Chapter Five
Laser Types and Their Characteristics

Laser Type's Introduction

This chapter explains the different types of lasers. It is constructed as a **data base**, with information on the different laser types.

Lasers can be divided into groups according to different criteria:

1. The **state of matter of the active medium**: solid, liquid, gas, or plasma.
2. The **spectral range of the laser wavelength**: visible spectrum, Infra-Red (IR) spectrum, etc.
3. The **excitation (pumping) method of the active medium**: Optic pumping, Electric pumping, etc.
4. The **characteristics of the radiation emitted from the laser**.
5. The **number of energy levels which participate in the lasing process**.

The Active Medium:

The active medium determines most of the laser properties, and that is why the laser name is derived from the name of the active medium.

Each laser is classified according to the classification schemes described earlier.

Laser Types

Listed according to the physical state of the active medium

Gas Lasers	Solid Lasers
ATOM: • He-Ne (Helium-Neon) • He-Cd (Helium-Cadmium) ***MOLECULE:*** • CO_2 (Carbon Dioxide) • N_2 (Nitrogen) • Chemical (HF-DF) • FIR - Far Infrared • Eximer Laser ***ION:*** • Ar+ (Argon ion) • Kr+ (Krypton ion) ***Metal Vapor Lasers:*** • Cu (Copper) Vapor • Au (Gold) Vapor	***Insulator:*** • Ruby Laser • Nd-Yag and Nd-Glass Lasers • Color Center Laser • Alexandrite Laser • Ti - Saphire Laser ***Semiconductor:*** • Laser Diodes
Liquid Lasers	**Special Lasers**
Dye Laser	• X-Ray Laser • FEL - Free Electron Laser

5.1: Gas Lasers:

Most **elements** can be made to lase when they are in the gas state. Also many **molecules** (composed of a few atoms each) have been demonstrated to lase. In a **gas laser**, **the laser active medium is a gas at a low pressure** (A few milli-torr).

The main reasons for using low pressure are:

- To enable an **electric discharge in a long path,** while the electrodes are at both ends of a long tube.
- To obtain **narrow spectral width** not expanded by collisions between atoms.

(A few types of special lasers use gas at high pressure).

The **first gas laser** was operated by **T. H. Maiman in 1961**, one year after the first laser (**<u>Ruby</u>**) was demonstrated. The first gas laser was a **<u>Helium-Neon laser</u>**, operating at a wavelength of 1152.27 [nm] (Near Infra-Red).

Excitation of a Gas Laser:

Two main excitation techniques are used for gas lasers:

- **Electrical Discharge:**

Applying high voltage to electrodes at both sides of the tube containing the gas causes **electrical breakdown through the gas**. Electrons are ejected from the cathode, accelerated toward the anode, and collide with the gas molecules along the way. During the collision, the mechanical kinetic energy of the electrons is transferred to the gas molecules, and excites them.

- **Optical Pumping:**

Optical pumping is not generally an efficient method for gas lasers. **Gas lasers are usually excited by an electric discharge.** When we want to excite a gas laser by optical pumping, we need to find an **optical source with very narrow bandwidth** because gas atoms absorb only a small portion of the spectrum which fits the narrow absorption spectral lines of the gas. A good source for optical pumping of a gas laser is another laser.

Groups of Gas Lasers:

For convenience, **gas lasers are divided into 3 groups:**

I. **Atoms** - The laser active medium is composed of ***neutral*** **gas atoms** such as Helium-Neon and Copper Vapor.
II. **Ions** - The laser active medium is composed of **ionized gas** such as Argon ion gas or Helium-Cadmium gas.
III. **Molecules** - The laser active medium is composed of **gas molecules**, like Carbon Dioxide (CO_2), Nitrogen (N_2), Excimer laser, Chemical lasers (HF, DF), Far Infra-Red (FIR) laser.

I. Neutral Gas Lasers (Atoms):

The active medium in these lasers is a **noble gas in its neutral state**, or a **metal vapor**.

Laser Characteristics:

- The active gas is used with other gases in a mixture. The extra gas(es) help increase the excitation efficiency.
- Maximum gain is achieved when the tube diameter is very small.
- Gas lasers usually operate in the continuous mode.

5.1.1: Helium-Neon Laser (He-Ne)

The Helium-Neon laser was the most common laser until the spread of diode lasers in the last few years. It was first built in 1961 by Ali Javan. The active medium is a noble gas Neon (Ne).

The important wavelengths are:

λ_1=0.6328 [μm], λ_2=1.152 [μm], λ_3=3.3913 [μm], λ_4=0.5435 [μm]

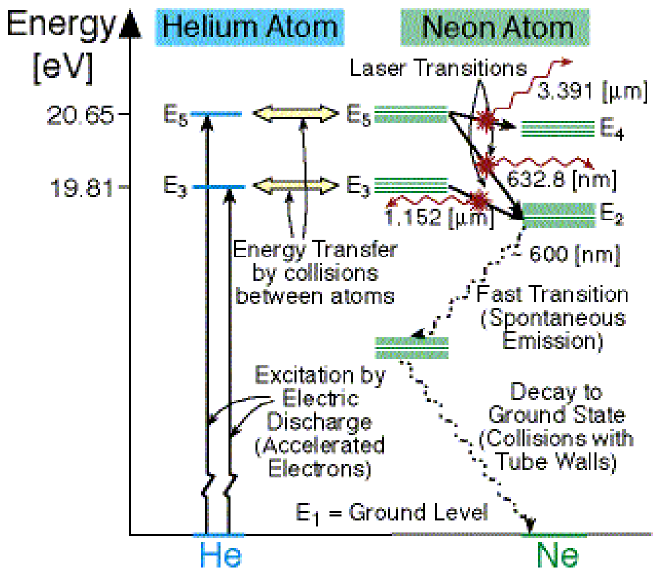

Figure 5.1: Energy Level Diagram of He-Ne Laser

He-Ne Laser Structure:

Helium Neon laser has three main Structures:

- Plasma Tube.
- Optical Cavity.
- Power Supply.

Plasma Tube of He-Ne Laser:

The **thin inner tube** has a diameter of about 2 [mm] and length of tens of centimeters. The inner tube is surrounded by **thick outer tube** with diameter of about 2.5 [cm] and is sealed from the outside. The purposes of the outer tubes are:

- To make a **stable structure** which protects the inner tube and the laser mirrors from movements.
- To act as a **large gas reservoir** which refreshes the Neon gas that has been absorbed by the cathode.

The **gas mixture** is 85-90% Helium gas, and 10-15% Neon gas, a ratio of 1:6 to 1:10.

The **gas pressure** is 0.01 Atmosphere (≈ 10 [torr]). At the end of the tube, the electrodes are attached to a high voltage power supply (AC or DC).

Optical Cavity of He-Ne Laser:

The cavity in a common He-Ne laser uses a **semi confocal optical cavity**. It is composed of **one planar mirror**, which reflects about 98% of the light striking it, and a **second concave mirror reflecting 100%**. This concave mirror has a focal length equal to the length of the cavity.

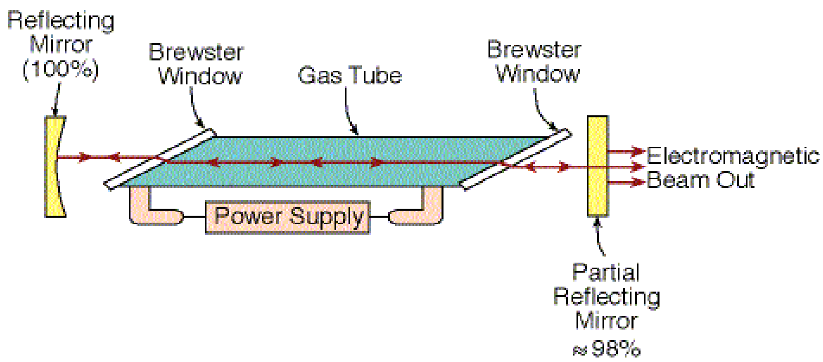

Figure 5.2: The Cavity Structure of He-Ne Laser

Power Supply of He-Ne Laser:

He-Ne lasers which gives up to 1 [mW] (The standard type used at for student laboratory experiments), usually use a **DC (= Direct Current)** High Voltage power supply of 2,000 [Volts]. The laser needs a constant current (constant supply of electrons), so a **stable current supply** is used.

Commercial He-Ne Lasers:

Wavelength:	632.8 [nm]	Beam Divergence:	0.5-3 [mRad]
Output Power:	0.5-50 [mW]	Coherence Length:	0.1-2 [m]
Beam Diameter:	0.5-2.0 [mm]	Power Stability:	5 [%/Hr]
Lifetime:	>20,000 [Hours]		

Most of the applications of He-Ne Laser use the **red wavelength**, because it is the strongest line and it is in the visible region of the spectrum.

5.1.2: Metal Vapor Laser (Copper, Gold)

As the name implies, **the active medium in this laser is a vapor consisting of metal atoms**. There is a distinction between two types:

a. **Neutral metal vapor lasers**, which include:
    1. Copper vapor laser (CVL).
    2. Gold Vapor Laser (GVL).

b. **Ionized metal vapor laser**, which includes: Helium-Cadmium (He-Cd) Laser.

We shall concentrate on Copper Vapor Laser as an example for neutral vapor lasers.

