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Topic: Basic Laser Systems

Semester - V;   Paper - DSE A1 (Laser and Fiber Optics)

The first practical laser was discovered in the year 1960 by famous scientist T. Maiman. It was a Ruby laser which was operating at a wavelength of 694.3 nm. Due to advancement in the research and commensurate technology development, many laser systems were designed and operated later on. All the laser systems need three basic components for its operation: (a) active medium, (b) optical pumping, and (c) resonator. The emission wavelength of a laser is decided based on the choice of active medium and its constituting energy levels, to be precise. Therefore, a broad classification of basic laser systems are done on the basis of types of active medium. The most important types of laser systems in current days are as follows:

(a) Gas laser: In this laser systems, a single or a mixture of gases is used as active medium. Example - He-Ne, CO_2, etc.

(b) Solid state laser: Here different solid material is used as active medium. Example - Ruby, Nd-YAG, etc.

(c) Semiconductor laser: The active medium is semiconductor material here. Although this also comes under solid state laser, but the operating principle is slightly different from typical solid state laser. Example - In(Ga)P, Al(Ga)As, etc.

(d) Liquid laser: In this laser system, chemical dye is being used as active medium. Example - Rhodamine, Coumarin, etc.

Below we will discuss the details of gas, solid state and liquid laser systems and note down their specific applications. As semiconductor laser is a large topic of discussion, we will include it in a different module. Let us begin with He-Ne laser.

(i) **He-Ne Laser:** He-Ne laser was the first operated four-level continuous wave gas laser. It was discovered in the year 1961 by Ali Javan, Bennett and Heriott at Bell Laboratories. The operating wavelength of this laser is 632.8 nm. A mixture of He and Ne gas is used as the active medium. The energy levels of a gas is usually very sharp and therefore electrical discharge has been used to pump the atoms in He-Ne mixture.

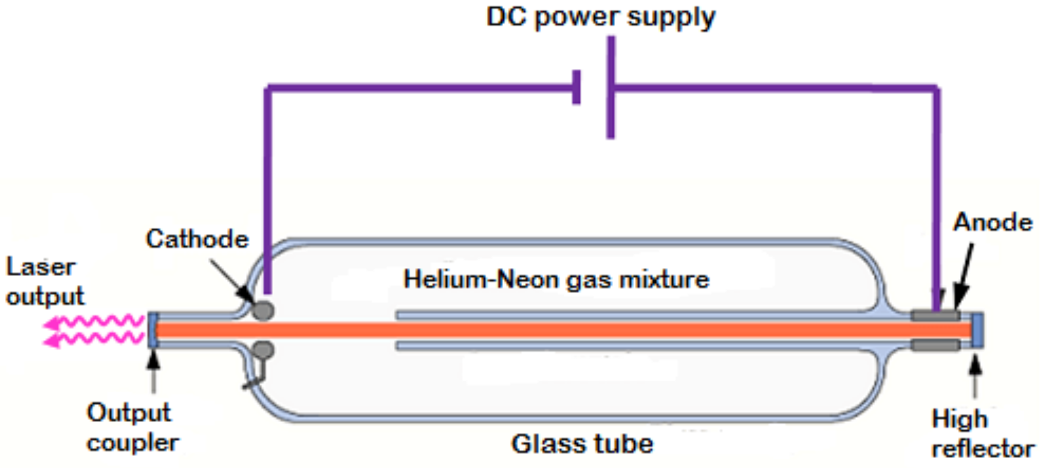
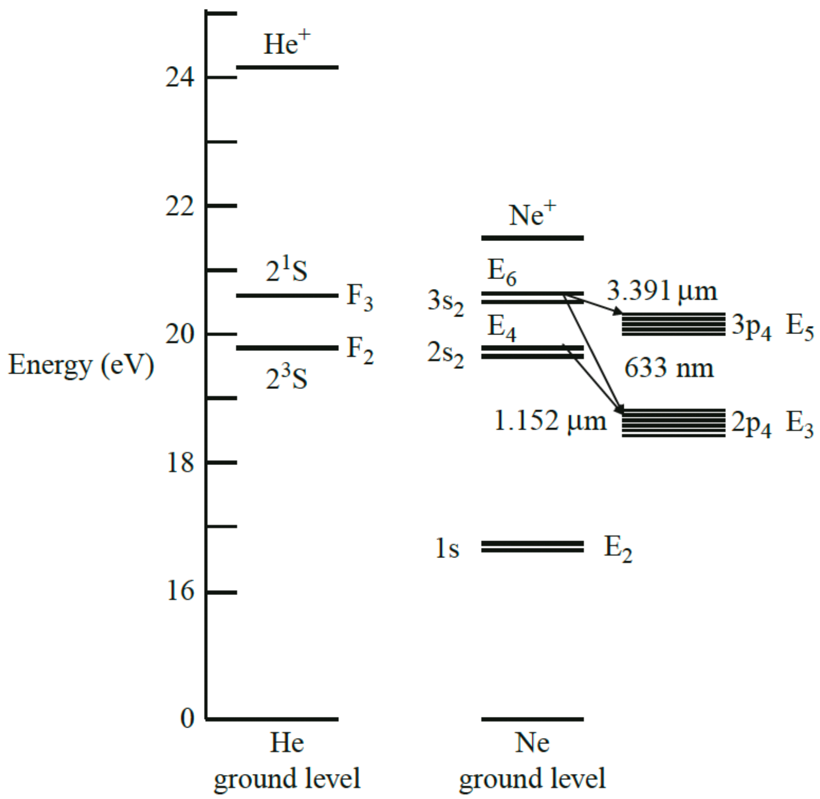


