Module 4:
Laser Principles and Engineering Application

Lecture Hours 6

Laser Characteristics, Spatial and Temporal Coherence, Einstein Coefficient & its significance, Population inversion, Two, three & four level systems, Pumping schemes, Threshold gain coefficient, Components of laser, Nd-YAG, He-Ne, CO_2 and Dye laser and their engineering applications

Text books to be followed:
Laser Fundamentals, William Silfvast, Cambridge University Press (2008)

BASIC LASER

Light

Amplification by

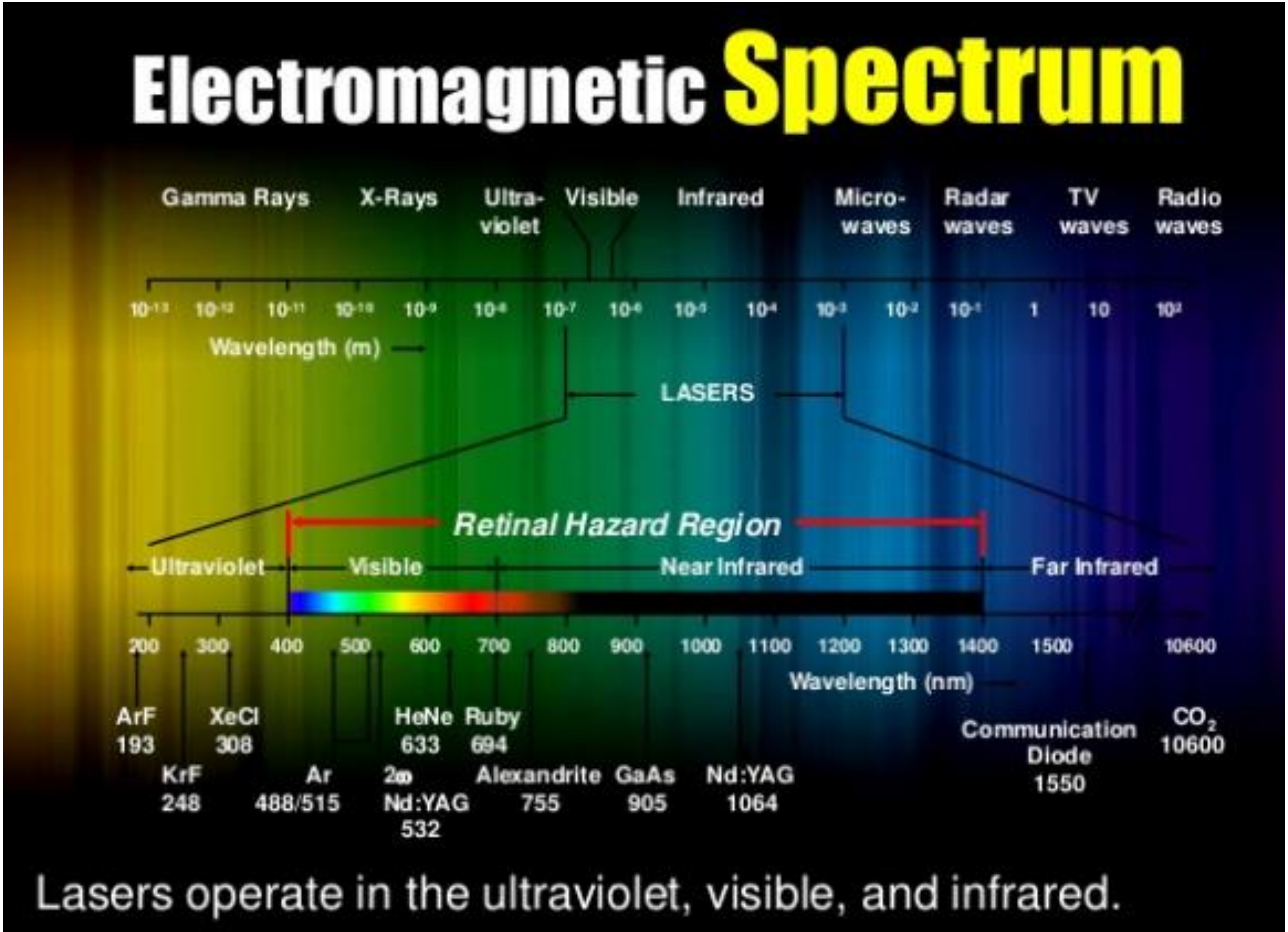
Stimulated

Emission of

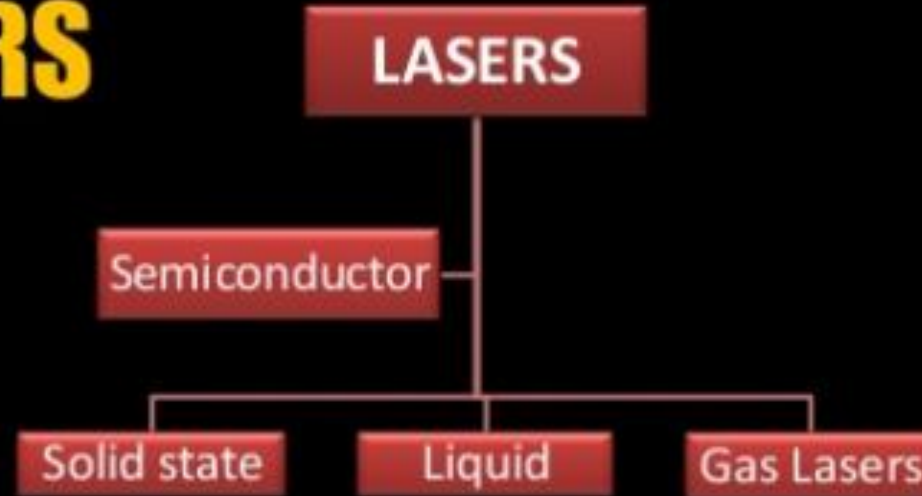
Radiation

Definition of laser

- A laser is a device that generates light by a process called **STIMULATED EMISSION**.
- The acronym LASER stands for Light Amplification by Stimulated Emission of Radiation
- Semiconducting lasers are multilayer semiconductor devices that generates a coherent beam of monochromatic light by laser action. A coherent beam resulted which all of the photons are in phase.


Electromagnetic Spectrum
Gamma Rays
X-Rays
Ultra-violet
Visible
Infrared
Micro-waves
Radar waves
TV waves
Radio waves
Wavelength (m)
LASERS
Retinal Hazard Region
Ultraviolet
Visible
Near Infrared
Far Infrared
200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 10600
Wavelength (nm)
ArF 193
KrF 248
XeCl 308
Ar 488/515
2ω Nd:YAG 532
HeNe 633
Ruby 694
Alexandrite 755
GaAs 905
Nd:YAG 1064
Communication Diode 1550
CO2 10600
Lasers operate in the ultraviolet, visible, and infrared.

Types of LASERS



BASIC LASER COMPONENTS

ACTIVE MEDIUM

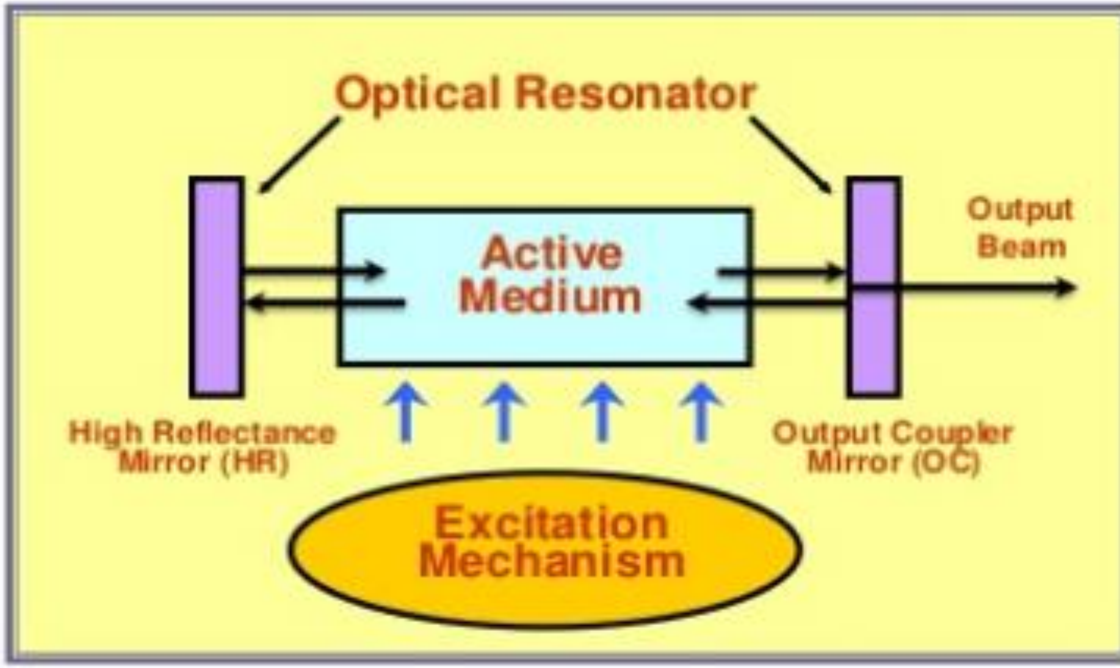
Solid (Crystal)
Gas
Semiconductor (Diode)
Liquid (Dye)

EXCITATION MECHANISM

Optical
Electrical
Chemical

OPTICAL RESONATOR

HR Mirror and Output Coupler



The Active Medium contains atoms which can emit light by stimulated emission.

The Excitation Mechanism is a source of energy to excite the atoms to the proper energy state.

The Optical Resonator reflects the laser beam through the active medium for amplification.

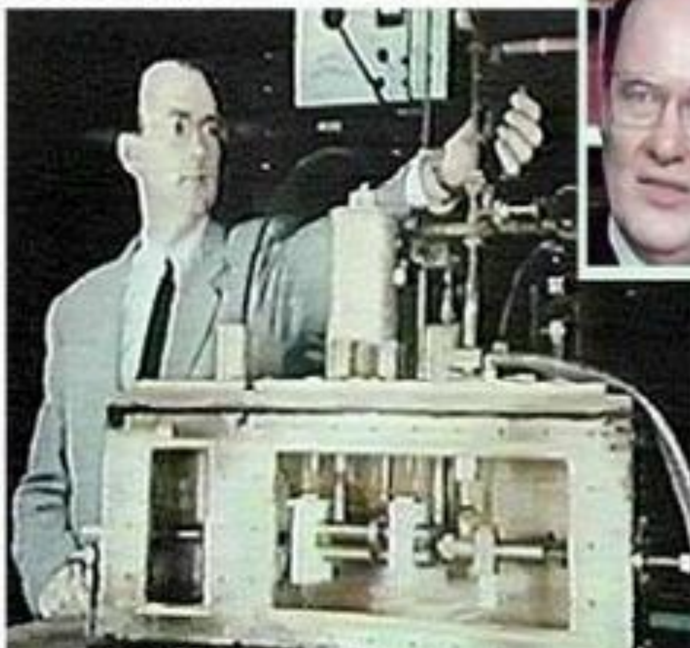
History : Some important dates

- 1917: Albert Einstein developed the theoretical concept of photons & stimulated emission
- 1954: Charles Townes & Arthur Schawlow built the first MASER using ammonia and microwave energy
- 1960: Thomas Maiman produced the first laser using a synthetic ruby rod
- 1960: Dr. Ali Javan-first continuous laser (He-Ne 632.6 nm red gas ion laser

- In 1917, Albert Einstein first theorized about the process which makes lasers possible called "Stimulated Emission."

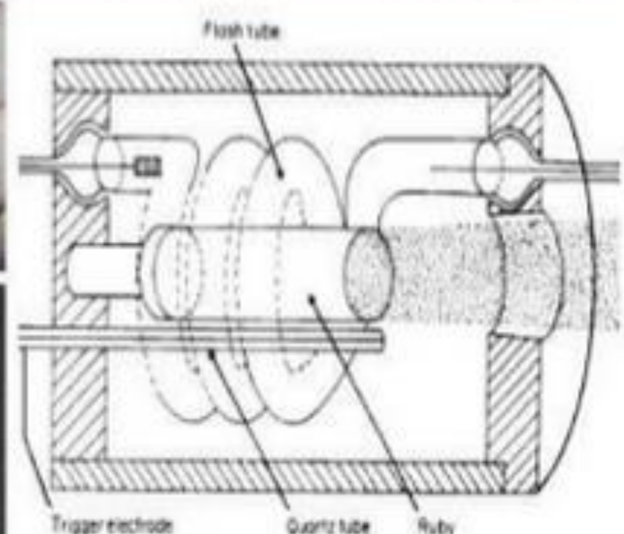
Pioneers

Charles Townes



Arthur Schawlow

Microwave Amplification by Stimulated Emission of Radiation
The "MASER" ... predecessor to the LASER, 1954



Thomas Maiman, 1960 ....
This man ignored the ridicule of his peers and easiliy succeeded in producing history's first visible light laser from this simple photographic coiled flashlamp and his ruby crystalline rod.

History of laser

- **1960s: Dr. Leon Goldman: Father of Laser Medicine & Surgery-usage of laser in medical practice**
- 1962: Bennett et al: blue-green argon laser (retinal surgery)
- 1964: Kumar Patel: CO2 laser
- 1964: Nd:YAG laser
- 1969: Dye laser
- 1975: Excimer laser (noble gas-halide)

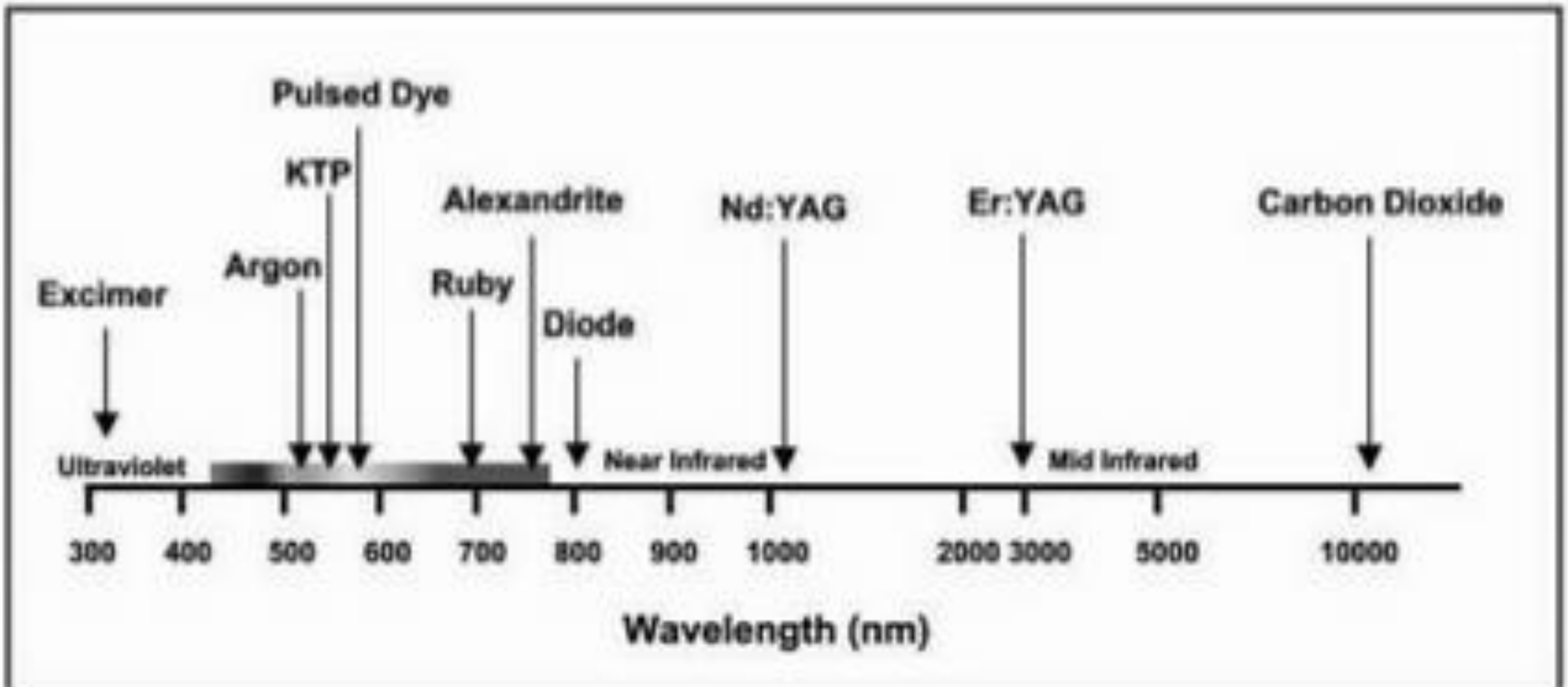
PIONEERS

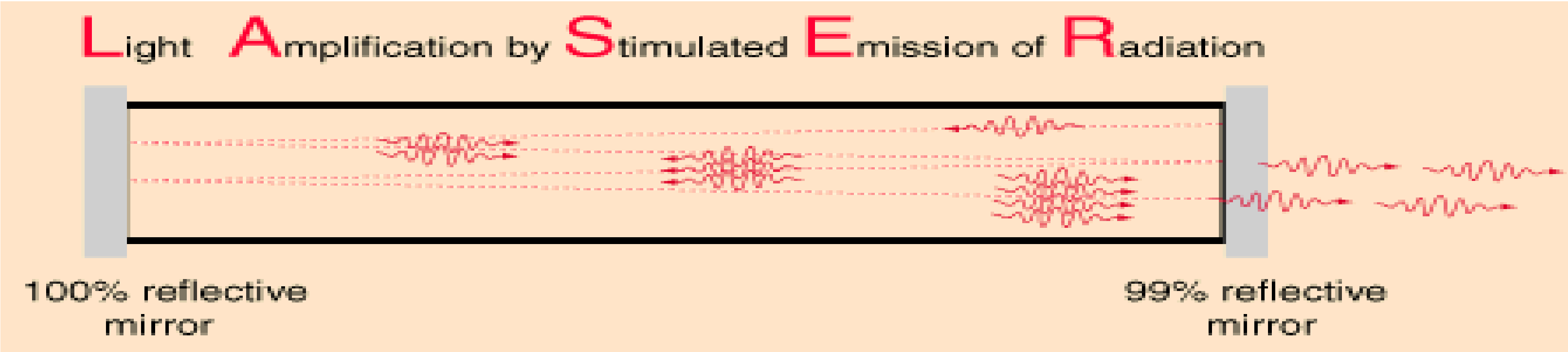
1905-1997

Dr. Leon Goldman

"The Father of Laser Medicine"

Identification of different types of medical lasers





When radiation interacts with matter we have three processes to generate laser light.