Copper vapor laser (CVL):

Lasing action in copper vapor was first demonstrated in 1966. The first commercial copper vapor lasers appeared around 1980. This laser was attractive because of its relative **high efficiency (up to 1%)** for lasers in the visible spectrum range, and the high pulse power achieved.

Copper Vapor Laser Structure:

Copper vapor laser is a **gas laser**; build as a tube with windows at both ends. The tube is filled with an inert gas and a small quantity of pure copper. In order to have **copper vapor**, the metal needs to be at very high temperatures, so the tube is built from Alumina or Zirkonia, which are high temperature resistant materials. The tube diameter is 10-80 [mm], and it contains **Neon gas** at a pressure of **25-50 [Torr]**.

Copper Laser Properties:

- Copper vapor pressure is about 1 [Torr].
- Optimal operating temperatures: 1650 ^{0}C ± 50 ^{0}C.
- The laser is very sensitive to the purity of the active gas.
- The laser **operates simultaneously on two spectral lines** (Green and Yellow).
- The energy per pulse of the **green** line (510.6 [nm]).
- The energy per pulse of the **yellow** line (578.2 [nm]).
- In practice, one mirror reflects 100%, and the other about 10%.
- The **high temperature** required for the lasing process, is achieved by heating as a result of the electric breakdown in the gas.
- It is possible to achieve lasing at lower temperatures (400^{0}C), by using Copper salts like CuCl, but there are still problems with these lasers, and they are in experimental stages.

The wavelengths emitted by Copper vapor lasers are:

- λ_1= 510.6 [nm] (**Green**),

- λ_2= 578.2 [nm] (**Yellow**)

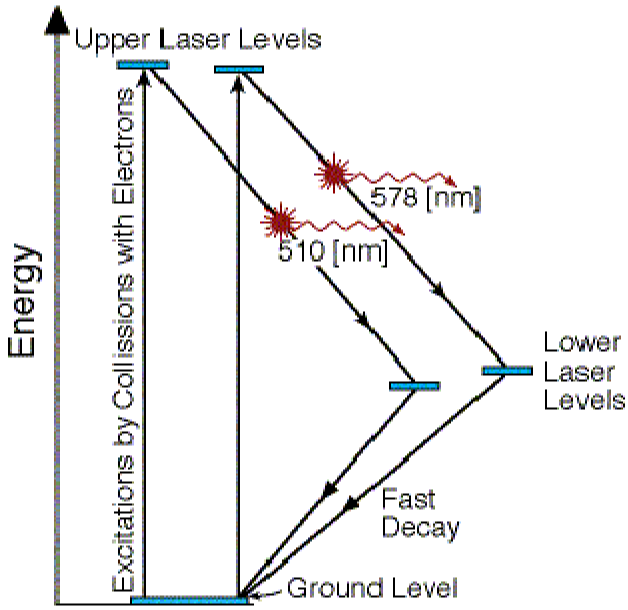

Figure 5.3: Energy Level Diagram of Copper Vapor Laser

Applications of Copper Vapor Lasers:

1. Pump Sources for **Dye lasers**, for short pulses.
2. Illuminating objects in high speed photography.
3. In Forensics. Identifying fingerprints, and traces of special elements in the scene of a crime.
4. Photo-Dynamic-Therapy (PDT). The selective destruction of cancer cells by laser radiation at specific wavelength, after a special drug is injected into the patient.
5. Enrichment of Uranium (U^{235})**.**

Gold Vapor Lasers:

The Gold Vapor laser is very similar to The **Copper Vapor laser** both in structure, and principles of operation. Sometimes, the same system (laser tube and power supply) is used for both lasers. The only change is to replace the solid Copper by a wire of pure Gold.

The wavelength of Gold lasers is **Red: 628 [nm]**.

The main applications of Gold vapor laser are in the experimental cancer treatment of **Photo-Dynamic Therapy (PDT)**.

5.1.3: Helium Cadmium Laser (He-Cd)

Helium-Cadmium lasers can be categorized among either:

- **Metal vapor lasers** - Cadmium is a metal, the lasing action in Helium Cadmium laser occurs between energy levels of **Cadmium ions**, so the lasing medium is ionized metal vapor.

- **Ion gas lasers** - The properties of Helium-Cadmium laser are similar to those of Helium-Neon laser which is a neutral atom gas laser.

The He-Cd laser is a gas laser, and the metal Cadmium can be transform into the gas phase by heat.
The excitation of the Cadmium atoms in the gas is similar to the excitation process of the Neon gas in a **Helium-Neon laser**: Helium atoms are excited by collisions with accelerated electrons, and then they pass their energies to Cadmium atoms by collisions.
The transitions in Helium-Cadmium laser are between energy levels of **singly ionized Cadmium atoms**, and about **twelve lines are available**. These wavelengths are in the **shorter wavelength region, violet and Ultra-Violet (UV)**. Thus, the main application of the He-Cd laser is in the optics laboratory, for fabricating holographic gratings.

Lasing action in a Helium-Cadmium Laser:
The Cadmium metal is heated to a temperature of 250^0C, to create the appropriate vapor pressure.
The Cadmium vapor pressure of a few millitorr is added to Helium gas at a pressure of 3-7 millitorr.
Since Helium is a noble gas, its excitation energy is very high (24.46 [eV]) compared to the Cadmium which is a metal with low excitation energy (8.96 [eV]). In the design of the tube of Helium-Cadmium laser most of the effort is to reduce to a minimum the amount of Cadmium ions. The best He-Cd lasers loose about 1 [g] Cadmium metal for 1,000 hours of operation of the laser.
For comparison, the gain and power output of the main two lines of He-Cd laser are higher than for the He-Ne laser, but less than for the Ar^+ laser.

Characteristics of He-Cd Lasers:
- **Output wavelengths**: Blue light 0.4416 [μm], and Ultra-Violet (UV) light 0.3250 [μm].
- **Maximum output power**: 150 [mW] in the blue line, and 50 [mW] at UV.
- **Maximum total efficiency**: in the blue line 0.02%, and in the UV 0.01%.
- **Spectral width**: 0.003 [nm] (about 5 [GHz])
- **coherence length**: about 10 [cm].
- **Distance between two longitudinal modes**: about 200 [MHz].

II. Ionized Gas Laser:
The most common ionized gas lasers are from the **noble gases Argon (Ar^+)** and **Krypton (Kr^+)**.
We shall concentrate on the Argon Ion laser since it is more common.

5.1.4: Argon Ion Laser (Ar+)

The Argon laser was invented in 1964 by William Bridges at Hughes Research Laboratories.

Argon ion laser contains a tube filled with Argon gas which transforms into **plasma** in an excited state. (**Plasma** is a state of matter in which the electrons are separated from the atoms and molecules, which means that it contains free electrons and ions).

A schematic diagram of the energy levels of the Argon laser is shown in figure 5.4.

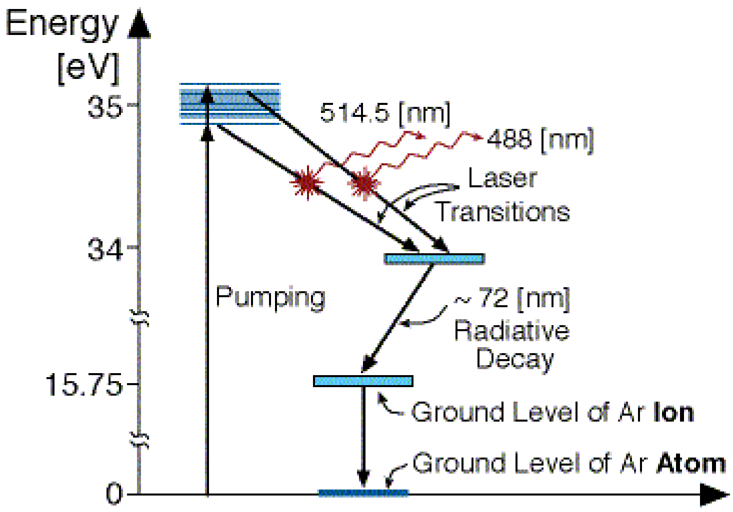

Figure 5.4: Energy Level Diagram of Ion Argon Laser.

The two main laser transitions are at **visible wavelengths**: **Blue 0.488 [µm] and green 0.5145 [µm]**

But the Argon ion laser emits also in the **UV spectrum**: **0.3511 [µm] & 0.3638 [µm]**.

Argon (Ar+) Laser Efficiency:

We see from the diagram in figure 5.4 that the lasing energy levels belong to the Argon ion, so the atoms of the gas inside the tube need to be ionized first. As seen in the diagram, the ground state of the laser is at about 16 [eV] above the ground state of the neutral Argon atom. This is a large amount of energy that must be supplied to the laser, but is not used for creating laser radiation. This "wasted" energy is one of the reasons for the **very low efficiency of the Argon laser (0.1%)**.

Power Output from Argon Laser:

The **gain of the active medium in Argon ion lasers is very high**, so **high power** can be achieved from Argon ion lasers (tens of Watts), although as we saw, with **low efficiency**.

It is common to use narrow tubes (small cross section) and very high currents **(100-500 [A/cm^2])**. Argon Ion lasers require a separate three phase electrical power lines.

After ionization, a few hundred volts DC are maintained across the laser tube. A high DC current (more than 50 Ampers) maintains lasing. Such high current densities create large amounts of heat which must be taken away from the laser. Argon Ion lasers require water cooling. In order to withstand the high temperatures, the laser tube is made from special high melting materials such as Beryllium Oxide. This material has very high thermal conductivity, and is not destroyed by the electrical discharge.