Fig. 1: Construction of He-Ne laser.

Construction: For efficient operation, the construction is the most crucial part of a laser system. There is a long and narrow electrical discharge tube made of glass. This tube has a diameter of ~ 2-8 mm and length of ~ 10-100 cm. It is filled with a mixture of He-Ne gas with a pressure ratio of 10:1. Of course there will be internal or external resonator comprises of one fully silvered 100% reflective mirror and another partially silvered high reflectivity mirror. The electrodes of the discharge tube is connected to a high voltage DC power supply.

Operation Principle: In this laser system, He is primarily used for selective pumping of Ne atoms while Ne atoms and their energy levels are primarily responsible for laser emission. The energy level diagram of the gas mixture is shown below. The low energy levels are involved in the losing action. With the passage of electrical discharge, the electrons get highly accelerated inside the tube and they collide with both He and Ne atoms. As a result, He and Ne atoms become excited and He atoms accumulate at the energy level 2^1S (F_2) and 2^3S (F_3) which have longer lifetime. The He F_2 and F_3 levels have almost same energy as of Ne E_4 and E_6 levels. Hence, the excited He atoms further excite the ground state Ne atoms and bring them to the energy levels $2S_2$ (E_4) and $3S_2$ (E_6), respectively. Much higher pressure of He enforces the selective accumulation of excited Ne atoms at E_4 and E_6.



The excited atoms in level E_6 of the Ne+ loose energy and transit via stimulated emission to level E_3. This creates the most intense and primary laser emission line at 632.8 nm. Next, the atoms from level E_3 make a spontaneous transition to level E_2, which is a metastable state. Finally, the atoms in level E_2 collide with the walls of the tube and relax back to the ground level E_1. Among the three energy levels (E_6, E_3, E_2), E_3 has the shortest lifetime (~ 10-7 sec) and therefore, it become easier to maintain a continuous population inversion between level E_6 and E_3.

Apart from the primary emission line, there are two more transition: one is E_4 - E_3, and the other one is E_6 - E_5. The wavelengths of the transitions are 1152 nm and 3391 nm, respectively. It is important to note here that 3391 nm transition have much lower frequency than 632.8 nm and hence, the doppler broadening is much smaller and gain is much higher for 3391 nm transition.

Thus, an optical element having strong absorption near 3391 nm is kept in the path of the laser beam to enhance the population of level E_6 and emission intensity of 632.8 nm.