(1) Optical Absorption
(2) Spontaneous Emission
(3) Stimulated Emission

Characteristics of laser radiation

Laser radiation has the following important characteristics over ordinary light source. They are:

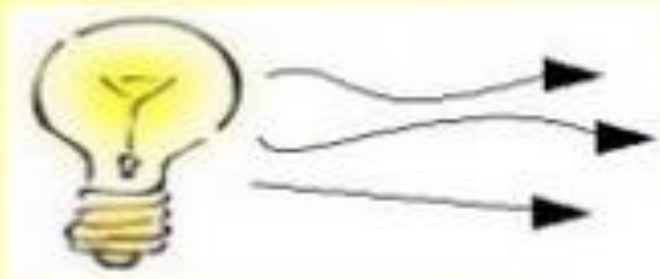
i) monochromaticity

ii) directionality

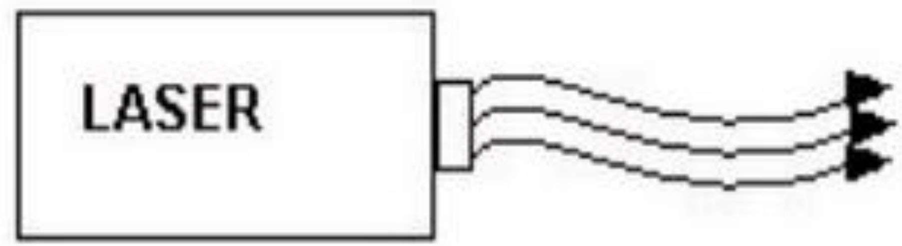
iii) coherence

iv) brightness

Incandescent vs. Laser Light



- Many wavelengths
- Multidirectional
- Incoherent



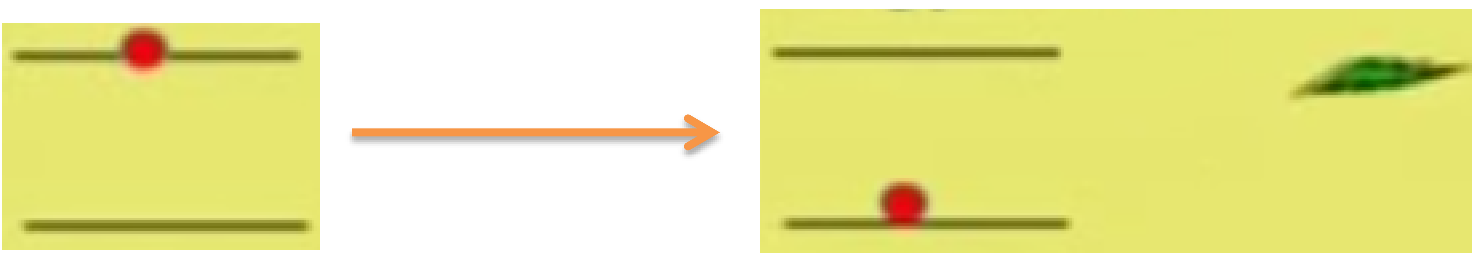
- Monochromatic
- Directional
- Coherent

Mono-chromaticity

- Laser is monochromatic light i.e. Laser has mono [single] wavelength [color]

Sun, White Light

- Laser is created from the transition of electrons from definite energy levels

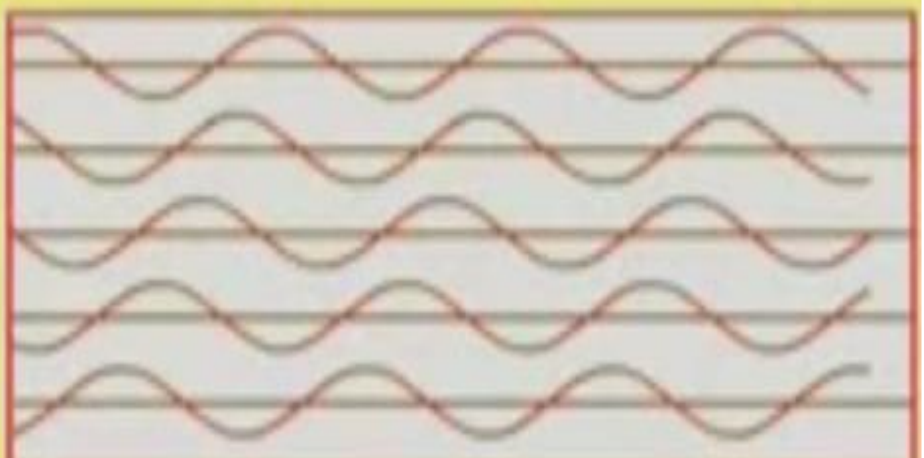


Coherence

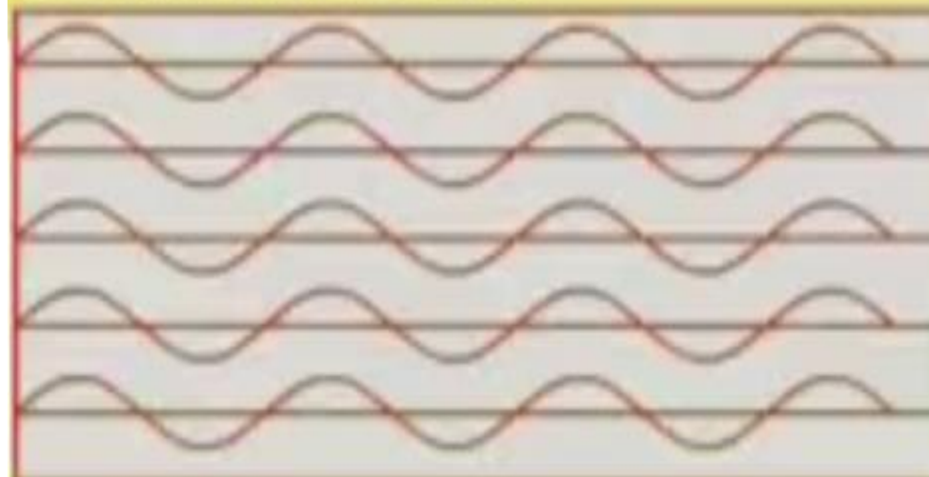
- Laser is highly coherent light.

- Coherent light are light waves that are " in phase" with one another.

Incoherent Beams



Coherent Beams



Spatial and Temporal Coherence

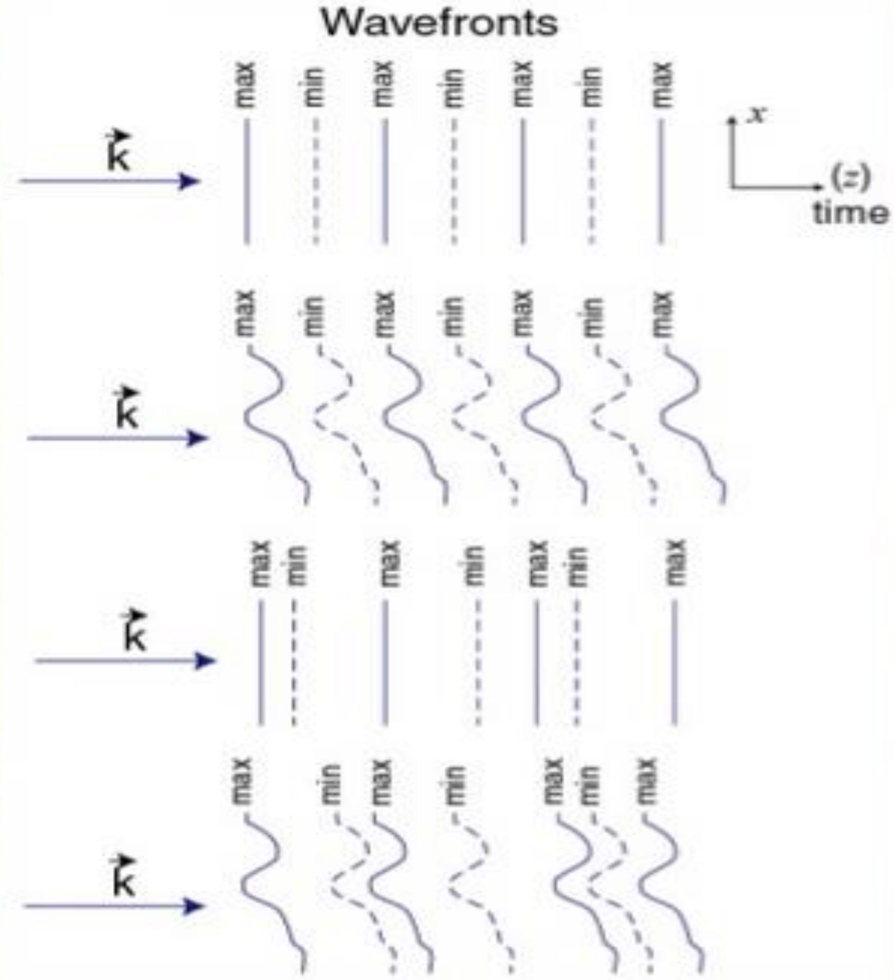
Beams can be coherent or only partially coherent (indeed, even incoherent) in both space and time.

Spatial and Temporal Coherence:

Temporal Coherence; Spatial Incoherence

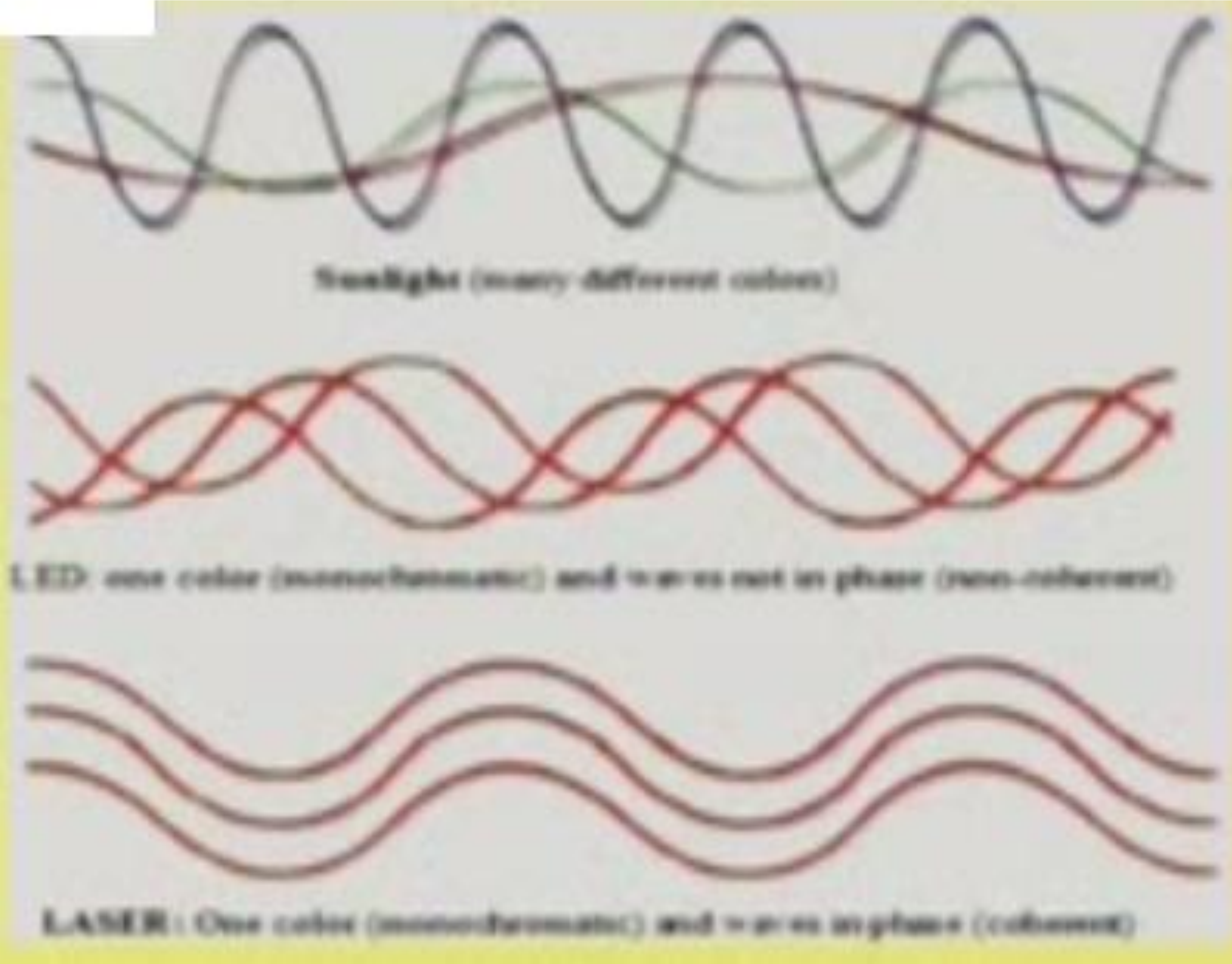
Spatial Coherence; Temporal Incoherence

Spatial **and** Temporal **In**coherence

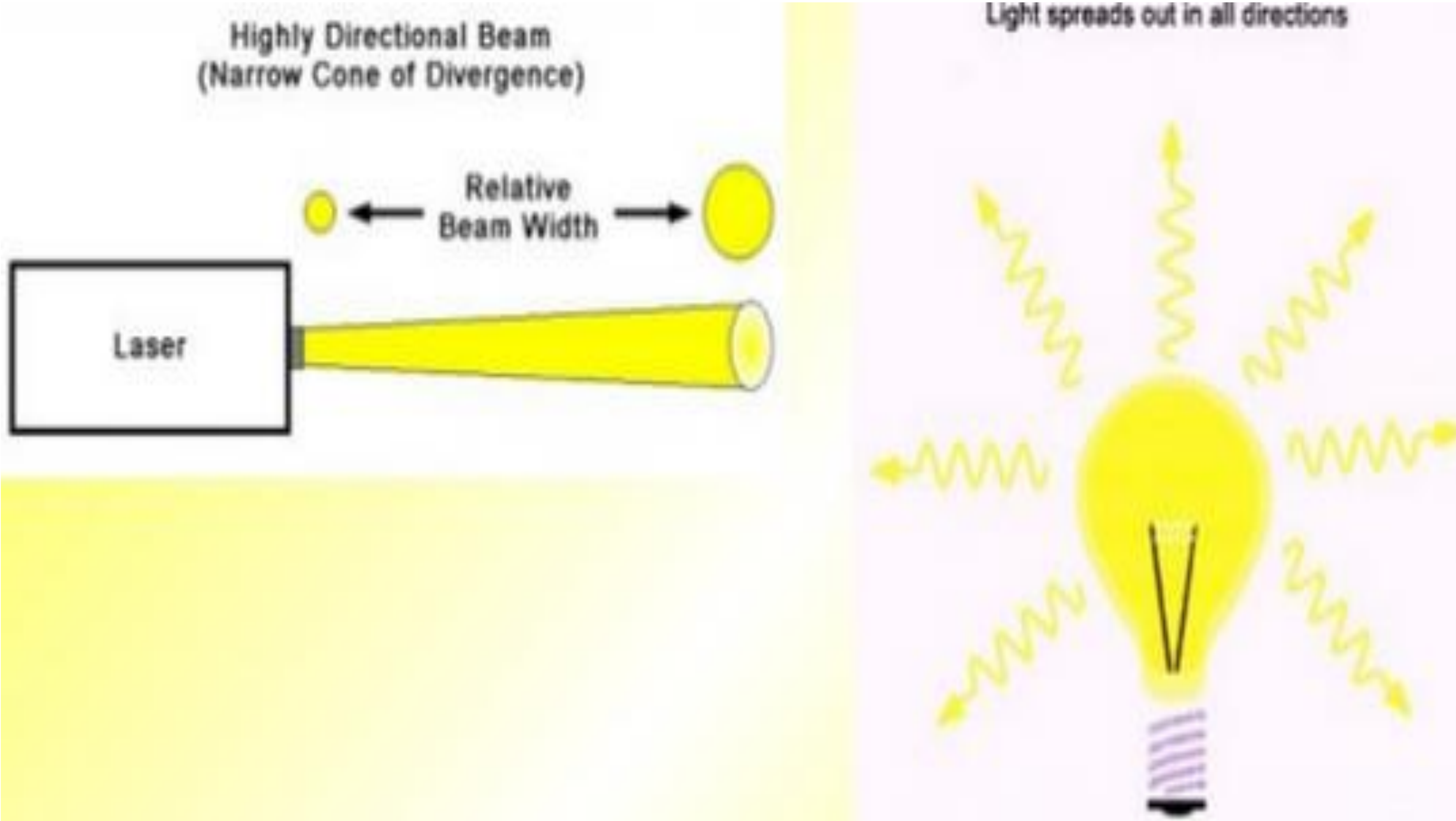


The temporal coherence time is the time the wave-fronts remain equally spaced. That is, the field remains sinusoidal with one wavelength:

The waves at different points in space are said to be space coherent if they preserve a constant phase difference over any time t.