The radiation of Argon Ion laser is hazardous to view and working with it **requires special protecting goggles** for everyone in the room.

The Argon Ion Laser Applications:
1. A source for **optical pumping** of **Dye laser**.
2. **Entertainment** - in laser light shows, discotheques, and laser displays.
3. **General Surgery** - for applications that use absorption at specific wavelengths.
4. **Ophthalmic** welding of detached retina.
5. **Forensic Medicine** - for fluorescence measurements.
6. **Holography** - Because of its high power in the visible spectrum.

5.1.5: Krypton Laser (Kr+)

The Krypton laser is very similar to the **Argon laser**, but its efficiency is lower.
This laser has many lines in the visible spectrum, especially in the **yellow to red** part of the spectrum.
The **maximum output power** in each line is about 100 [mW].
The main **applications** of this laser are in the **art and entertainment** business, to create **fantastic visual effects**.

III. Molecular Gas Lasers:

All the lasers described so far are based on **electronic transitions between different main energy levels**.
In a molecule, the main energy levels are subdivided into **vibrational energy levels**.
Each vibrational energy level can be subdivided into rotational energy levels:

1. **Vibrational energy levels** - energy levels associated with the **oscillation of the atoms** in the molecule.
2. **Rotational energy levels** - energy levels associated with the **rotation** of the molecule.

Among the molecular lasers, the most common laser is the **Carbon-Dioxide (CO_2)** laser.

5.1.6: Carbon Dioxide Laser (CO_2)

Lasing action in a CO_2 molecule was first demonstrated by C. Patel in 1964. He transmitted an electric discharge pulse through pure CO_2 gas in a laser tube, and got a small laser output.

The standard CO_2 laser includes in the active medium a mixture of CO_2 with N_2 and He. The optimal proportion of these 3 gases in the mixture depends on the laser system and the excitation mechanism. **In general, for a continuous wave laser the proportions are:**

CO_2: N_2: He - 1:1:8

In figure 5.5 the **three vibrational modes of CO_2 molecule** are illustrated:

1. Symmetric stretch mode (ν_1).
2. Bending mode (ν_2).
3. Asymmetric stretch mode (ν_3).

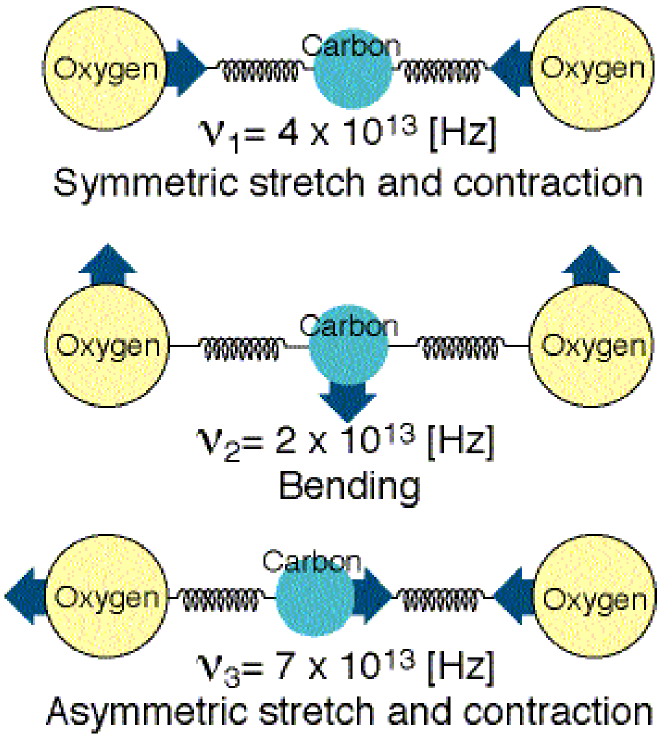

Figure 5.5: Oscillation Modes of CO_2 Molecule

Lasing Transitions in CO_2 Laser:

Lasing transitions in CO_2 laser occur when the molecule is going from higher energy level of the asymmetric mode into one of the other two, as can be seen in figure 5.6.

1. The transition to the symmetric stretching mode corresponds to the wavelength of **10.6 [μm]**.
2. The transition to the bending mode corresponds to the wavelength of **9.6 [μm]**.

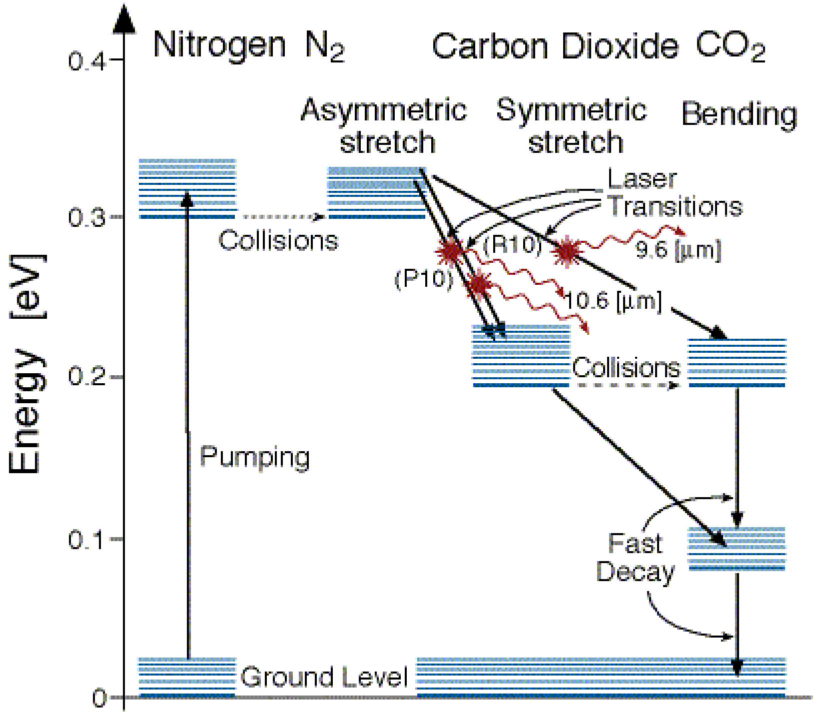

Figure 5.6: Energy Level Diagram of CO_2 Laser

Each of the vibrational energy level is subdivided into **many rotational levels**. Transitions can occur between vibrational energy levels with different rotational levels, so there are many lasing lines around the main vibrational transitions.

Gas pressure inside the CO_2 laser tube is 5-30 [Torr], of which 10% CO_2 gas, 10% N_2 and the rest is He.

Types of CO_2 Lasers:

There are many types of CO_2 lasers, **all based on the same physical principles**. The difference between them is in their structure, excitation mechanism, and the output radiation.

Properties of CO_2 Laser:

- High output power. Commercial CO_2 Lasers produce more than 10,000 watts continuously.
- Output spectrum is in the Infra-Red (IR) spectrum: 9-11 [µm].
- Very high efficiency (up to 30%).
- Can operate both continuously or pulsed.
- Average output power is 75 [W/m] for slow flow of gas, and up to few hundreds [W/m] for fast gas flow.
- Very simple to operate, and the gasses are non-toxic.

Summary of CO_2 Lasers:

- Gas laser.
- Emit in the Infra-Red (IR) spectrum (λ = 9-11 [μm]).
- Electrical excitation.
- Continuous wave, although pulsed operation is possible.
- Four level laser.

CO Laser:

This laser is very similar to the CO_2 laser, except for the active gas - CO.
The spectrum output of these lasers is: **5-6 micron [μm]**.
One of the problems with this laser is the gas CO which is **poisonous**.

5.1.7: Nitrogen Laser (N_2)

The Nitrogen laser was first developed in 1963 and has been sold as a commercial product since 1972.

Laser Action:
The active medium in Nitrogen lasers is Nitrogen gas at pressures of 20 [torr] up to 1 [At]. Like most gas lasers, the Nitrogen laser is based on **transitions between vibration energy levels**, and is electrically excited. The energy level diagram of the Nitrogen laser is shown in figure 5.7.

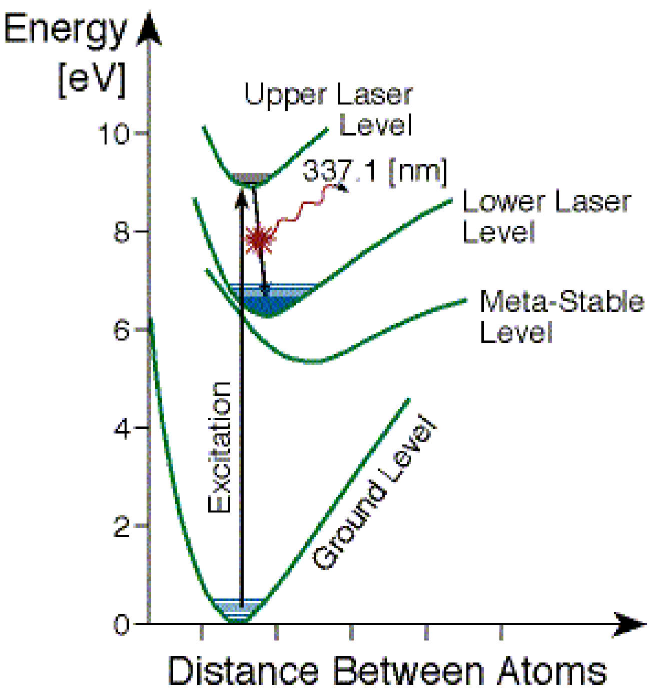

Figure 5.7: Energy level diagram of Nitrogen laser.

