LASER

A **laser** is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term "laser" originated as an acronym for "**light amplification by stimulated emission of radiation**".

A laser differs from other sources of light in that, it emits light which is absolutely coherent. Spatial coherence allows a laser to be focused to a tight spot, enabling applications such as laser cutting and lithography. Spatial coherence also allows a laser beam to possess extreme directionality over great distances, enabling applications such as laser pointers. Lasers can also have high temporal coherence, which allows them to emit light with a very narrow spectrum, i.e., they can have extreme monochromaticity. Alternatively, temporal coherence can be used to produce pulses of light with a broad spectrum but durations as short as a femtosecond

Types of emission of radiation from an atom or nucleus: Einstein's A and B coefficients.

1. Spontaneous emission: Spontaneous emission is the process in which a quantum mechanical system (such as a molecule, an atom or a subatomic particle) transits from an excited energy state to a lower energy state (e.g., its ground state) and emits a quantized amount of energy in the form of a photon. A photon having an adequate energy (≥ the energy difference between the two levels) can be absorbed by an atom thereby exciting it to a higher energy level, which in general is exceedingly short lived (10ns). So this atom will revert back to lower states by emitting a photon of energy equal to the energy difference of the levels, without the influence of any external agent. Let us consider two such states with energies E_1 and E_2, with $E_2 > E_1$.

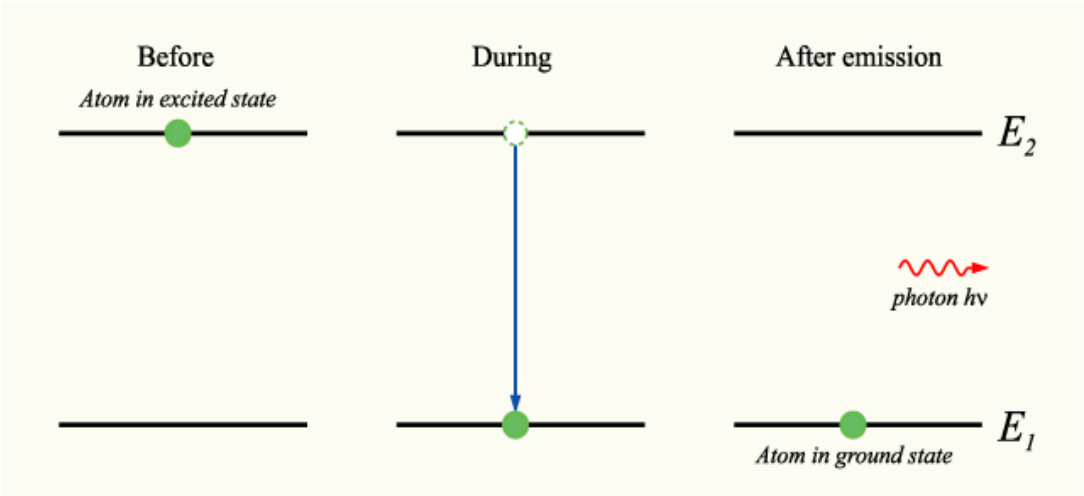


Fig. 5.1. Energy level diagram of spontaneous emission.

An atom, in excited state is assumed to be in the level E_2. This excited electron, if allowed some 'time', will undergo transition to the lower energy state or ground state E_1 spontaneously, by emitting energy in form of radiation. This radiation is quantized in the form of a photon of energy: $h\nu = E_2 - E_1$ .....(5.1)

Where ν is the frequency of emitted radiation.

Spontaneous transition of an electron from excited state to ground state can also be non radiative. The process is called **non radiative relaxation**. In nonradiative relaxation, the energy is released as **phonons,** more commonly known as heat. Nonradiative relaxation occurs when the energy difference between the levels is very small, and these typically occur on a much faster time scale than radiative transitions. But here we shall confine ourselves to radiative transitions only.

Let N_1 = population of atoms per unit volume in energy level E_1

N_2 = = population of atoms per unit volume in energy level E_2

The transition rate of atoms from E_2 to E_1 is directly proportion to the existing population of E_2 but independent of any field environment around the system.

$\therefore \quad \left(\frac{dN_2}{dt}\right)_{sp} = -A_{21}N_2$ .....(5.2) A_{21} is a constant.

A_{21} = probability of spontaneous transition from level E_2 to E_1. It is called **Einstein's A coefficient**

The negative sign denotes that the population of level (2) decreases with time. The Value of A_{21} changes if the energy levels are different i.e. $A_{21} \neq A_{43} \neq A_{75}$.

Radiations which are emitted spontaneously are linearly polarized. All the spontaneous emissions between a fixed pair of levels will have same frequency. **Spontaneous emission** depends on the lifetime of the atom in the excited state. The process is statistical and the **emitted** quanta bear no phase relationship with one another, i.e. the **emission is incoherent**.

