2

CHAPTER

Types of Lasers

2.1 INTRODUCTION

There are several ways in which we can classify the different types of lasers. It can be done according to what material or element is used as the active medium. It can be done according to the operation of laser in a pulsed mode or in a continuous wave (CW) mode. The classification may be done basing on other parameters such as gain of the laser medium, power delivered by the laser, efficiency or applications. We prefer here to classify the lasers on the basis of the material used as active medium. Accordingly, lasers are broadly divided into four categories-solid lasers, gas lasers, liquid lasers and semiconductor lasers. The subject of laser systems is a vast topic and it is not possible to cover each and every system. We describe only some of the important and practical lasers.

2.2 CLASSIFICATION OF LASERS (on the basis of medium)

As mentioned above, lasers can be classified in several ways as per convenience. Now a days, a large number of lasers are available and many new lasers are coming out regularly. Basically all these lasers can be classified into two categories : (*i*) high density gain medium laser and, (*ii*) low density gain medium laser. High density gain medium lasers are further sub-divided into solid and liquid lasers. Om the basis of medium, the lasers are classified into three catergories : Solid, liquid and gas lasers. In brief they can be put as under:

Solid lasers : Solid state layer was the first known laser. They belong to the laser system involving high density gain media. Different examples of solid state laser are :

- Ruby
- Nd :- YAG laser
- Nd :- Glass laser
- Tunable solid state laser
- Alexaandrite laser
- Titanium-Sapphire laser
- Colour-centre laser
- Fibre laser

Amongst all, Rubby laser is the most important and widely used solid state laser. The active material used is C_r^{3+} doped in Al_2O_3 crystal. Neodymium is a typical example of an optically pumped rare-earth laser system. Neodymium ion (Nd^{3+}) is doped in Yttrium alluminum garnet (YAG) with nearly 0.725% concentration by weight.

Liquid lasers : There are certain unavoidable draw backs in same solid state lasers. For examples, crystals have *optical strain*. Hence, they crack down or shatter. Moreover, they are prone to internal damages and susceptical to (crystal) defect and imperfections. Homogeneous liquid overcomes these problems. The active media of the liquid laser are formed by solutions of certain dyes dissolved in liquids such as water or alcohols. Dye lasers are lunable and have high gain as compared with solid state lasers. Dyes used are of the type

- Polymethene dye
- Xanthene dye
- Coumarin dye
- Scintillator dye.

Gas lasers : Gas lasers belong to low density gain media. Depending upon the characteristics of the active medium, the gas lasers are further categorized into (*i*) atomic, (*ii*) ionic and (*iii*) molecular lasers. The optical quality of gas lasers is much better as it does not suffer from optical inhomogenities. The gas lasers commonly used are Helium-Neon (He – Ne) laser, Argon ion laser, Krypton ion laser, Helium-Cadmium laser, Copper vapour laser, Gold vapour laser, Carbon-diOxide (CO_2) laser, Excimer laser, HF laser, Nitrogen laser.

Semiconductor lasers : Semiconductor laser is a special designed p-n junction dioe which emits coherent radiation when it is forward biased. A small size devoice capable of giving output of wavelength in gigahertz and has an ability to modulate the optical output. Two types of semiconductor lasers namely homojunction laser and heterojuction lasers are observed. They may also be classified in terms of bond gap properties of the gain media as Direct band-gap medium laser and Indirect band-gap medium laser.

We describe some important and usually used lasers as under.

2.3 SOLID STATE LASERS

The term solid state has different meanings in the field of electronics and lasers. A solid state laser is one in which the active centres are fixed in a crystal or glassy material. Solid state lasers are electrically non-conducting. They are also called *doped insulator lasers* to avoid connotation of semiconductor.

The basic principles that underlie the operation of solid state lasers are the same. A generic solid state laser is illustrated in Fig. 2.1.