Properties of Nitrogen Laser:

- Nitrogen lasers emit radiation in the **Ultra-Violet (UV) region** of the electromagnetic spectrum, at a wavelength of 337.1 [nm].
- Very simple and cheap laser.
- Pulse with **very high peak power** - up to few Mega-Watts.
- Pulse frequency - up to 1,000 [Hz] - limited by heating effects.
- Pulse length is of the order of 10 [nsec].
- Energy per pulse - a few milli-Joule.
- Average energy - up to a few hundred milli-Watts.
- Total efficiency - about 0.1 %.

Main Applications of Nitrogen Laser:

- Optical pumping of **Dye laser**.
- Spectroscopy in the **Ultra-Violet (UV) spectrum**.
- Nondestructive testing, performed by **heating** the sample with a pulse from a Nitrogen laser.
- **Fluorescence measurements** of materials.
- Measurements of very fast processes, (illuminating with short pulses for photography).

5.1.8: Excimer Laser

We shall examine a family of lasers in which the radiation is emitted from a molecule which only exists for a very short time. This molecule is composed of an atom of **noble gas**: Argon, Krypton or Xenon, and an atom of **halogen**: Fluorine, Chlorine, Bromine or Iodine.

An Excimer is **a molecule which has a bound state (existence) only in an excited state**. In the ground state this molecule does not exist, and the atoms are separated. The excited state exists for a very short time, less than 10 nanoseconds.
The name **Excimer** comes from the combination of the two words: ***exited dimer***, which means that the molecule is composed of two atoms, and exists only in an excited state. (Some scientists consider this molecule to be a complex, and they call the laser "**Exiplex**").

Historic Development of Excimer Lasers:
The Excimer laser was invented in 1971 in the USSR by a group of scientists: Basov, Danilychev, and Popov. They showed stimulated emission at a wavelength of 172 [nm] from Xe_2 gas at low temperature, pumped by a beam of electrons. The first laser action in a noble gas with halogen (XeBr) was reported in 1975 by Searl and Hart.

The Common Excimer lasers with its characteristic wavelengths:

Excimer Laser	Wavelengths [nm]	Excimer Laser	Wavelengths [nm]
ArCl	175	KrCl	222, (240)
ArF	193	XeCl	308, 351
KrF	248, (275)	XeBr	282, (300)
Xef	351, 353, (460)		

Energy Levels of Excimer Laser:

Figure 5.8 shows a diagram of the energy levels of Excimer laser, as a function of the distance between the atoms in the molecule.

R represents the noble gas atom and **H** represents the halogen.

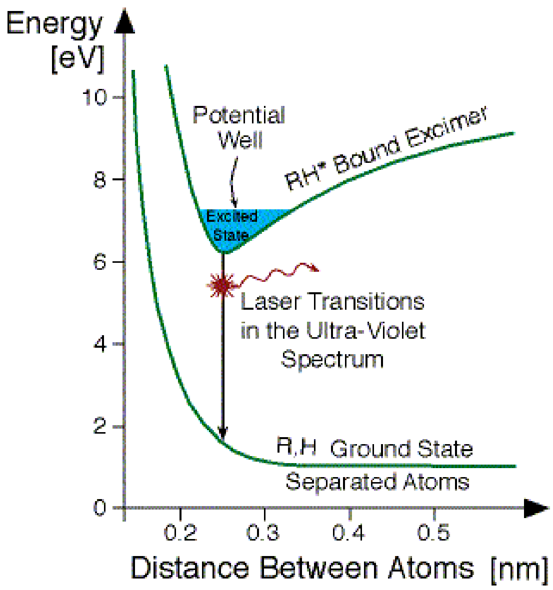

Figure 5.8: Energy levels in the Excimer Laser.

The valley (potential well) in the diagram of the excited state shows the existence of a **momentary stable state**. The fact that there is no potential well in the ground state shows that there is no bound state to the molecule when it is not excited.

Only within the marked area inside the potential well of the excited state can a bound state exist, and it occurs for a **specific distance between the atoms**.

Operation of the Excimer Laser:

The composition of the gas mixture inside the tube of the Excimer laser is:

- Very little halogen (0.1-0.2%).
- Little noble gas (Argon, Krypton or Xenon).
- About 90% Neon or Helium.

The halogen atoms can come from halogen molecules such as: F_2, Cl_2, Br_2, or from other molecules which contain halogens such as: HCl, NF_3.
The advantage of using a compound and not a pure halogen is the strong chemical activity of the halogen molecule (especially Fluorine).

Properties of Excimer Lasers:

- Excimer lasers emit in the Ultra-Violet (UV) spectrum.
- The radiation is emitted only in short pulses.
- The length of each pulse is between picoseconds to microseconds (10^{-12}-10^{-6} sec).
- The gas pressure inside the laser tube is high: 1-5 [At].
- The efficiency of commercial Excimer lasers is up to a few percent.

Applications of the Excimer Laser:
Commercial Excimer lasers can emit Ultra-Violet (UV) radiation up to an average power of 100 Watts. Since the emitted wavelengths are very short, each individual photon carries a large amount of energy, which is enough to break the bond between molecules in the material that absorbed the radiation. Every pulse of Excimer laser radiation contains a large number of photons, since it has a very high peak power.
Thus, the **Excimer laser is the perfect cutting tool for almost every material**!

Special Applications:

- **Photolithography** - Material processing at a very high degree of accuracy (up to parts of microns!).
- **Cutting biological tissue** without affecting the surrounding.
- **Correcting vision disorders** - Cutting very delicate layers from the outer surface of the cornea, thus reshaping it, to avoid the necessity for glasses.
- **Marking on products** - Since the short wavelength radiation from the Excimer laser is absorbed by every material, it is possible with a single laser to mark on all kinds of materials, such as plastics, glass, metal, etc.

The price of an Excimer laser is relatively high (tens of thousands of dollars), but it is used a lot because of its unique properties.

5.1.9: Chemical Laser

The chemical laser is an example of a laser where the **pump energy** comes from a **chemical reaction** between two atoms. The chemical laser is a member of the family of **Gas Lasers.** The first chemical laser, which was operated in the pulsed mode, was developed in 1965 by J. V. V. Kasper, and G. C. Pimental.
The lasing action of the chemical laser is usually based on **vibrational transitions of diatomic molecule**.

The Material in a Chemical Laser:

Most chemical lasers are based on **Hydrogen halides**:
HF: The most well-known member of this family is **Hydrogen Fluoride (HF)**. The emitted radiation is in the Infra-Red (IR), with a few lines in the spectrum range: 2.6 - 3.0 [μm].
DF: When Hydrogen is replaced by its heavier isotope - **Deuterium**, another member of the family: **Deuterium Fluoride (DF)** is created and emits in the spectrum range: 3.5 - 4.2 [μm].
Other halides such as Hydrogen Chloride (HCl) and Hydrogen Bromide (HBr) have demonstrated lasing in the lab, but are not common.
Because Fluorine and Hydrogen are very reactive gasses:

Hydrocarbons are used as a Hydrogen source, and

Fluorine compounds such as SF_6 or NF_3 are used as a source for Fluorine.

Fluorine extraction is done by electrical discharge which separates the SF_6 molecule into Fluorine and Sulfur.

Chemical Laser Structure:

Schematic drawing of the structure of a chemical laser is shown in figure 5.9.

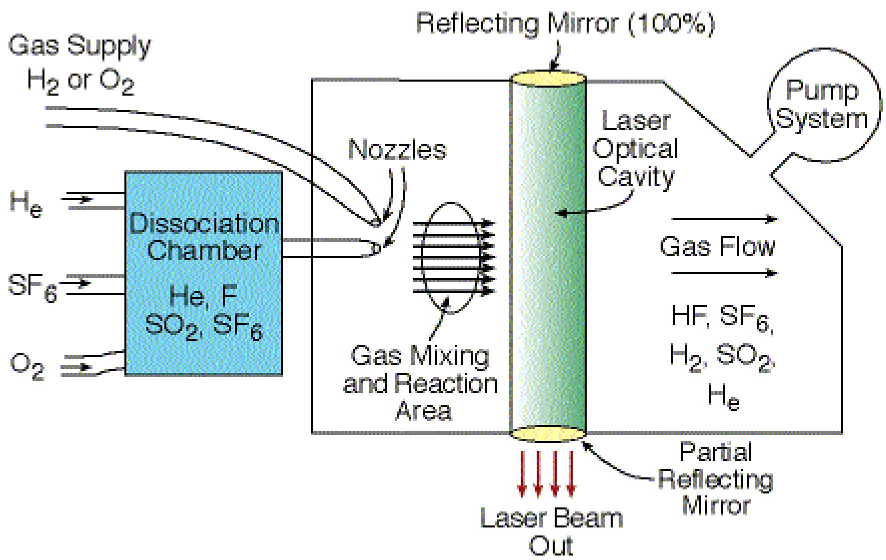

Figure 5.9: The Basic Structure of the Chemical Laser

The gasses are injected into the laser through pipes with **pinholes at their ends**. The design of the pinholes is critical **to avoid thermodynamic equilibrium of the gas**. The gas flows rapidly out of the pinholes and creates a turbulent flow which results in excited Hydrogen-halide molecule.

