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Diffusion Cooled V-Fold CO_2 Laser

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1. Introduction

A laser is light amplifier. The acronym LASER stands for Light Amplification by Stimulated Emission of Radiation. It is an electromagnetic radiation with wavelength ranging from ultraviolet to infrared. The fundamental concept of laser operation was first introduced by Einstein in 1917 in one of his three papers on the quantum theory of radiation (Einstein 1917). Almost half a century later, in 1960, T.H. Maiman was the first person to demonstrate the laser by using a ruby crystal. It is a coherent, convergent and monochromatic beam of light. Lasers have various applications in various fields and to appreciate the competency of a laser radiation it is essential to comprehend the basic operation mechanism and properties of laser radiation. The fundamental concept of laser operation is stimulated emission. The three processes required to produce the high energy laser beam are: (a) population inversion, (b) stimulated emission and (c) amplification. Population inversion is a necessary condition for stimulated emission and corresponds to a non-equilibrium distribution of electrons such that the higher energy states have a larger number of electrons than the lower energy states. The process of achieving the population inversion by exciting the electrons to the higher energy states is referred to as pumping (Svelto and Hanna 1989). In general, population inversion is achieved by optical pumping and electrical pumping. In optical pumping, gas-filled flash lamps are most popular. Flash lamps are essentially glass or quartz tubes filled with gases such as xenon and krypton. Some wavelength of the flash (emission spectrum of flash lamp) matches with the absorption characteristics of the active laser medium facilitating population inversion. This is used in solid-state lasers like ruby and Nd:YAG (yttrium–aluminum–garnet). The basic differences between lasers and other light sources are the characteristics often used to describe a laser: (i) the output beam is narrow (ii) the light is monochromatic and (iii) the emission is coherent. The laser light is categorized by different properties and many applications of lasers use these properties. These properties are: (a) mono-chromaticity (b) collimation (c) coherence (d) brightness or radiance (e) focal spot size (f) low divergence (g) transverse modes and (g) temporal modes.

2. Gas lasers

After the demonstration of the first ruby laser, the laser action has been demonstrated in many materials. Lasers are generally classified depending on the physical nature of the active medium used: (I) solid-state lasers (II) gas lasers (III) semiconductor lasers and (IV) dye lasers. It is beyond the purview of this chapter to describe the principles of operation of all these lasers. Here only gas laser systems and typically V-fold CO_2 laser is explained.

The first gas laser, a helium-neon type, conceived and developed by Ali Javan. It was demonstrated for the first time on December 12, 1960, at Bell Telephone Laboratories in Murray Hill, New Jersey. Gas lasers have certain advantages such as homogeneous medium, easy transportation for replenishment, cooling and relatively inexpensive. However, due to physical nature of the gases (low densities), a large volume of gas is required to achieve the significant population inversion for laser action. Hence, gas lasers are usually relatively larger than the solid-state lasers. Gas lasers can be classified into atomic, ionic, and molecular lasers depending on whether the laser transitions are taking place between the energy levels of atoms, ions, and molecules respectively. There are several laser systems in each class. Only some of the typical gas lasers and their wavelengths are shown below in Table-1.

Laser Type	Wavelength (nm)
ArF	191
KrF	249
XeCl	308
HeCd	325, 441.5
XeF	351
Argon	488, 514.5
Copper vapor	510.6, 578.2
Krypton	520–676
Gold vapor	628
HeNe	632.8
CO_2	10,600

Table 1. Gas lasers and Their Wavelengths

2.1 Carbon dioxide lasers

C.K.N. Patel in 1964 working at Bell laboratories made the most efficient gas laser, known as carbon dioxide (CO_2) laser. The carbon dioxide laser is one of the most versatile type laser on the market today and most widely used materials processing laser. Also, they are efficient and inexpensive in terms of cost per unit power. It emits infrared radiation between 9 and 11 micro-meters (μm), either at a single line selected by the user or on the strongest lines in un-tuned cavities. It can produce continuous output powers ranging from well under 1 watt (W) for scientific applications to many kilowatts (kW) for material processing. It can generate pulses from the nanosecond to millisecond regimes. Custom-made CO_2 lasers have produced continuous beams of hundreds of kilowatts for military laser weapon research (Hecht, 1984) or nanosecond-long pulses of 40 kilojoules (kJ) for research in laser-induced nuclear fusion (Los Alamos National Laboratory, 1982). This versatility comes from the fact that there are several distinct types of carbon dioxide lasers. Thus users see several distinct types, such as waveguide, low-power sealed-tube, high-power flowing-gas, and pulsed transversely excited CO_2 lasers. The great interest in carbon dioxide lasers stems from their continuous power capability, high efficiency and ease of construction. Table-2 illustrates their advantages over other gas lasers.

Laser Type	Linear Power Density (W/m)	Max. Power (W)	Efficiency (%)
HeNe	0.1	1	0.1
Argon	1-10	50	0.1
CO_2	60-80	1200	15-20

Table 2. Comparison of Gas Lasers

2.2 Excitation mechanism of CO_2 lasers

The CO_2 laser is a gas discharge device which operates by electric excitation. The active medium in a CO_2 laser is a mixture of carbon dioxide, nitrogen, and helium. Each gas plays a distinct role. Carbon dioxide is the light emitter. The CO_2 molecules are excited so they vibrate in three different types such as symmetric stretching, bending, and asymmetric stretching (Fig. 1). The molecules then lose part of the excitation energy by dropping to one of two other, lower energy vibrational states as shown in Fig.2. Once the molecules have emitted their laser photons, they continue to drop down the energy-level ladder until they reach the ground state. The nitrogen molecules help to excite CO_2 to the upper laser level. Nitrogen molecules are excited first. This is most often done with high voltage direct current, but may also be accomplished by radio frequency excitation. Energy level of the nitrogen molecule is nearly resembles to the (001) vibrational levels of CO_2 molecule. Laser transition takes place between initial level (001) and final levels (100) and (020), resulting in 10.6 and 9.6 µm laser radiations, respectively. The nitrogen molecules mechanically transfer energy to CO_2 molecules via collisions. In practice, the presence of N_2 significantly enhances laser operation, and that gas is almost always present in CO_2 lasers. Helium plays a dual role. It serves as a buffer gas to aid in heat transfer and helps the CO_2 molecules drop from the lower laser levels to the ground state, thus maintaining the population inversion needed for laser operation. However, the laser radiation at 10.6 µm is the strongest and forms the most usual mode of operation. This process is efficient only if the carbon dioxide is cold, so that its energy levels match that of the nitrogen. High-power systems use elaborate heat exchangers to keep the gas cool. The type of CO_2 lasers as slow flow, transverse or cross flow and fast axial flow determines the properties of a CO_2 laser. CO_2 lasers are capable of both continuous wave (CW) and pulsed operation (Wilson and Hawkes 1987) and in most systems; the electric excitation is controlled to do this.

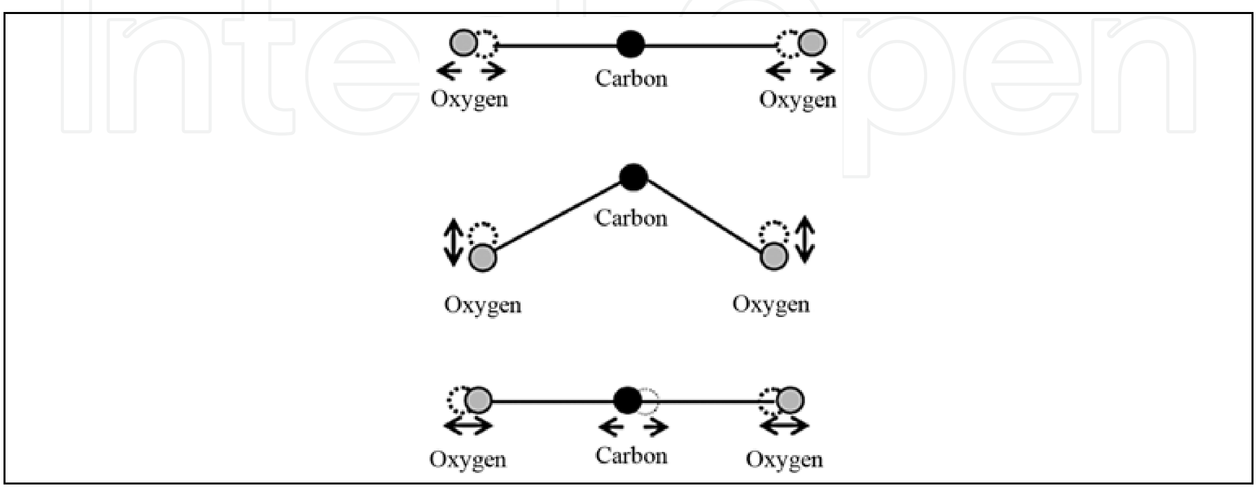

Fig. 1. Vibrational Modes of CO_2 Molecule

The energy level diagram for the operation of CO_2 laser is shown in Fig.2.