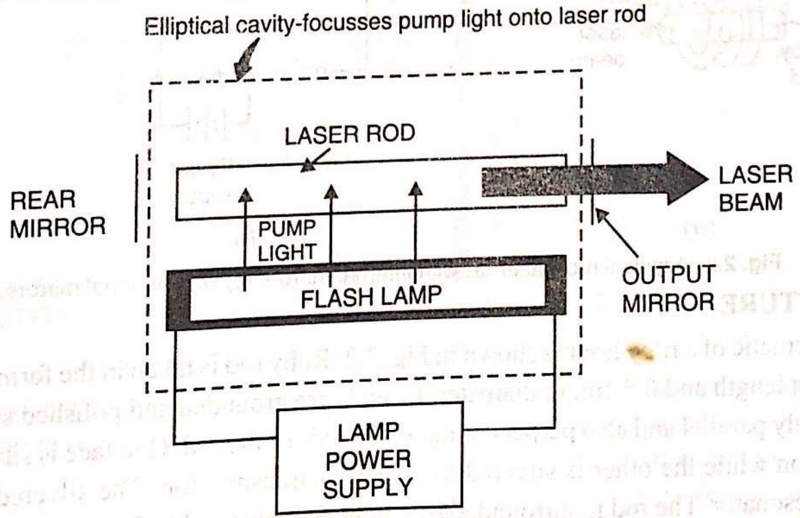


Fig. 2.1. A typical solid state laser

The active centres are dispersed in a dielectric crystal or a piece of glass. The crystal atoms do not participate directly in the lasing action but act as a host lattice to the active centres which are present in concentrations of around 1%. The crystal is usually shaped into a rod with reflecting mirrors placed at each end. Light from an external source such as a flashlamp excites the active centres in the rod. The flashlamp is usually linear in shape. The linear lamp and laser rod are placed close to each other in a reflective cylinder, which focusses pump light onto the rod. The mirrors on the sides of laser rod form a resonant cavity and provide the necessary feedback to generate laser beam.

It is required that the host material should be transparent to the pump light and should not absorb light at the laser wavelength. Most of the excitation energy ends up as heat rather than light. Excess heat damages the laser crystal. Therefore, the crystal should have good thermal conductivity. Normally, cooling with forced air or circulating water needs to be provided.

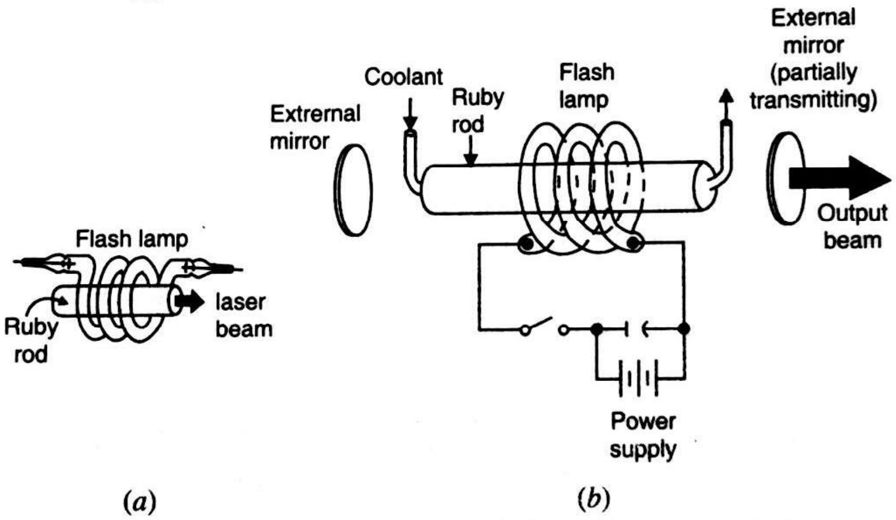
The active centres are ions of metallic elements : chromium (Cr), neodymium (Nd), erbium (Er), holonium (Ho), cerium (Ce), cobalt (Co) and titanium (Ti). Chromium is the active centre in ruby and alexandrite lasers while neodymium is the active centre in common type of solid state lasers.

These lasers are rugged, simple to maintain, and capable of generating high peak powers.

