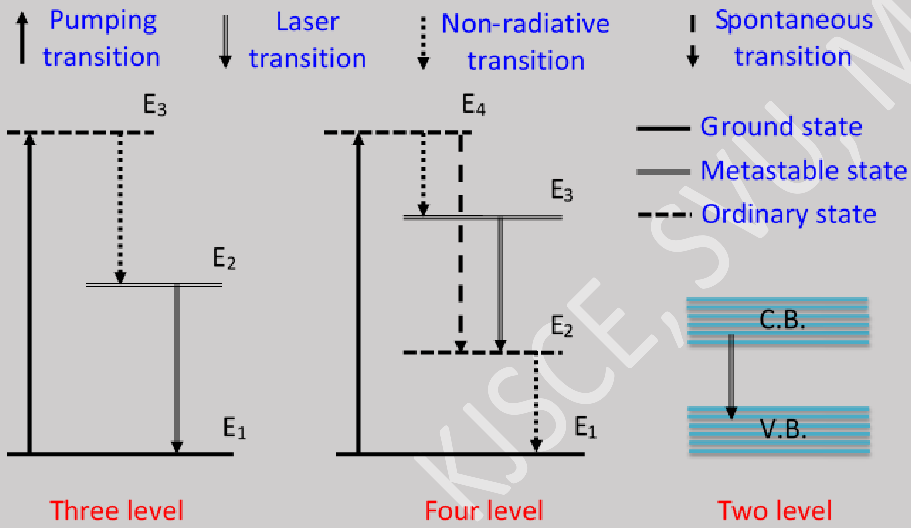
2) **Electrical pumping:** An electric field is set up by a pair of oppositely charged electrodes. For example, in He-Ne laser, the molecules of helium are ionized and accelerated by the electric field. They gain kinetic energy in this process making many molecules to get transferred into the excited 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 sides getting many electrons in

the conduction band and holes in the valence band. The population inversion is established between these energy bands.

6) Pumping schemes

Generally, three or more energy levels are involved in the event of laser output (except for diode lasers). The systems in which three energy levels are involved are said to have *three-level pumping* scheme e.g. Ruby laser and those using four energy levels are said to have *four-level pumping* scheme e.g. He-Ne laser and Nd:YAG laser. The energy levels, which are actually involved in laser transitions, are called as *upper and lower lasing levels* and the transition between these states is called as *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 some non-radiative process like emission of heat energy. E_2 being a metastable state, the atoms, they have lasing 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 E_3 by some non-radiative process like emission of heat. E_3 being a metastable state, the atoms have a lasing transition to state E_2. From E_2 again they de-excite to ground state by transferring energy during non-radiatve process like collisions etc.
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 efficient that 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 laser. The electrons are transferred from the valence band to the conduction band and they come back

to 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.

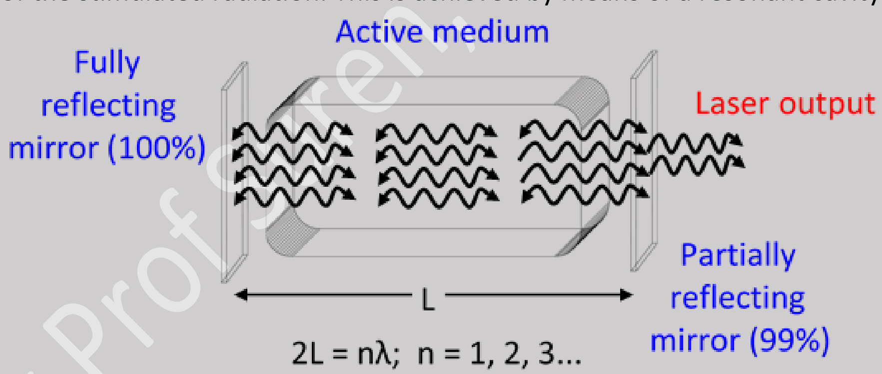
7) Meta stable state

Excited atoms have natural tendency to rapidly de-excite to their ground states. This process usually occurs within 10^{-8} seconds. However, there are certain energy states in which excited atoms can reside for as long as 10^{-3} seconds. This interval is long compared to normal de-excitation times of atoms. Therefore these states are called *metastable states*.

For stimulated emission to occur, the atoms are required to occupy the upper energy level until the triggering radiation is incident. The metastable state allows accumulation of atoms in a higher energy level and we can practically realise the state of population inversion. Meta stable states are extremely important because they assist in maintaining the condition for population inversion (viz. $N_2 > N_1$). Otherwise population of the excited states would rapidly decrease and there would be no laser transitions. In fact, the invention of lasers could not have taken place if elements offering metastable states were not discovered. For example the 2s and 3s states of Ne^+ ions having energies 18.7 eV and 20.66 eV, in He-Ne laser, 4p energy state of Ar^+ ions in Argon gas laser or 1.4 eV energy level of Cr^{3+} ions in Ruby laser are actually metastable states.

8) Resonant 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 phase. Thus, there is a requirement of tuning all or most of the stimulated radiation. This is achieved by means of a resonant cavity.



In its simplest form, resonant cavity may consist of two plane parallel mirrors held at a specific distance. The distance between them is usually adjusted in proportion of the wavelength of radiation to be emitted. One of the mirrors is made semi-transparent to take out part of the radiation. Such type of arrangement is often called the *Fabry-Perot Resonator*. In case of solid state or semiconductor diode lasers, this is done by cleaving opposite surfaces optically parallel to each other and polishing them to mirror-finish.

The stimulated radiation generated in the resonator cavity reflects back and forth multiple times due to mirrors, which triggers further radiation. Thus, light is said to be amplified. Slowly, there is a built-up of highly collimated beam of light, which is mono-energetic, coherent, in-phase and (maybe) uniformly polarized.

9) 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 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. Further, 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.