2. Stimulated emission: Stimulated emission is the process by which an incoming photon of a specific frequency, corresponding to the energy difference between the excited state and lower energy state, can interact with an excited atomic electron (or other excited molecular state), causing it to drop to a lower energy level. There will be two photons present then – the incident photon and emitted photon. Obviously the stimulated photon will have **same frequency, direction, phase and same state of linear polarization** as that of the incident one. **This gives light amplification.**

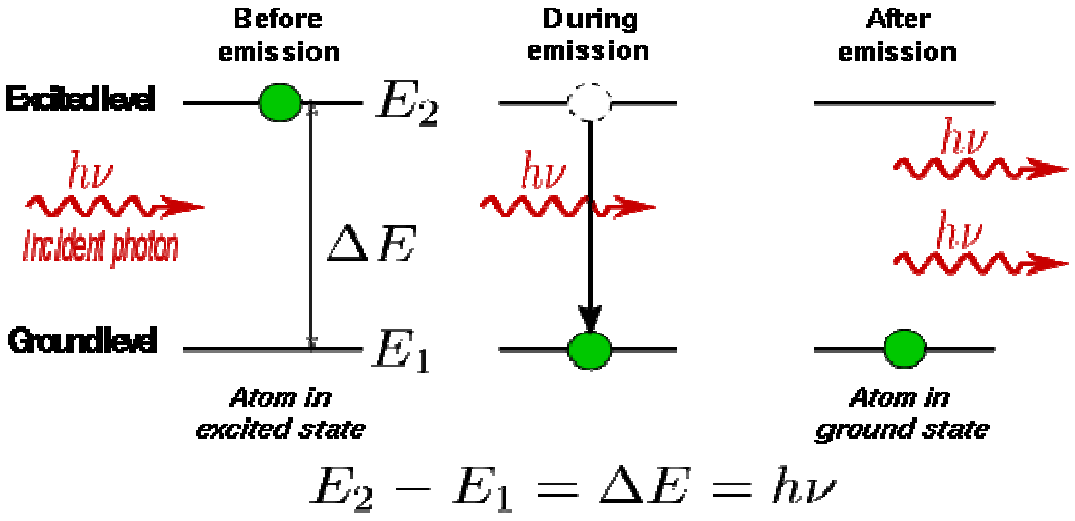


Fig. 5.2. Energy level diagram for stimulated emission

Let it be considered that some atoms initially excited to a level E_2, is triggered by incoming photons to undergo transition to a lower level E_1. If N_2 be the population of the level E_2, then the rate of stimulated emission is given by

$$\left(\frac{dN_2}{dt}\right)_{st} = -B_{21}F(\nu)N_2 \quad \text{for parallel incident radiation}$$
$$= -B_{21}U(\nu)N_2 \quad \text{for diffused incident radiation.} \qquad \text{.....(5.3)}$$

$F(\nu) \rightarrow$ Intensity of stimulated emission with frequency ν

$U(\nu) \rightarrow$ Energy density of stimulated emission with frequency ν

$B_{21} \rightarrow$probability of stimulated transition from level E_2 to E_1. It is called **Einstein's B coefficient**

The general treatment is to consider diffused radiation. It is to be noted that in addition to stimulated emission, spontaneous emission is also present.

If $\frac{dN_2}{dt}$ be the net rate of emission from level (2) to level (1) then:

$$\frac{dN_2}{dt} = \left(\frac{dN_2}{dt}\right)_{sp} + \left(\frac{dN_2}{dt}\right)_{st} \qquad \text{.....(5.4)}$$

However, not all the photons of the incident radiation stimulate emission. Some may be absorbed also thus exciting some atoms to higher states. In case of absorption the rate of change of the atoms during excitation from some initial state to higher states depends directly on $U(\nu)$, the energy density of incident radiation at the frequency characteristic of the energy

difference between the two states. Excitation rate via absorption is also directly proportional to the number of atoms in the initial state. So the stimulated absorption rate is :

$$\left(\frac{dN_1}{dt}\right)_{st} = - B_{12}U(\nu)N_1 \quad \text{.....(5.5)}$$

$B_{12} \rightarrow$ Einstein's B coefficient corresponding to the probability of stimulated absorption of photon resulting in excitation from lower level E_1 to higher level E_1.

Relation between Einstein's A and B coefficients.

When a piece of matter is placed inside an electromagnetic radiation envelope (e g. blackbody chamber) it will attain equilibrium when the rate of emission equals the rate of absorption, and the matter will attain the same temperature as the blackbody chamber.

At equilibrium:

$$\frac{dN_2}{dt} = \left(\frac{dN_1}{dt}\right)_{st}$$

Or $$\left(\frac{dN_2}{dt}\right)_{sp} + \left(\frac{dN_2}{dt}\right)_{st} = \left(\frac{dN_1}{dt}\right)_{st}$$

Or $A_{21}N_2 + B_{21}U(\nu)N_2 = B_{21}U(\nu)N_1$ .....(5.6) from eqn. (5.2), (5.3), (5.5)

Which gives: $U(\nu) = \dfrac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2} = \dfrac{\frac{A_{21}}{B_{21}}}{\frac{B_{12}N_1}{B_{21}N_2} - 1}$ .....(5.7)

Applying Maxwell-Boltzmann distribution: $N_1 \alpha e^{\frac{-E_1}{KT}}$, $N_2 \alpha e^{\frac{-E_2}{KT}}$ .....(5.8)

So $$\frac{N_1}{N_2} = e^{\frac{(E_2 - E_1)}{KT}} = e^{\frac{h\nu}{KT}} \text{.....(5.9)}$$

Substituting equation (5.9) in (5.7)

$$U(\nu) = \frac{\frac{A_{21}}{B_{21}}}{\frac{B_{12}}{B_{21}}e^{\frac{h\nu}{KT}} - 1} \quad \text{.....(5.10)}$$

From Plank's expression of energy density of blackbody radiation:

$$U(\nu) = \frac{\frac{8\pi h\nu^3}{c^3}}{\left(e^{\frac{h\nu}{KT}} - 1\right)} \quad \text{.....(5.11)}$$

Comparing (5.10) and (5.11)

$$\frac{B_{12}}{B_{21}} = 1 \Rightarrow B_{12} = B_{21} = B \quad \text{.....(5.12)}$$

And $$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \quad \text{.....(5.13)}$$

Equations (5.12) and (5.13) give the relation between Einstein's 'A' and 'B' coefficients. Now, $\frac{8\pi h\nu^3}{c^3}$ being an universal constant, so $\frac{A_{21}}{B_{21}} = \text{constant}$. In other words the probability of spontaneous emission(A_{21}) is directly proportional to the probability of stimulated emission(B_{21}). So an atom susceptible to one mechanism is proportionately susceptible to the other.