2.3.1 Ruby Laser

GENERAL DESCRIPTION

Historically, the ruby laser was the first laser. The ruby laser rod consists of a synthetic ruby crystal, Al_2O_3, doped with chromium ions at a concentration of about 0.05% by weight. At this concentration there are about 1.6×10^{25} Cr^{3+} ions per cubic meter. The chromium ions constitute the active centers as they have a set of three energy levels suitable for realizing lasing action whereas the aluminium and oxygen atoms are inert.



(a) (b)

Fig. 2.2. A typical ruby laser (a) with internal mirrors (b) with external mirrors.

STRUCTURE

The schematic of a ruby laser is shown in Fig. 2.2. Ruby rod is taken in the form of a cylindrical rod of 4 cm. in length and 0.5 cm. in diameter. Its ends are grounded and polished such that the end faces are exactly parallel and also perpendicular to the axis of the rod. One face is silvered to achieve 100% reflection while the other is silvered to give 10% transmission. The silvered faces form the Fabry-Perot resonator. The rod is surrounded by a helical photographic flash lamp filled with xenon. The lamp produces flashes of white light whenever activated by the power supply. The system is cooled with the help of a coolant circulating around the ruby rod.

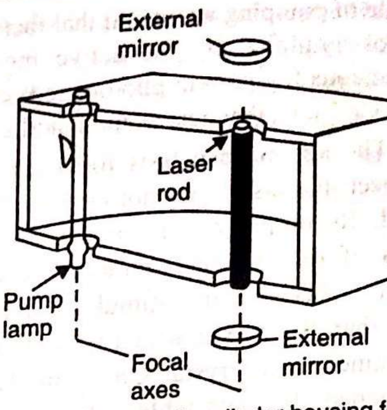


Fig. 2.3. Elliptic cylinder housing for concentrating light onto the laser rod.

In practical lasers, flash lamps of helical design are no longer used. The most common types are linear lamps. The laser rod is generally placed in an elliptical cavity with a linear flash lamp mounted at the focus of internally reflecting cavity, as shown in Fig. 2.3, to ensure an efficient transfer of pumping energy to the ruby crystal. The mirrors are arranged outside.

WORKING

Ruby is a three-level laser system and the energy levels of Cr^{3+} ions in the crystal lattice are shown in Fig. 2.4. There are two wide energy bands E_3 and E_3', and a pair of closely spaced levels at E_2. When the ruby rod is irradiated with an intense burst of white light from the xenon lamp, the ground state Cr^{3+} ions absorb light in two pump bands one centered near 5500 Å and the other at about 4000 Å, and are excited to the broad upper bands. The energy levels in these bands have a very small lifetime ($\leq 10^{-9}$ sec). Hence, the excited Cr^{3+} ions rapidly lose some of their energy to the crystal lattice and undergo non-radiative transitions to the pair of adjacent levels denoted as E_2. These levels are metastable states having a lifetime of 3×10^{-3} sec. The transition from E_2 to E_1 is radiative and under normal population condition produces spontaneous, incoherent, red fluorescence typical of ruby with a peak near 6943 Å.