Applications: There are numerous applications of He-Ne laser. However, few of them are as follows-

(a) It is the most common laser used in holography

(b) This laser is widely used in demonstration in optics laboratory

(c) It is used in bar-code scanners, blood analysis and non-contact measurements.

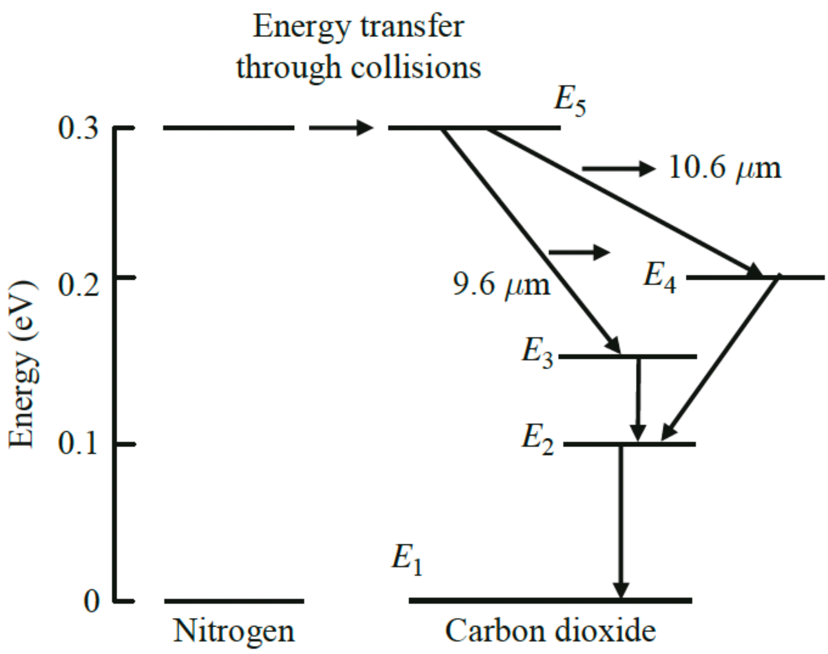
(d) It is also used in aligning other high power lasers such as CO_2 and Nd-YAG laser.

(ii) **CO_2 laser**: CO_2 laser is one of the earliest gas lasers to be discovered in the year 1964 by Kumar Patel at Bell laboratories, USA. It is the highest power continuous wave infrared laser having wavelength centred at 9.4 and 10.6 micrometers.

Construction: The basic construction of a CO_2 laser is quite similar to a He-Ne laser. A CO_2 laser consists of a long discharge tube made of quartz. The tube has an approximate diameter of 2.5 cm and length of 5 metres. It is filled with a gas mixture of CO_2, N and He with water vapour, H_2 and/ or Xe in the ratio 1:2:3. However, the exact ratios depend on the use case of a particular CO_2 laser. Though there are multiple gas molecules, CO_2 is the active part which emits the laser beam.

Operation principle: When an electrical discharge passes through the tube, the electrons get excited and collide with nitrogen molecules. Nitrogen molecules thus gain energy and transit to the higher excited vibrational energy level. Because of its homonuclear nature, N_2 molecule cannot loose energy by photon emission and hence, it’s excited levels behave as metastable states collecting excited molecules.

On the other hand, CO_2 molecule can vibrate in combination of three different quantum vibrational modes which are bending, symmetric stretch and asymmetric stretch. These modes can be designated by three quantum numbers as (mnq). The CO_2 (001) being at the same energy level with



N_2 higher excited state, the collision between them enables transition of CO_2 molecules from ground state to excited state (001). Subsequently, stimulated emissions among E_5-E_4 and E_5-E_3 is triggered by any photon of spontaneous emission. The E_5-E_4 transition emit 10.6 micrometers and E_5-E_3 transition emit 9.4 micrometer. Finally, the excited CO_2 molecules at level E_2, E_3 and E_4 make fast non-radiative transition to the ground state via collision with cold He atoms. It helps to maintain the population inversion. Since CO_2 is an infrared laser, special attention is needed to the materials selection for optical components inside the laser system. Normally, silvered mirror, and Germanium/ Zinc Selenide made windows/lenses are used, while for high power operation gold mirrors and zinc selenide windows, lenses are preferred.