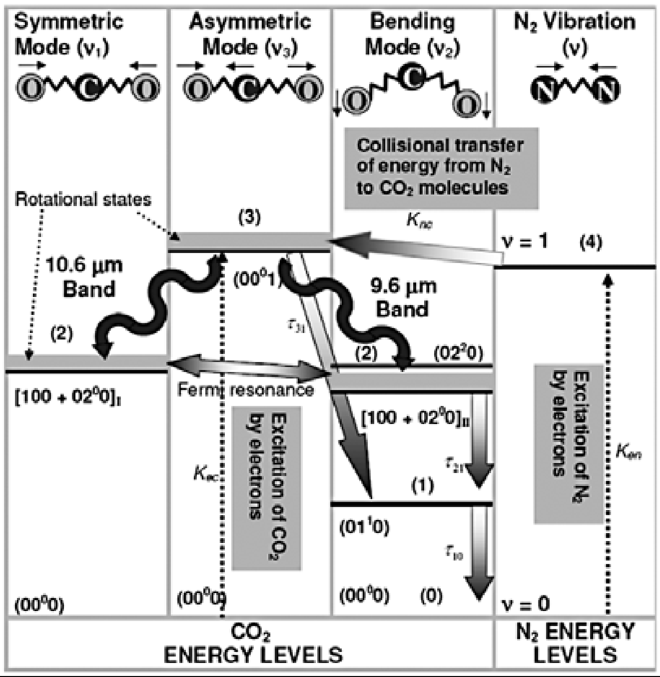

Fig. 2. Energy Level Diagram of CO_2 Laser

2.3 Types of CO_2 lasers

2.3.1 Sealed-tube lasers

The sealed-tube CO_2 laser is a glass tube filled with CO_2, He, and N_2, with mirrors forming a resonant cavity, as shown in Fig.3.

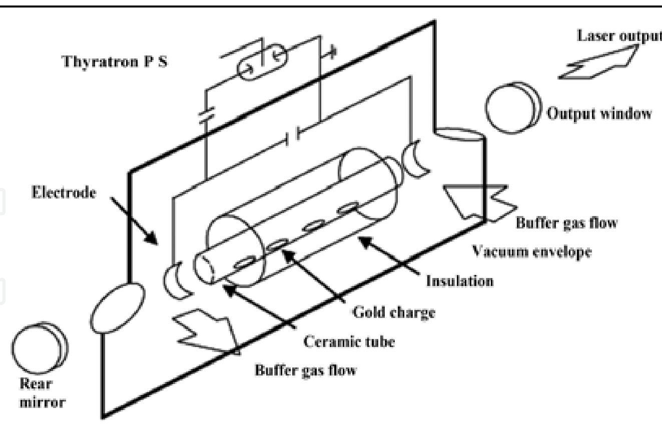

Fig. 3. Sealed Tube Laser

Electrodes are placed near the two ends of the tube. Proper gas mixtures are filled in the tube and seal it. A high voltage is applied to the electrodes to pass a discharge through the gas. A sealed CO_2 laser with an ordinary gas mixture would stop operating within a few minutes. The electric discharge in the tube breaks down the CO_2 in CO and O_2. Catalyst is added in the path to regenerate CO_2. Nickel cathode (at 300°C) can catalyze the recombination reaction. Such measures can be used to produce sealed CO_2 lasers which can operate for up to several thousand hours before their output seriously degrades. Sometimes hydrogen or water to the gas mixture is added so that it can regenerate CO_2 by the carbon monoxide produced by the discharge. In traditional sealed CO_2 lasers, the maximum output power possible with this longitudinal discharge is about 50 W per meter of cavity length, and maximum continuous-wave output is about 100 W. A new methodology is radio-frequency (RF) discharge transverse to the tube axis. This design does not require high-voltage electrodes and offers some other advantages, including the ability to electronically control output at rates to 10 kilohertz (kHz), lower operating voltage and potentially lower tube cost. On the other hand, RF power supplies are more complex and less efficient than DC supplies. RF excitation has been growing in popularity for sealed-tube CO_2 lasers. It can generate more power because it can excite a broader area than a DC discharge, but it also works well at low powers. All sealed-tube CO_2 lasers are limited in output by the difficulty in removing heat.

2.3.2 Waveguide lasers

This type of laser structure is efficient way to produce a compact CW CO_2 laser. It consists of two transverse radio-frequency (RF) electrodes separated by insulating sections. An RF power supply is connected to the electrodes to provide a high-frequency alternating field across the electrodes within the bore region. The waveguide modes access the entire gain volume since the modes reflect off the discharge walls in a zigzag fashion. The waveguide itself traverses the laser length in a zigzag. Waveguide lasers are a type of sealed CO_2 laser in which the inner diameter of a sealed CO_2 laser is shrunk to a few millimeters and the tube is constructed in the form of a waveguide, as shown in Fig. 4.

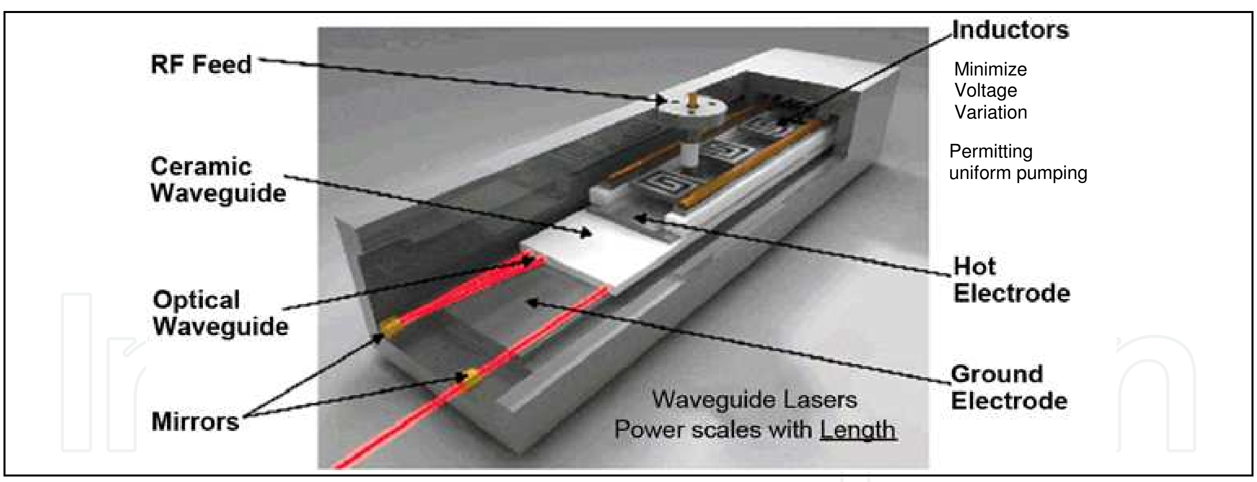

Fig. 4. Waveguide Laser

The waveguide design limits diffraction losses that would otherwise impair operation of a narrow-tube laser. The tube normally is sealed with a gas reservoir separate from the waveguide itself. Waveguide lasers may be excited by DC discharges or intense RF fields. Waveguides may be made of metal, dielectric or combinations of the two. The waveguide laser is very attractive for low powers, particularly under about 50 W. It provides a good beam quality. It can operate continuously or pulsed and can be readily tuned to many discrete lines in the CO_2 spectrum. Its size is comparable to the size of a helium-neon laser but able to generate power in watts.

2.3.3 Longitudinal (axial) slow flow laser

These lasers are operated as conventional gas discharge lasers in the form of long, narrow, cylindrically shaped glass enclosures with electrodes at opposite ends from which the discharge excitation current is introduced as shown in Fig.5. These lasers can be either pulsed or continuous wave and can have lengths of up to several meters. In some versions the discharge enclosure is sealed off and in other versions the gas flows through the tube longitudinally and can be re-circulated to conserve the gases. A water coolant jacket usually surrounds the discharge region. Electric discharge is applied along the tube's axis.

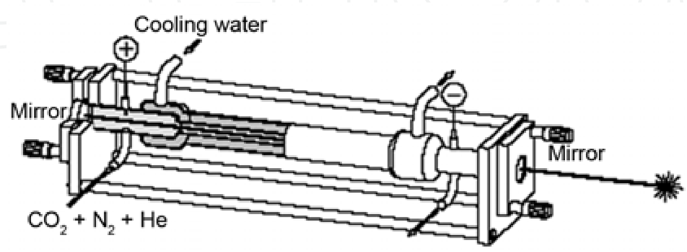

Fig. 5. Longitudinal (Axial) Slow Flow Laser

Low gas pressure and low consumption of gas by recycling methods are some of the salient features of this laser. Slow axial-flow CO_2 lasers produce continuous-wave output proportional to the tube length. Average or continuous power of about 500 W can be produced by folding the laser beam with mirrors through multiple tube segments. This also makes the system compact and the design is simple enough. Heat is removed by conduction mode of heat transfer. Laser gases transfer its heat to the walls of the tube and ultimately that heat can be removed by water circulation or other coolant around the tube.

