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.

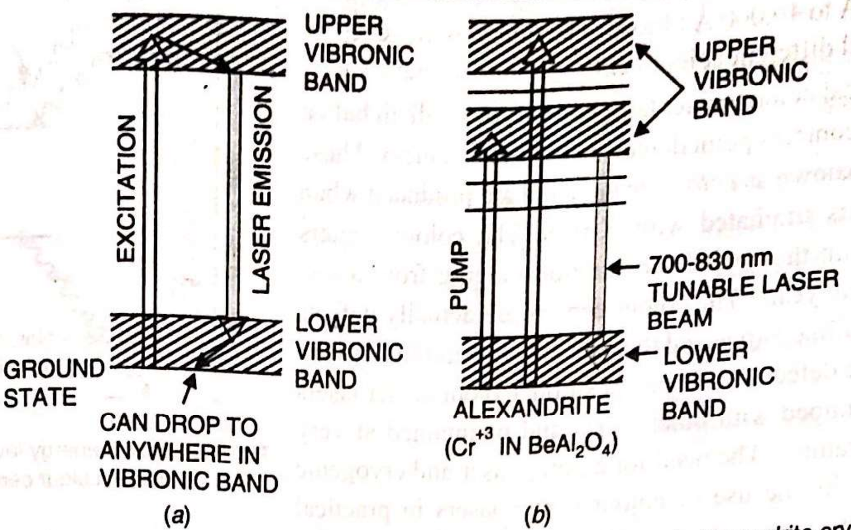

Fig. 2.8. Energy level scheme (a) for a typical vibronic laser (b) Cr^{3+} ions in Alexandrite crystal.

STRUCTURE

The alexandrite laser rod is typically of 0.10 m long and 6 mm dia and is pumped using a flash lamp. Linear flash lamps and a double elliptical pumping cavity are used.

WORKING

The energy levels of Cr^{3+} in alexandrite are shown in Fig. 2.8(*b*). In this case both the upper and lower laser levels are a band of energy levels. The bands consist of vibrational sublevels of a single electronic energy level which arise due to vibrations of the crystal lattice. When Cr^{3+}ions drop from the upper laser level to the lower band of energy levels, they undergo a compound transition where both electronic and vibrational energy change. This compound transition is called a vibrational-electronic transition or in short a *vibronic* transition. The interesting feature of the vibronic transition is that it can occur over a range of energies, because the excited ion can drop from the upper level to any level within the lower vibronic band. It implies that a vibronic laser can be made to operate over a range of wavelengths within its gain bandwidth. Therefore vibronic laser is tunable to any desired wavelength within its emission spectrum. This characteristic of vibronic laser makes it possible to produce wavelengths that are not obtained from other solid-state lasers. An alexandrite laser emits light in the range of 7000 Å to 8300 Å. Alexandrite rod can store more energy than an equal sized Nd:YAG rod. Alexandrite laser can operate in a pulsed or cw mode.

The alexandrite laser is widely used in cancer therapy. Other applications are in pollution detection and kidney stones removal.

2.3.4.2 Titanium-Sapphire Laser

The titanium-sapphire laser uses a titanium doped sapphire crystal designated as $Ti{:}Al_2O_3$ where Ti^{3+} ions replace some of the Al^{3+} ions. Doping concentrations are about 0.1% by weight. The titanium-sapphire laser is the most widely used tunable solid-state laser which is tunable between 6600 Å in the red and 11,800 Å in the near infrared. These lasers can be operated in pulsed or cw mode. The lifetime of the upper laser level is too short, only 3.8 μs. Therefore, they cannot be pumped with flash lamp. They are pumped with argon laser for cw operation or with frequency-doubled Nd:YAG lasers for pulsed operation. These lasers are used in laser radar (lidar), range finders, and remote sensing.