Applications: The CO_2 laser is general continuous wave laser with power output in the range few mW to hundreds of kWs. However, if the laser is Q-switched by using acousto-optic or electro-optic modulator then GW output power can also be achieved. Also, the atomic quantum efficiency of CO_2 laser is very high (~45%) which results an efficient conversion of input to output power. Hence, it has a variety of applications as follows:

(a) Because of its high power, often used for cutting and welding metals, plastic boards etc.

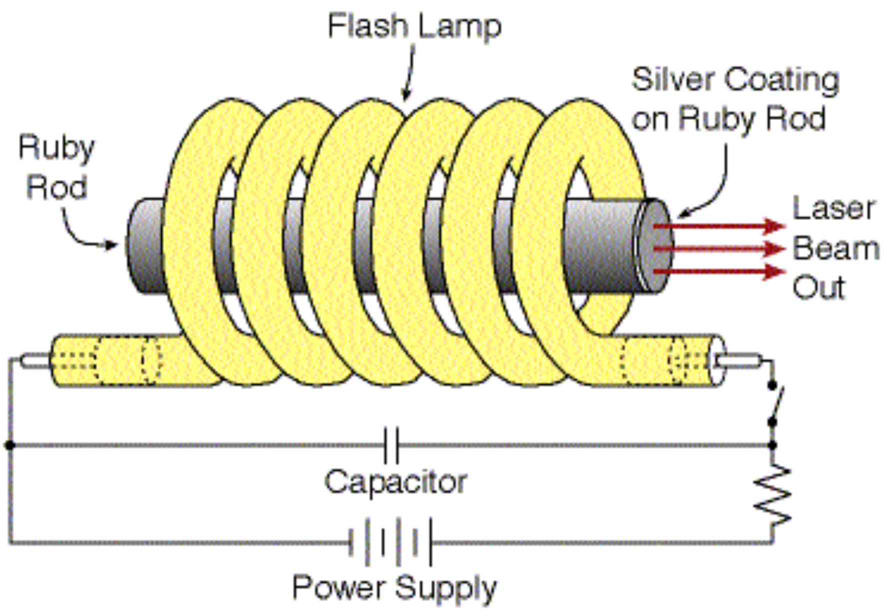
(b) Used in medical surgeries and skin grafting surgeries because the infrared light is easily absorbed by water content of biological tissues.

(c) Atmosphere is nearly transparent to infrared light. Hence, it is also widely used in military equipments.

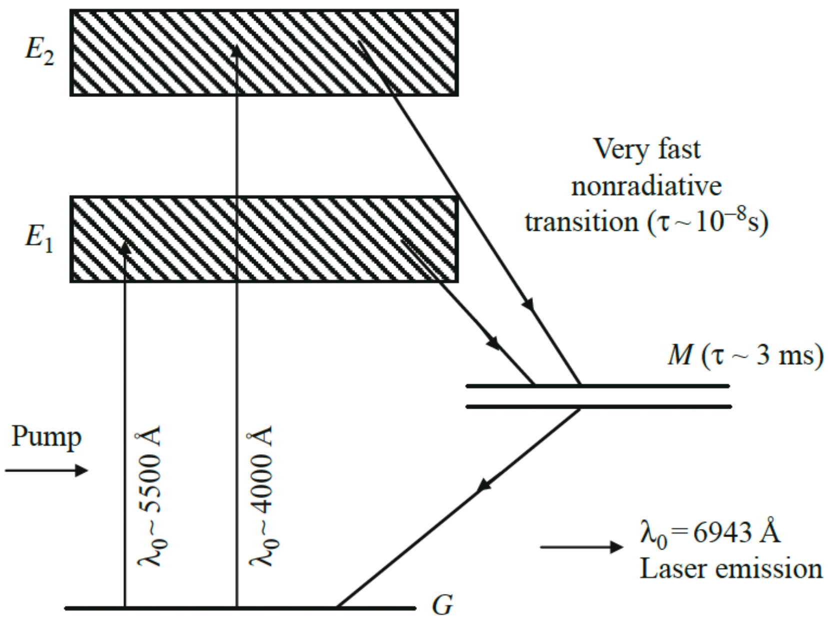
(d) Used in spectroscopy and fabrication of microfluidic devices.