Sunlight (many different colors)
LED: one color (monochromatic) and waves not in phase (non-coherent)
LASER: One color (monochromatic) and waves in phase (coherent)

Directionality

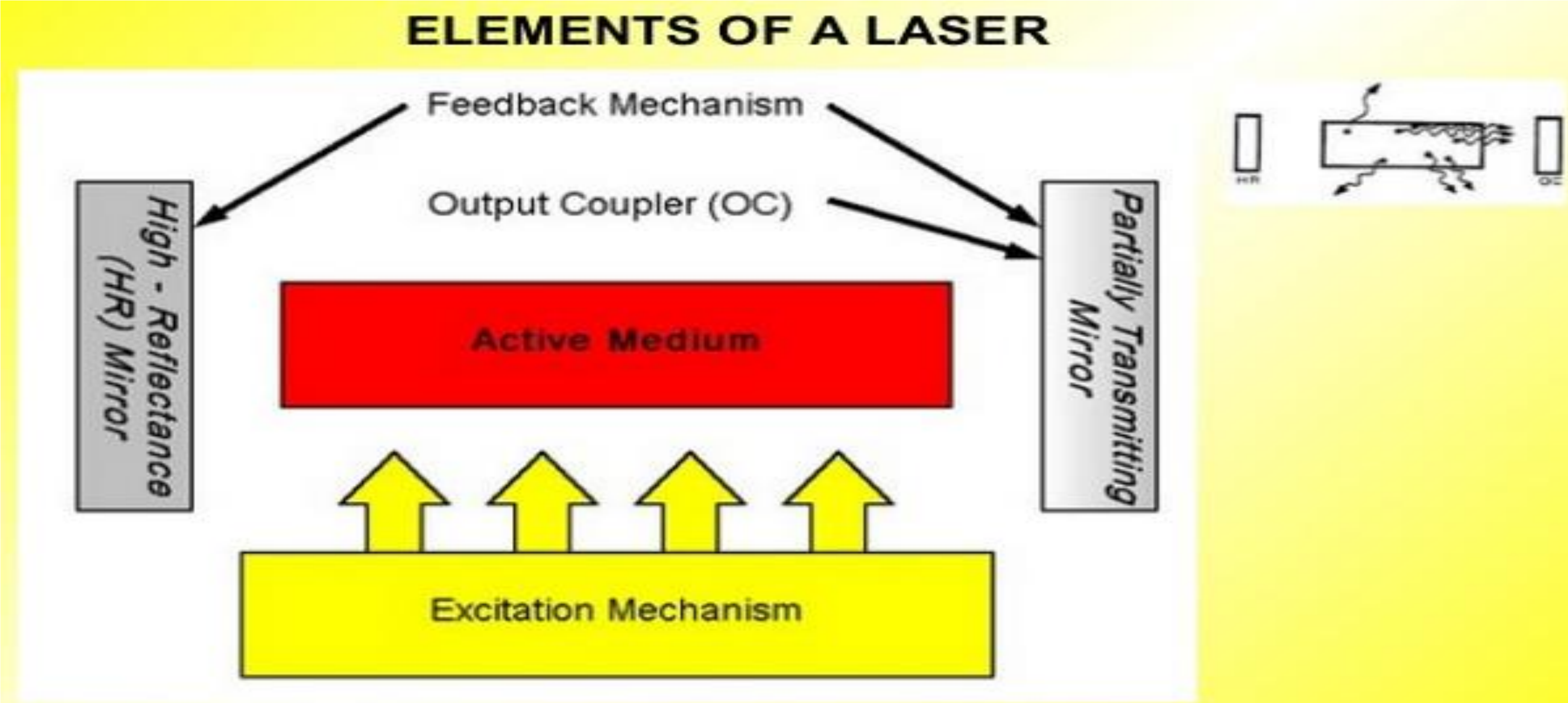


Intensity

- The intensity of a light source is the power emitted per unit surface area per unit solid angle.

Basic Components

- Spontaneous emission
- Stimulated emission
- Amplification
- Population inversion
- Active medium
- Pumping
- Optical resonators



The three main components of any laser device are:

(i) The active medium
(ii) The pumping source
(iii) The optical resonator.

Technically, the whole device is known as a **LASER OSCILLATOR**, but this term is often shortened to simply "laser".

1. AMPLIFYING OR GAIN MEDIUM (solid, liquid or gas)

- This medium is composed of atoms, molecules, ions or electrons whose energy levels are used to increase the power of a light wave during its propagation.
- The physical principle involved is called stimulated emission

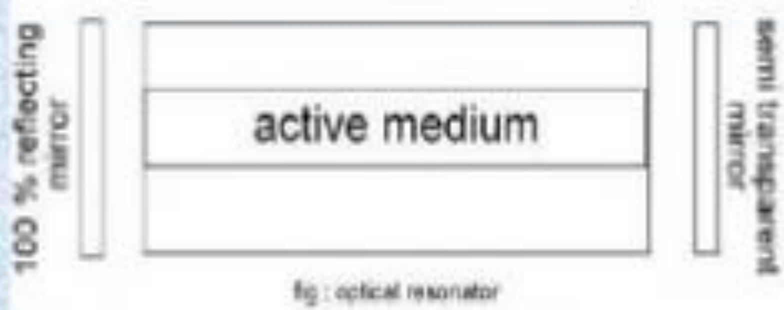
2. PUMPING SYSTEM - **a system to excite the amplifying medium**

- This creates the conditions for light amplification by supplying the necessary energy.
- There are different kinds of pumping system:

1. Optical (the sun, flash lamps, continuous arc lamps or tungsten-filament lamps, diode or other lasers)
2. Electrical (gas discharge tubes, electric current in semi-conductors)
3. Chemical

3. OPTICAL RESONATOR (OR CAVITY) in order to **produce a very special radiation**

- The laser oscillator uses reflecting mirrors to amplify the light source considerably by bouncing it back and forth within the cavity
- It also has an output beam mirror that enables part of the light wave in the cavity to be and its radiation used



Spontaneous Emission	Stimulated emission
Incoherent	*Coherent*
Less intensity	*High intensity*
Poly chromatic	*Mono chromatic*
Less directionality	*High directionality*
More angular spread	*Less angular spread*
No need of external energy	*External energy is required*

Distinction between spontaneous and stimulated emission of radiation

Spontaneous emission	***Stimulated emission***
• It takes place when an atom in a higher energy state transits to a lower energy state by itself.	• It takes place when an atom in a higher energy state gets stimulated by the incident photon and transits to a lower energy state.
• It is independent of incident radiation density.	• It depends upon the incident radiation density.
• It takes place after 10^{-8} second.	• It takes place within a time of 10^{-8} second.
• It is a slower process as compared to stimulated emission.	• It is a faster process as compared to spontaneous emission.
• A_{21} is the Einstein's coefficient of spontaneous emission.	• B_{21} is the Einstein's coefficient of stimulated emission.

PRINCIPLE OF LASER

From the theory of interaction of radiation with matter, we can get an idea regarding the working of laser. Consider an atom that has only two energy levels, E_1 and E_2. When it is exposed to radiation having a stream of photons, each with energy $h\nu$, three distinct processes can take place.

(i) Absorption

(ii) Spontaneous emission, and

(iii) Stimulated emission.

Absorption An atom or molecule in the ground state E_1 can absorbs a photon of energy hv and go to the higher energy state E_2. This process is known as *absorption* and is illustrated in Fig.

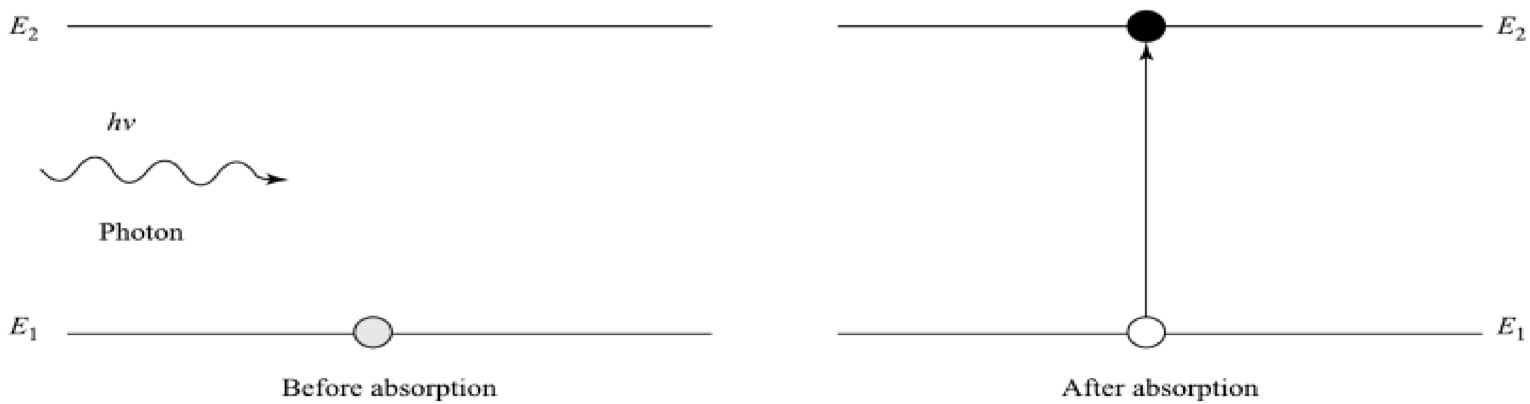


Fig. *Absorption*

The rate of upward transition R_{12} from ground state E_1 to excited state E_2 is proportional to the population of the lower energy level N_1 (number of atoms per unit volume) and to the energy density of radiation ρ_ν,

i.e.
$$R_{12} \propto \rho_\nu$$
$$\propto N_1$$

Thus,
$$R_{12} = B_{12}\,\rho_\nu N_1 \tag{2.1}$$

where B_{12} is the probability of absorption per unit time.

Normally, the higher energy state is an unstable state and hence, the atoms will make a transition back to the lower energy state with the emission of a photon. Such an emission can take place by one of the two methods given below.

Spontaneous Emission In spontaneous emission, the atoms or molecules in the higher energy state E_2 eventually return to the ground state by emitting their excess energy spontaneously. This process is independent of external radiation. The rate of the spontaneous emission is directly proportional to the population of the energy level E_2,

i.e.
$$R_{21}\,(\mathrm{SP}) \propto N_2$$

$$R_{21}\,(\mathrm{SP}) = A_{21} N_2 \tag{2.2}$$

where A_{21} is the probability per unit time that the atoms will spontaneously fall to the ground state and N_2 the number of atoms per unit volume in the state E_2. This process is illustrated in Fig.

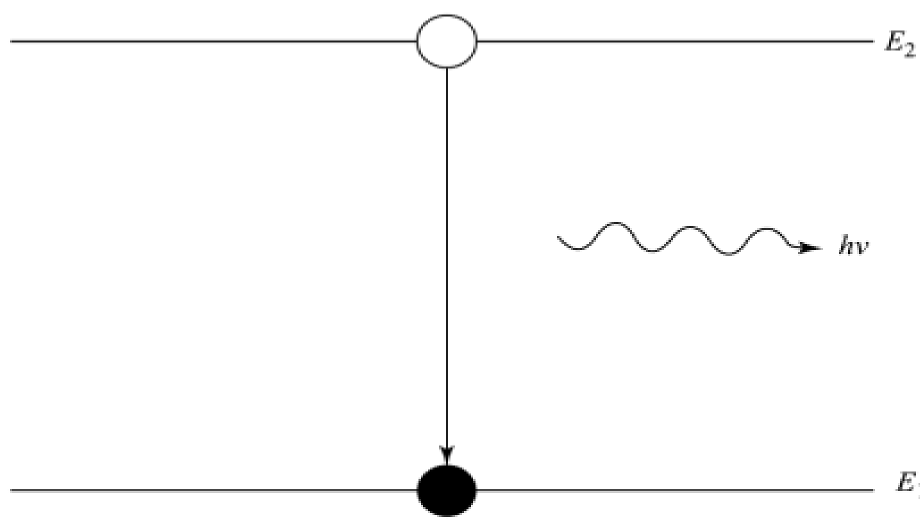


Fig. *Spontaneous emission*

Stimulated Emission In stimulated emission, a photon having energy E, equal to the difference in energy between the two levels E_2 and E_1, stimulates an atom in the higher state to make a transition to the lower state with the creation of a second photon, as shown in Fig.

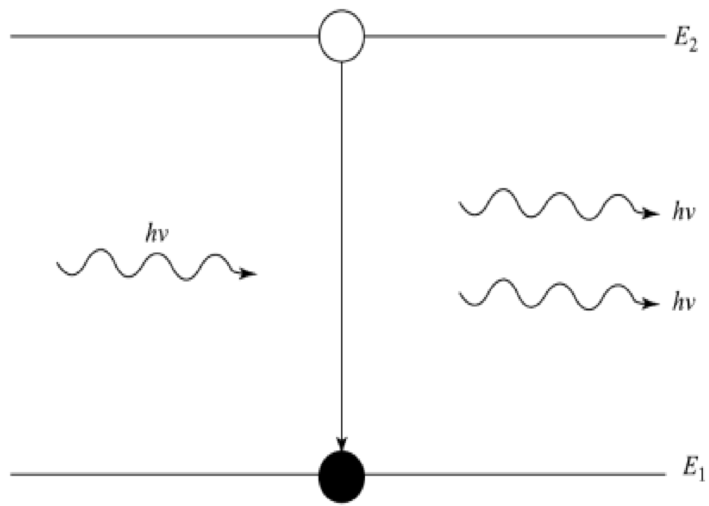


Fig. *Stimulated emission*

The rate of stimulated emission R_{21} (ST) is gives as,

$$R_{21}\,(\mathrm{ST}) = B_{21}\rho_\nu N_2 \tag{2.3}$$

where B_{21} is the probability per unit time that the atoms undergo transition from higher energy state to lower state by stimulated emission.

Under conditions of thermal equilibrium, the population of energy levels obey Boltzmann's distribution function.

EINSTEIN'S THEORY OF STIMULATED EMISSION

In 1917, Einstein proposed a mathematical expression for the existence of stimulated emission of light. This expression is known as *Einstein's expression.*

Consider a two-level energy system (E_1 and E_2). Let N_1 and N_2 be the number of atoms in the ground state and excited state, respectively. Let us assume that only the spontaneous emission is present and there is no stimulated emission of light.