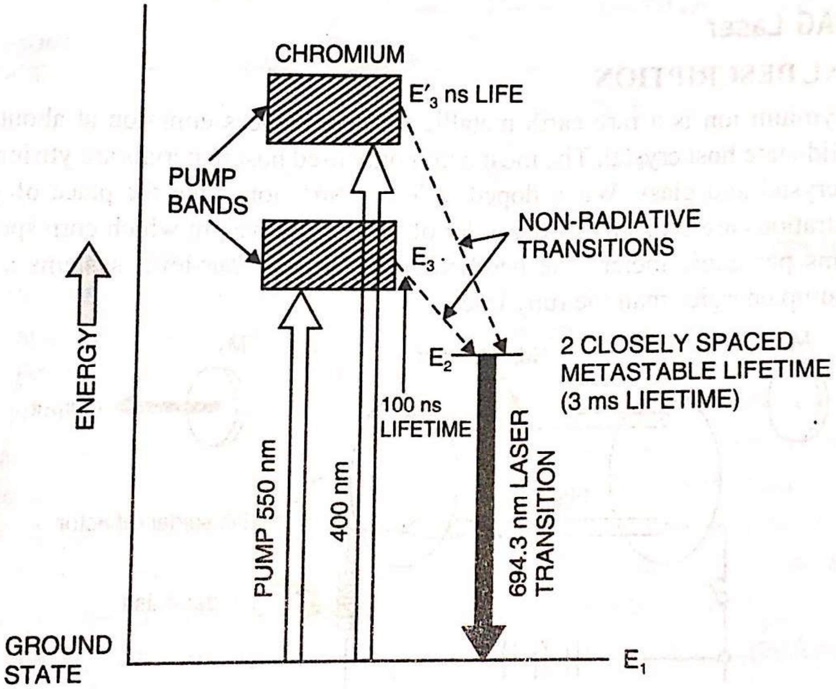


Fig. 2.4. Energy levels of chromium atoms in ruby laser.

Under very intense excitation where pumping energy increases above a critical threshold, population inversion occurs in E_2 with respect to the ground level E_1. Then one of the spontaneously emitted fluorescent photons travelling parallel to the axis of the ruby rod would initiate stimulated emissions. The photons make many passes through the medium building up the stimulated emissions in a large way and the system lases. The photons travelling in any other direction would be lost after a few reflections. The laser beam ensuing from the ruby rod is red in colour and corresponds to a wavelength of 6943 Å. It is to be remembered that the green and blue components of light play the role of pumping agent and that these components are not amplified by the active medium. It is a spontaneous fluorescent photon (red) emitted by one of the Cr^{3+} ions that acts as input and gets amplified.

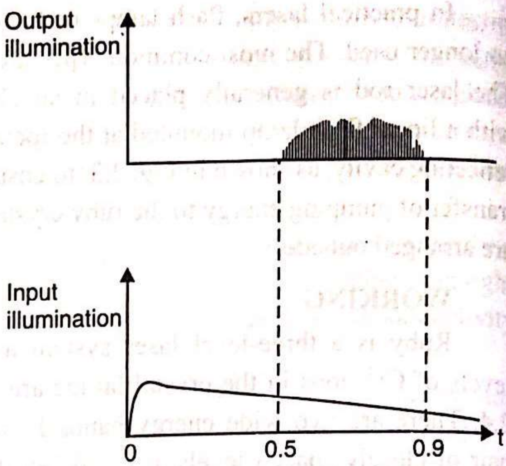


Fig. 2.5. Ruby laser light pulses

The xenon flash lasts for a few milliseconds. However, the laser does not operate throughout this period. Its output occurs in the form of irregular pulses of microsecond duration as shown in Fig. 2.5. It is because the stimulated transitions occur faster than the rate at which population inversion is maintained in the crystal. Once stimulated transitions commence, the metastable state E_2 gets depopulated very rapidly and at the end of each small pulse, the population at E_2 has fallen below the threshold value required for sustained emission of light. As a result the lasing ceases and laser becomes inactive. The next pulse appears after the population inversion is once again restored. The process repeats.

The ruby laser has high energy-storage capability because of long upper laser level lifetime of 3 ms. Therefore, pulse energies of upto 100 J are possible. The ruby laser is relatively inefficient having a typical efficiency of 0.1 to 1%.

The ruby laser is used in a variety of applications, the most important one being in holography.

2.3.2 Nd : YAG Laser

GENERAL DESCRIPTION

The neodymium ion is a rare earth metallic ion. It produces emission at about 1 μm, when doped into a solid-state host crystal. The most commonly used host materials are yttrium aluminium garnet (YAG) crystal and glass. When doped in YAG, Nd^{3+} ions take the place of yttrium ions. Doping concentrations are typically of the order of 0.725% by weight which corresponds to about 1.4×10^{26} atoms per cubic meter. The neodymium lasers are four-level systems and therefore, require lower pump energies than the ruby laser.