2.3.4 Fast axial flow laser

The efficiency of axial flow lasers can be increased dramatically by using a pump or turbine to move the gas rapidly through the discharge area as shown in Fig.6.

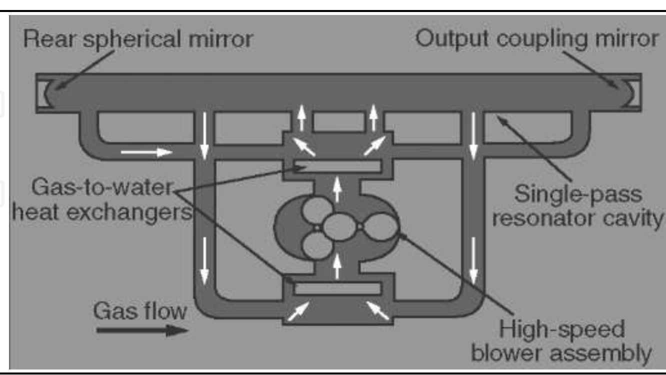

Fig. 6. Fast Axial Flow Laser

This design allows short resonators to produce relatively high powers; 800 W/m is a typical value of power per unit length. Excitation usually is with a longitudinal discharge, as in slow axial-flow lasers, but some fast axial-flow lasers are powered by radio-frequency discharges. The main advantage of the fast flow is that it cools the laser gas better than slow-flow lasers because the gas moves very quickly through the discharge zone. After leaving the discharge zone, the gas is cooled by heat exchanger. The fast axial-flow laser has become the most common industrial CO_2 laser in the power range of 500 W to 5 kW, because of short resonator and small floor space required. Besides the advantages, these lasers have some limitations of complex system design and poor mode quality.

2.3.5 Transverse flow laser

In transverse flow lasers, gas flow direction, electric discharge and direction of laser cavity axis are in three mutually perpendicular directions as shown in Fig.7. It can produce very high power of the order of 10 kW per meter.

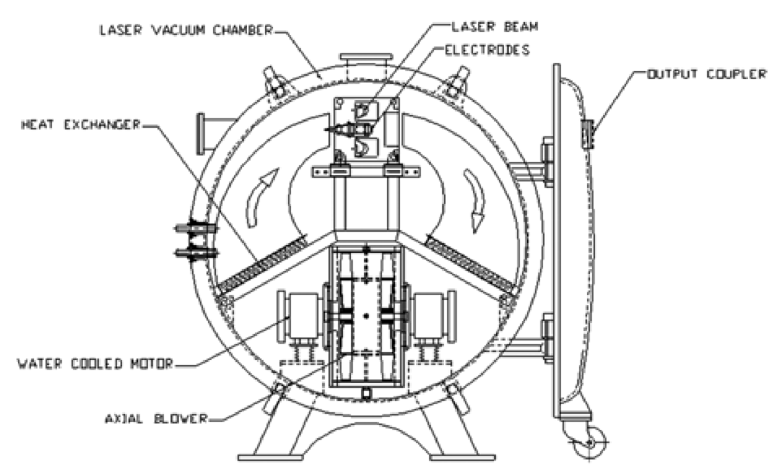

Fig. 7. Transverse Flow Laser

The gas flows across a much wider region and recycled by passing it through a system which regenerates CO_2 and adds some fresh gas to the mixture. In this laser, beam mode structure and beam symmetry are considerably poorer than in fast or slow axial-flow lasers.

2.3.6 Gas dynamic laser

At the end of the 1960s, the gas-dynamic laser was an important breakthrough that made it possible for the first time to reach power levels of 100 kW or more. Basic structure of gas dynamic laser is shown in Fig.8. In gas dynamic lasers the gas is flowed in the transverse direction to the laser axis. Laser gas which is initially at a pressure of several atmospheres is heated electrically or thermally to excite the molecules and population inversion takes place. The high speed pumps are used to rapidly flow the gas. It is then allowed to expand supersonically through an expansion nozzle into a low-pressure region. This expansion causes the gas to supercool and thereby provide rapid relaxation of the lower laser level from the highest rotational states to the lowest rotational states, leaving a population inversion of those empty higher lying rotational states with respect to the upper laser level. A laser beam is extracted from the gas by placing a pair of mirrors on opposite sides of the expansion chamber. Lasers of this design have produced CW output powers greater than 100 kW. This type of excitation was developed primarily for military applications, but lower-power versions have found applications in materials processing.

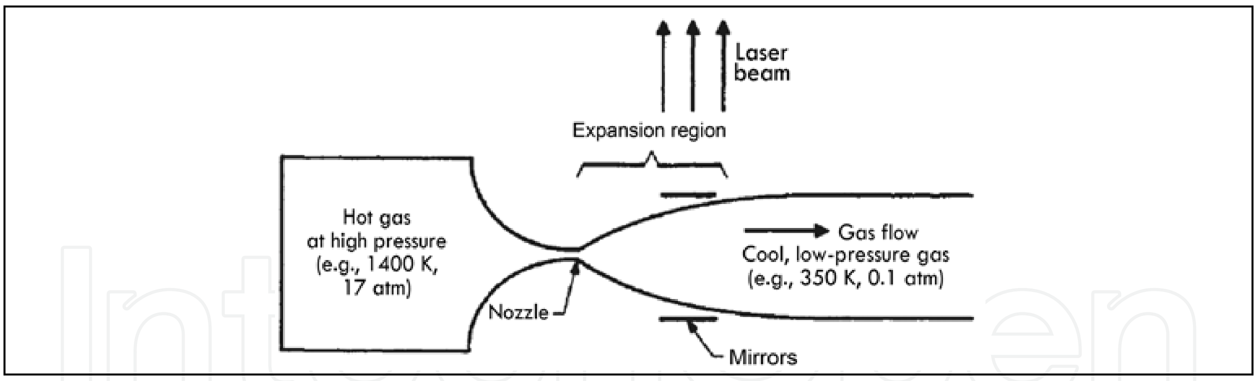

Fig. 8. Gas Dynamic Laser

2.3.7 Transversely Excited Atmospheric (TEA) flow laser

These lasers operate at high total gas pressures of 1 atmosphere or more in order to benefit from obtaining a much higher energy output per unit volume of gas. A schematic of TEA CO_2 laser is shown in Fig.9.

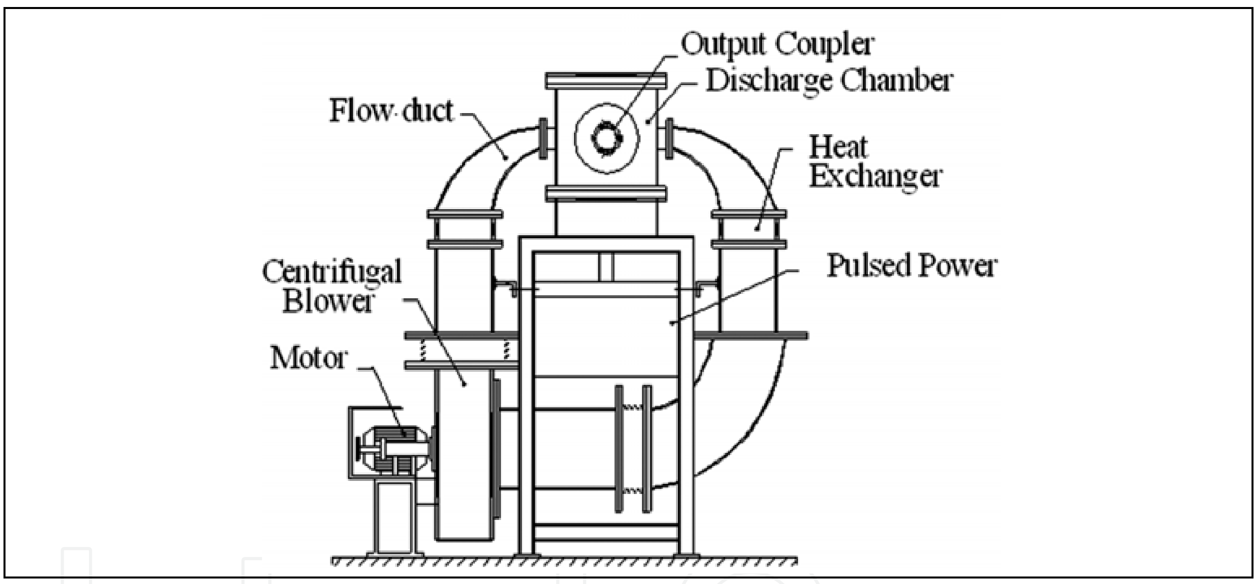

Fig. 9. Transversely Excited Atmospheric (TEA) Flow Laser

Extremely high voltages are required initially to ionize the gas and thereby initiate the discharge process to operate the laser at high pressure. Due to the high gas pressure, arcing tends to form within the discharge. In a transverse discharge, the two electrodes are placed parallel to each other over the length of the discharge and a high voltage is applied across the electrodes. Pre-ionization is used to ionize the space between the electrodes uniformly before applying the high voltage. With this pre-ionization, the discharge can then proceed in a uniform fashion over the entire electrode assembly rather than forming a narrow high-current arc at just one location. The pre-ionization is produced by flashes of ultraviolet light from a row of pre-ionizing UV spark discharges. Such lasers can produce many joules of energy for unit discharge volume. Tens of nanoseconds to microseconds pulse can be produced by passing electric pulses through the gas in a direction transverse to the laser cavity axis. TEA lasers are available in versions with sealed tubes, slow or fast axial flow, or transverse gas flow, depending on power levels. The prime attractions of TEA lasers are their generation of short, intense pulses and the extraction of high power per unit volume of laser gas. High-pressure operation also broadens emission lines, permitting the use of mode locking techniques to generate pulses lasting about 1 nanosecond. It allows tuning over most of the CO_2 wavelength range.