At thermal equilibrium condition, the rate of absorption = the rate of emission of light. From Eqs. (2.1) and (2.2), we can write,

$$\rho_v \times B_{12} N_1 = A_{21} N_2$$

$$\rho_v = \frac{A_{21} N_2}{B_{12} N_1} \tag{2.4}$$

According to Boltzmann's distribution function, the population of atoms in the upper and lower energy levels are related by,

$$\frac{N_2}{N_1} = \frac{e^{-E_2/kT}}{e^{-E_1/kT}} \tag{2.5}$$

Substituting N_2/N_1 in Eq. (2.4), we get,

$$\rho_v = \frac{A_{21}}{B_{21}} e^{-(E_2-E_1)/kT} \tag{2.6}$$

$$\rho_v = \frac{A_{21}}{B_{21}} \frac{1}{e^{hv/kT}}$$

According to black body radiation, the energy density

$$\rho_v = \frac{8\pi hv^3}{c^3} \frac{1}{e^{hv/kT}-1} \tag{2.7}$$

where h is the Planck's constant and c the velocity of light. Comparing the above two equations [Eqs. (2.6) and (2.7)], one can observe that they are not in agreement.

To rectify this discrepancy, Einstein proposed another kind of emission known as *stimulated emission of radiation.* Therefore, the total emission is the sum of the spontaneous and stimulated emissions of radiation.

At thermal equilibrium condition, the rate of absorption = the rate of emission.
From Eqs. (2.1), (2.2) and (2.3),

$$B_{12}N_1 \rho_\nu = A_{21}N_2 + B_{21}N_2 \rho_\nu$$

$$\rho_v = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2} \tag{2.8}$$

Dividing each and every term on the RHS of Eq. (2.8) by N_2, we get,

$$\rho_v = \frac{A_{21}}{B_{12}\left(N_1 / N_2\right) - B_{21}}$$

Substituting for N_1/N_2 from Eq. (2.5), we get,

$$\rho_v = \frac{A_{21}}{B_{12}\left[e^{(E_2 - E_1)/kT}\right] - B_{21}}$$

We know that $E_2 - E_1 = hv$

$$\rho_v = \frac{A_{21}}{B_{12}e^{hv/kT} - B_{21}} \tag{2.9}$$

The coefficients A_{21}, B_{12} and B_{21} are known as *Einstein's coefficients*.

Comparing the above equation with Eq. (2.7), we get,

$$B_{12} = B_{21}$$

and

$$\frac{A_{21}}{B_{21}} = \frac{8\pi hv^3}{c^3} \tag{2.10}$$

From Eqs. (2.7) and (2.9), the ratio of the stimulated emission to spontaneous emission is given by,

$$\frac{R_{21}(\mathrm{ST})}{R_{21}(\mathrm{SP})} = \frac{B_{21}N_2\rho_v}{A_{21}N_2} = \frac{1}{e^{hv/kT} - 1} \tag{2.11}$$

From Eq. (2.11), Einstein proved the existence of stimulated emission of radiation.

The spontaneous emission produces incoherent light, while stimulated emission produces coherent light. In an ordinary conventional light source, spontaneous emission is dominant. For laser action, stimulated emission should be predominant over spontaneous emission and absorption. To achieve this, an artificial condition known as, *population inversion* is required.

Physical Significance of Einstein coefficient

1. The probability of stimulated emission is numerically equal to probability of stimulated absorption. Their rates are different because stimulated emission is proportional to number of atoms present in excited state while stimulated absorption is proportional to number of atoms present in ground state.

2. The coefficient of stimulated emission (B21) is inversely proportional to the third power of frequency of radiation or directly proportional to the third power of wavelength of radiation.

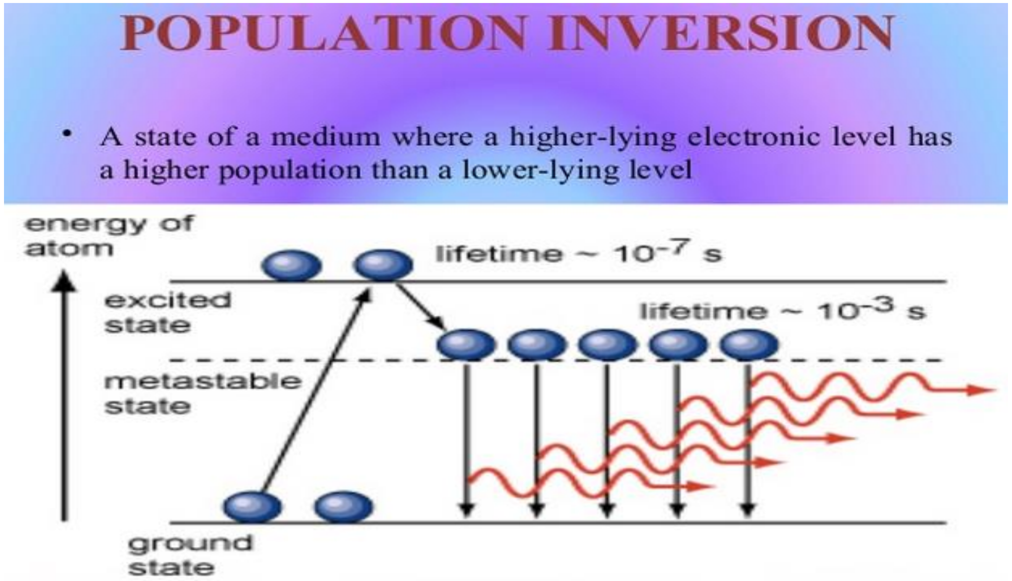
$$\frac{B_{21}}{A_{21}} = \frac{1}{8\pi h}\left(\frac{c}{\nu}\right)^3 = \frac{1}{8\pi h}(\lambda)^3$$

3. The ratio of the rate of stimulated emission to the rate of spontaneous emission

$$\frac{R_{st}}{R_{sp}} = \frac{B_{21}N_2\rho(\nu)}{A_{21}N_2} = \left(\frac{B_{21}}{A_{21}}\right)\rho(\nu) = \frac{1}{e^{h\nu/kT}-1} = \frac{1}{e^{hc/\lambda kT}-1}$$

(i) For ***larger wavelength***, the probability of stimulated emission is more compared to spontaneous emission in ***microwave region.***

(ii) (ii) For ***Shorter wavelength***, the probability of stimulated emission is negligible compared to spontaneous emission in ***visible region***.



A state in which the number of atoms in higher energy state is greater than that in the lower energy state is called a state of population inversion.

To achieve it, consider an atom which has three energy state, which is the ground state; the excited state, E_3 in which the atom can reside only for 10^{-7} sec; and the metastable state, E_2 in which the atom can reside only for 10^{-3} sec (much longer than 10^{-8} sec).

Since the life time of metastable state E_2 is much longer than E3,the atom reaches state E_2 much faster than they leave state E_2. Thus, the state E_2 is filled with a far greater number of atoms than the ground state E_1. Consequently, we have a population inversion between the two states E_2 and E_1. The process by which the population inversion is achieved is called optical pumping.

The population inversion can be achieved by exciting the medium with a suitable form of energy. This process is called pumping. The pumping is necessary for producing population inversion and consequently stimulated emission occurs. Some of the commonly used methods are:

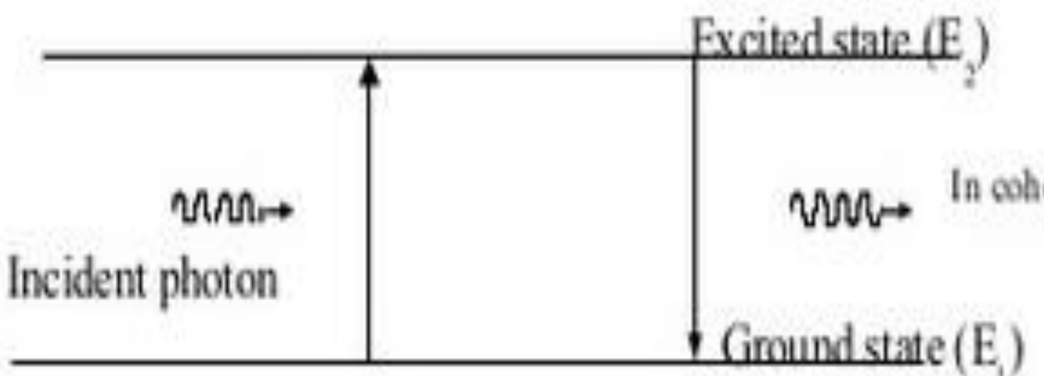
1. Optical pumping (Nd:YAG laser)
2. Electrical discharge (Argon – ion laser)
3. Inelastic atom – atom collision (He-Ne laser)
4. Direct conversion (Semiconductor laser)
5. Chemical reactions (CO2 laser)

There are three levels in which population inversion takes place, those are

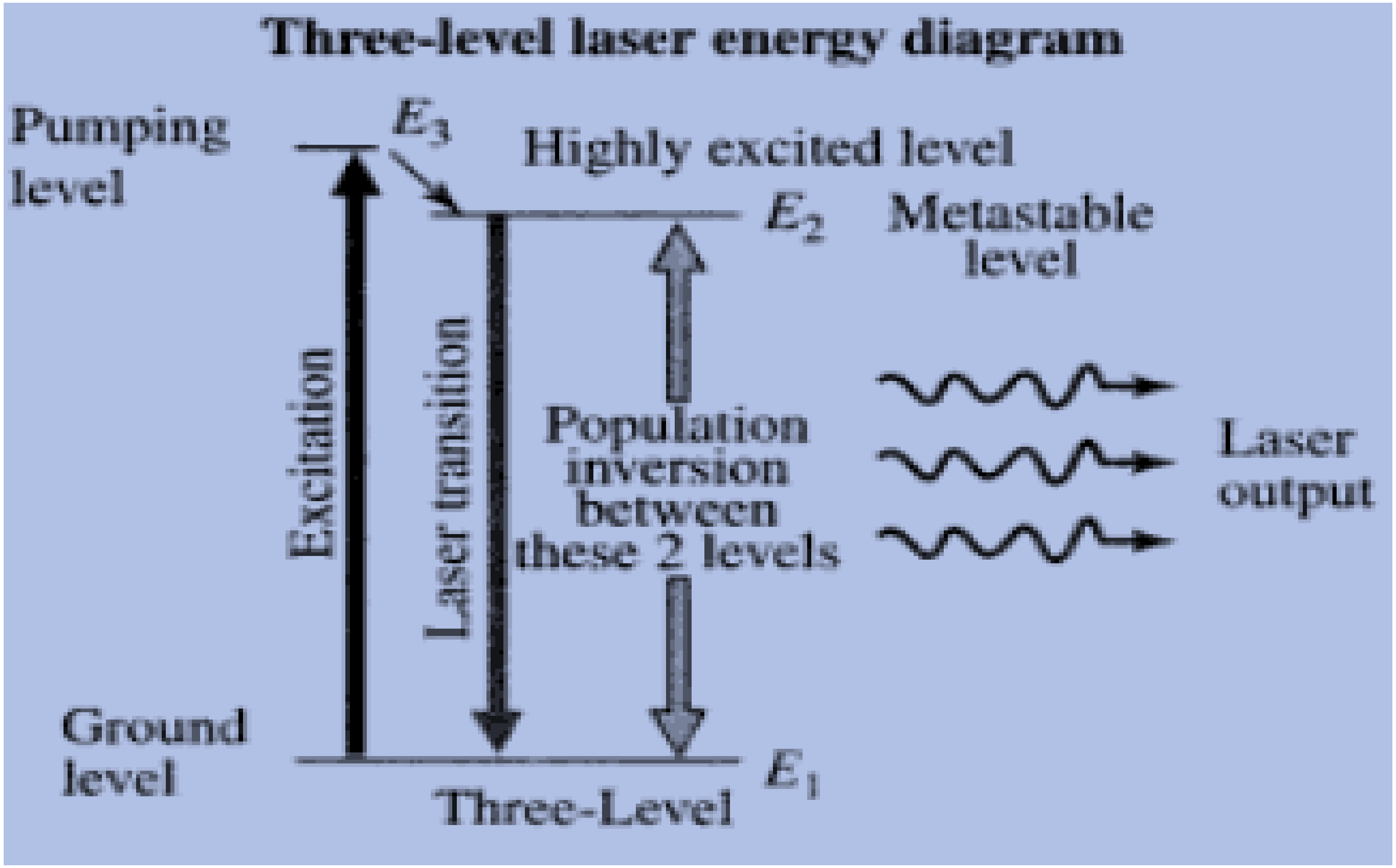
1. Two level pumping Scheme 2. Three level pumping Scheme 3. Three level pumping Scheme

Two level pumping Scheme: This scheme contains only two energy levels i.e., ground state and excited state. The atom absorbs the photon energy and jumps to excited state from ground state. In this case it is difficult to achieve stimulated emission.

This is because, the electron spontaneously returns to ground state (time lag 10^{-8} sec) by the emission of radiation and passing photon have practically no time to stimulated excited atom.

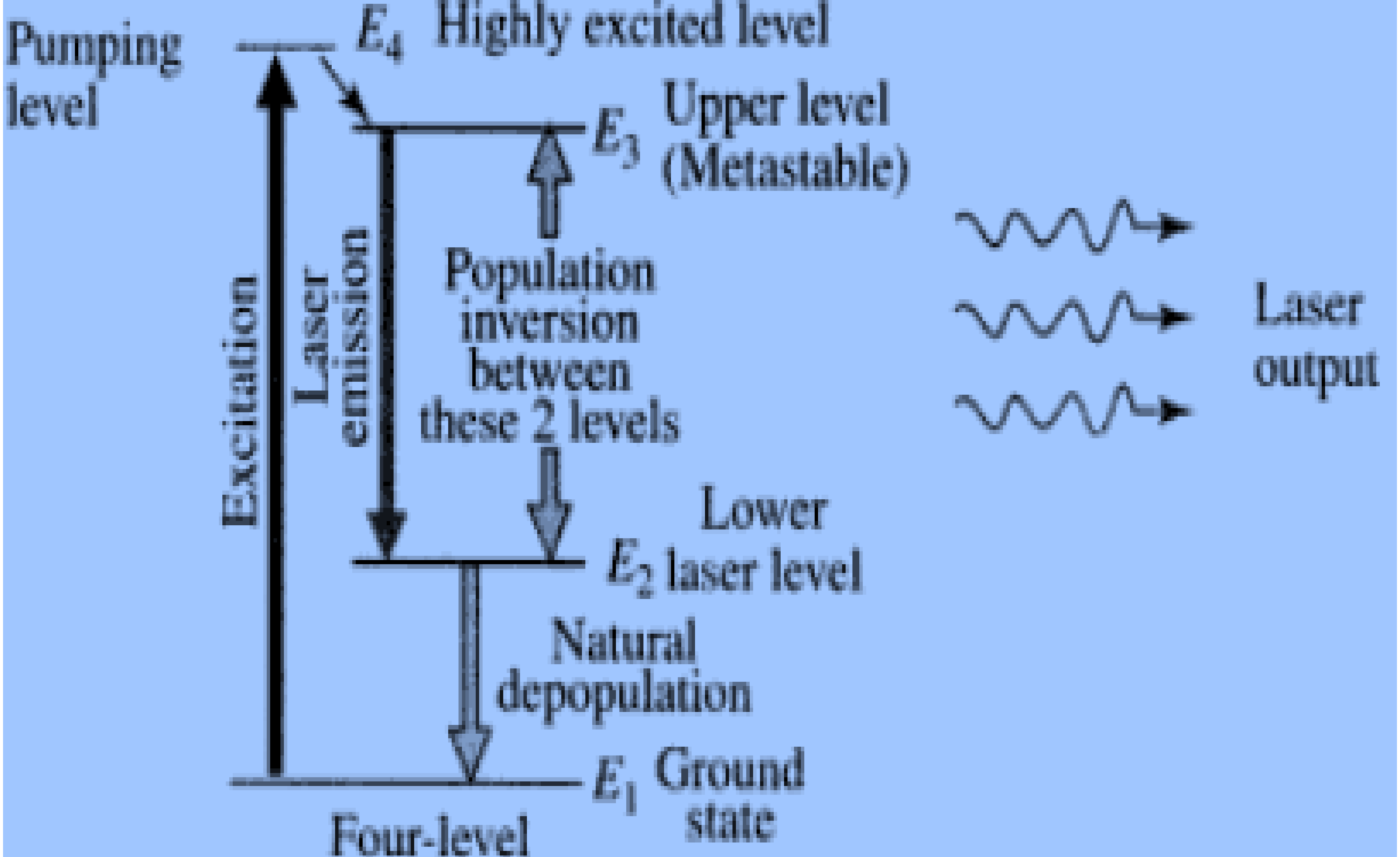


There fore only spontaneous emission takes place in two level pumping scheme.



Metastable state: Metastable state is the energy state which lies between ground state and excited state, transition takes place to this state from excited state without emission of radiation. This state is more stable than the excited state and electron stay in this state for about 10^{-3} to 10^{-2} sec. and this time is sufficient undergo stimulation emission.

Four level pumping scheme or leser energy diagram



Types of LASERS

- Solid state Lasers(Nd: YAG Laser)
- Gas Lasers(He-Ne laser)
- Liquid lasers(Europium laser)
- Semiconducting lasers(Ga As laser)
- Dye lasers(Coumarian laser)

SOLID-STATE LASERS

Solid-state laser systems make use of a solid rod of a laser-active material. The most commonly used solid-state lasers are ruby laser and Nd-YAG laser.