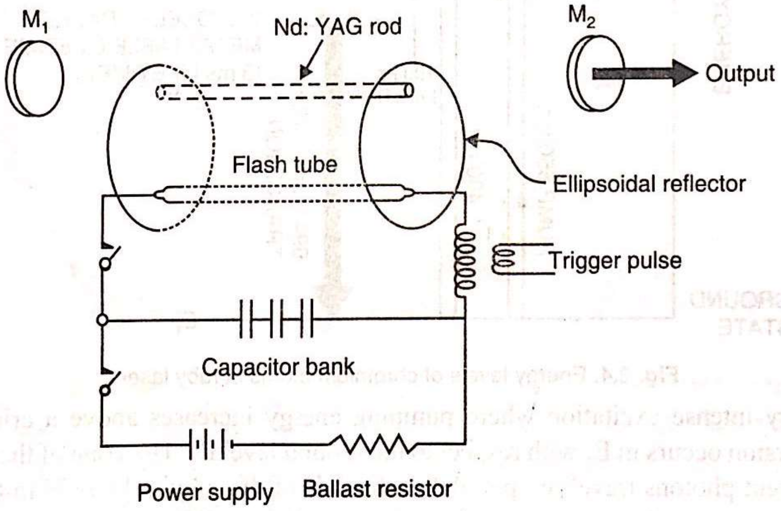


Fig. 2.6. A typical arrangement for the Nd : YAG laser

STRUCTURE

Fig. 2.6 illustrates the typical design of Nd:YAG laser. The laser rods are typically of 10 cm in length and a diameter of 12 mm. The YAG rod and a linear flash lamp are housed in a reflector cavity of elliptical cross-section. The light issuing from the lamp is closely coupled to the laser rod, as they are located at the foci of the ellipse. The ends of the YAG rod are ground flat and parallel. The optical cavity may be formed by silvering the ends of the rod. In practice, external mirrors are used as shown in Fig. 2.6. One mirror is made 100% reflecting while the output mirror is about 90% reflecting. The system is cooled by circulating air. High power lasers are cooled by water circulation.

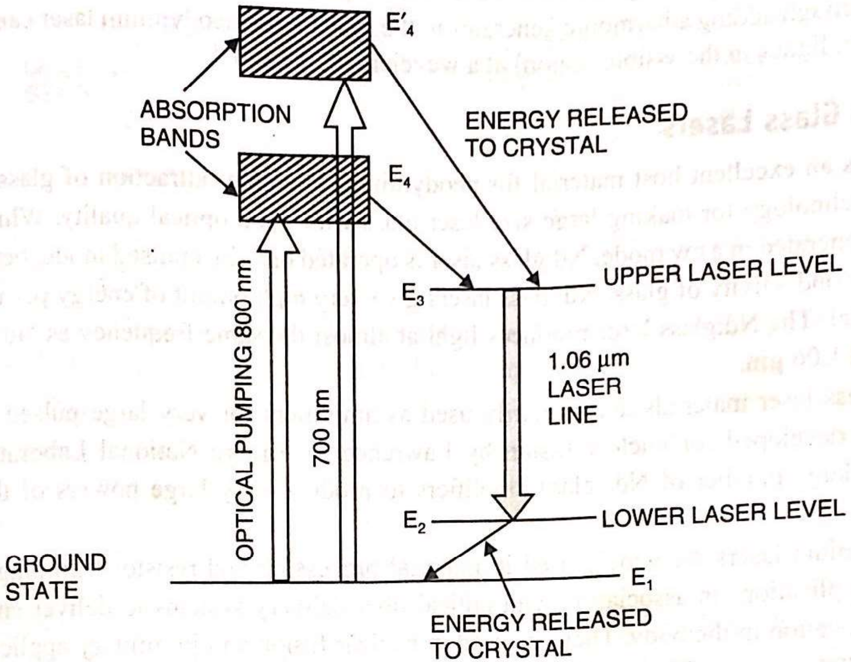


Fig. 2.7. Energy levels of neodymium ions in a crystal.