Table-3 illustrate a comparison among details of attainable laser power per cubic cm of active volume in the different types of CO_2 lasers.

CO_2 Laser System	Power Scaling (W/m)
Sealed-off systems	70
Slow flow systems	100
Fast flow systems	800
Pulsed system (TEA Laser)	1.2 TW pulse

Table 3. Comparison of Power Scaling of Different Types of CO_2 Lasers

3. V-fold diffusion cooled CO_2 laser

In the previous paragraphs, we studied about a brief history of lasers and some details about the CO_2 lasers. Here we are going to study about the topic of this chapter i.e. "V-fold diffusion cooled laser" in detail. Fig. 10 is a real photograph of 500 W diffusion cooled CO_2 laser indigenously developed at Department of Atomic Energy, Raja Ramanna Centre for Advanced Technology, Indore, MP, India.

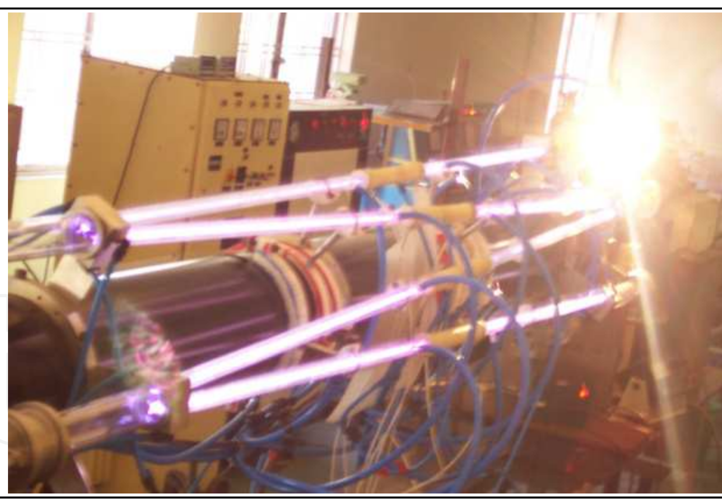

Fig. 10. Photograph of Diffusion Cooled V-fold CO_2 Laser

V-fold laser is also a type of CO_2 laser with some salient features. The name V-fold is given to this laser because of its resonator geometry which is V-folded resonator. Basically this laser is slow flow diffusion cooled CO_2 laser. Convection accompanied by conduction is the mode of heat transfer of this laser. Compare to convective cooled lasers, diffusion cooled laser devoid of bulky heat exchangers and blowers. It makes laser head more attractive, compact & simple in the power range of 300-500 W. In the diffusion cooled laser the laser power can be scaled up by increasing the discharge length at the rate of 50 W/m. We adopted symmetric concave resonator geometry to reduce diffraction loss. V-folding over a cylindrical surface minimizes the astigmatism effect. We obtained more than 380 W laser power in a 7.5 meter discharge length.

3.1 Design considerations

In order to design a V-fold CO_2 laser, the physical dimensions of the active volume, gas flow velocity, output coupling of optical resonator are to be decided. The desired output power P_o can be calculated for the required volume of the active medium, if we know the typical input power density P_{in} that can be dissipated in the homogeneous and stable discharge. P_{in} depends on several factors such as electrode design, gas mixture, its pressure, excitation method, gas flow velocity and its uniformity. Following considerations are taken into account in determining the design parameters such as the discharge length, discharge aperture, optimum reflectivity and gas pressure.

i. The maximum laser power density should be less than the damage threshold of optical elements, however, it should be more than the saturation intensity I_s which is proportional to $p \times n$, where p is gas pressure in mbar and n = 2 in slow flow laser. The damage threshold intensity of the ZnSe mirror, usually used as output coupler in CO_2 lasers is about 2 kW/cm^2. Considering this the incident intensity I_c on the output coupler should be maintained at around 1.0 kW/cm^2.

ii. The optimum output coupling or transmissivity (T) of the resonator can be estimated with the knowledge of the discharge length 'L' small signal gain 'g_o' and the intra-cavity losses (a) by the following relation:

$$T_{opt} = 1 - exp\left[-2L\left\{\left(g_0 \times a\right)^{1/2} - a\right\}\right] \quad (1)$$

iii. The small signal gain is usually experimentally measured and it is in the range of 0.5 to 1% per cm. In optimum laser design it can be seen that the transmissivity (T) is almost constant, independent of small signal gain and the laser power. We can write for the intra-cavity intensity I_c incident on the output coupler as:

$$I_c = I_s \times g_0 \times L \quad (2)$$

$$\frac{I_c}{I_s} = g_0 \times L \quad (3)$$

iv. The damage threshold of the output coupler limits the maximum value of I_c and thus the maximum value of $g_0 \times L$ is also limited. In the optimum laser design the intra-cavity losses $a \times L$ is kept minimum and this is also independent of laser power. Usually the total intra-cavity loss should not be more than 5% of total gain. Thus, $g_0 \times L$ and $a \times L$ being constant, the optimum transmittivity T_{opt} is also constant. For the typical values of I_s and I_c are about 300-500 W/cm^2 and 1 kW/cm^2 respectively. $g_0 \times L$ is in the range of 2-3 in high power lasers. For these conditions:

$$T_{opt} \approx 50 - 60\% \quad (4)$$

v. Minimum diffraction loss in the resonator criterion should also be considered in designing the V-fold resonator.

In a convective cooled laser, the laser power can be scaled up with the following equation:

$$P_L = \left[\frac{\eta}{\eta - 1}\right] . \rho . C_p . \Delta T . V_f . L . d \approx 120\, \dot{M} \quad (5)$$

Where

η = electro-optic efficiency,
ρ = laser gas density,
C_p = specific heat of laser gas,
ΔT = rise in laser gas temperature,
V_f = flow velocity of laser gas,
L = discharge length and
d = discharge height or electrode separation,
$\dot{M}$ = mass flow rate of gas through discharge zone

The above relation is valid only when the rise in laser gas temperature ΔT ~250°C, without bottlenecking at the lower laser level and maintaining a stable and uniform discharge. The temperature above 250°C populates the lower laser level and destroys population inversion. From Eq.(5), a larger mass flow rate is required for higher laser power. Mass flow rate depends upon area of discharge zone, gas flow velocity or gas mixture density. Since the density for a gas mixture is constant at a particular pressure. So increasing either area of discharge zone or gas flow velocity can only increase power. Discharge Area (A) is the function of electrode separation or discharge height (d) and discharge length (L). So the laser power would increase with the increase of d or L. But it is observed that the maximum discharge current, discharge voltage and the laser power remained almost constant for different electrode separations (d). This is because of the electric field would remain constant to maintain the same discharge current. Laser power may also increase with the discharge length (L) but we found that on increasing the length after a certain optimum value, power decreases due to saturation and due to predominance of cavity losses. Also there are limitations of space and alignment on increasing the discharge length. Therefore length cannot be increased after a certain optimum value to increase the power. Thus, after certain value, increasing either discharge length (L) or electrode separation (d) cannot increase laser power i.e. the discharge area cannot be increased too much. Thus to increase the power gas flow velocity may be increased. So to achieve more gas flow velocity, higher capacity pumps/blowers with high discharge and high pressure are required. An effective heat exchanger is needed to dissipate the heat and to keep the gas temperature below 250°C in discharge zone.

CO_2 Laser Systems	Power (kW/m^3)
Diffusion Cooled (length scaling)	500
Transverse Flow	1500
Fast Axial Flow	3000
Slab Laser	3300

Table 4. Power per Unit Volume of Laser Gas

CO_2 Laser Systems	Typical volume of discharge region compared to total volume (%)
Fast Axial Flow	10
Transverse Flow	14
Diffusion Cooled	20
Slab Laser	27

Table 5. Discharge Volume to Total Volume Ratio of Different Types of CO_2 Lasers

As we go from diffusion-cooled lasers to convective cooled lasers, the power-scaling move from length to volume. From calculation, slab lasers give more power per cubic meter of laser gas compared to various types of CO_2 lasers. Following tables shows the laser power output for unit volume of laser gas (Table-4) and typical volume of discharge region to total volume in percentage (Table-5) for various types of CO_2 laser.