Effect of exposing a block of a substance to incidence radiation.

Let a block of some matter of unit cross sectional area and thickness 'dz' be considered to be in thermal equilibrium having two possible energy states. The frequency corresponding to the energy difference between the two levels is 'ν'. The volume of the block is hence 'dz' cubic units of length. The atoms of the matter are assumed to have a long mean life so that spontaneous emission can be ignored. The system is exposed to electromagnetic radiation proceeding along Z direction as shown in fig. (5.3).

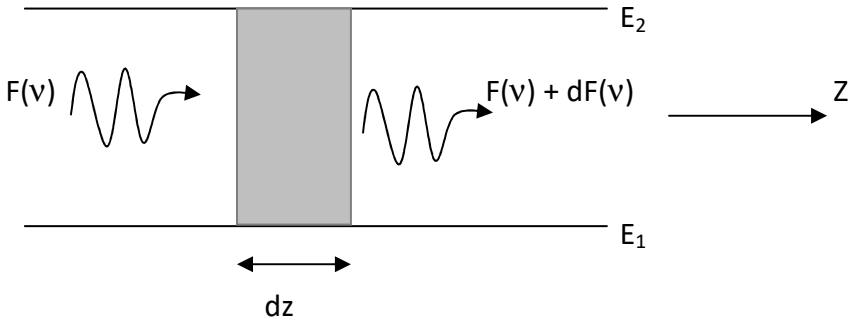


Fig. 5.3

F(ν) → Incident photon flux corresponding to frequency 'ν'

After passing through the block the photon flux changes by an amount dF(ν)

F(ν) + dF(ν) → outgoing photon flux corresponding to frequency 'ν'

$N_1 \rightarrow$ population of level (1) at any instant.

$N_2 \rightarrow$ population of level (2) at that instant

Rate of stimulated emissions of frequency 'ν' from the block is = $BF(\nu).N_2.dz$

Rate of stimulated absorptions of frequency 'ν' in the block is = $BF(\nu).N_1.dz$

B $\rightarrow$ Einstein's B coefficient which is same for stimulated emission and absorption.

Hence the net change in photon flux is:

$$dF(\nu) = BF(\nu).N_2.dz - BF(\nu).N_1.dz = BF(\nu.)dz.(N_2 - N_1) \quad \text{.....(5.14)}$$

dF(ν) may be positive or negative depending on whether the net process is emission or absorption i.e. on the values of N_2 and N_1.

$$\frac{dF(\nu)}{dz} = BF(\nu.)\,(N_2 - N_1) \quad \text{.....(5.15)}$$

= change in photon flux per unit time per unit volume of the block of matter.

For $N_2 > N_1$: dF(ν) is positive indicating that stimulated emission predominates and the matter acts as an amplifier of the incident radiation.

For $N_2 < N_1$: dF(ν) is positive indicating that stimulated absorption predominates and the matter acts as an absorber of incident radiation.

For $N_2 = N_1$: dF(ν) is zero and the medium is transparent to incident radiation.

Concept of population inversion

Normally, for a system of atoms is in thermal equilibrium there are always more atoms in low energy states than in higher ones. It has been seen in the previous section that amplification stimulated emission occurs if the population of the higher energy level should be greater than the population of the lower energy level. So a **redistribution of the population of the levels is required where the higher energy level has a larger population than the lower energy level. This situation is called population inversion.** A substance which is capable of undergoing population inversion and amplifying incident radiation by stimulated emission is called is called **active substance.**

Pumping

Pumping is a process in which energy is used to raise (or "pump") electrons from a lower energy level in an atom or molecule to a higher one. It is commonly used in laser construction, to pump the active laser medium so as to achieve population inversion.

1. Optical pumping: If light energy is used to bring about population inversion, the corresponding pumping is called optical pumping. This process is commonly used for liquid and solid lasers. Usually a flash lamp is used for this purpose.

2. Electrical pumping: If electrical energy is used to bring about population inversion, the corresponding pumping is called electrical pumping. This process is commonly used for gas and semiconductor lasers.

Only two energy levels are not sufficient to obtain sustained population inversion.

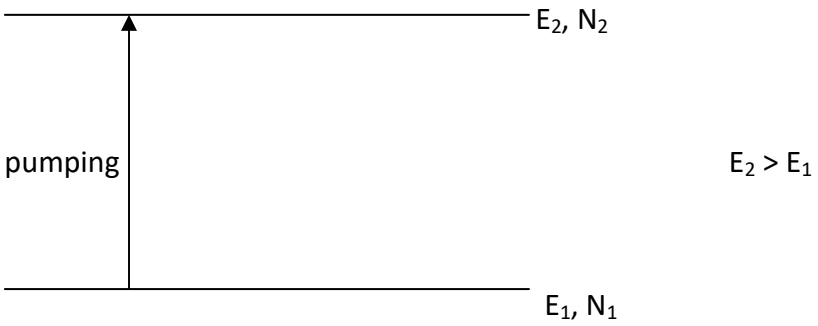


Fig. 5.4.