Neodymium laser This laser system uses rare earth metals like neodymium. These are two types.

- Nd-YAG laser
- Nd-glass laser

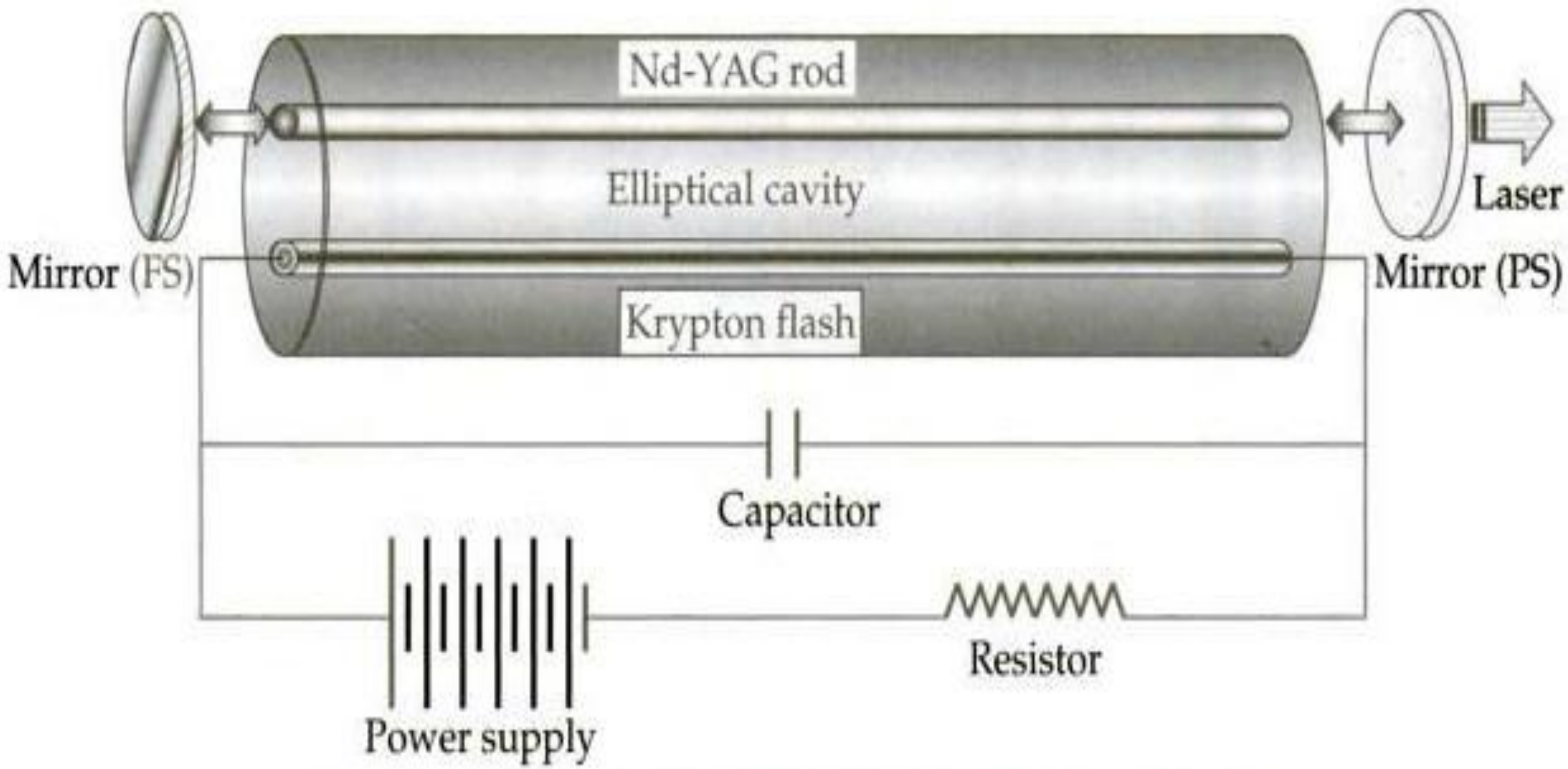
These are powerful four-level laser system with high-power pulse.

They can produce laser output both in the pulsed and the continuous modes.

Because of their high-power output, they are mostly used in industries for cutting, drilling, welding, and surface treatments like hardening of the Industrial products.

Nd-YAG Laser

As mentioned earlier, this is a four-level solid-state laser. Nd-YAG is a neodymium-doped yttrium-aluminium garnet (Nd-$Y_3Al_5O_{12}$), a compound that is used as the lasing medium for some solid-state lasers.



Experimental set-up of a Nd-YAG laser system

Pumping

As this is a solid-state laser, pumping could be done by optical means.

Nd–YAG absorbs mostly in the bands between 730–760 nm and 790–820 nm.

Krypton flash lamps,
with high output at these bands, are therefore more efficient for pumping than the xenon lamps, which produce white light resulting in a loss of energy. The output from a krypton-flash-lamp-pumped laser is mostly pulsed . To get a continuous output, a quartz-halogen lamp is used.

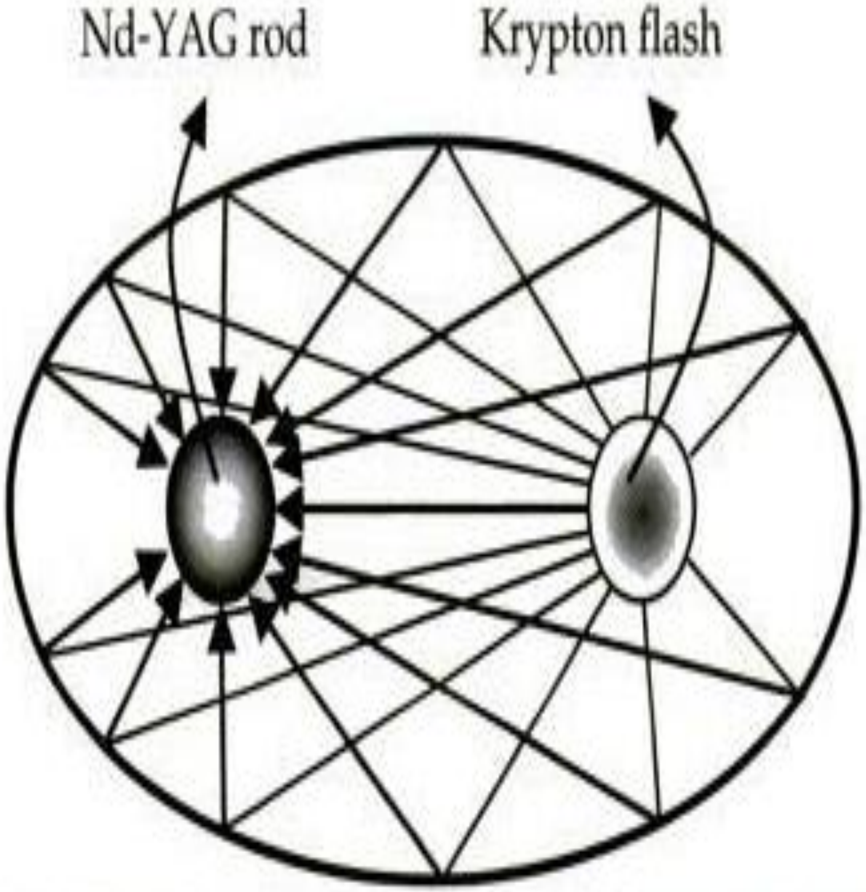
Nd-YAG lasers typically emit light of wavelength 1,064 nm in the infrared. However, there are also transitions near 940, 1,120, 1,320, and 1,440 nm.

Construction

The Nd-YAG crystal is conveniently cut in the form a cylindrical rod of desired length (5–10 cm) and diameter (6–9 mm).

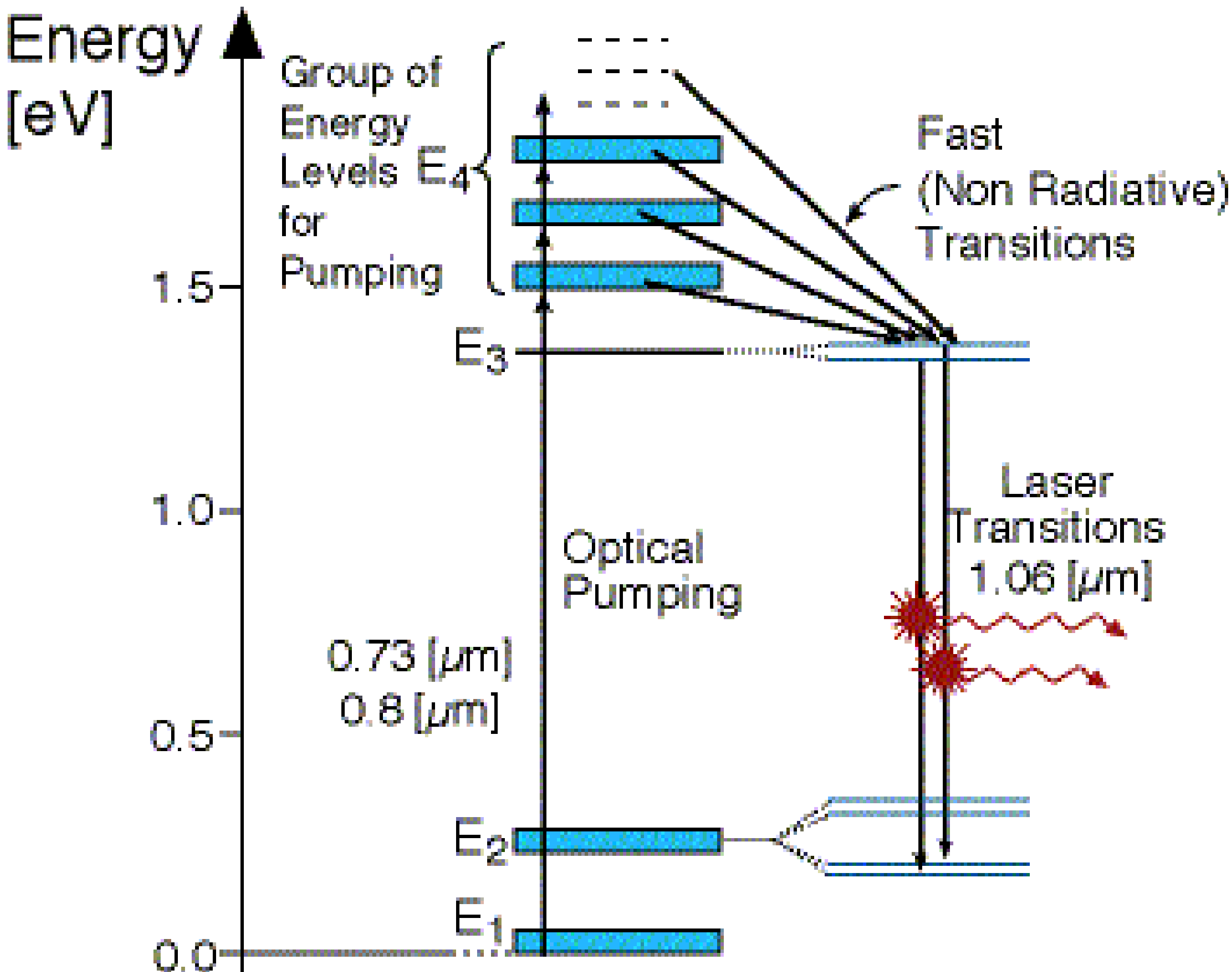
Unlike a ruby laser where the xenon flash lamp was coiled around the ruby rod, the Nd-YAG rod is placed inside at one of the foci of an elliptical reflector cavity. At the other focus, a krypton flash tube, which is connected to the power supply via a capacitor connected in parallel and a resistor connected in series, is placed. The reason for this arrangement is to maximize the pumping power (Fig.'). Almost all the power emitted by the flash lamp kept at one focus reaches the rod kept at the other focus. In this way, maximum pumping takes place, and hence a large population inversion is achieved. This results in an intense laser beam.

Working The laser action is achieved by means of optical pumping utilizing a flash lamp (either a xenon flash lamp at moderate pressure or a krypton flash lamp at high pressure). Only a small fraction of the energy given out by the flash lamp is used for excitation and the rest merely heats up the apparatus. This requires a separate cooling mechanism to cool the laser apparatus.



Cross-sectional view of the experimental arrangement of the Nd-YAG system

Energy Level Diagram of Nd-YAG laser



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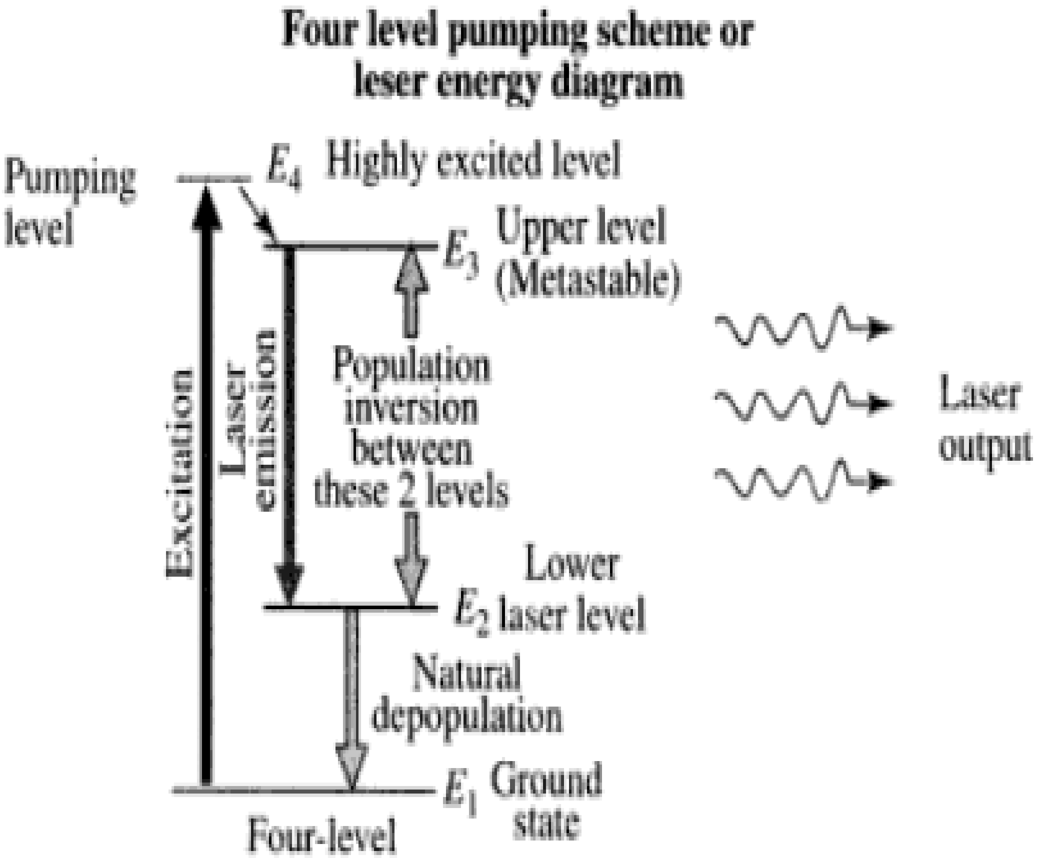


The neodymium ions absorb radiations at around 730 nm (E_1) and 800 nm (E_2) and go to the respective excited states.

From these excited absorption levels, the atoms decay by means of a rapid non-radiative transition to the metastable levels (E4) where they populate and achieve population inversion. Once this condition is achieved, photons are emitted following stimulated emission. The emitted photons are allowed to pass back and forth upwards for a million times through a set of optical resonators where their number builds up and the amplitude increases.

Finally, a laser output at 1064 nm is obtained corresponding to the transition between the levels E3 and E2.

Advantages The advantages of Nd-YAG laser are

- It has a high output and repetition rate.
- It is much easier to achieve population inversion.
- As it is crystalline, the line width is small and therefore it has lower thresholds.
- It can be used in lasers utilizing frequency doubling and frequency tripling, and high-energy Q-switching.
- Its thermal conductivity is better and its fluorescence lifetime is about twice as long as Nd-YVO_4.
- It can be operated on power levels of up to kilowatts. It can be directly Q-switched with Cr^{4+}-YAG.
- Nd-YAG lases at 1,064 nm and its best absorption band for pumping is 1 nm wide and located at 807.5 nm.

Disadvantages

- Its electronic energy level structure is complicated.

GAS LASER

Carbon Dioxide Laser

Carbon dioxide laser is the first molecular gas laser developed by C.K.N. Patel. It produces a continuous output and is simple to construct. Unlike the solid-state lasers, in gas lasers the output is achieved when the transitions take place between the vibrational or rotational levels of the molecules. As shown in Fig. 5.9, the two types of transitions in gas laser systems are

- Type I—Transitions between the vibrational levels of the same electronic states.
- Type II—Transitions between the vibrational levels of different electronic states.