From above two tables, it is concluded that the maximum power could be achieved in slab laser and power is moderate in transverse flow laser. In all other laser, except transverse flow lasers, the power scaling up to multi-kilowatt is not easy. The laser power depends on length of active medium (diffusion cooled) or area of discharge electrode (in slab laser) but in transverse flow lasers, power is scaled-up by volume so it is relatively easy. From the above data, it is clear that the power per unit laser gas and discharge volume to total volume ratio is maximum for slab laser. So, if we somehow move from transverse configuration to Slab (area) or diffusion cooled configuration then we can definitely enhance the power of our laser.

3.2 Construction of V-fold laser

The complete laser assembly is mounted on a 3 meter long aluminum pipe (Fig.11). Outer diameter of aluminum pipe is 200 mm. Since the whole laser assembly is mounted on this pipe only therefore best possible straightness of pipe was required. It is very difficult to get single pipe of 3 meter length and straightness 1 mm therefore the whole pipe is casted in 3 segments, each of 1 meter. All the three segments are welded with straightness in 1 mm. To maintain the straightness and rigidity, both the ends are joined with a flange and tie rod. The aluminum pipe is supported at the ends by a support system made of stainless steel plate of 10 mm thick. Bottom of support system is bolted with the support table. There is no middle support for the pipe due to assembly constraints of glass tube. Since the straightness of tube is very important we calculated the deflection at the mid-point of pipe and it is found that the deflection is insignificant. Five rings of stainless steel 304 (SS304) are inserted in the pipe.

Anode support ring is supporting the anode part of this laser at the center. Additional rings of nylon are also placed near to this central ring to give extra support to the joint of glass tube and anode block. Anode block is made of metalon-6 which acts as insulator (Fig.12). Anode pins made of SS304 are placed at the center separated/isolated by metalon-6 tube. The anode block contains two anodes at each end. Anodes are made of stainless steel. Viton® O-rings are used in between glass tube and anode for sealing. Gas inlet ports are also provided on the anode block. Gas flows from the anode block to cathode through the glass tube. Low thermal expansion borosilicate glass tubes are used. These tubes have jacketed construction. Inner tubes have outer diameter 12 mm, inner diameter 9 mm and length 750 mm. Outer (jacket) tubes are having 22 mm OD (Fig.13). Outer tubes also have ports for water inlet and outlet. Water flows through the annular space between inner and outer tube. A chiller unit supplies water at a total flow rate 12 lit/min and 15°C in water jackets for cooling of gases.

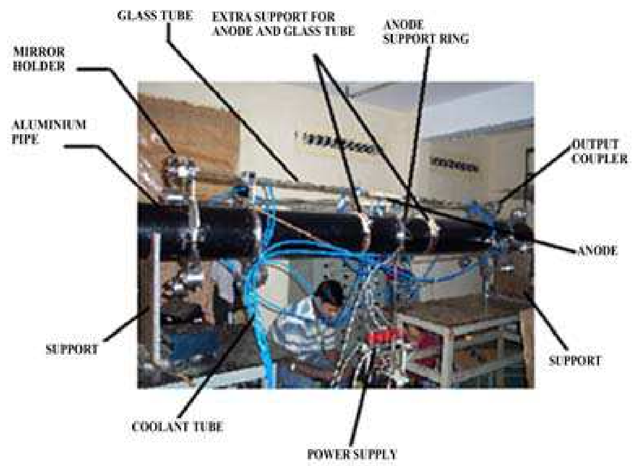

Fig. 11. Components of V-fold CO_2 Laser

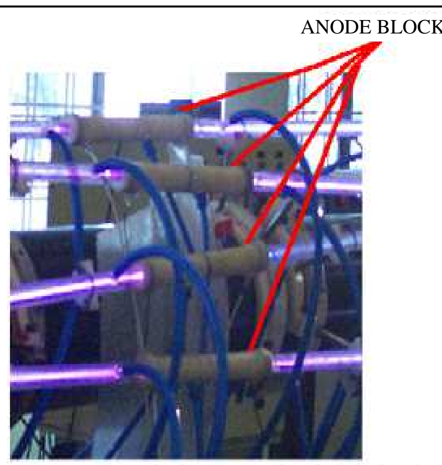

Fig. 12. Photograph of Anode Block

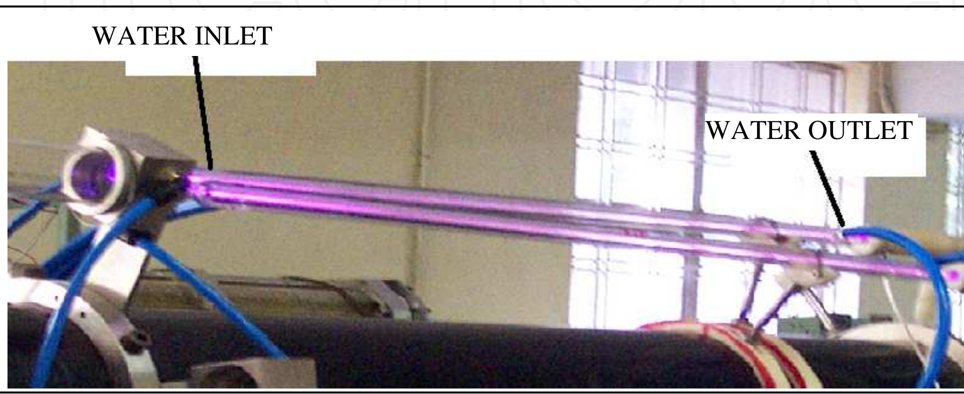

Fig. 13. Schematic of Water Jacket

The jacketed glass tube is supported by cathode block which is ultimately supported by a plate and ring over the aluminum pipe (Fig.14.). Two glass tubes in V-shape are supported by a cathode block on one side. Cathode block is made of SS304 have the advantage of low scaling problem caused by electrical discharge. A mirror holder is connected on the other side of the cathode block through a glass tube of 45 mm OD (Fig.14 & 15). Each mirror holder consists of one mirror and they are placed at the extreme ends on both sides. Mirror holder assembly is also supported on pipe through a ring and plate. Rear mirrors and folding mirrors are made of OFHC Copper substrate of 25 mm diameter and radius of curvature (ROC) 5 meter. Mirrors are gold coated with ~99% reflectivity. Two micrometer screws are fitted on the back side of the each mirror holder to align the laser beam. Alignment is the most critical part of this laser. The alignment accuracy of 0.5 mrad mirror tilt was targeted and achieved by the micrometer screw. Output power is obtained through a ZnSe output coupler having concave geometry of ROC 5 meter and 17% reflectivity.