2.3.4.3 Colour-Center Lasers

Colour center lasers are broadly tunable solid state lasers. They operate in the wavelength range 8000 Å to 40,000 Å (4 μm). The tuning is achieved by using several different colour center crystals in sequence.

A typical colour center laser consists of an alkali halide crystal that contains point defects known as *F centers*. These centers are known as *colour centers* and are produced when the crystal is irradiated with X-rays. The colour centers remain within the crystal for duration ranging from a few days to many years. The colour centers are actually defects in the crystalline lattice and they absorb and emit light as the atoms at the defect site change position. Colour center lasers must be pumped with other lasers and maintained at very low temperatures. The need for a pump laser and cryogenic cooling limits the use of colour center lasers in practical applications.

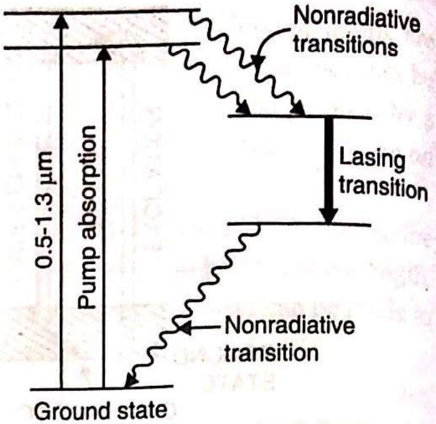

Fig. 2.9. Typical energy level diagram of a F-center colour center laser

2.3.5 Fiber Lasers

Erbium in a glass host forms a three-level laser with a wavelength range centered around 1.55 μm. Erbium lasers and amplifiers assume importance in fibre-optic communications because optical signals of 1.55 μm travel longer distances through optical fibres with least loss. In long distance fibre-optic communications, amplifiers are required after each specific distance to increase the strength of the signal. They are known as repeaters. Earlier, optical signals are converted into electrical signals and are amplified in each repeater station. It can be alternately done by passing the weak signal through a length of the erbium-doped optical fibre. If the erbium atoms are pumped by a laser diode pump laser at a different wavelength, the weak signal can stimulate the atoms to emit light at the signal wavelength, 1.55 μm, causing an increase in the signal strength. These erbium-amplifiers are highly useful in under-sea communication and long haul communication links.

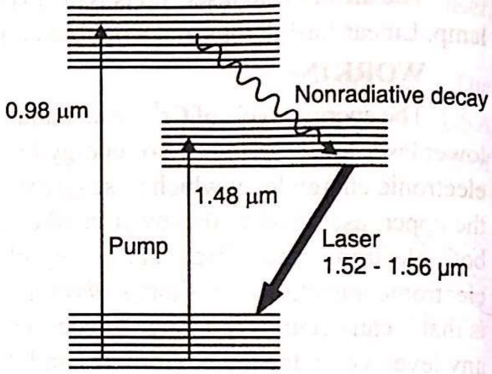

Fig. 2.10. Energy level diagram of an erbium-doped fibre laser

2.4 GAS LASERS

Gas lasers are the most widely used lasers and the most varied. They range from the low power helium-neon (He-Ne) laser used in college laboratories to very high power carbon dioxide laser used in industrial applications. These lasers operate with rarefied gases as their active media and excited by an electric discharge. There are three different types of gas laser: ion lasers, neutral atom lasers and molecular lasers. In gases, unlike in crystals, the energy levels of atoms involved in the lasing process are well defined and narrow. Broad pump bands do not exist and the pump levels are also narrow. In order to excite atoms, sources with sharp wavelength are required. Finding an appropriate optical source for pumping poses a problem. Therefore, optical pumping is not used in gases. The most common method of exciting gas laser medium is by passing an electric discharge through the gas. Electrons in the discharge transfer energy to atoms in the laser gas by collisions.

Gas lasers, in general can be classified as (*i*) Atomic, (*ii*) Ionic and (*iii*) Molecular lasers.