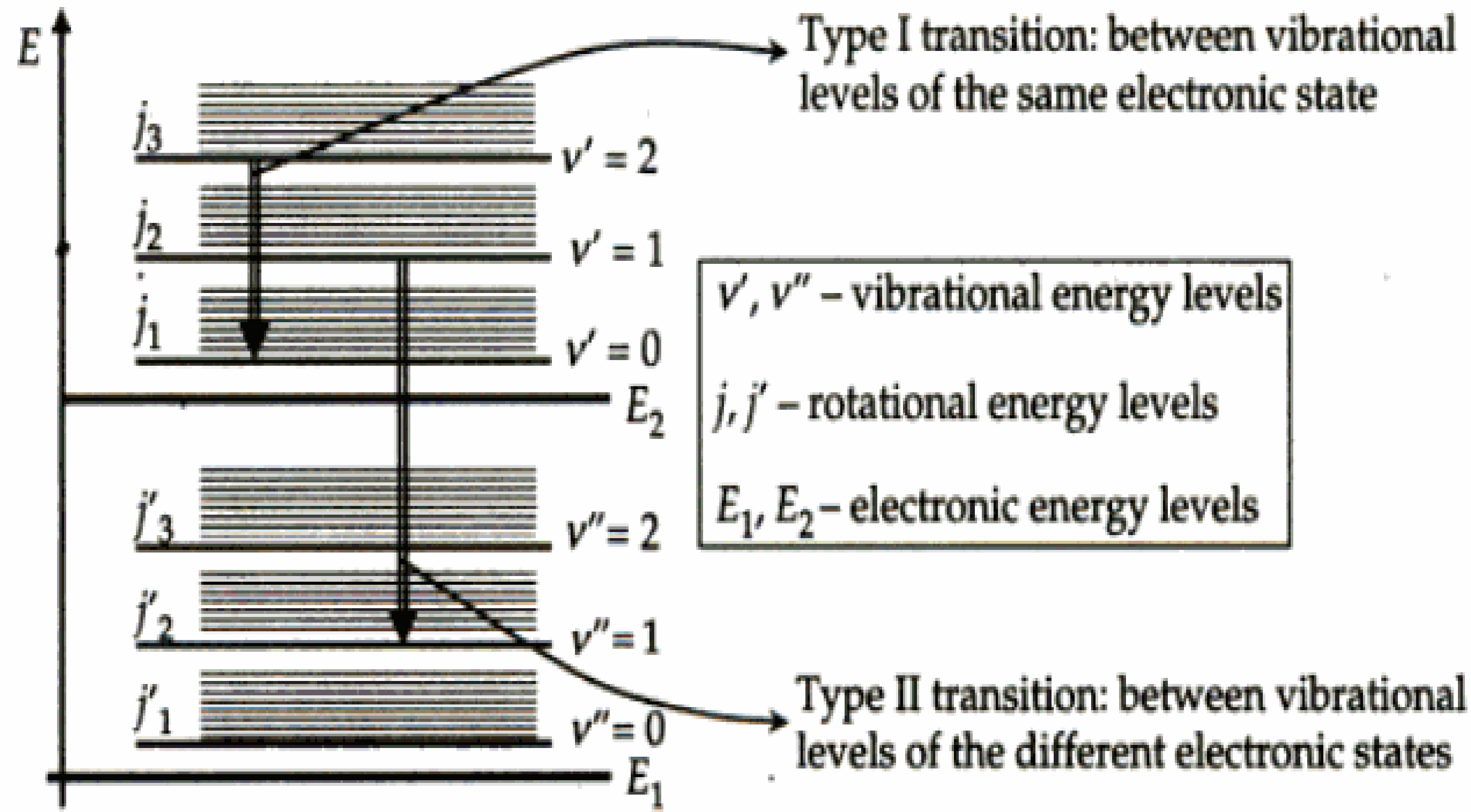
The output from a CO_2 laser is the result of type I transitions, in which the transitions take place between the vibrational levels of the same electronic levels.

Principle As a gas molecule can both rotate and vibrate along with getting excited to different electronic states, it is necessary to know the different mechanisms by which a CO_2 molecule can get excited. CO_2 is a linear molecule, with the two oxygen atoms at the ends and the single carbon atom at the middle. It can undergo three types or modes of vibrations, namely

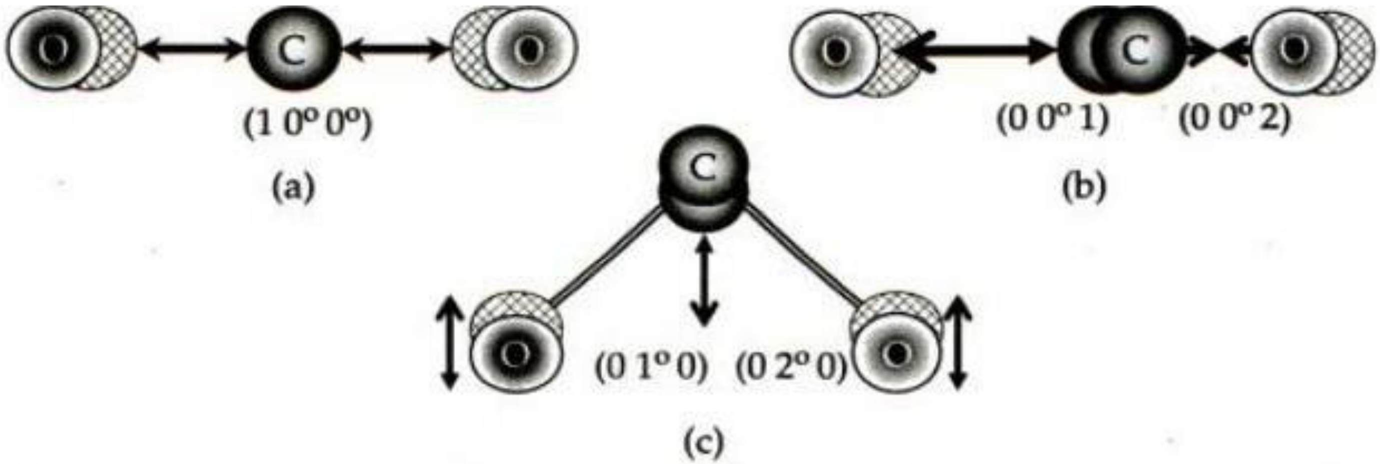
- Symmetric mode or stretching
- Asymmetric mode or stretching
- Bending mode

In all the three modes, the centre of gravity of the molecule remains fixed.

Symmetric mode In the symmetric mode, the end oxygen atoms stretch opposite to each other symmetrically either away or towards the carbon atom in a straight line (Fig. 5.10a), and the centre carbon atom remains stationary. The frequency corresponding to this stretching is known as the symmetric stretching frequency.



Different types of energy levels and transitions in a diatomic molecule

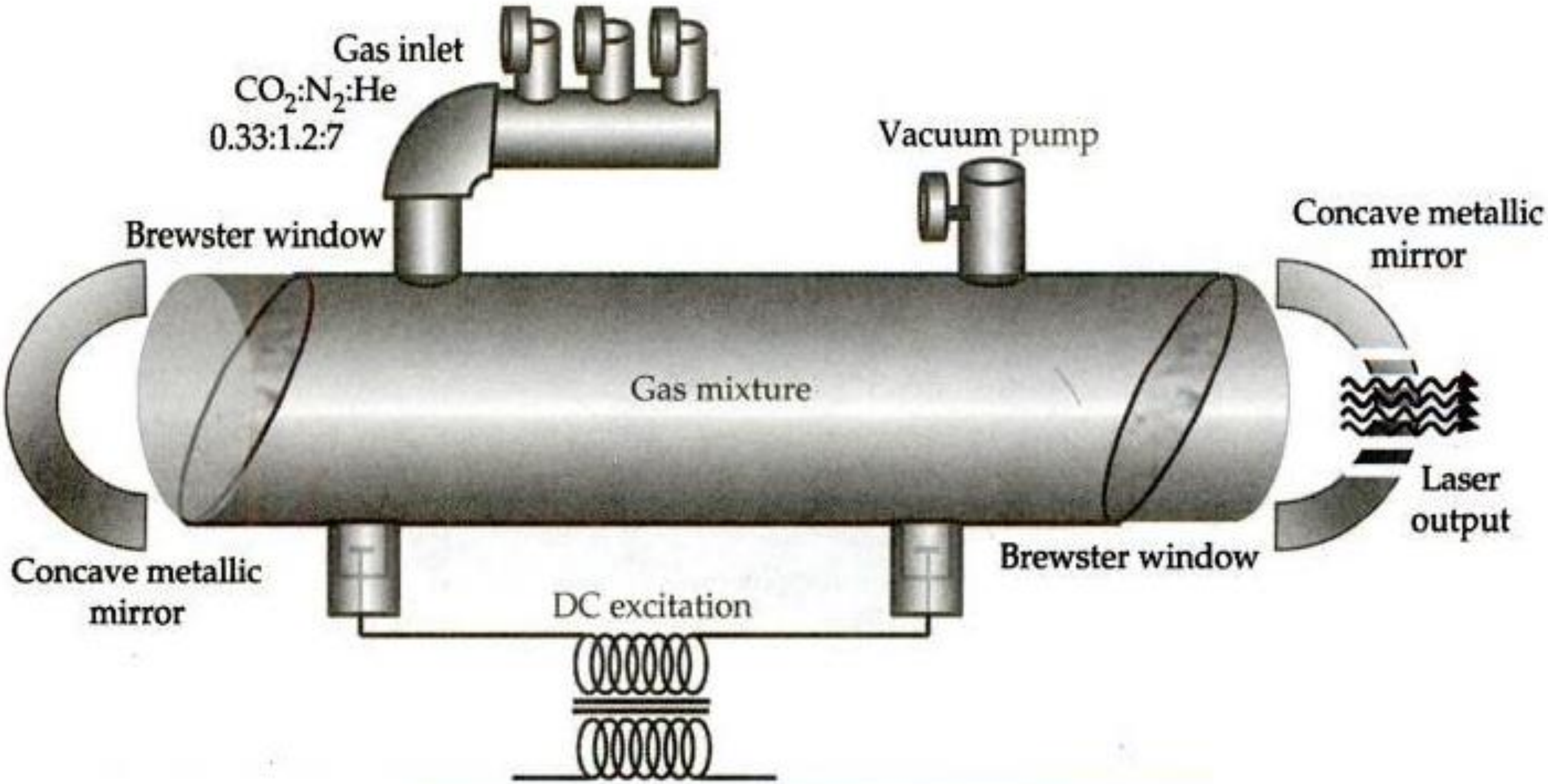


(a) Symmetric stretching (b) asymmetric stretching (c) bending mode

Asymmetric mode In this mode, the oxygen atoms move in the same direction, i.e., if one atom comes towards the carbon atom, then the other one moves away from it (Fig. 5.10b). At the same time, the carbon atom also moves in a straight line towards and away from any one of the oxygen atoms. This results in two atoms (one carbon and one oxygen) either coming together or getting away from each other. The entire stretching is along a straight line. The frequency corresponding to this stretching is known as the asymmetric stretching frequency.

Bending mode In this mode, the carbon atom and the oxygen atoms vibrate at right angles to the line joining the three atoms (centre of gravity). When the carbon atom moves up, the two oxygen atoms move down simultaneously and vice versa (Fig. 5.10c). This results in the bending of the molecule and the mode is known as bending mode. The frequency corresponding to this mode is known as bending frequency.

Construction The laser system consists of a long cylindrical tube several metres in length and several centimetres in diameter (Fig. 5.11). The feature of the CO_2 laser is



Construction of CO_2 laser system

that the output from it depends on the diameter of the tube; wider the diameter, more powerful the output. The laser is powered by a 50 Hz power supply. DC excitation or electric discharge is used to pump the laser. A mixture of CO_2, N_2, and He in the ratio 0.33:1.2:7 torr is used for producing the laser. A separate inlet for the gases with necessary valves to control the flow of the gases into the discharge tube is provided. The discharge tube is also connected to a vacuum tube to remove any unwanted trace gases present inside the tube prior to working.

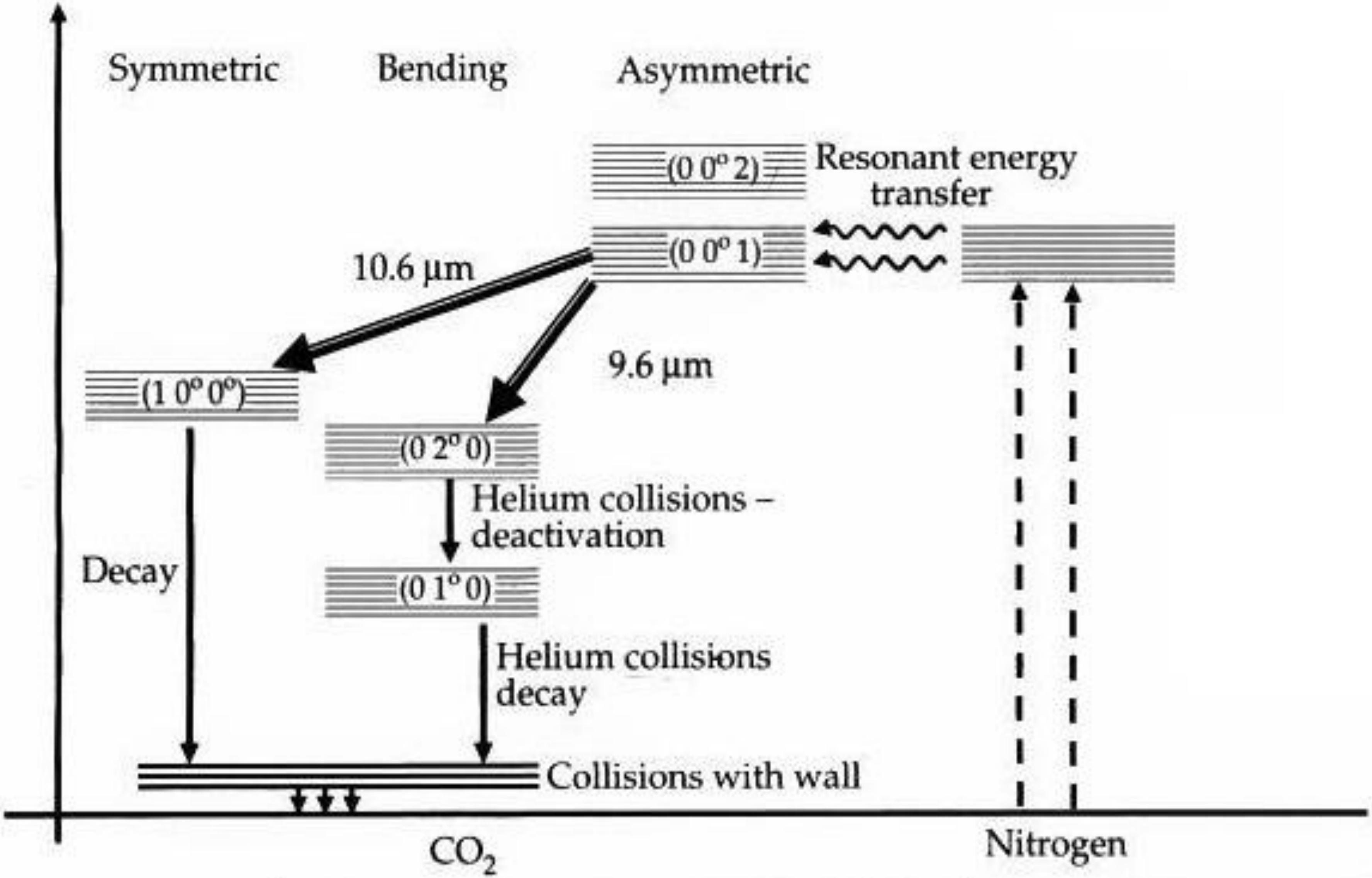
The ends of the tube contain NaCl crystal kept at Brewster angle to filter out the radiations that are not incident at the Brewster angle. The radiations are thus polarized. As the output from a CO_2 laser is in the IR range, the reflection of the incident radiation is possible only by using metallic mirrors (concave). In order to get a high-power output, a metallic mirror made of gold is employed. The mixture of gases in the discharge tube can be either longitudinal or transverse in nature. When sent in transversely (TEA laser), the output power from the laser increases tremendously.