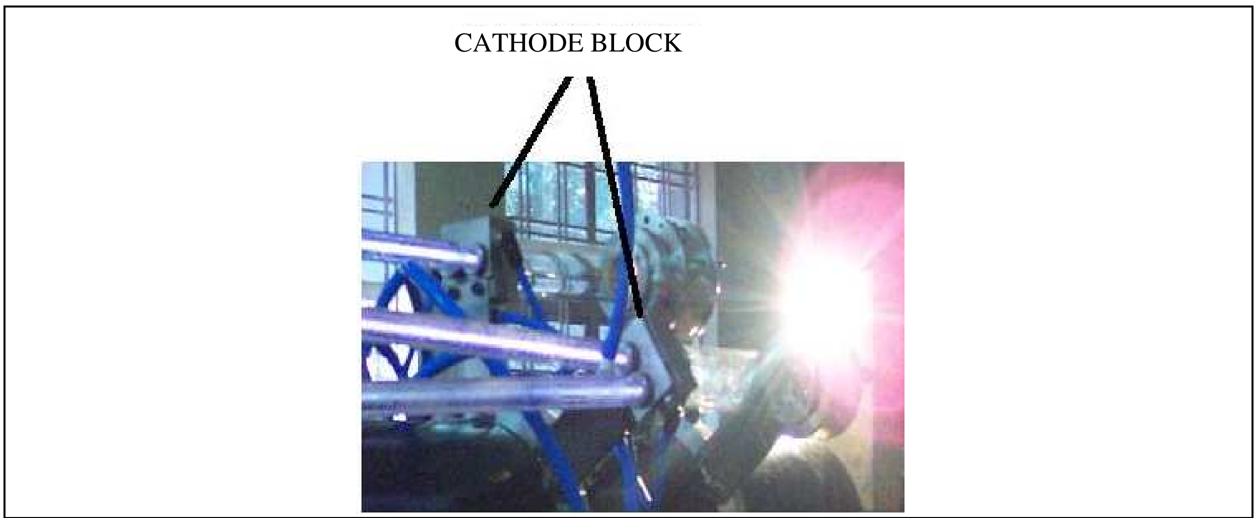

Fig. 14. Cathode Block

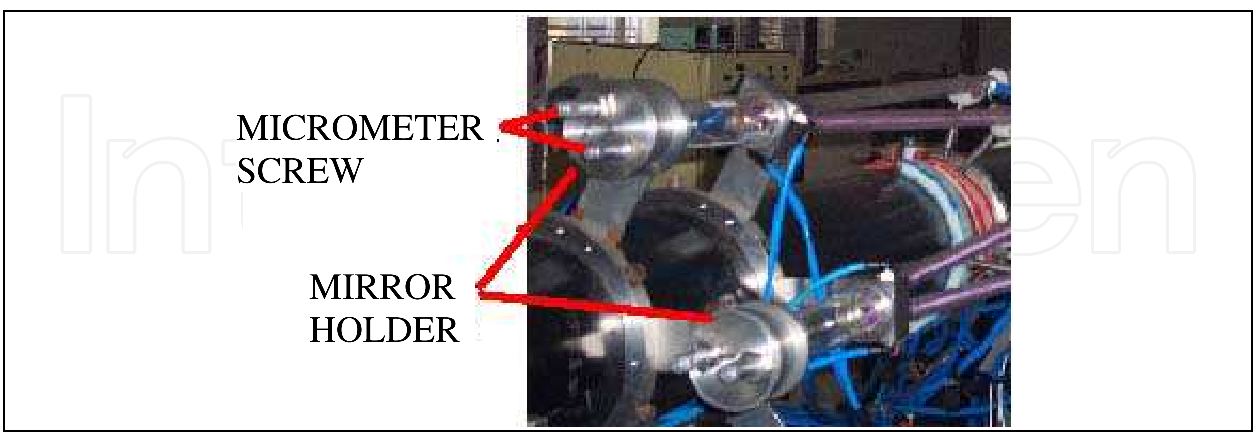

Fig. 15. Mirror Holder

3.3 Working of V-fold laser

The working principle of the laser is similar to other CO_2 lasers. The gas mixture of CO_2, N_2, and He enters in each discharge tube at its center and flows symmetrically towards the cathode blocks, which are connected to a rotary vane vacuum pump of pumping speed of 500 lit/min. Pressure, temperature and gas mixture have been optimized for the maximum output power. Optimum gas pressure is 30 mbar. In the diffusion cooled laser the laser power can be scaled up by increasing the discharge length at the rate of 50 W/m. With the increase of discharge length and therefore optical resonator length, the Fresnel number $N_F = r^2 / \lambda.l$ where r, l and λ are the radius of mirror clear aperture, resonator length and laser wavelength respectively. N_F reduces and with this the diffraction loss increases. Due to this the input power in a laser with plano-concave resonator did not scale up with discharge length beyond 3-4 meters. We adopted the symmetric concave resonator geometry to reduce diffraction loss and V-folding over a cylindrical surface instead of a flat surface for laying the discharge tubes to minimize the astigmatism effect. Each section of V-fold laser has about 1.5 meter discharge length, distance between two mirrors is 2.5 meter. All resonator mirrors i.e. rear reflector, ZnSe output coupler and all folding mirrors are having concave surface of 5 meter ROC. Since, the laser mode formed in any section are sustained in all the other sections therefore the length of one section determines the Fresnel number. Corresponding to the resultant Fresnel number the diffraction loss is low. Introduction of curved folding mirrors through a small folding angle of 5° could introduce considerable aberration due to astigmatism after large number of folding. In order to minimize the overall effect of astigmatism, the tubes were mounted on a cylindrical surface instead of a flat surface to have ~2π folding. The central supporting aluminum pipe due to high moment of inertia have minimum deflection thus minimizes the misalignment. With a fully reflecting mirror on the left and a partially transmitting mirror on the right, the device becomes a V-fold laser which radiates in the far infrared at 10.6 microns. Till date, 420 W power in 10.5 meter discharge length is obtained from this laser system.

3.4 Electrical characteristics of V-fold laser

All gas discharges operated in the glow discharge region have electrical characteristics similar to those indicated in Fig.16. The voltage and current values and the exact shape of the curve depend on the type of gases, gas pressure and the length & diameter of the discharge tube.

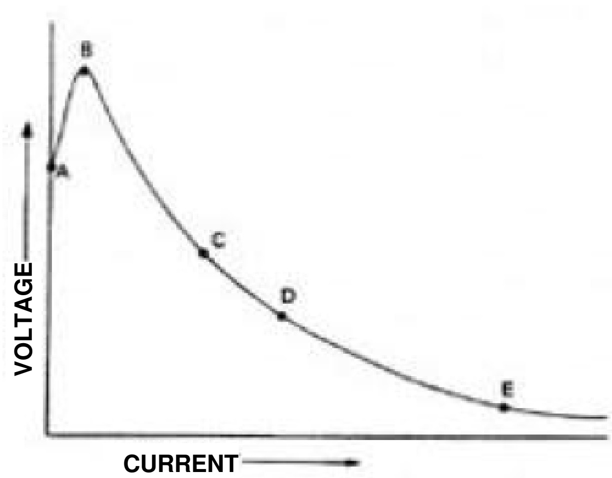

Fig. 16. Voltage-Current Curve of a Gaseous Discharge

Before ionization, the current through the gas is essentially zero. Increasing the voltage on the gas results in a small pre-breakdown current due to a very small amount of easily ionized matter, which is always present in a gas near room temperature (point A). Increasing the applied voltage further will increase this current slightly until the breakdown voltage is reached (point B). At this voltage level, a significant number of atoms become ionized because of the high electric field present in the gas. The free negative electrons are attracted toward the anode and the heavier positive ions toward the cathode. This increases conductivity of the gas and lowers the electrical resistance of the discharge. The electrons are sufficiently accelerated by the electric field to free other electrons through collisions with gas atoms or molecules. Thus, as current increases (from point C to point D), ionization increases and voltage across the discharge tube decreases. This means that an increase in current results in a decrease in resistance. This property of gas discharges is called negative dynamic resistance. This does not mean that the resistance of the tube is a negative value, but that the slope of the voltage-current curve has a negative value. Current through the gas will increase until it is limited by some other electrical component in the circuit or until the power supply can no longer sustain the current. In the case of low-current CW devices such as He-Ne laser tubes, the current is limited at a lower level (point C). In the flashlamps of pulsed solid-state lasers, current is allowed to increase to a value of many kilo-amps (point E) before energy stored in the capacitors is exhausted.

3.5 Power supply of V-fold laser

The Pulser/Sustainer technique is utilized for the production of uniform electrical discharge in the glow discharge regime. The Pulser/Sustainer concept produces pressure and volume scalable plasmas by essentially applying two successive discharges to the gas. The first fast high-voltage pulse creates the electron density uniformly between its electrodes using only a small amount of energy. However a second discharge applies the proper voltage to this plasma to tune the electrons to a temperature sufficiently high for efficient laser pumping but not high enough to generate any appreciable further increase in electron density. Thus, the dominant amount of energy is put into the gas (by the sustainer) exactly where it is desired (vibration excitation of N_2 and CO_2) without triggering. Such plasma instabilities as arcs and sparking are usually associated with substantial ionization rates. The plasma is then with two "knobs"- one controlling electron density, the other electron temperature. The result is a stable uniform tuned high-power-density plasma that is not wall controlled and, hence a high power efficient N_2/CO_2 laser. To realize this concept we have used a 25 kV DC Power supply, 500 mA of current and a pulser with 9 kV of peak voltage, 2 μsec pulse and 5 kHz frequency. The schematic circuit diagram of laser power supply is shown in the Fig.17. An experiment was also performed to know the minimum pulse energy required per pulse to create the uniform discharge. This was studied by the use of another pulser which was available to us with peak voltage of 6 kV, 5 kHz frequency and with variable pulse width. By changing the pulse width we got the situation where we got the uniform smooth discharge. To initiate the discharge in all tubes simultaneously, pre-ionization technique has been adopted. For pre-ionization, a high frequency pulser of peak voltage 6 kV and repetition rate 2-5 kHz has been developed. Pulse width can be varied from 2 to 8 μsec. Pulser is connected to the anode pins by a DC power supply of 30 kV / 750 mA rating through a capacitor of 1.7 nF to block the high voltage DC excitation current. Thick film non-inductive resistors of 191 kΩ are used between DC Supply and anode pins as ballast resistance. Pre-ionization initiates discharge in all the tubes simultaneously and maintain it stable at even low currents. Ballast resistor is required to control the current flowing in the circuit, as discharge has a negative dynamic resistance; hence ballast resistance is an important parameter in getting a uniform stable discharge. If ballast resistance is not proper, it may result in large flow of current, which may result in formation of arcs and no laser action take place. Moreover we require discharge intensity equal in all zones, if instability creeps into one zone, it will affect the other zone and we will not get uniformity in the discharge. If the ballast resistance is of high value, there will be much of power losses in the ballast resistors. We experimented with four different values of ballast resistors. They are 140, 249, 300 and 191 kΩ. With 140 kΩ we could not get the required current density for maximum output optical power. The other three gave us stable discharge and the optimum current in each discharge zone is found to be 26 mA. We finally used the 191 kΩ resistor in our circuit considering the maximum overall efficiency of 10.6%.