Advantages of Chemical Lasers:

- The source of energy is conveniently stored (gas balloons).
- Very high output power.

Disadvantages of Chemical Lasers:

- Fluorine is a very reactive gas.
- Hydrogen gas can explode easily.

Chemical Laser Operation:

In a commercial chemical laser, **high voltage of about 8,000 Volts is applied to the electrodes of the laser tube**.

Some lasers use **Ultra-Violet (UV) radiation** before the electric discharge to pre-ionize the gas and increase the efficiency of the chemical reaction.

The chemical reaction between free Fluorine and Hydrogen releases a large amount of heat. If we check the **efficiency** of the electrical input versus the laser output, we can get more than 100%, because of the chemical energy released by the reaction between the free Fluorine and Hydrogen.

Chemical Laser Applications:

Most of the applications of chemical laser are **military applications**, so the number of published articles in the open literature is limited.

Mid Infra-Red Advanced Chemical Laser (MIRACL) is the most known chemical laser in the American **High Energy Laser System Test Facility (HELSTF)** located at **White Sands Missile Range (WSMR)**, in south-central New Mexico. It is designed to **destroy enemy missiles in the air**. It was the first megawatt-class; continuous wave, chemical laser built in the free world, and was operated first in 1980.

Properties of Chemical Laser:

- This laser can emit a **continuous power of up to 2 Megawatts**, for a short time (Up to a maximum of 70 seconds).
- The **clear aperture of the special telescope used to direct this laser is 1.5 meters** (!), with computer automatic tracking of the target.
- The beam quality is good.
- The laser demonstrated reliable operation in more than 150 lasing tests, with over 3,000 seconds of lasing time during the last decade.

5.1.10: Far Infra-Red Laser (FIR)

Far Infra-Red (FIR) lasers emit radiation in the Far-Infra-Red spectrum (wavelength range 12-1000 [μm].

The wavelength ranges greater than 100 [μm] is sometimes called sub-millimeter wave.

Far Infra-Red (FIR) lasers are **gas lasers**, and their lasing action occur between rotational levels of the gas molecules of the active medium. The active medium in FIR lasers is usually a gas of simple organic molecule such as:

C_2H_4, CF_4, NH_3,

The best way to achieve **population inversion** in these lasers is to **pump them with another laser (Optical Pumping)** at shorter wavelength. Usually CO_2 laser is used for pumping. The lasing gas is confined within a tube (similar to CO_2 or He-Ne lasers). The **gas pressure** within the tube is 30-300 [torr].

Properties of FIR Lasers:

A schematic drawing of FIR laser is shown in figure 5.10.

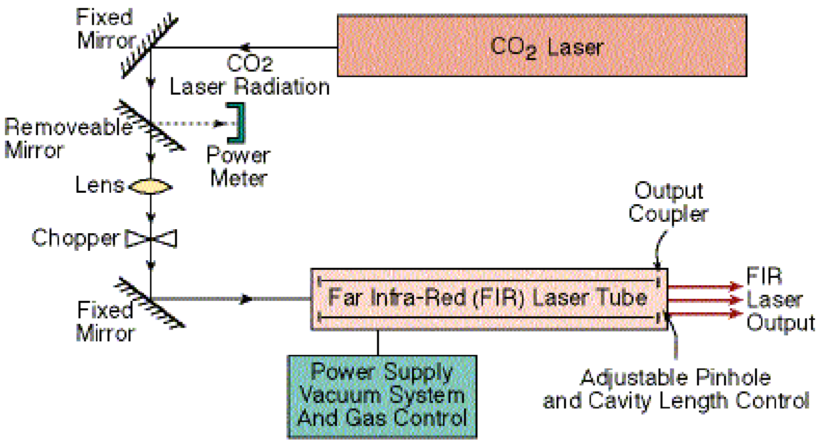

Figure 5.10: schematic drawing of FIR laser

In the laboratory, thousands of lines of FIR lasers have been measured. However, very few commercial FIR lasers are available, and they are mostly used for research purposes.

The power out of FIR lasers is of the order of few milliwatts up to hundreds of milliwatts.

The main research use of FIR lasers is for **spectroscopic measurements**.

It is possible to use the **same FIR laser system for different laser gasses**, and each gas has usually some lasing lines.

5.2: Solid State Lasers

It is convenient to excite a laser whose active medium is solid with "**Optical Pumping**". The atoms in a solid are close to each other, and the interaction between neighbors is strong. Thus, **the absorption and emission spectrum ranges in solids are much wider than those of gasses**. Wide absorption spectrum allows pumping of the active medium with a "conventional" light source, which has a wide emission spectrum.

In **Optical Pumping** the active medium is excited by illuminating it with external electromagnetic source. The photons from the external source are absorbed by the material of the active medium, thus transferring energy to its molecules.

Two types of electromagnetic sources are used in optical pumping:

- Source of **wide band electromagnetic spectrum**- such as Flash lamps, incandescent lamps, arc lamps, etc.
- Source of **narrow band electromagnetic spectrum - another laser**.

Optically Pumped Solid State Lasers:

The active medium in these lasers is a crystal or glass.

The shape of the active medium is usually a **rod with circular or square cross section**. The pumped beam usually enters the active medium via its surface area along the rod, while the laser radiation is emitted through the ends of the rod. The ends of the rod are usually at right angles to the rod axis, and are optically polished.

Solid state lasers emit radiation in either **pulsed mode** or in **continuous mode**.

The pump lamps for pulsed lasers are usually Xenon (or Krypton) flash lamps, in which a low pressure gas is contained within quartz tube.

The pump lamps for continuous lasers are usually Halogen lamps, or high pressure Mercury discharge lamps.

5.2.1: Ruby Laser

Ruby laser was the first man made laser, which was built by Theodore Maiman in 1960. Ruby is a synthetic crystal of Aluminum Oxide (Al_2O_3), and is more familiar in daily life as a precious stone for jewel.

The chemical structure of Ruby is of **Al_2O_3** (which is called **Sapphire**), with impurity of about 0.05% (by weight) of Chromium Ions (Cr^{+3}).

The active ion is Cr^{+3}, which replace **Al** atom in the crystal. This ion causes the red color of the crystal. The impurity ion of Cr^{+3} is responsible for the energy levels which participate in the process of lasing.

Energy Levels of Ruby Laser:

The energy level diagram of a Ruby laser is described in figure 5.11.

This system is a **three level laser** with lasing transitions between E_2 and E_1. The excitation of the Chromium ions is done by **light pulses** from flash lamps (usually Xenon).

The **Chromium ions** absorb light at wavelengths around 545 [nm] (500-600 [nm]). As a result the ions are transferred to the excited energy level E_3. From this level the ions are going down to the **metastable energy level** E_2 in a **non-radiative transition**. The energy released in this non-radiative transition is transferred to the **crystal vibrations** and changed into **heat** that must be removed away from the system.

The lifetime of the metastable level (E_2) is about 5 [msec].

Ruby laser has another absorption band which can be used for pumping, in the spectrum range: 350-450 [nm].

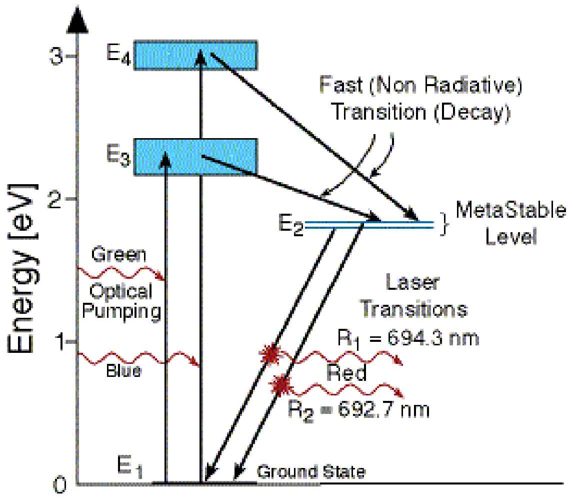

Figure 5.11: Energy Level Diagram of a Ruby Laser

Ruby - The First Laser:

The Ruby laser is a laser which operates in a very narrow range of parameters. The Ruby laser is a **three level laser**, and it is a surprise that it was the first man made lasers in history.

As a matter of fact, right after the first published article of Townes and Schawlow on the feasibility of lasing in the visible spectrum, many research laboratories started an effort to create the first laser.

Small Ruby rods are with diameter of about 6 [mm], and length of about 7 [cm]. **The biggest rods** can be up to 20 [mm] in diameter, and 20 [cm] in length. In figure 5.12 a schematic description of the first Ruby laser developed by Theodore Maiman.

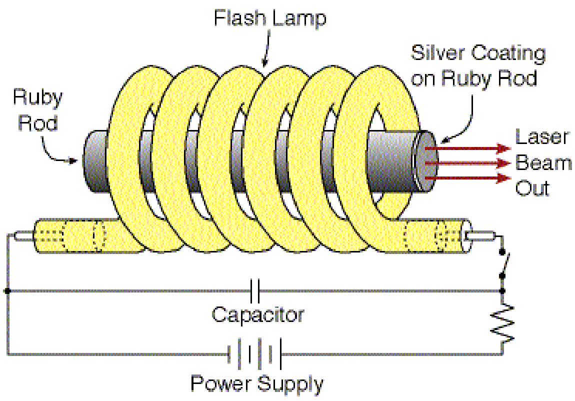

Figure 5.12: Schematic Description of the First Ruby Laser

Since the Ruby crystal is a jewel, the story is that Maimane's wife was wearing it on her neck when they came to conferences.