WORKING

A simplified energy level diagram for Nd:YAG is shown in Fig. 2.7. It is essentially a four-level system with the terminal laser level sufficiently far removed from the ground state. The two primary pump bands are in the 7000 to 8500 Å range. Pumping is achieved by using an intense flash of white light from a xenon flash lamp. It excites the Nd^{3+} ions from the ground state to the multiple energy states at E_4. The excited Nd^{3+} ions quickly decay to the metastable upper laser level E_3, releasing their excess energy to the crystal lattice. As the lower laser level E_2 is located at 0.25 eV above the ground state E_1, it cannot be populated by Nd^{3+} ions through thermal transitions from the ground level. Thus, it is sparsely populated at normal operating temperature. The population inversion can be readily achieved between E_3 and E_2 levels. In the E_3 state, Nd^{3+} ions are stimulated to emit on the main 1.064 µm laser transition, and drop to the lower laser level E_2.

From the level E_2, Nd^{3+} ions quickly drop to the ground state again by transferring energy to the crystal.

The energy level scheme of Nd^{3+} ions in YAG crystal as shown in Fig 2.6 is an oversimplified diagram. In reality, the upper and lower laser levels are also split. Because of the splitting several other laser transitions occur in the near infrared, but all of them are weaker than the main 1.064 µm transition. The only other strong transition occurs at 1.318 µm and produces about 20% as much power as the 1.064 µm transition. It is useful in fibre-optic systems.

The laser output is in the form of pulses occurring at a very high rate. The overall efficiency is within 0.1 to 1% range.

A xenon flash tube is used for pulsed output and tungsten-halide incandescent lamps are used for cw operation. Thereshold pumping levels of about 3J at 3% conversion efficiency can be achieved. Continuous output powers of over 1 kw are obtainable. The lasers can be pumped by a diode laser also. The GaAs laser diode has the ideal pumping wavelength for the Nd^{3+} ion arround 0.8 μm.

The primary wavelength of neodymium laser lies in the infrared. It is possible to double the frequency by second harmonic generation. Twice the frequency corresponds to half the wavelength. Therefore, through adding a harmonic generator to the system, the neodymium laser can be made to produce green light (in the visible region) at a wevelength of 5320 Å .

2.3.3 Nd : Glass Lasers

Glass is an excellent host material for neodymium. The chief attraction of glass is the well developed technology for making large size laser glass with good optical quality. While Nd:YAG laser can be operated in a cw mode, Nd:glass laser is operated only in a pulsed mode, because of the low thermal conductivity of glass. Nd:glass lasers give very high output of energy per unit volume of the material. The Nd:glass laser produces light at almost the same frequency as Nd:YAG laser, *i.e.* at around 1.06 μm.

Nd: glass laser materials are primarily used as amplifiers for very large pulsed lasers. The NOVA laser developed for nuclear fusion by Lawrence Livermore National Laboratories, USA employed a large number of Nd: glass amplifiers to produce very large powers of the order of 10^{13} W.

Neodymium lasers are widely used in material processing and resistor trimming. It is used in medical applications in association with optical fiber delivery systems to deliver energy to the appropriate location in the body. They are used in nuclear fusion and in military applications such as range finding.

2.3.4 Tunable Solid State Lasers

There is an important group of solid state lasers which produce output over a range of wavelengths. These lasers are tunable over a range and are therefore very popular. The tunability arises because of the existence of a cluster of vibrationally excited terminal levels near the ground state. Therefore, these lasers are also known as *vibronic lasers*.

In liquid lasers, we find that dye lasers are tunable. However, the dye lasers suffer from dye degradation and other limitations. In contrast solid state tunable lasers have unlimited shelf life and operational life. Therefore, they are useful in applications like remote sensing and in space craft.

2.3.4.1 Alexandrite Laser

GENERAL DESCRIPTION

The alexandrite laser is a three-level solid state laser similar to a ruby laser. While a ruby laser is a fixed wavelength laser, the alexandrite laser is a tunable laser and lases in the wavelength range of 7000 Å to 8200 Å. The mineral alexandrite ($BeAl_2O_4$) is doped with chromium in concentrations of about 0.1% corresponding to a chromium ion density of 3.5×10^{25} per cubic meter. Alexandrite has pump bands at 3800 Å and 6300 Å. Therefore, pumping can be done using a flash lamp.