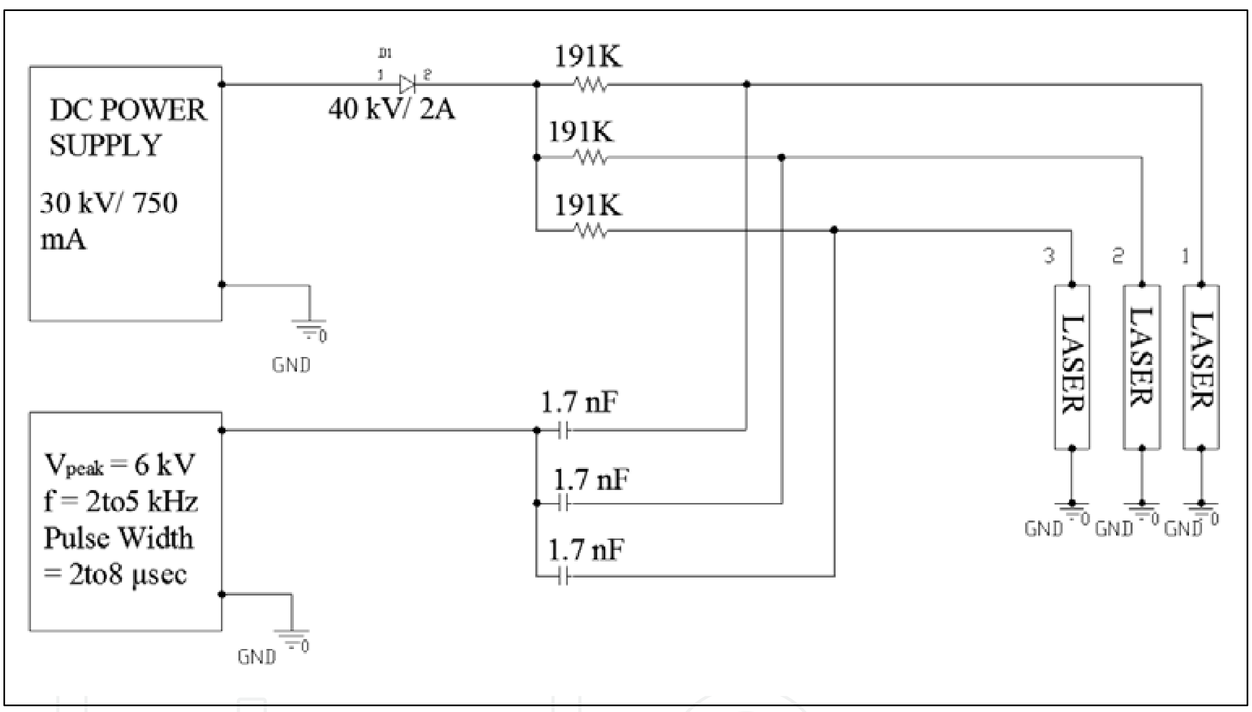

Fig. 17. Schematic of Power Supply of V-fold Laser

3.6 Laser resonator of V-fold laser

Design of a suitable optical resonator is needed to extract the laser power from the annular discharge region and also to provide the feedback to the laser. Resonators are classified depending on beam stability inside the resonator and named as follows:

I. Stable
II. Unstable

The simplest optical resonator (The Fabry-Perot resonator or confocal) consists of a pair of plane or spherical mirrors located opposite one another. They are cantered to a common optical axis and are aligned perpendicular to this axis. For lasers in the low to medium power range (1 mW - 200 W), the hemispherical resonator is mainly used and for high power laser both stable and unstable types of resonator are used. There are many combinations depending on their stability criteria given below:

$$0 \leq g_1 g_2 \leq 1 \quad \text{stability condition} \tag{6}$$

$$g_i = 1 - \frac{L}{R_i} \qquad \text{g-parameter} \tag{7}$$

Where

L = Length of resonator,
R_i = Radius of curvature of resonator

We use the resonator mostly which satisfy this condition. The stability curve shown below represents that which resonator is preferred in stability criteria.

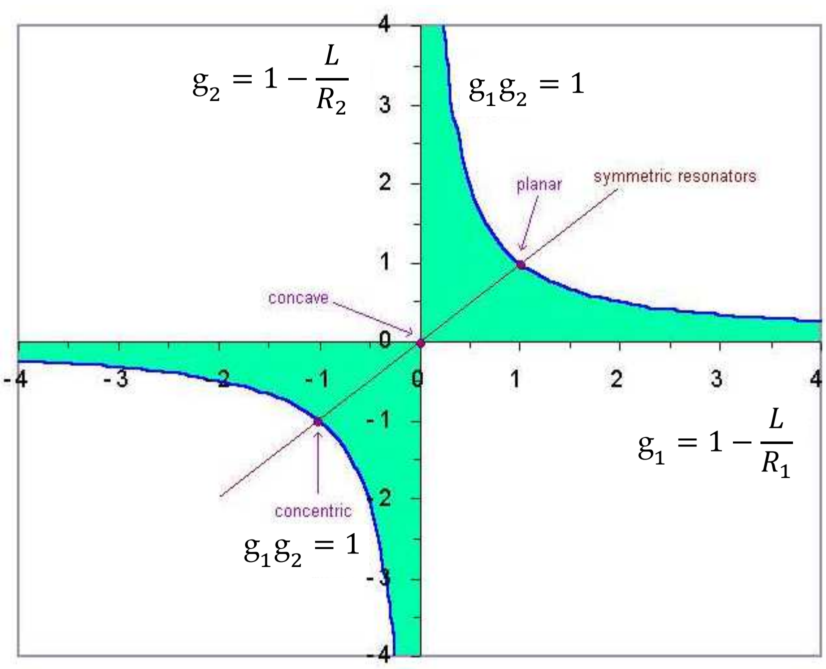

Fig. 18. Resonator Stability Curve

In our present laser we are using a concave–concave type resonator (where 2L=R) in a V-fold manner. Resonator mirrors for visible laser are generally made of glass but in CO_2 laser the radiation is of 10.6 µm which comes in infrared region and this wavelength is absorbed by glass. So a special type of output coupler made up of ZnSe is generally used. The V-Fold laser resonator is a stable resonator comprising of concave mirrors of radius of curvature of 5 meter. The distance between the mirrors is 2.5 meter. Concave mirrors keep the beam bound inside the cavity and tends to reduce the diffraction losses. For a Gaussian beam to exist in a resonator, its wave fronts must fit exactly into the curvature of the mirrors. Thus beam radius at the waist and at the mirrors can be found out using the following equation:

$$\omega = \omega_0 \left[1 + \left(\frac{\lambda z}{\pi \omega_0^2} \right)^2 \right]^{1/2} \tag{8}$$

$$R = z \left[1 + \left(\frac{\pi \omega_0^2}{\lambda z} \right)^2 \right]^{1/2} \tag{9}$$

where

ω = beam radius at the mirrors

ω_0 = minimum spot size

z = distance from the waist

λ = wavelength of CO_2 laser

R = radius of curvature of the mirror

Equation 1 and 2 gives the value of ω_0 and ω is 2.72 mm and 3.153 mm respectively.

3.7 Optimization of V-fold laser

Performance of CO_2 lasers may be optimized in several ways: maximize multimode power; maximize single- mode power; maximize efficiency; and/or minimize size and complexity. The parameters that affect such optimization for flowing gas systems are:

- Tube length, diameter and wall temperature
- Gas mixture, pressure, and flow speed
- Optical mode control, wavelength control, and output coupling
- Electrical discharge control and current density

Optimization is by no means simple, because the various parameters are strongly interrelated. All results, therefore, should be viewed only as indicative of performance trends. The engineer should be prepared to perform experimental exploration of his own system.