Summary of the Ruby Laser:

- A solid state laser.
- Emit radiation in the red range of the visible spectrum.
- Optically pumped.
- The radiation is emitted as pulses.
- A three level laser.

5.2.2: Neodymium YAG and Nd Glass Laser

In Nd laser **Nd^{+3} ions** (as impurities of up to a few percent by weight) are replacing the atoms of the solid host in the active medium.

Three **known solid hosts** are used for Nd-YAG laser where Nd^{+3} ions are added as impurities:

- **Glass**.
- **YAG (Yttrium Aluminum Garnet)** Crystal.
- **YLF ($LiYF_4$)** Crystal.

The choice between the three possible hosts is according to the use of the laser:

- **Glass** is used as the host material when a **pulsed laser** is needed, with each pulse at high power, and the pulse repetition rate is slow. The active medium of Nd-Glass Laser can be manufactured in a shape of **disk or rod**, with diameters of up to 0.5 meter (!) and length of up to several meters (!). Such dimensions are possible because glass is isotropic material, cheap, and can be easily worked to the right shape. High percentage (up to about 6%) of Nd ions can be added to glass as impurity. The **problem** with glass as a host is its **poor thermal conductivity**. Thus cooling the laser when it operates continuously or at high repetition rate is difficult.
- **YAG crystal** is used for **high repetition rate pulses** (more than one pulse per second). In this case a large amount of heat need to be transferred away from the laser, and **the thermal conductivity of the YAG crystal is much higher than that of glass.** YAG crystal with the high quality needed for lasers can be made with diameters of 2-15 [mm] and at lengths of 2-30 [cm]. **The price of a YAG laser rod is high, since growing crystals is a slow and complicated process**. The percentage of Nd ions in the YAG host is 1-4% by weight.

Energy Level Diagram of Nd-YAG laser:

The energy level diagram of a Nd-YAG laser can be seen in figure 5.13.

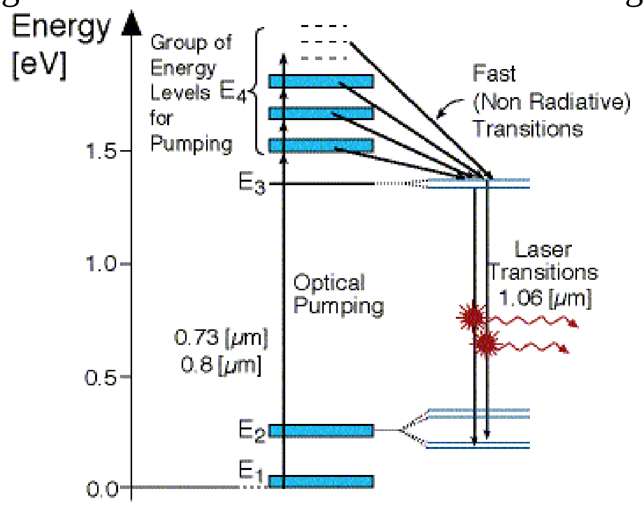

Figure 5.13: Energy Level Diagram of a Nd-YAG Laser

As can be seen from the energy level diagram, Nd lasers are **four level lasers**. Nd ions have **two absorption band**, and excitation is done by **optical pumping**, either by flash lamps for pulsed lasers, or by arc lamps for continuous wave lasers. From these excited energy levels, the Nd ions are transferring into the upper laser level by a non-radiative transition. The **stimulated emission** is from the upper laser level to the lower laser level, and the wavelengths of the emitted photons are around 1.06 [μm]. From the lower laser level, a non-radiative transition to the ground level.

Pulsed Nd Lasers:
Nd glass lasers can emit a large amount of energy in a single pulse. Usually in pulsed Nd lasers the energy per pulse is in the range 0.01-100 [J], and the pulse repetition rate is up to 300 [Hz].
The average energy of a pulsed Nd laser can be high.
The total efficiency of Nd lasers is low, and is in the range: 0.1-2%.

Summary of Nd lasers:

- Solid state laser.
- Emit in the Near-Infra-Red (NIR) spectrum range.
- Optically pumped.
- Operate in both pulsed and continuous mode.
- Four level laser.

5.2.3: Alexandrite Laser

Alexandrite laser is a solid state laser in which Chromium ions (Cr^{+3}), at the amount of 0.01-0.4 %, are embedded in **$BeAl_2O_4$ crystal**. It has energy level structure similar to the energy level structure of Ruby laser. **Alexandrite laser was operated for the first time as a three level laser in 1973 at a wavelength of 680 [nm].** A few years later, it was found that at longer wavelengths the Alexandrite laser can be operated as a **four level laser**, which can be **tune over a range of wavelengths: 720-800 [nm].** It was the **first tunable solid state laser to reach the market**. An energy level diagram which explain the tunability can be seen in figure 5.14.

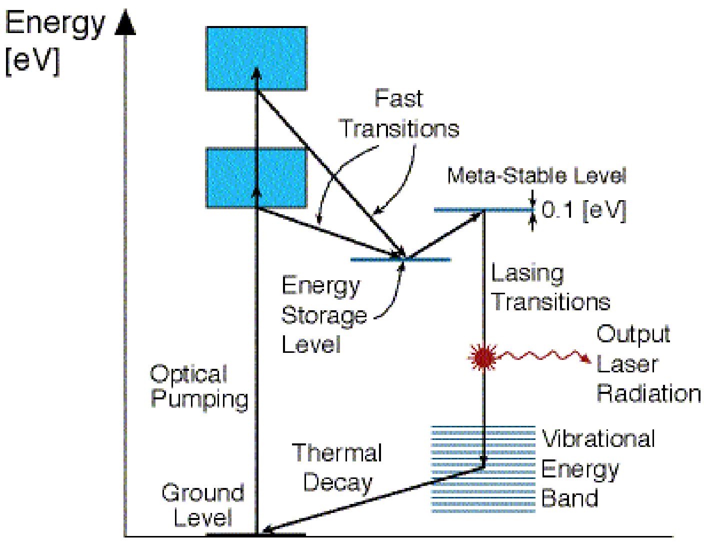

Figure 5.14: Energy Level Diagram of Alexandrite Laser.

Tuning the Laser Wavelength:

An example of such tuning element can be seen in figure 5.15, which show a prism inside the optical cavity.

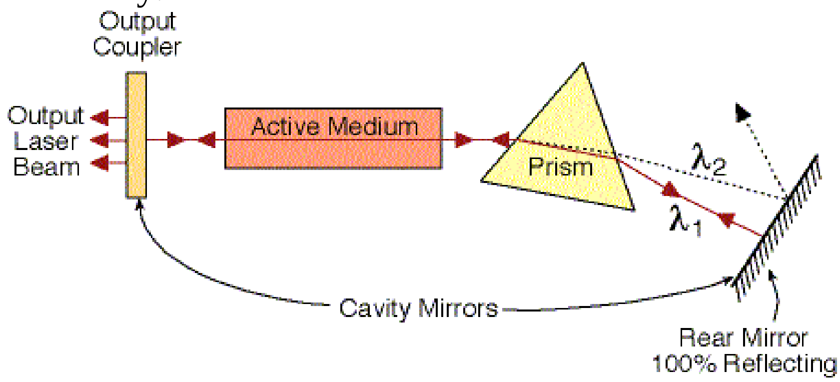

Figure 5.15: Choosing a single wavelength in a tunable laser with a prism.

The dispersion of the prism causes each wavelength to bend at different angle and only one wavelength will continue to move back and forth within the optical cavity. Moving the prism enable selecting the desired wavelength.

Summary of Alexandrite Laser Properties:

- Average output power of Alexandrite laser can reach 20 watts (!).
- Pulses of 100 [μsec], each with power of 1-3 [J] can be obtained.
- Overall electrical efficiency of flash-lamp pumped Alexandrite laser is about 1%.
- Slope efficiency (Increase in output power with increase in electrical input) can be 5%.

5.2.4: Color Center Laser

When crystals of Alkali Halides are exposed to high energy radiation such as x-rays or electrons, **point defects** are created within the crystal. These point defects add more energy levels to the atoms in the crystal (similar to impurity energy levels in semiconductors). These extra energy levels can cause optical absorption at specific wavelengths, thus **adding color to the transparent Alkali Halides**. These colors gave the name **color center lasers** to these lasers. There are few kinds of defects in crystals, but for our purpose we shall explain the simple defect called **F-center** (from the German word "**Farbe**" for color). Tunable color center lasers in Alkali Halide crystals can in principle cover the spectrum range from 0.6 - 4 [μm]. However, there are problems with shelf life of these lasers and with their stability during operation. **Color center lasers operate at liquid Nitrogen temperature (77 [^{0}K]).**

The **main advantage of color center laser** is its **single frequency purity**. In single mode continuous wave operation, linewidth below 4 [KHz] have been achieved (!).

Summary of Color Center Laser:

- Solid state laser.
- Optically pumped usually by another laser (which emit in the absorption spectrum of the color center).
- It is a tunable laser, and the emitted wavelength can be controlled.

Applications of Color Center Lasers:

- Basic research: **Spectroscopy** of atoms and molecules (because of the narrow bandwidth of the emitted wavelength, and the broad range of tunability).
- **Laser chemistry** - to initiate chemical reaction by **selective excitation of specific levels of atoms and molecules**.