Let N_1 and N_2 be the population of the energy levels E_1 and E_2 of a given amount of some material. Initially, $N_1 > N_2$. For obtaining population inversion atoms have to be pumped from level (1) to (2). AS pumping proceeds, the population of level (2) increases at the expenses of level (1). Finally a stage will be reached when the population of (1) equals that of (2). So at this stage, the value of $\frac{dF(\nu)}{dz}$ as given by equation (5.14) becomes zero. At this stage the rate of stimulated emission will completely compensate the rate of stimulated emission and equilibrium is established. . Hence further continuation of pumping will be of no use. To achieve population inversion the number of available energy states should be at least three or more. At least one metastable state is required between the two terminal levels.

Metastable state.

Metastable state is an excited state of an atom or other system with a longer lifetime than the other excited states. However, it has a shorter lifetime than the stable ground state. Atoms in the metastable state remain excited for a considerable time in the order of 10^{-6} to 10^{-3}. During metastable state, all the parameters associated with state hold stationary values. A large number of excited atoms can accumulate in the metastable state. The population of metastable state can exceed the population at a lower level thereby establishing population inversion in a lasing medium. So metastable state is also called a **lasing state.** Population inversion could not be created without a metastable state.

Three level laser

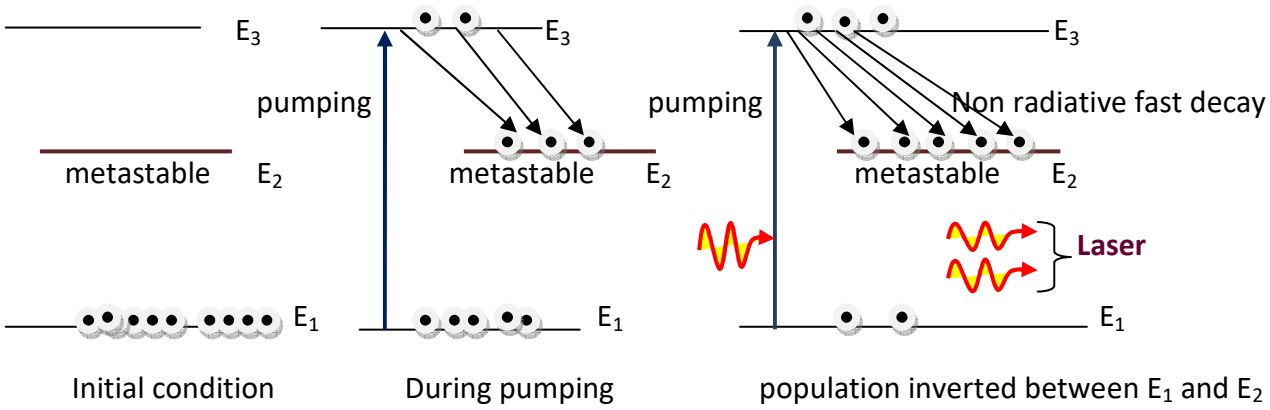


Fig. 5.6. Schematic diagram of three level laser.

In the three level laser system, the atoms are pumped from the ground state E_1 to higher state E_3 with the help of pumping source. The E_3 is called pumping state. The life time of atoms is least in the energy level E_3. It means E_3 is unstable stable state and here atoms stay for 10^{-9} -10^{-8} seconds. It is assumed that initially all the atoms are in ground state and the levels E_2 and E_3 are empty. The lifetime of the atoms in level (3) being very small they undergo non-radiative fast decay to the metastable state E_2. Lifetime of atoms in the metastable state is about 1000 time higher than in E_3. **Due to continuous pumping of atoms from level (1) to (3) and fast decay from level (3) to (2), the population of level (2) increases at the expense of level (1). Thus ultimately a population inversion is achieved between the level (1) and metastable state (2) and lasing action starts between E_2 and E_1**. E_2 is known as upper laser level (ULL) and E_1 is known as lower laser level (LLL).

Drawback of a three level laser: In the three level laser system, the terminal level is ground level and hence more than half of the atoms are to be transferred to level E_2 to achieve

population inversion. This requires more pumping power and more time for lasing action to start. If the difference of population between the two levels is small, less power is required. But piling of large number of atoms in level E_2, give rise to large number of spontaneous non-radiative transitions to E_1 also. This energy is usually carried by lattice photons due to which the efficiency of three level laser system is less.

Four level laser:

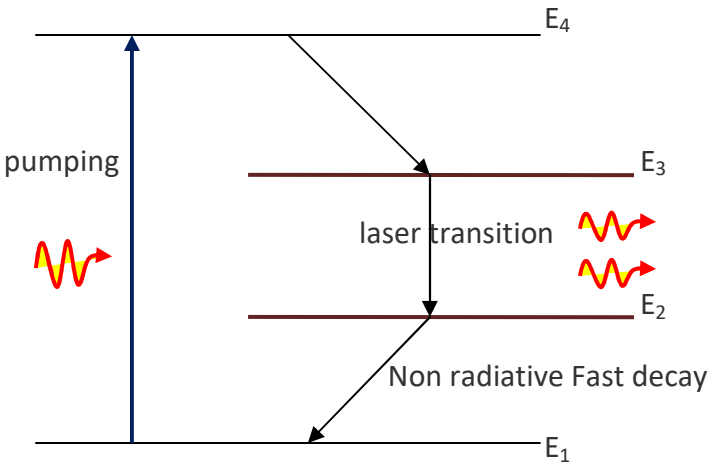


Fig. 5.7. Schematic diagram of four level laser.