Working The CO_2 laser utilizes a mixture of CO_2, N_2, and He for producing an output. The addition of two gases, N_2 and He, in the CO_2 laser is specifically for a purpose. As the CO_2 molecules are difficult to excite, the nitrogen atoms are excited first and then they transfer their energy to the CO_2 molecule by the following process (Fig. 5.12).

$$N_2 + e^* \rightarrow N_2^* + e$$

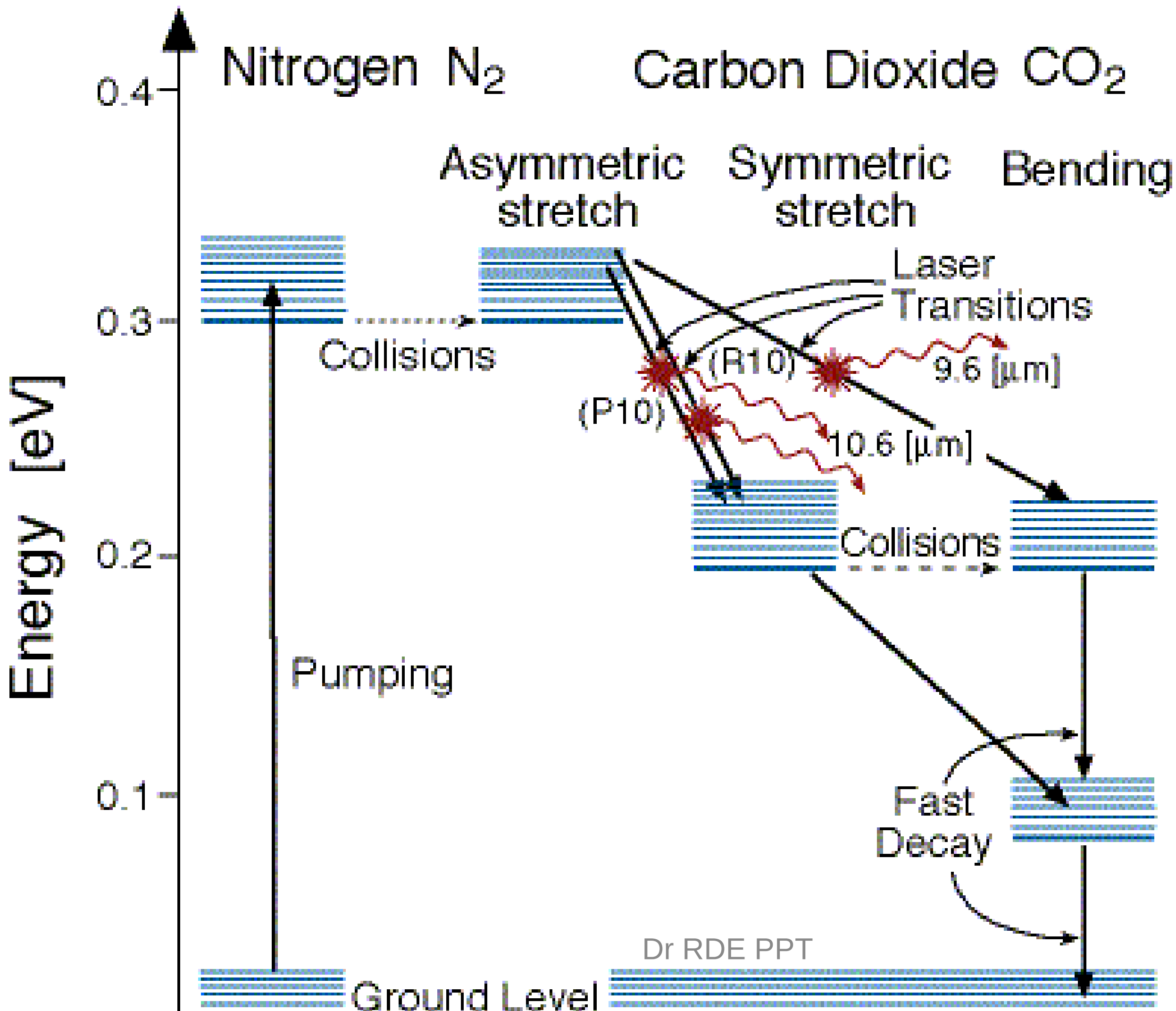
$$N_2^* + CO_2 \rightarrow CO_2^* + N_2$$

The (0 0 1) level of the asymmetric mode CO_2 molecule is close to the excited level of the N_2 atoms and hence it gets excited. The population of this level increases rapidly compared to the lower levels (0 2 0), (0 1 0), and (1 0 0). This results in a population inversion condition, which is essential for laser action to take place.



Energy level diagram of CO_2 laser

Energy Level Diagram For Carbon Dioxide Laser



The excited asymmetric mode of the CO_2 molecule relaxes to the symmetric (1 0 0) and bending modes (0 2 0) by emitting radiations of 10.6[11] and 9.6 μm, respectively. After this, the symmetric mode relaxes close to the ground level by a radiation-less decay, while the bending mode utilizes the helium atoms in the mixture to deactivate themselves to the (0 1 0) level from where they decay to a level close to the ground level. As this level is just above the ground level, populating this level results in a lowered laser output, because they do not allow sufficient inversion of population in the higher levels. Hence, the helium atoms, being good conductors of heat (the reason why their ratio is far higher than the other two gases in the mixture), take away the heat of the CO_2 molecules by colliding with them. Also, the CO_2 molecules themselves collide with the walls of the tube and lose their energy and reach the ground level.

Thus, the discharge tube gets heated up rapidly and this necessitates it to be cooled by external means. Hence, air or water is used for cooling the discharge tube externally apart from the cooling produced by the He gas internally. The output from the CO_2 laser is maximum only when it is properly cooled (i.e., the operating temperature plays a major part in determining the output power). As the gases can be contaminated (CO_2 splits into CO and O_2) on continuous operation, they have to be removed from the discharge tube by means of the vacuum pump, and fresh gas mixture is introduced to maintain the output.

Advantages

- CO_2 lasers emit energy in the far-infrared region.
- They emit up to 100 kW at 9.6 and 10.6 μm, and their output power can be controlled.
- As their output power depends on the diameter of the tube, increasing the tube diameter increases the power level.
- When the gases are transversely passed through the tube (conventionally the gases are passed along the length of the tube—longitudinal), the output power can be increased drastically.
- The TEA laser is an inexpensive gas laser producing UV light at 337.1 nm.

Disadvantages

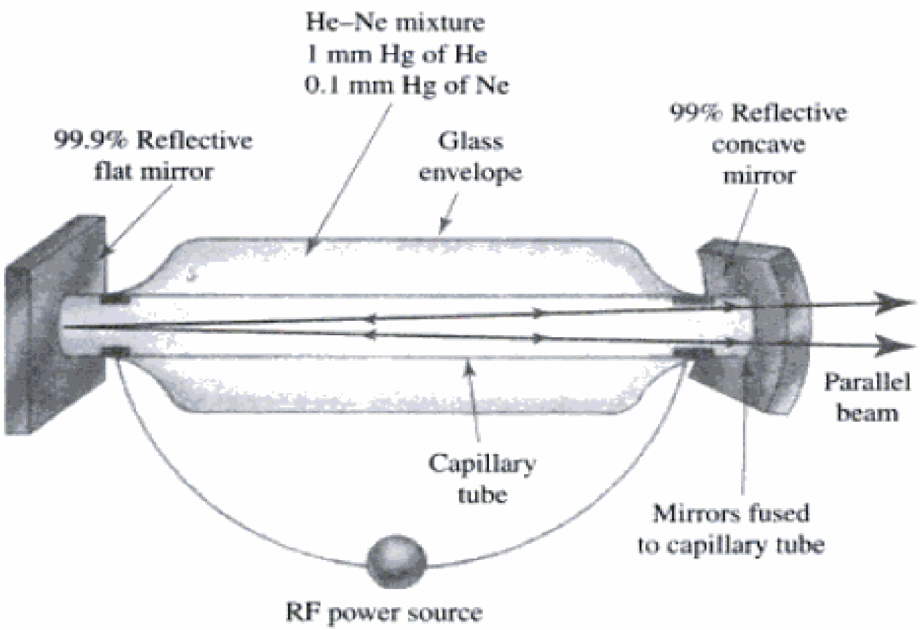
- The efficiency of CO_2 laser is only 30%.
- Increasing the output power increases the heating produced.
- A higher power level results in the need for higher cooling.
- It is difficult to control and maintain the precise mixing of the gases in the desired ratio.
- For proper operation, the contaminated gases have to be removed and fresh mixture introduced.

Applications They have various applications because of their ability to produce high power continuously.

- They are used in open-air communication (as the main output from the CO_2 laser is at 10.6 μm, and the wavelength has a low attenuation at that value).
- Used in military for spying (the IR radiations can travel through fog and buildings).
- Because of their high-power output, they are used in industries for cutting, drilling, welding, and other heavy applications.
- They are also used as LIDAR (Light Detection And Ranging), the operation of which is similar to RADAR.
- In medicine, they are used for bloodless surgery (highly focused laser light can cut and seal the blood vessel immediately, thereby minimizing and totally avoiding blood loss).

GAS LASER

The Helium–Neon Laser



Schematic drawing of an He–Ne laser

It consists of a gas tube containing 15% helium gas and 85% neon gas.

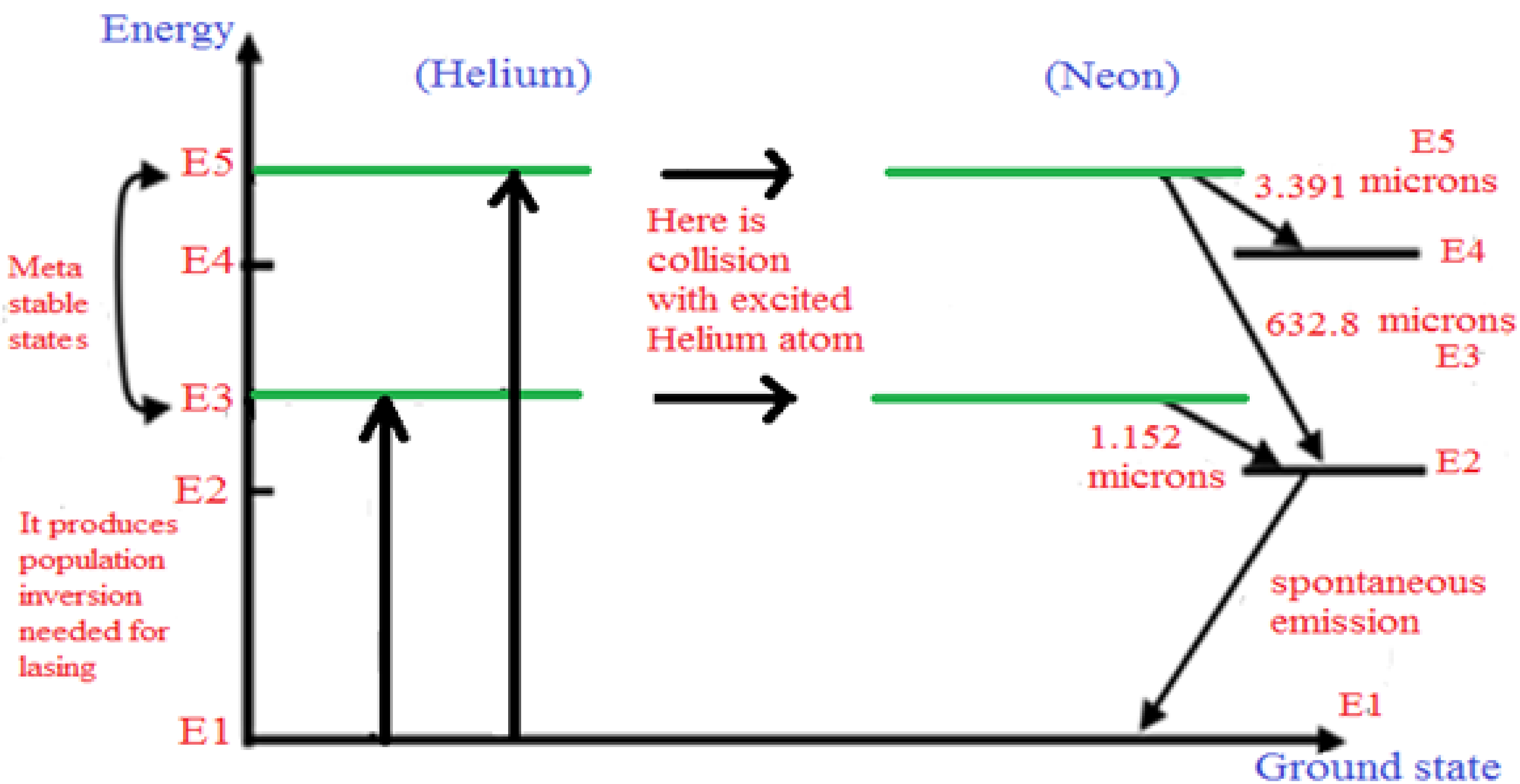
A totally reflecting flat mirror is mounted at one end of the gas tube and a partially reflecting concave mirror is placed at other end.

The helium-neon laser is a kind of neutral atom gas laser, the common wavelength of an He-Ne laser is 632.8 nm. It is tunable from infrared to various visible light frequencies.

Pumping is done by a dc electrical discharge in the low-pressure discharge tube. First, the He atom is excited. Because the Ne atom has an energy level very near to an energy level of He, through kinetic interaction, energy is readily transferred form He to Ne; and the Ne atom emits the desired laser light.

The typical power of an He-Ne laser is below 50 mW, hence it is widely used in holography, scanning measurement, optical fiber communication. It is the most popular visible light laser.

Helium Neon Laser – Energy Level Diagram



2 *Find out the separation between metastable and excited levels for two wavelengths of 9.6 μm and 10.6 μm emitted from a CO_2 laser source. Calculate the frequency and hence the energy of the light photons emitted. How many photons are required to be emitted per second to obtain a laser output power of 10 kW?*

Solution Given, two wavelengths: 9.6 μm and 10.6 μm

$$h = 6.625\times10^{-34}\,\text{Js} = 4.14\times10^{-15}\,\text{eVs}$$

$$c = 3\times10^{8}\,\text{m/s}$$

$$k = 8.625\times10^{-5}\,\text{eV/K}$$

$$h\nu = E_2 - E_1 = \frac{hc}{\lambda} = \frac{1.2422\times10^{-6}\,\text{eVm}}{9.6\times10^{-6}\,\text{m}} = 0.129\,\text{eV}$$

and

$$E_2 - E_1 = \frac{hc}{\lambda} = \frac{1.2422\times10^{-6}\,\text{eVm}}{10.6\times10^{-6}\,\text{m}} = 0.117\,\text{eV}$$

So the estimated separation between the two required levels is 0.129 eV and 0.117 eV respectively. The energy of the photon is also respectively 0.129 eV and 0.117 eV. The frequency of the two different types of photons will be

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^8 \text{ m/s}}{9.6 \times 10^{-6} \text{ m}} = 3.125 \times 10^{13} \text{ Hz}$$

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^8 \text{ m/s}}{10.6 \times 10^{-6} \text{ m}} = 2.83 \times 10^{13} \text{ Hz}$$

To get 10 kW output power, 10000 J/s power is required

The energy of one photon is

$$h\nu = 6.625 \times 10^{-34} \times 3.125 \times 10^{13} = 2.07 \times 10^{-20} \text{ J}$$

Similarly, for other photon the energy in joules is

$$h\nu = 6.625 \times 10^{-34} \times 2.83 \times 10^{13} = 1.87 \times 10^{-20} \text{ J}$$

So, the number of photons per second required is

(10000 J/s)/$2.07 \times 10^{-20} = 4.83 \times 10^{23}$ photons/second, and

(10000 J/s)/$1.87 \times 10^{-20} = 5.34 \times 10^{23}$ photons/second.

So, approximately one mole of atoms are involved in the process in one second.

3 *A typical laser system is capable of lasing at infrared wavelengths. The light output at 3.124 μm is very prominent. What is the difference in the energy levels of the excited state and metastable state? What will be the energy of a photon emitted? What will be the frequency of the light emitted? If 1 mole of photons are emitted per second, what is the power of the laser output? Can you predict the type of the laser produced?*

Solution $\lambda = 3.124\ \mu\text{m} = 3.124 \times 10^{-6}\ \text{m}$

$$h\nu = E_2 - E_1 = \frac{hc}{\lambda} = \frac{1.2422\times10^{-6}\,\text{eVm}}{3.124\times10^{-6}\,\text{m}} = 0.398\,\text{eV}$$

Energy difference between the metastable and excited states is 0.398 eV and hence the photon energy emitted is also 0.398 eV.

The frequency of the photon is $\nu = \frac{c}{\lambda} = \frac{3\times10^{8}\,\text{m/s}}{3.124\times10^{-6}\,\text{m}} = 9.6\times10^{13}\,\text{Hz}$

The energy in joules is $h\nu = 6.625\times10^{-34}\times9.6\times10^{13} = 6.36\times10^{-20}\,\text{J}$

One mole of photon $6.022\times10^{23}\times6.36\times10^{-20} = 38299.92 = 38.3\ \text{kJ}$

Therefore 38.3 kW of output power of laser beam is observed. Obviously, it will be a CO_2 laser light.