(iii) **Ruby laser:** As already mentioned in the beginning of this module, Ruby laser is first practically operated laser in 1960. Therefore it is one of the most important solid state lasers. It is a three level laser and the laser emission wavelength is 694.3 nm in visible region.

Construction: A basic ruby laser consists of a ruby rod, surrounded by spiral Xenon flash lamp, a DC power supply connected to the flash lamp, silvered end surfaces of the ruby rod. The flash lamp and the ruby rod is encapsulated in a elliptical cylindrical reflector. The rod and the Xe flash lamp are placed in the two foci of the elliptical reflector for efficient pumping. The diameter and length o the ruby rod is ~ 0.1-2 cm and 2-20 cms, respectively. One surface of the ruby rod is partially silvered for output coupling while the other one is fully silvered for effective reflection. The active medium i.e ruby rod is basically a chromium doped aluminium oxide. The energy levels of Cr^{3+} are responsible for the laser emission here. Aluminium oxide is used as host matrix for Cr ions. The concentration of Cr is typically 0.05% by weight.



Operation principle: To understand the operation principle of ruby laser, we focus the figure below. The energy levels of Cr^{3+} ion are shown along with the ground state. Initially, the Cr ions in ground state (G) absorb radiation at 550 and 400 nm and reaches excited to the upper energy levels E_1 and E_2.



Following this, the ions make fast non-radiative transition to the metastable state M. E_1 and E_2 have a short lifetime (~10^{-7} to 10^{-8} sec) while the level M has a typical lifetime of 3 ms. Hence, the ions are collected at level M gradually leading to population inversion between level M and G. Any spontaneous emission then trigger a stimulated laser emission between M and G with a wavelength of 694.3 nm. As soon as the laser light is emitted the population in the upper M level deplete quickly and comes below the threshold population. It again starts collecting excited Cr ions from level E_1 and E_2. This cycle is then repeated for subsequent time. As the population inversion does not stay for a continuous period of time, hence the output become a series of laser pulse. The pulses are known as spiking in laser output.

Application: Few of the important applications of ruby laser are:

(a) Visible ruby laser is used in photographic emulsion process and photodetectors.

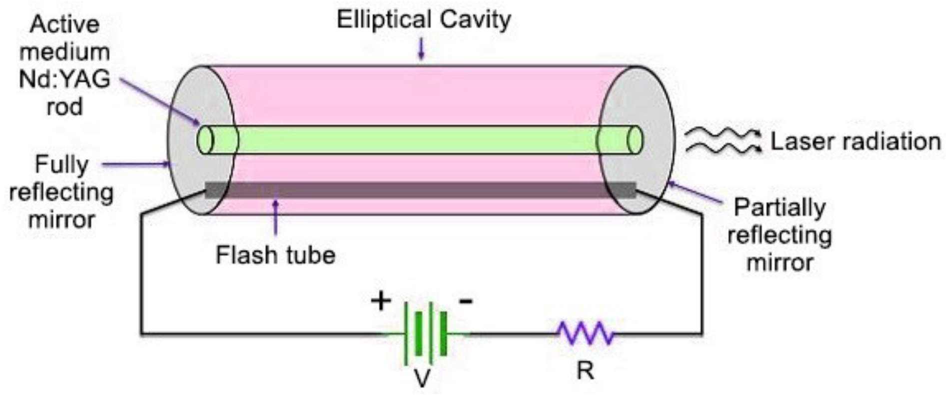
(b) It is also used in pulsed holography.

(c) Used in cosmetic dermatology and tattoo removal.