In the four level laser system, the atoms are pumped from the ground state E_1 to highest state E_4 with the help of pumping source. The E_4 is called pumping state. The life time of atoms is least in the energy level E_4. It means E_4 is unstable stable state and here atoms stay for $10^{-}9$ to 10^{-8} seconds. It is assumed that initially all the atoms are in ground state and the levels E_2, E_3 and E_4 are empty. The lifetime of the atoms in level (4) being very small they undergo non-radiative fast decay to the metastable state E_3. Lifetime of atoms in the metastable state is about 1000 time higher than in E_4. **Due to continuous pumping of atoms from level (1) to (4) and fast decay from level (4) to (3, the population of level (3 increases at the expense of level (1). Level(2) being initially completely empty population inversion sets in at the very instant level (3) receives a single atom. So lasing action starts immediately.** E_2 is known as upper laser level (ULL) and E_1 is known as lower laser level (LLL). Now, the atoms in level E_2 l\has a very short life time and undergoes non radiative fast decay to level (1) and the pumping cycle starts again. So level (2) always remains less populated than level (3) and lasing action continues.

Laser as oscillator

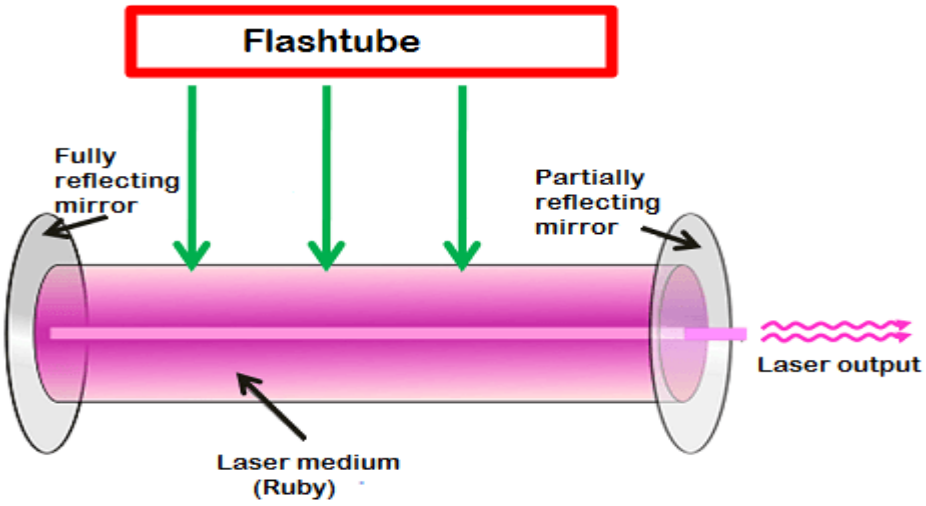


Fig. 5.8. Diagram of an optical oscillator.

In general to obtain an oscillator from an amplifier it is necessary to obtain a positive feedback. An optical **cavity**, resonating **cavity** or optical **resonator** is an arrangement of mirrors that forms a standing wave **cavity resonator** for light waves. Optical **cavities** are a major component of **lasers**, surrounding the gain medium and providing positive feedback of the **laser** light. Let us see how it can be achieved. Let an active material be exposed to electromagnetic radiation. From equation (5.14) the change in photon flux on passage through the material is:

$$dF(\nu) = BF(\nu.)dz.(N_2 - N_1)$$

This shows that dF(ν) is directly proportional to 'dz' So a high value of dF(ν) can be achieved for a very high value of 'dz'. This does not mean that the thickness of the active material has to be infinite. The material of finite thickness 'dz' is placed in a **Febry-Perot cavity**, i.e. between two highly reflecting mirrors. The radiation will then traverse the active material a large number of times via multiple reflections at the reflectors. This effectively increases the thickness of material traversed by photons. This cavity is also called **Laser cavity.**

Assuming that population inversion has been achieved in the active substance, the photon flux increases each time on passing through it and amplification occurs. Having been triggered by some spontaneous radiation emitted along the axis of the laser, the system starts to oscillate if the feedback is sufficiently large to compensate for the internal losses of the system. The amount of feedback is determined by the reflectivity of the mirrors. Lowering the reflectivity of the mirrors is equivalent to decreasing the feedback factor. The mirror at the output end of the laser must be partially transparent for a fraction of the radiation to "leak out" or emerge from the oscillator.

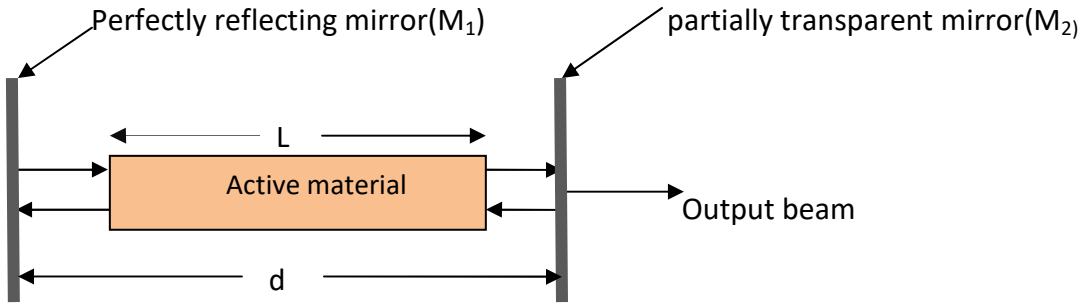


Fig. 5.8. Schematic diagram of laser as oscillator.

Let L → The length of the active substance

d → Distance between the two mirrors.

2L → Effective thickness of the active substance traversed by incident radiation in one round trip

So from equation 5.14,

$$\frac{dF(\nu)}{F(\nu)} = BN_2 - N_1)dz \quad \text{.....(5.16)}$$

N_2 and N_1 are the population of the levels between which population inversion has been achieved.