USES OF LASERS

Since their invention, lasers have become ubiquitous, finding utility in thousands of highly varied applications in every section of the modern society, including consumer electronics, information technology, science, medicine, industry, law enforcement, and the military. They have been widely regarded as one of the most influential technological achievements of the 20th century. The benefits of lasers in various applications stems from their properties such as coherency, high monochromaticity, and capability of reaching extremely high powers.

Industry

- Laser is used to cut steel and other metals.
- Laser line levels are used in surveying and construction.
- Lasers are also used for guidance in aircraft (ring laser gyroscope).
- A laser of modest power can be focused to high intensities and used for cutting, burning, or even vapourizing materials.

Science

- Lasers are employed in a wide variety of interferometric devices and for Raman spectroscopy and laser-induced breakdown spectroscopy.
- They are also used in some types of thermonuclear fusion reactors.
- Other uses of lasers include atmospheric remote sensing and investigation of non-linear optics phenomena.
- Holographic methods employing lasers also contribute to a number of measurement techniques.
- Lasers are used in consumer electronics, telecommunications, data communications, and as transmitters in optical communications over optical fibre and free space.
- They are used to store and retrieve data from compact discs, DVDs, as well as magneto-optical discs.
- A highly coherent laser beam can be focused down to its diffraction limit allowing it to record gigabytes of information in the microscopic pits of a DVD.
- Laser lighting displays (Fig. 5.16) accompany many music concerts.

Medicine

- Laser is used as a scalpel for laser vision correction (LASIK).
- Lasers are also used for dermatological procedures including removal of tattoos, birthmarks, and hair.

Law enforcement

- Lasers are widely used as LIDAR to detect the speed of vehicles.
- In military, lasers are used as target designators for other weapons; their use as directed-energy weapons is currently under research.
- Laser weapon systems under development include the air-borne laser, the air-borne technical laser, the tactical high-energy laser, the high-energy liquid laser area defence system, and the MIRACL (mid-infrared advanced chemical laser).

Dye lasers

The gain medium in a dye lasers is a solution made with an organic dye molecule. The solution is intensely coloured owing to the very strong absorption from the ground electronic state S_0 to the first excited singlet state S_1. Fluorescence to the ground state also has a high quantum efficiency, Φ_F.

Possible processes:
1,2: Absorption from S_0 to S_1, S_2
3,4: Rapid collisional relaxation to ground vibrational level of S_1
5: Fluorescence to various vibrational states of S_0 (basis for laser emission)
6: Vibrational relaxation to S_0 ground vibrational level
7: ISC to triplet state T_1
8: Absorption between triplet states
9: Phosphorescence to S_0

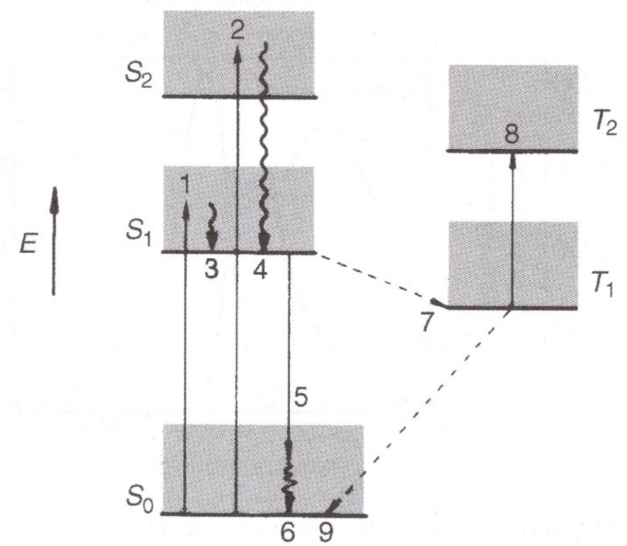
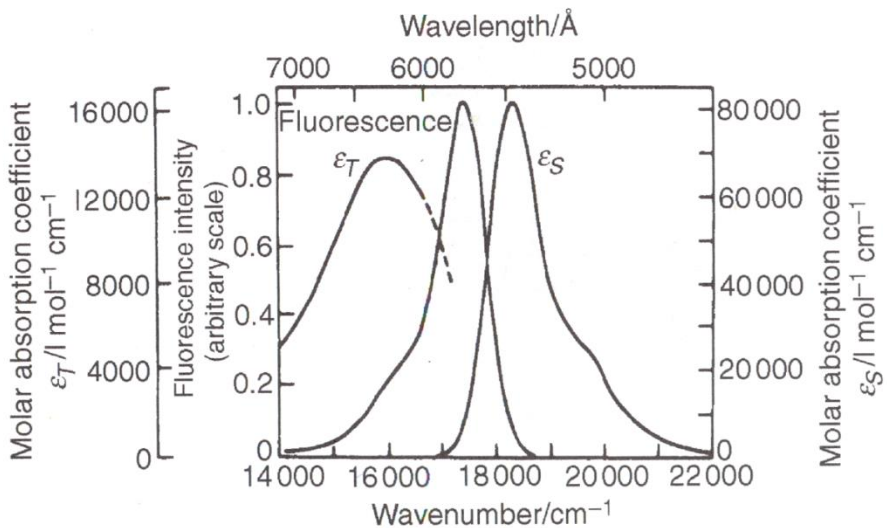


Figure 9.18 Energy level scheme for a dye molecule showing nine processes important in laser action

This is essentially a 4-level laser: pumping at 1 or 2; laser emission at 5.

The absorption and fluorescence spectra are comprised of a broad continuum of vibrational and rotational states as the following Rhodamine B/methanol spectrum shows:



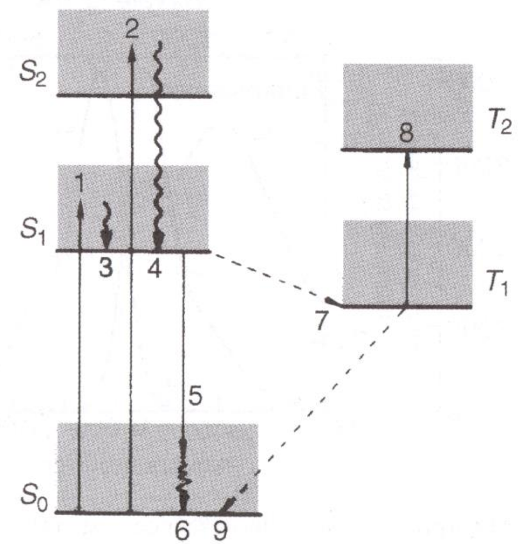


Figure 9.17 Absorption and fluorescence spectra of rhodamine B in methanol (5×10^{-5} mol l^{-1}). The curve marked ε_T is for the $T_2 - T_1$ absorption (process 8 in Figure 9.18) and that marked ε_S for process 1. (Reproduced, with permission, from Dienes, A. and Shank, C. V., Chapter 4 in *Creation and Detection of the Excited State* (Ed. W. R. Ware), Vol. 2, p. 154, Marcel Dekker, New York, 1972)

The fluorescence is red-shifted relative to the absorption spectrum. Absorption by the triplet state is a significant loss process.

How is wavelength tuning accomplished?

Many laser dyes are available:

Typically, each dye can be tuned over several tens of nm.

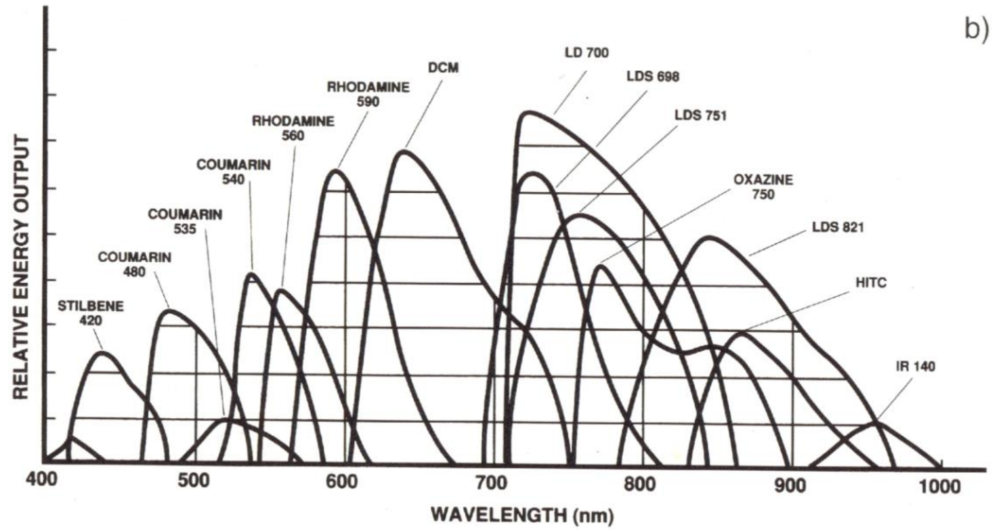


Fig. 5.80a,b. Spectral gain profiles of different laser dyes, illustrated by the output power of pulsed lasers (**a**) and cw dye lasers (**b**) (Lambda Physik and Spectra-Physics information sheets)

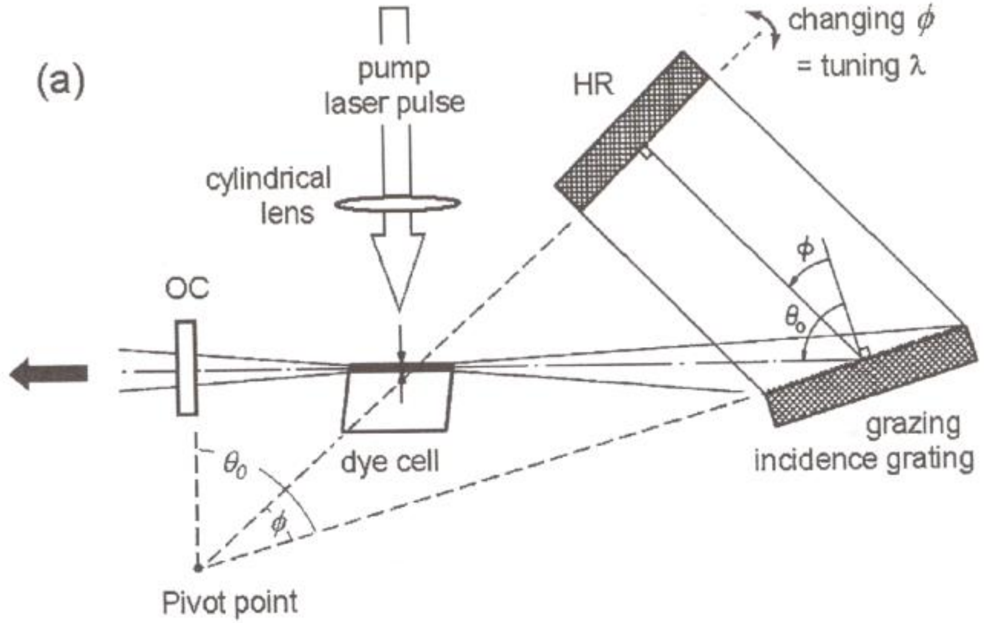
The wide tuneability range, high output power, and pulsed or CW operation make the dye laser particularly useful in many chemical studies.

Pulsed dye lasers may be pumped by flashlamps or other pulsed lasers (N_2, excimer, Nd:YAG). CW dye lasers are usually pumped by Ar ion lasers.

The dye solution must be circulated to prevent overheating and degradation, and to replace molecules in the triplet state, T_1

Tuning the wavelength:

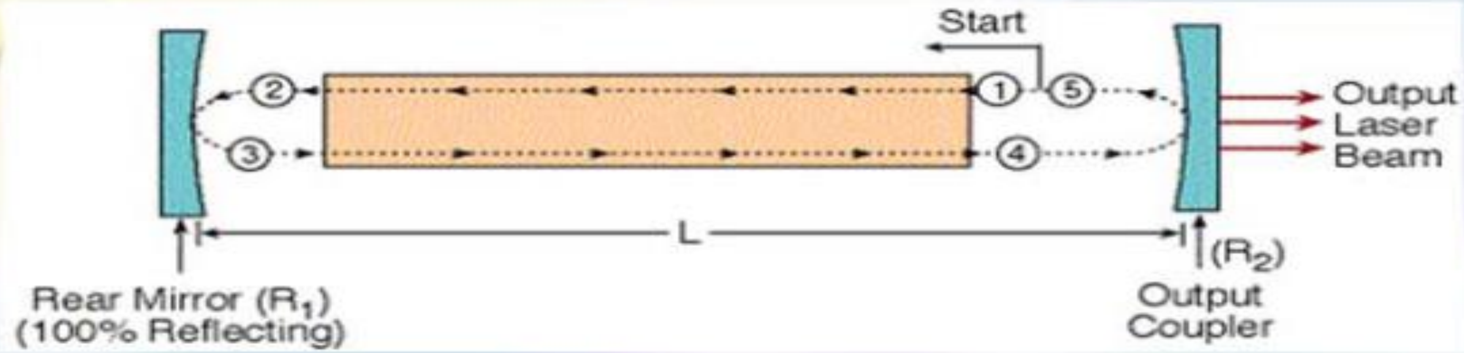
Usually a *tuning element*, such as a diffraction grating or prism, is incorporated in the cavity. This allows only light in a very narrow frequency range to resonate in the cavity and be emitted as laser emission.



Rotating a mirror or tuning element selects which wavelengths are resonant in the laser cavity.

Round trip Gain (G)

Figure below show the round trip path of the radiation through the laser cavity. The path is divided to sections numbered by 1-5, while point "5" is the same point as "1".



Round trip path of the radiation through the laser cavity.

By definition, **Round trip Gain** is given by:

$$G = I_5 / I_1$$

G = Round trip Gain.

I_1 = Intensity of radiation at the beginning of the loop.

I_5 = Intensity of radiation at the end of the loop.

we found that the intensity after one round trip

$$I_5 = R_1 * R_2 * G^2 * I_1$$

Gain (G) With Losses

We assume that the losses occur uniformly along the length of the cavity (L). In analogy to the Lambert formula for losses, we define loss coefficient (α), and using it we can define absorption factor k:

$$k = \exp(-2\alpha L)$$

k = Loss factor, describe the relative part of the radiation that remain in the cavity after all the losses in a round trip loop inside the cavity.

All the losses in a round trip loop inside the cavity are 1-k (always less than 1).

α = Loss coefficient (in units of 1 over length).

2L = Path Length, which is twice the length of the cavity.

Adding the loss factor (k) to the equation of I_5:

$$I_5 = R_1 * R_2 * G_A^2 * I_1 * k$$

From this we can calculate the round trip gain:

$$G = I_5/I_1 = R_1 * R_2 * G_A^2 * k$$

As we assumed uniform distribution of the loss coefficient (α), we now define gain coefficient (γ), and assume active medium gain (G_A) as distributed uniformly along the length of the cavity.

$$G_A = \exp(+\gamma L)$$

$$\boxed{G(\nu) = e^{\gamma_0(\nu)l}}$$

Substituting the last equation in the Loop Gain:

$$\boxed{k = \exp(-2\alpha L)}$$

$$G = R_1 * R_2 * \exp(2(\gamma - \alpha)L)$$

$$G = R_1 * R_2 * \exp(2(\gamma - \alpha)L)$$

When the loop gain (G) is greater than 1 (G > 1), the beam intensity will *increase* after one return pass through the laser.

When the loop gain (G) is less than 1 (G < 1), the beam intensity will *decrease* after one return pass through the laser. laser oscillation decay, and no beam will be emitted.

Conclusion:

There is a threshold condition for amplification, in order to create oscillation inside the laser.

This Threshold Gain is marked with index "th".

$$G_{th} = 1$$

For continuous laser , the threshold condition is:

$$\boxed{G_{th} = 1 = R_1 R_2 G_A^2 k = R_1 * R_2 * \exp(2(\gamma - \alpha)L)}$$

Example

Active medium gain in a laser is 1.05. Reflection coefficients of the mirrors are: 0.999, and 0.95. Length of the laser is 30cm. Loss coefficient is: $\alpha = 1.34*10^{-4}\ cm^{-1}$.

Calculate:

1. The loss factor k.
2. The round trip gain G.
3. The gain coefficient (γ).

Solution

1. The loss factor k:

$$k = \exp(-2\alpha L) = \exp[-2(1.34*10^{-4})*30] = 0.992$$

2. The Loop gain G:

$$G = R_1 R_2 G_A{}^2 k = 0.999*0.95*1.052*0.992 = 1.038$$

Since $G_L > 1$, this laser operates above threshold.

3. The gain coefficient (γ):

$$G = \exp(\gamma L)$$

$$\mathrm{Ln}\ G = \gamma L$$

$$\gamma = \mathrm{Ln}\ G/L = \ln(1.05)/30 = 1.63*10^{-3}\ [cm^{-1}]$$

The gain coefficient (γ) is greater than the loss coefficient (α), as expected.