(*i*) Atomic lasers: He-Ne (Helium-Neon) lasers are of this type. In atomic lasers the active medium is noble gas *viz.* Helium, neon, argon, krypton and considered in the neutral state. The atomic lasers are characterised by mixing active gas with other gases which increases the excitation efficiency of the system.

***(ii)* Ionic lasers:** In ionic lasers, ionized gas is used as lasing medium. For this purpose, ionized noble gases like A_r^+ (Argon ion) and K_r^+ (Krypton ion) are prefered. The most commanly used ionic lasers are A_r^+ (Argon) and K_r^+ (Krypton) lasers which mostly operate in CW mode. They are operated in Ultra-Violet (UV) Spectral region. Large amount of heat is generated and hence cooling arrangement is essentially needed. These lasers produce a wide range of colours and hence are popularly used in art and entertainment to give visual effects.

***(iii)* Molecular lasers :** All the gas lasers are based on *electronioc levels* however in molecular lasers other energy levels are also taken into account. The atoms comprising the molecular vibrate about their mean position giving rise to *vibrational energy levels* and also can rotate as a whole. The gives rise to *rotational energy levels.*

The first gas laser was He-Ne laser which was demonstrated in 1961 at Bell Telephone Laboratories, U.S.A. by Ali Javan, William R. Bennett, Jr., and Donald R. Herriott. The generic gas laser is shown in Fig. 2.11.

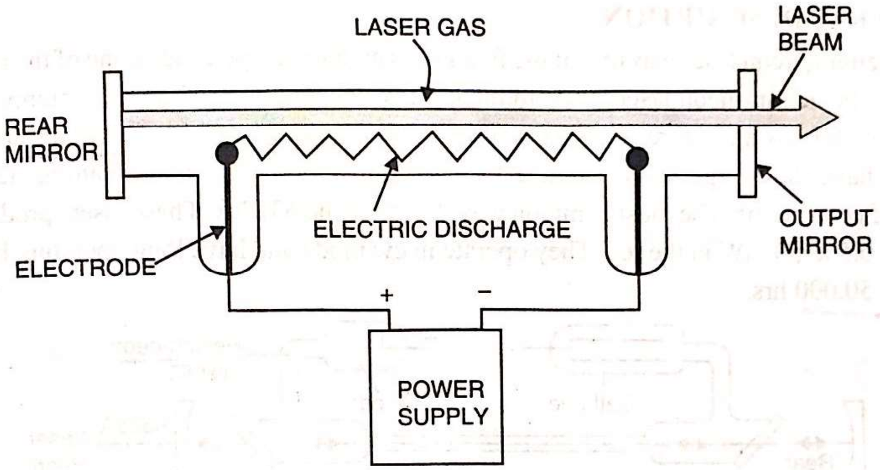

Fig. 2.11. Schematic arrangement of a gas laser.

The laser gas is contained in a tube with cavity mirrors attached at each end, one totally reflecting and one transmitting light to form the output beam. The laser is excited by an electric discharge. First, a high dc voltage ionizes the gas so that it will conduct electricity. The electrons accelerated through the electric field transfer their kinetic energy to the gas atoms by inelastic collisions. In practice, for optimum operation, the laser medium contains a mixture of two gases, say *A* and *B*, at low pressure. Atoms of kind *A* are initially excited by electron impact and they in turn transfer their energy to atoms of kind *B* which are the actual active centers.

The cavity mirrors can be either inside the gas container or outside. If they are inside, than the output light is generally unpolarized. For the outside case, to minimize reflection loss, discharge tube edges are cut at the Brewster angle. The Brewster angle is given by

$$\theta_B = \tan^{-1}\sqrt{\frac{\mu_2}{\mu_1}}$$

where μ_2 and μ_1 are the refractive indices of glass and the gas mixture respectively. It is known that light incident at Brewster angle is polarized parallel to the plane of incidence and has a transmission coefficient of 1. The passage of light through a glass container at Brewster angle does not involve any