If F_i = initial photon flux and F_f is the final photon flux after a round trip then Integrating equation (5.16)

$$\int_{F_i}^{F_f} \frac{dF(\nu)}{F(\nu)} = \int_0^{2L} B(N_2 - N_1)dz$$

Or $$\ln \frac{F_f}{F_i} = 2LB(N_2 - N_1)$$

Or $$\frac{F_f}{F_i} = e^{2LB(N_2 - N_1)}$$ = **amplification in one round trip** .....(5.17)

Equation (5.17) has been deduced under the assumption that the mirrors are perfect reflectors and there are no outputs. If it is not so, then let

R_1 → Reflectivity of the mirror M_1

R_2 → Reflectivity of the mirror M_2

} R_1 and $R_2 < 1$

There will also be a transmission loss as output through M_2.

In one round trip two reflections occur-one at M_1 and one at M_2. Considering this the final photon flux F_f after one round trip is given by:

$$\frac{F_f}{F_i} = R_1 R_2 e^{2LB(N_2 - N_1)}$$ = **amplification in one round trip.** .....(5.18)

When the laser is operating continuously, the output power is constant despite the fact that the number of photons in the cavity increases when passing through the amplifying medium then decreases when reflected off the mirrors. Thus, the number of photons gained is equal to the number of photons lost and the cavity breaks into oscillations. So condition of oscillation is

$$\frac{F_f}{F_i} = 1$$

Or $$R_1 R_2 e^{2LB(N_2 - N_1)} = 1$$ .....(5.19)

Equation (5.19) gives the **Threshold condition** at which oscillation starts. This gives:

$$N_2 - N_1 = \frac{1}{2LB} \ln\left(\frac{1}{R_1 R_2}\right)$$ .....(5.20)

This value of population inversion ($N_2 - N_1$) at which oscillation just starts is called the **Critical value.** Once oscillation starts, lasers are coherent sources of light.

Now , the incident and reflected waves being of same frequency and amplitudes (assuming high reflectivity of the mirrors) with opposite directions will give rise to standing waves. The frequency corresponding to the normal modes of oscillation is given by:

$$\nu_n = \frac{nc}{2d}$$ where n = 1,2,3..... } .....(5.21)

And 'c' is the velocity of light.

The cavity will break into oscillations only for those frequencies given by equation (5.21). The frequency of emission due to transitions between the two population inverted levels is

$$\nu = \frac{E_2 - E_1}{h}$$ .....(5.22)

The value of 'd' is so chosen that one of the values of ν_n is equal to ν. For this value resonance occurs and a large amplification takes place.

It is also to be noted that except in free particles the energy levels are not single valued levels but energy bands. So the frequency of emission varies within a range $\nu \rightarrow \nu + d\nu$. **So within this range the cavity chooses one particular frequency which agrees with one of ν_n and gives resonance. This is the reason for extreme monochromaticity of laser.**

RUBY LASER:

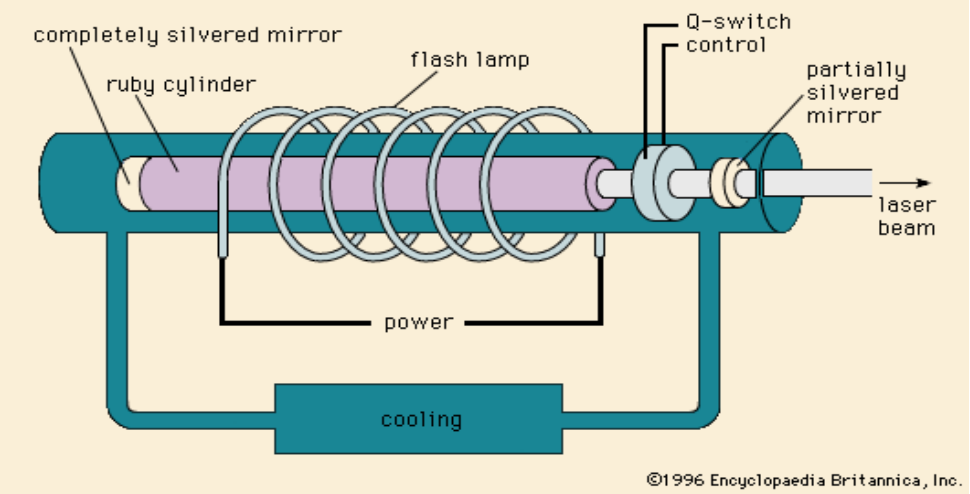


Fig. 5.9. Ruby laser.

The first operative laser is a Ruby laser is based on the principle of optical resonator. The active medium is a small cylindrical pale pink ruby which is Al_2O_3 (Aluminum oxide)crystal containing about 0.05% by weight of Cr_2O_3 (Chromium oxide). The rods' end faces are polished to render them flat, parallel and normal to the axis of the ruby cylinder. Then one face is silvered completely and the other face is partially silvered to form a resonant cavity. Ruby being a solid, is subjected to optical pumping. This is achieved by surrounding the cylinder by a helical gaseous discharge flashtube. Ruby appears red because the chromium atoms have absorption bands in the blue green region of the spectrum. Firing the flashtube generated an intense burst of light lasting for a few milliseconds. Much of this energy is lost as heat which requires a cooling arrangement. But many of the chromium atoms are raised to the absorption bands. To analyse the laser generation a simplified energy level diagram is given in Fig. 5.10.