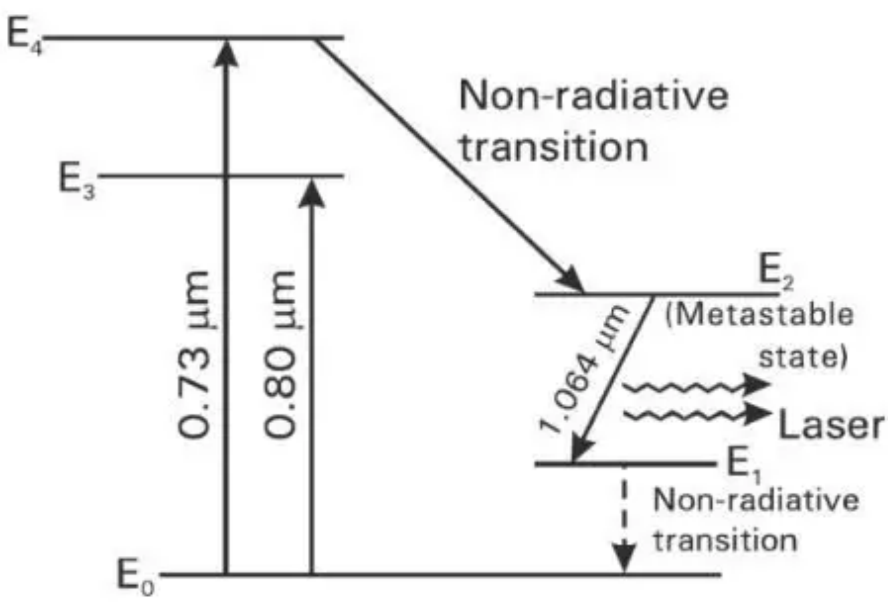
(d) The high power ruby laser is used in cutting, drilling hole thick metal sheets.

(iv) **Nd-YAG laser:** The next important and widely used solid state laser is Nd:YAG laser. It is a four level laser. The Nd ions hosted inside Yttrium Aluminium Garnet ($Y_3Al_5O_{12}$) is the active medium and the laser transition happens among the energy levels of Nd ions. The mission wavelength is 1060 nm. Use of YAG as the host material has few advantages as follows: very small laser oscillation line width, possibility of ultra short pulse using small line width, and higher thermal conductivity leading to low optical distortion.

Construction: The structure of a basic Nd:YAG laser is similar to the ruby laser. A Nd:YAG rod is placed inside an elliptical reflector cavity along with the flash lamp rod as shown in the figure. The ends of the Nd:YAG rod have been partially and fully silvered. The flash lamp is connected to a DC power supply. Nd ion concentration is kept typically at ~ 1.38 x 10^{20} cm^{-3} inside YAG host matrix. However, an advanced Nd:YAG laser is pumped using a high power compact semiconductor diode laser. The diode laser produce very less heat which increases the pumping efficiency. Also, the line width of the output of a diode laser being very small, can be efficiently utilised to pump the Nd:YAG rod.



Operation principle: The energy levels of Nd^{3+} ions are shown in the figure. It consists of ground state (E_0), a range of upper pump energy levels, with two intermediate levels.



Energy level diagram

The Nd ions get excited to upper pump levels after absorbing energy from the optical pump. The excited Nd ions then rapidly jump to upper laser level (E_3) via fast non-radiative transition. Because the lifetime is quite long for the upper laser level which is a metastable state, it accumulate the ions. Gradually the population of the metastable state become higher than the population of lower laser level. The population inversion condition is achieved between upper and lower laser level. Once the population difference crosses the threshold value, stimulated emission is triggered by any spontaneous emission. A huge number of ions transit from upper to lower laser level and emit a laser beam of wavelength 1064 nm. Immediately after this lasing action, the ions make another fast non-radiative transition to the ground state from lower laser level. Again, these ions are pumped into the upper excited levels. This cycle is repeated continuously and laser emission continues. However, in this laser the population inversion is never destroyed because the number of ions those reaches the lower laser level make an immediate transition to the ground state. Hence, there is no chance of population accumulation in lower laser level. It lead to a higher population in the upper laser level always.