5.2.5: Titanium Sapphire Laser

Titanium ion (Ti^{+3}) embedded in a matrix of Sapphire (Al_2O_3) gives: Ti: Al_2O_3. This material is the active medium of the laser called **Titanium doped Sapphire laser.**
The amount of Titanium ions inside the host material is about 0.1%, and they replace Aluminum atoms in the crystal.
Ti: Sapphire lasers belong to a family of lasers called **Vibronic Lasers**, in which trivalent Chromium or Titanium are embedded in solid host.
Ti: Sapphire laser was first demonstrated in 1982 by Peter Moulton MIT Lincoln Laboratory.
Titanium is a **transition metal**; thus Titanium Sapphire lasers belong to transition metal lasers.
Titanium doped Sapphire laser is an **efficient**, **reliable Tunable** laser in the **visible spectrum** and **Near-Infra-Red (NIR)** spectrum.

Summary of Properties of Titanium Sapphire Lasers:

- Usually **optically pumped by another laser**.
- Can operate **continuously** or **pulsed**.
- Continuous power of a few watts can be achieved by pumping with **Argon Ion laser**.
- Has the broadest tuning range of all lasers known today, with **possible lasing wavelengths: 670 - 1100 [nm]**.
- **Operate at room temperature**.
- Very efficient (up to 80% **quantum efficiency** at room temperature).
- The excited state lifetime of Titanium doped Sapphire is only 3.2 microseconds [μsec], too short for pumping with flash-lamp. Thus, the **pumping source is another laser**.
- Absorption spectrum peaks near 500 [nm], so Argon ion lasers or copper vapor lasers can be used as pumping sources.

Applications of Titanium Sapphire Lasers:

- The main applications of Titanium doped Sapphire laser are in research laboratories, particular in spectroscopy.
- The **large tuning range** makes these lasers attractive for **generating tunable sub-picosecond pulses** at short wavelengths.
- Titanium Sapphire laser is used in **NASA project LASE** (**L**idar **A**tmospheric **S**ensing **E**xperiment) for measuring water vapor and aerosols, and their effects on atmospheric processes.

Titanium Sapphire amplifiers can produce:

- Tera-watt (1012 [W]) power levels.
- In femto-seconds (10^{-15} [sec]) pulses.
- At 10 [Hz] repetition rate.
- At wavelengths 760-840 [nm].

5.3: Diode Lasers (Semiconductor Laser)

All diode lasers are built from **semiconductor materials**, and all show electric properties which are characteristics of electrical diodes.
For this reason, the diode lasers have other names such as:

- **Semiconductor Lasers** - According to the **composed materials**.
- **Junction Lasers** - Since they are composed of **p-n junction**.
- **Injection Lasers** - Since the **electrons are injected into the junction** by the applied voltage.

Both research and commercial use of diode lasers has change dramatically during the last 20 years of the 20th century.
Today the number of diode lasers sold in a year is measured in millions, while all other kinds of lasers together are sold in tens of thousands.
In fact, the family of **diode lasers is used in a wide** variety of products including: Compact Discs, Laser Printers, Bar Code Scanners stores and Optical communication.

Historic Development:
The diode laser was invented independently in 1962, at three different research laboratories in the US. The researchers succeeded in getting a coherent electromagnetic radiation from a forward biased diode (p-n junction) made from the semiconductor GaAs.

Energy Levels:

The electrons in a semiconductor are in wide energy bands, which are composed of a large number of energy levels grouped together by quantum effects. The width of the band increases as the distance between the atoms decreases, and the interaction between neighbors increases.

Energy bands in semiconductor are divided into 2 types:

- **Valence Band** - Electrons in the valence band are tied to the atoms of the semiconductor.
- **Conduction Band** - Electrons in the conduction band are free to move around in the semiconductor.

The separation between the valence band and the conduction band is called the **Energy Gap**, and no energy levels of the electrons can be found inside this region. If an electron from the valence band gets enough energy, it can "jump" over the energy gap into the conduction band.

Laser Action in a Semiconductor Laser:

When type "**p**" semiconductor is attached to type "**n**" semiconductor, we get a:

p-n junction

This junction conducts electricity in a preferred direction (forward biased). Figure 5.16 displays the energy bands of an ideal p-n junction without any external voltage applied to it.

The maximum energy level occupied by electrons is called Fermi Level. When the positive contact of the voltage is connected to the p side of the p-n junction, and the negative voltage is connected to the n side, current is flowing through the p-n junction. This connection is called **Forward Biased Voltage**. When the reverse polarity is connected, it is called **Backward Biased Voltage**, and it causes an increase of the potential barrier between the p side and the n side.

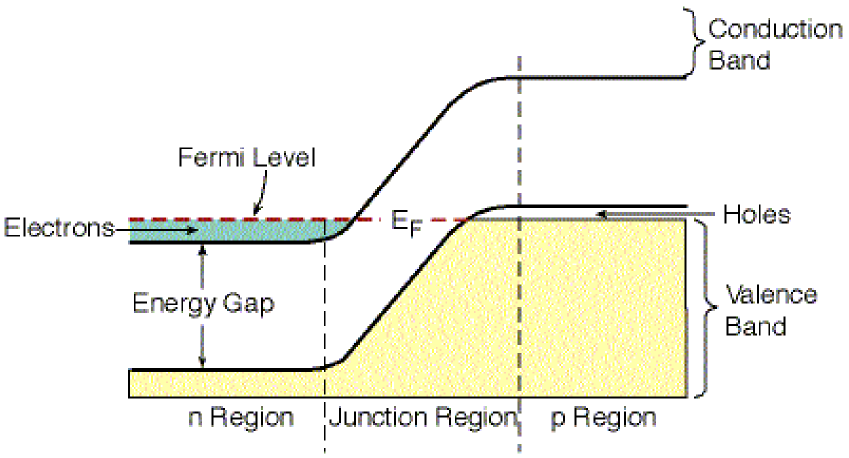

Figure 5.16: Energy levels in a p-n junction which is not attached to a voltage

Laser Diode Construction:

The basic structure of the layers of the simplest laser diode is shown in figure 5.17. These **layers of semiconductor materials** are arranged such that at the p-n junction an **active region** is created, in which photons are created by the recombination process. On the top and bottom layers, a **layer of metal** allows **connecting external voltage to the laser**. The voltage is applied to metal contacts above and below the semiconductor layers. The side of the crystalline semiconductor is cut to serve as mirrors at the end of the optical cavity.

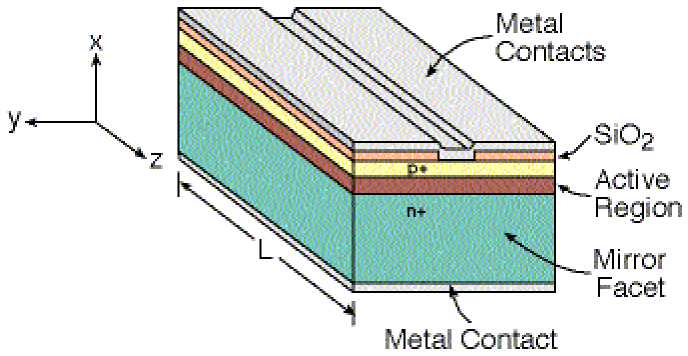

Figure 5.17: Basic structure of a laser diode.

I-V Curve of Diode Laser:

If the condition of "**Population Inversion**" (which is required for the laser action) does not exist, the photons will be emitted by **spontaneous emission**. These photons will be emitted randomly in all directions that are the basis of operation of a **light emitting diode (LED)**.

The condition for population inversion depends on the **pumping**. By increasing the current injected through the p-n junction, we arrive at **threshold current,** which fulfills this condition. An example of the **power output from a laser diode as a function of the injected current** is shown in figure 5.18.

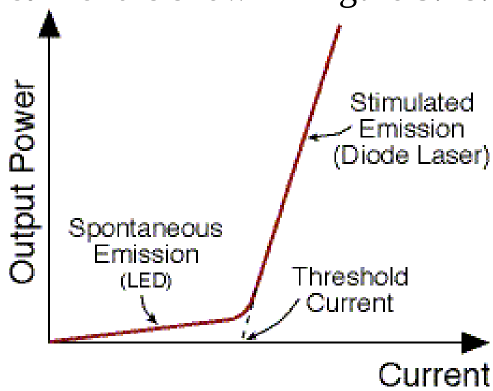

Figure 5.18: Output power from a diode laser as a function of input current.

Note: The **threshold current for lasing** is determined by the intercept of the tangent to the graph at stimulated emission with the current axis.

When the current threshold is low, less energy will be wasted in the form of heat, and more energy will be transmitted as laser radiation (The laser efficiency increases).
One of the problems of diode lasers is the **increase in threshold current for lasing with the increase in temperature.**
Operating laser diodes at low temperatures require lower currents. As current flows through the diode, heat is created. If the heat dissipation is not adequate, the diode temperature increases, and the required threshold current increases as well.

Because of temperature variations, **special structures** need to be designed for the diode lasers to achieve high power of continuous laser radiation.