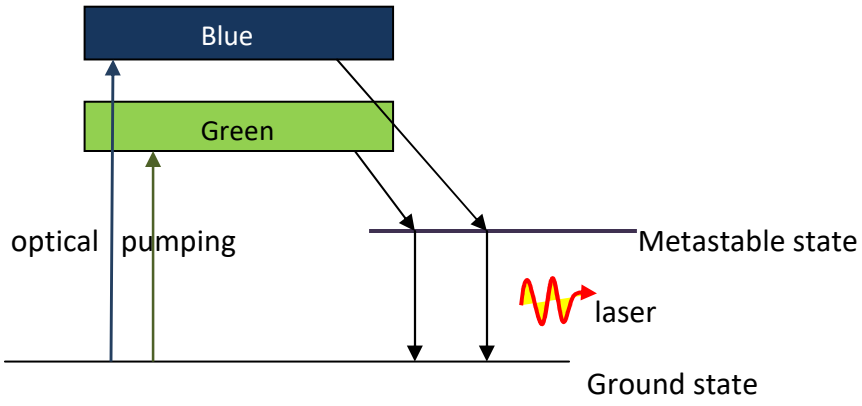


Fig. (5.10) Energy level diagram of Ruby laser.

Ruby laser is a three level laser**.** The atoms excited to blue and green bands rapidly relax (in about 100 ns) giving up energy to the crystal lattice and making non radiative transition to the metastable state. This brings about population inversion between the metastable state and ground state. They remain there for several milliseconds before dropping down to the ground state spontaneously. One of the spontaneous emissions which is along the axis of the cylinder stimulates a rapid, in phase emission of another, transforming energy from the metastable atoms into the evolving light. Thus lasing action starts in the form of red fluorescent radiation characteristic of ruby. The two ends of the cylindrical ruby being polished, light continues to get amplified by stimulated emissions as it sweeps back and forth across the active medium. Since one end is partially silvered, an output beam of laser can be extracted from there. As an oscillator the ruby laser generates millisecond pulses in the energy range around 50J -100J

HELIUM NEON LASER.

A **helium–neon laser** or **HeNe laser**, is a type of gas laser whose active medium consists of a mixture of **90% helium and 10% neon at a total pressure of about 1 torr,** sealed inside a small electrical discharge tube. The most dominant transition in HeNe laser operates at a wavelength of 632.8 nm, in the red part of the visible spectrum.

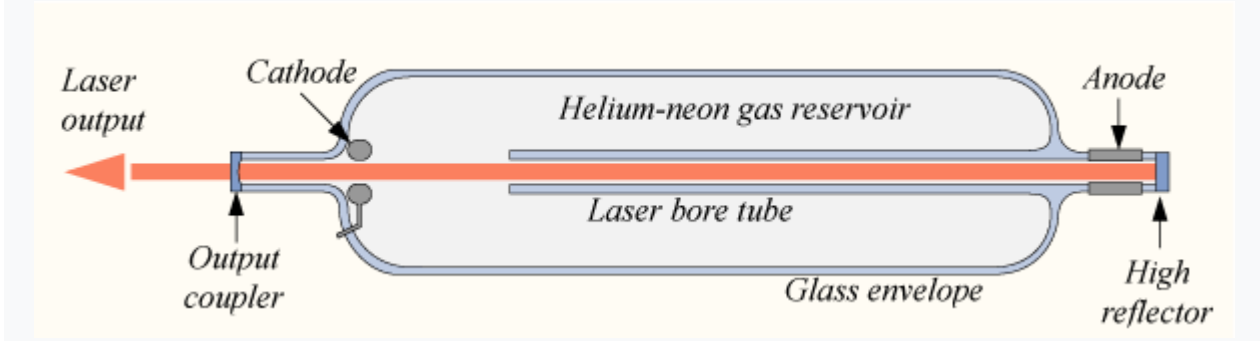


Fig. (5.11) Schematic diagram of a helium–neon laser

The gas mixture is mostly helium, as helium atoms can be easily excited. The excited helium atoms collide with neon atoms, exciting some of them to higher energy states. Without helium, the neon atoms would be excited mostly to lower energy states responsible for non radiative fast decay. A DC current of 3 to 20 mA is typically required for continuous wave operation. The optical cavity of the laser usually consists of two concave mirrors or one plane and one concave mirror: one having very high (typically 99.9%) reflectance, and the output coupler mirror allowing approximately 1% transmission.

In the discharge tube, gas discharge produces free electrons and ions which will be accelerated due to the high voltage. Inelastic collisions of energetic electrons, with ground-state helium atoms in the gas mixture excite them to higher excited states as shown in Fig. 5.12. Among them the 2^3S_1 and 2^1S_0 are long-lived metastable states. Owing to the nearness of energy levels of the two He metastable states and the $5s_2$ and $4s_2$ levels of neon, collisions between these

helium metastable atoms and ground-state neon atoms results in a selective and efficient transfer of excitation energy from the helium to neon.