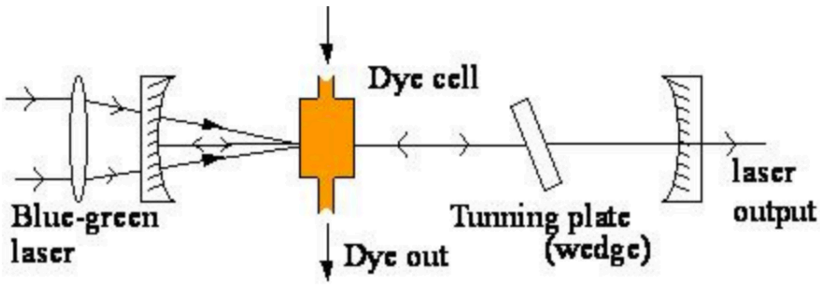
Application: The important applications of Nd:YAG laser are:

(a) Used in range finders, illuminators.

(b) Also used in resistor scribing and micro machining, etc.

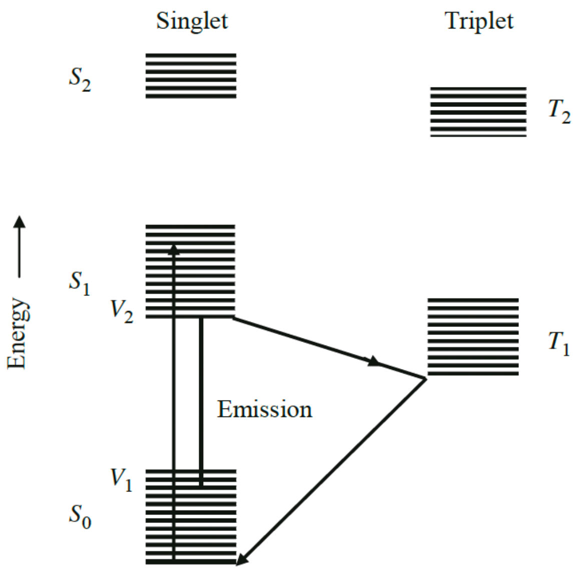
(v) **Dye laser:** Dye laser is the most usable laser whose wavelength is easily tunable in the visible region. In general, different organic dyes are used as active medium. The wavelength in these laser is tunable in the range 300 nm - 1.2 micrometers. These are normally three level lasers with pulsed operation. However, optical pumping using continuous laser can also lead to continuous output of dye laser.

Construction: The dye laser consists of a long quartz tube filled with Rhodamine-B 6G dye dissolved in water, methanol and ethyl alcohol. A flash-lamp or another laser is fitted suitably within the cavity for optical pumping.



A combination of a partially reflective mirror and a diffraction grating is utilised in the dye laser.

Working principle: The typical energy level diagram of a dye molecule is shown below in the figure. It comprises of both singlet and triplet states. Among them S_0 is the singlet ground state. Each of the singlet and triplet electronic energy states are constituted of multiple vibrational sub-levels. The optical pumping excites the molecules to different vibrational levels of S_1 state. Following this, due to rapid thermal redistribution the molecules reach back to lowest vibrational level V_2 of S_1 state. This non-radiative process occurs within a very short timespan of 10^{-11} sec. The relaxed molecules at the bottom most energy level of S_1 then make a transition to level V_1 i.e. the topmost level of energy state S_0. This is a radiative transition and called fluorescence.



Because most of the molecules decay from level V_2 by fluorescence, the laser emission occurs at fluorescence wavelength only.

The molecules from V_2 level can also make a transition to energy state T_1 and thereby reducing the population of upper laser level V_2. It may also lead to reduction in laser output power and even prevent population inversion. Hence, the optical pumping should be rapid enough to maintain a continuous population inversion.

Application: Dye laser can be both pulsed as well as continuous based on the nature of optical pumping and hence, it has numerous applications. Few of the important applications are mentioned as follows:

(a) Organic dye laser is used in isotope operation.

(b) Dye lasers are used in spectroscopy, holography and biomedical applications.