Advantages of Diode Lasers:

- Very high efficiency (more than 20% of the input energy is emitted as laser radiation).
- High reliability.
- Very long lifetime (estimated more than 100 years of continuous operation!).
- Very cheap price - Diode lasers are fabricated using mass production techniques used in the electronic industry.
- Possibility to perform direct modulation of the emitted radiation, by controlling the electric current through the p-n junction. The emitted radiation is a linear function of the current and can reach a modulation rate of tens of GHz (!). An experimental system, using single mode optical fibers, transmits information at a rate of 4 [GHz], which is equivalent to a simultaneous transmission of about 50,000 phone calls in one fiber (each call occupies a frequency band of 64 [KB/s]).
- Small volume and small weight.
- Very low threshold current.
- Low energy consumption.
- Narrow spectrum band which can be a few kilo-Herz in special diode lasers.

5.4: Dye Laser (Liquid Laser)

A **dye laser** can be considered as a special device to convert electromagnetic radiation from one wavelength, to another wavelength which can be tuned. The output of a dye laser is always a coherent radiation tunable over a specific spectrum region, determined by the Dye material.

History:
Dye laser was first demonstrated in 1965 at IBM laboratories in the US, by Peter P. Sorokin and J. R. Lankard. They discovered the dye laser action during a fluorescence research of organic dye molecules, which were excited by **Ruby laser**.

In 1967 scientists discovered the possibility to tune the emitted wavelength, using a grating at the end of the optical cavity.

Active Medium and Energy Levels in Dye Laser:

Color molecule is made of big organic fluorescent compound which contains large number of cyclic structures. The **active medium in Dye laser** is made of color molecule dissolved in **liquid** which is usually a type of alcohol. Because of the interaction of the color molecules and the solvent, there is a **broadening of the vibrational energy levels**. As a result, **wide spectrum bands are formed**.

Solutions of organic color molecules have wide absorption and emission bands. An example of the spectral bands for the common color: **Rhodamin 6G** can be seen in figure 5.19.

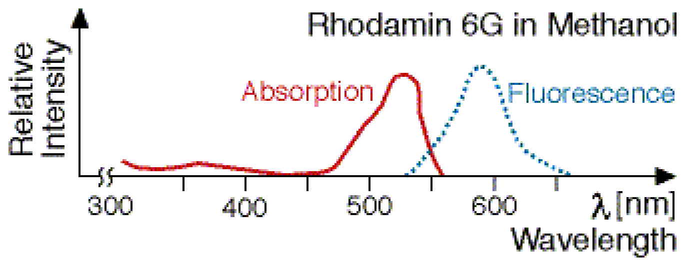

Figure 5.19: Absorption Spectrum (solid line) and Emission Spectrum (dashed line) of Rhodamin 6G in Methanol.

Simplified Energy Level Diagram of Dye Laser:

The structure of energy levels of organic dye molecules in a solvent is very complex. The explanation below is based on a **simplified energy level diagram** described in figure 5.20.

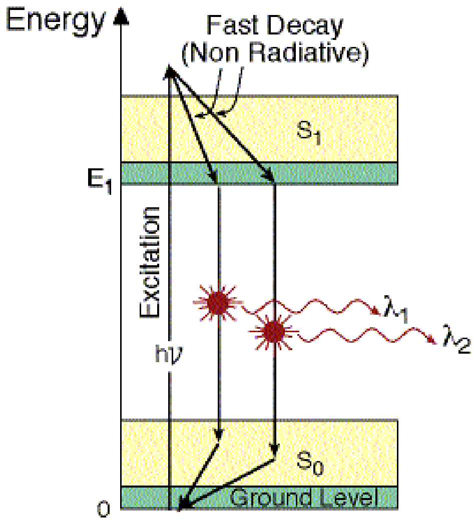

Figure 5.20: Simplified Energy Level Diagram of Dye Laser.

The width of each energy band is of the order of tenths of electron volts [eV]. At room temperature, the thermal energy of vibration is of the order of 1/40 [eV]. Thus only the bottom of each energy level is filled.

Excitation of Dye Laser:

Population inversion in a Dye laser is done by **optical pumping -** illumination by electromagnetic radiation at the proper wavelength.

Since each photon carry a certain amount of energy, and since there is some loss of energy (which turn into heat) in the optical pumping process. Thus, **the wavelength emitted from the laser is of longer wavelength than the wavelength of the pump**.

Advantages of Dye Laser:

- Liquid is homogeneous by nature, and there is no difficulty of manufacturing homogeneous perfect solid with no defects.
- It is relatively easy to change the type of liquid used as an active medium. Thus, changing the wavelength range of the emitted radiation.
- The liquid carries with it the heat evolved during the lasing process, so cooling the laser is simple. The active medium is replaced continuously.
- Special properties of the output radiation of a Dye laser are:
    1. Very narrow linewidth.
    2. Very short pulses.

Disadvantages of Dye Laser:

- Most Dye lasers use **liquid as the active medium**, which complicate maintenance of the laser.
- The **excitation is done by another laser**, which complicate the system.
- **Short dye lifetime**. Dye quality degrade with time, and need to be changed.
- Continuing operating expenses.
- **Potentially toxic (poisonous) chemicals**.
- **Volatile solvents**.
- Hazardous waste disposal.

In recent years, **Solid State Dye Lasers** are being developed.

By embedding the dye molecules in a solid matrix, the disadvantages of the liquid are eliminated.

Applications of Dye Laser:

- The main use of **continuous wave Dye laser** is to reduce the bandwidth (linewidth) of the electromagnetic radiation.
- In medicine - Dye lasers are used for **destroying tumors** which have selective wavelength dependent absorption.
- In medicine - for **Photo-Dynamic Therapy (PDT)**
- In medicine - for **destroying kidney stones** by shock waves created by the short pulses.

Properties of Dye Laser:

- Liquid active medium.
- Operate mostly in the visible spectrum.

- Excited optically - usually by another laser.
- Can emit radiation continuously or in pulses
- Four level laser.
- Tunable laser.

5.5: Special Lasers

Some lasers are based on different physical principles than the "standard" lasers that were described so far.

The nonstandard features can be:

- The **pump energy** is of special form such as in **Free Electron laser (FEL)**.
- The **wavelength** is so special such as **x-ray laser**.
- The **active medium** takes a special form as in **fiber laser**.
- **Laser Without Inversion (LWI) -** in which lasing action can occur in a special case without achieving population inversion.

5.5.1: Free Electron Laser (FEL)

Gas lasers, or solid state lasers, emit electromagnetic radiation at specific wavelengths, which correspond to specific transitions between energy levels in the active medium of the laser.

Free Electron Laser is a device that can emit high power electromagnetic radiation at any wavelength. The emitted wavelength depends on the design of the laser, and not on the properties of the active medium. The efficiency of Free Electron lasers can be very high, up to 65%.

History of Development of Free Electron Laser:

Robert Phillips succeeded in 1957 to build Free Electron Maser. He obtained 150 kilowatts at a wavelength of 5 [mm]. In 1975, John Madey invented the Free Electron Laser (FEL) at Stanford university. His laser operated at 10.6 [mm] (The same wavelength which is emitted from CO_2 laser). Madey used a linear electron accelerator excited at radio frequency.

Applications of Free Electron Laser:

Most of the promised applications of Free Electron laser are **military applications**. Thus, most of the research on the subject was done in the National Research Laboratories at the US and the Soviet Union.

Today, the main civilian applications are for **medical purposes,** because of the **tunability** of the wavelength, and the adaptability to the wavelength specific interaction of the electromagnetic radiation with the biological tissue.

The **main disadvantages of the Free Electron laser are:**

- Big dimensions because of the electron accelerator.
- High cost.
- Hazards of x-rays created by the accelerated electrons.

Examples of achievements with Free Electron Lasers:

- Peak power of 2 Mega-Watts at a wavelength of 2.5 [μm] in the university of Columbia.
- Peak power of 70 Mega-Watts at a wavelength of 4 [μm] in the American Navy laboratories.
- Peak power of 1 Giga-Watts at a wavelength of 8 [mm] in the US National laboratory at Livermore, with efficiency of 35% (!).

5.5.2: X-Ray Laser

Theoretically, since the physical nature of electromagnetic waves is the same with no dependence on their wavelength, it is logic to think that it is possible to create laser at any wavelength.
In practice, there is a problem creating a laser that operates in the short wavelength of x-Rays and γ-Rays.

Explanation:

The lasing process depend on the properties of the medium in which lasing occurs.
The requirements from the active medium depend on the wavelengths which needed to be created:

- In the visible spectrum, and in the Near Infra-Red (NIR) spectrum, the radiation is emitted as a result of **electronic transitions between outer electrons energy levels of the atoms or molecules**.
- To create radiation (photons) in the X-Rays spectrum a much higher energy is needed. Such energy can come from **transitions from the outer energy levels into inner energy levels**. To create a laser in the X-Rays spectrum region **requires a large amount of pump energy, in a very short time**.

Applications of X-Ray Lasers:

Lasers operating in the x-Rays spectrum range can be used as a **sophisticated weapon system**. Thus, most of the research on x-Ray laser is done in the US national laboratories.
One of the most promising energy sources for exciting an x-Ray laser is nuclear energy (!).
One of the programs in the **Strategic Defense Initiative (SDI)** was to use a nuclear explosion to pump a large number of x-Ray lasers.

X-Ray Laser for Research purposes:

In laboratory experiments, scientists achieved laser pulses at wavelengths: 1-30 [nm]. High power pulsed laser was used as an energy source to excite x-ray laser. Each pulse have a peak power of more than a Tera-watt (10^{12} [W]), and last less than a nanosecond (10^{-9} [sec]).These lasers were developed for **nuclear fusion research**, and are in early stage of development.