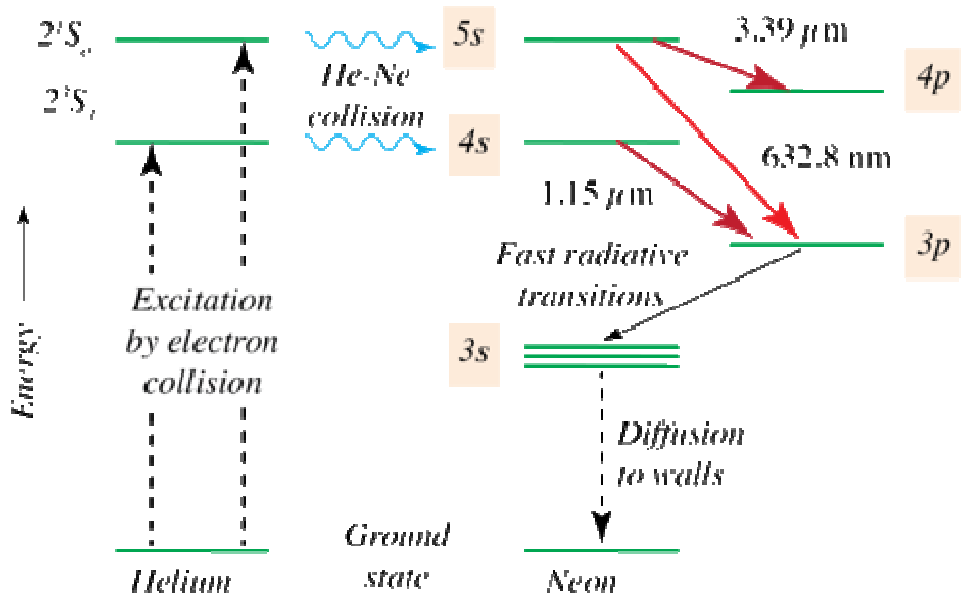


Fig. 5.12. Energy level diagram of HeNe laser.

Excitation-energy transfer increases the population of the neon $4s_2$ and $5s_2$ levels many fold. When the population of these two upper levels exceeds that of the corresponding lower level, $3p_4$, population inversion is achieved. The medium becomes capable of amplifying light in a number of narrow bands. The three most dominant ones are

i) 1.15 μm corresponding to the $4s_2$ to $3p_4$ transition.

ii 3.39 μm corresponding to the $5s_2$ to $4p_4$ transition.

iii) 632.8 nm corresponding to the $5s_2$ to $3p_4$ transition.

The $3p_4$ level is efficiently emptied by fast radiative decay to the 3s state, eventually reaching the ground state.

The remaining step is to obtain light amplification by creating an optical oscillator. This is achieved by placing highly reflecting mirrors at each end of the amplifying medium. Thus a radiation along the axis of the discharge tube will reflect back upon itself, gaining more power in each passage through the tube than is lost due to transmission through the mirrors and diffraction. When these conditions are met for one or more longitudinal modes, then radiation in those modes will rapidly build up until gain saturation occurs, resulting in a stable continuous laser-beam output through the front (typically 99% reflecting) mirror.

Properties of Laser

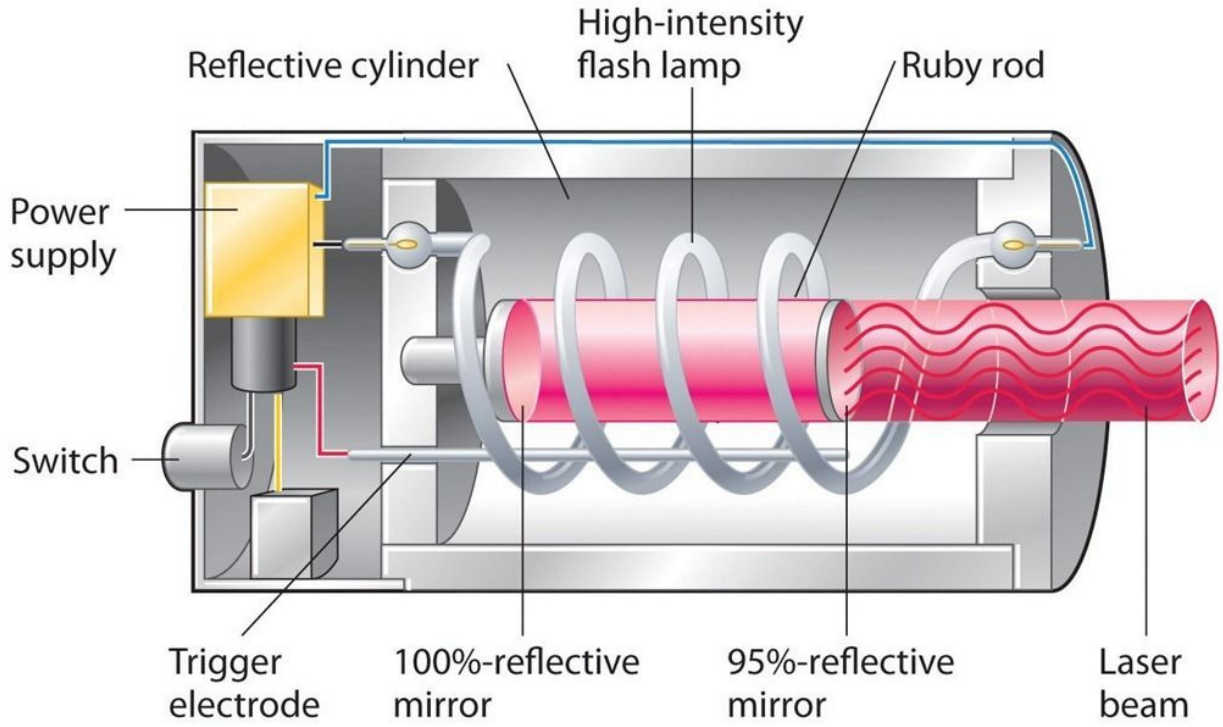
1. Laser has extreme directionality, the direction being along the length of laser cavity. So laser beams constitute plane waves.

2. Laser has extreme monochromaticity and hence can possess an infinitely long wave train.

3. Due to extreme monochromaticity, laser beams are temporally coherent.

4. Due to extreme directionality laser beams are spatially coherent.

5.Due to the highly collimated nature of laser beams, they are extremely bright.



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