3.7.1 Alignment procedure of V-fold laser

Aligning this laser was very challenging job for us. Since the inner diameter of the discharge tube is 9 mm, we require alignment accuracy in microns. Since small amount of misalignment can lead to appreciable loss in output power, a great deal of work was done in making the system rigid. Height or position of the glass CO_2 laser tube should never change because any small movement throws it out of alignment and this could take days to realign. Instead, change the laser system by varying the mirror orientations, grating orientation and He-Ne laser orientation. The idea is to make the two mirrors at the ends of the laser cavity reflect a beam back-and forth many times without striking the walls of the tube. There are a few tricks in aligning this particular laser. Step by step, they are as follows:

i. Make sure that there is no high voltage at the electrodes of the laser tube by checking that the power supply is turned off.

ii. Set up a He-Ne laser alongside the cavity with a pin hole exiting the He-Ne Laser. Use two mirrors and direct the beam down the center bore of the CO_2 laser tube. The He-Ne laser beam should be positioned on the center of the mirrors for adjustment purposes. In the beginning, blank off the back mirror with a piece of paper so that reflections don't confuse matters the set-up.
iii. Direct the He-Ne beam through the middle of the output mirror (the first mirror it passes through). You will see more than one dot reflecting back.
iv. Adjust the mirrors until the He-Ne laser beam goes through the middle of the bore without reflecting off the walls of the tube. It may not look as if it goes through the middle of the Brewster windows, and it may not go exactly through the middle of the output mirror. Going down the center of the bore is the most important.
v. Remove the paper blocking the back mirror and adjust the mirror so that the reflection is centered on the output port of the He-Ne laser (it is easier to align if you place a card with a small hole punched in it at the output port of the Helium- Neon laser).
vi. Now adjust the output mirror so that the inner surface reflection of that mirror (the bigger, dimmer one of the two) is centered on the back mirror reflection spot at the Helium- Neon laser. Fringes can usually be seen on the reflections when the two are aligned (Fabry-Perot interferometer). Alignment is pretty much complete. It may take you a day or two to get to this point.
vii. Blank off the output port of the He-Ne laser with a fire brick to protect it from the CO_2 beam. Place the power detector in front of the CO_2 output port and place a fire brick behind the detector. Whenever you change scales on the power meter, you should reset it to zero.

3.7.2 Power scaling of V-fold laser

The output power of the laser scales up with the input power and input electrical power is limited by two factors. First is the rise in laser gas temperature and second is discharge instability. The most common being the ionization thermal instability. For efficient and reliable laser operation the input power density should be smaller and determined by the cooling and the discharge stabilization processes. In V-fold laser, the maximum input power density is limited by the heating effect and not by the discharge instability. Also, laser power in a V-fold diffusion cooled laser is directly proportional to the discharge length and is independent of the tube diameter and gas pressure. Thus, the laser power in V-fold diffusion cooled CO_2 laser can be scaled up by increasing the active length only and it has been incorporated by introducing several discharge tubes arranged optically in series.

3.8 Losses in optical cavities of V-fold laser

The following factors contribute to losses within the optical cavities of the lasers:

a. Misalignment of the mirrors - If the mirrors of the cavity are not aligned properly with the optical axis, the beam will not be contained within the cavity, but will move farther toward one edge of the cavity after each reflection.
b. Dirty optics - Dust, dirt, fingerprints and scratches on optical surfaces scatter the laser light and cause permanent damage to the optical surfaces.

c. Reflection losses - Whenever light is incident on a transparent surface, some portion of it always is reflected. Brewster windows and antireflection coatings greatly reduce this loss of light but cannot eliminate it entirely.
d. Diffraction loss - Part of the laser light may pass over the edges of the mirror or strike the edges of the aperture and be removed from the beam. This is the largest loss factor in many lasers. When a light beam passes through a limiting aperture, the waves at the edge of the beam bend outward slightly, causing the beam to diverge. This phenomenon is termed "diffraction". When laser light moves, diffraction occurs at the aperture and the beam diverges. When the beam returns to the aperture after reflection from the mirror, its diameter is larger than the diameter of the aperture and the edges of the beam are blocked. The portion of the beam that does pass through the aperture is diffracted again and experiences additional loss on the next pass.
e. Absorption Loss – This loss occurs due to the mirrors either fully or partially reflecting. No mirror is considered to be the 100% reflecting mirror and some part of incident laser get absorbed in the mirror. So as the number of mirrors will increase, the loss will also increase.

3.9 Misalignment sensitivity of V-fold laser

In order to ensure the high-power and stable CO_2 laser operation, misalignment sensitivity has to be known. The power and stability of the laser greatly depends on the misalignment of the optical resonator. In such type of resonator in which a V-fold resonator is used, misalignment is the main cause of reduction in power. So the effect of mirror misalignment of folded resonators is investigated experimentally and compared to first-order perturbation theory. An expression *D* is derived, which characterizes the misalignment sensitivity of any folded resonator. It is proved experimentally that this misalignment sensitivity depends on the effective resonator length L^* and the g_i parameters only.

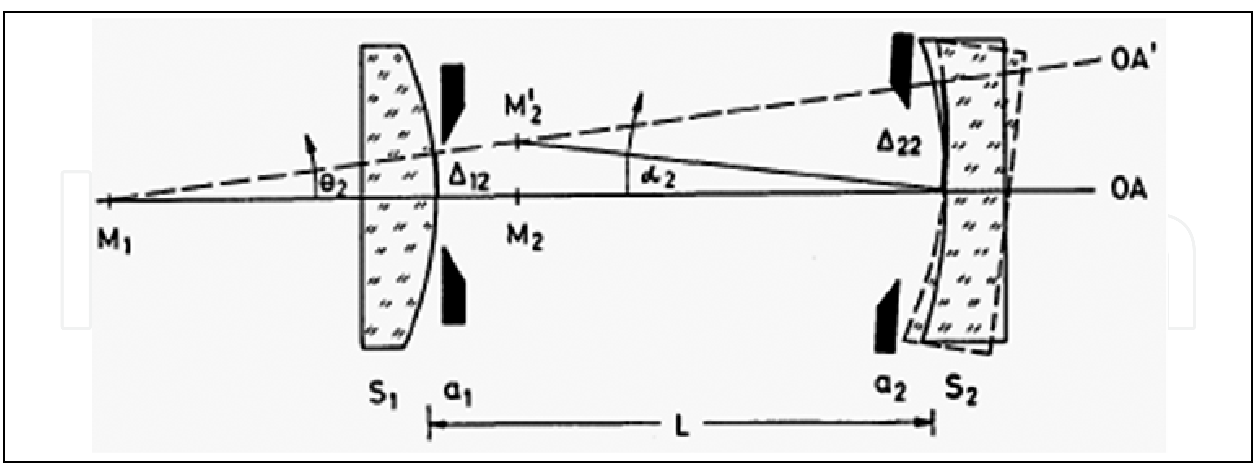

Fig. 19. Misaligned Spherical Resonator

The misalignment sensitivity of a resonator is defined as the sensitivity with which the diffraction losses or the output power are changed due to mirror tilt. By adapting the diameter of the TEM_{00} mode to the diameter of the active medium, the efficiency of a laser oscillator can be increased considerably. This requires either a large mirror distance *L* or an optical resonator operating near the limit of stability. In either case the resonator becomes very sensitive to a misalignment of the mirrors. From symmetry we may deduce that the increase of diffraction loss due to misalignment is proportional to the square of the mirror-tilting angle α_{oi}. Therefore, a suitable expression for the loss factor V_i per resonator bounce is:

$$V_i = V_o[1 - (\alpha_i/\alpha_{oi})^2] \tag{10}$$

Where i indicates mirror S_i, which is tilted by an angle α_i with respect to the resonator axis (see Fig.19). The misalignment sensitivity of the resonator is characterized by α_{oi}. In the following sections the relation between α_{oi} and the resonator parameters is investigated experimentally and theoretically.

3.9.1 Background

There are few papers dealing with the influence of misalignment on diffraction losses. Numerical calculations were carried out for special systems such as symmetric or confocal resonators and plane-plane resonators using first-order perturbation theory. But they assume that the aperture of the system does not disturb the field distribution of the infinite mirror. The laser oscillator consists of two spherical mirrors, radii of curvature R_1 and R_2 in a distance (L) and refractive index. It is assumed to be homogeneous. The mode properties of the resonator are characterized by the effective length L^* and the g_i parameters. For infinite mirrors, the spot size of the TEM_{00} mode is given by:

$$W_i^2 = \frac{\lambda L^*}{\pi}\left(\frac{g_j}{g_i(1-g_1g_2)}\right)^{1/2} \tag{11}$$

The resonator axis is defined by the two centers of mirror curvature M_1 and M_2. If mirror S_i is tilted by an angle α_i, the resonator axis is rotated by an angle θ_i, and the centers of the field intensity patterns are shifted. A simple geometric consideration delivers the relations:

$$\theta_i = \alpha_i \frac{1-g_i}{1-g_1g_2} \tag{12}$$

$$\Delta_{ii} = \alpha_i g_i L^* / (1-g_1g_2) \tag{13}$$

$$\Delta_{ij} = \alpha_j L^* / (1-g_1g_2) \qquad i \neq j \tag{14}$$

Δ_{ij} means the displacement of the intensity pattern at mirror S_i, if mirror S_j is tilted by α_j. Near the limit of stability $(g_1g_2 \to 1)$, the beam steering angle θ_i and the displacement Δ_{ij} may become considerably large. Nevertheless, as long as infinite mirrors are considered, the resonator remains aligned, and there are no diffraction losses. But if a limiting aperture is inserted into the resonator, e.g., the active medium or a mode selecting pinhole, diffraction losses occur and increase rapidly with increasing mirror tilt angle. Tilting a mirror is equivalent to a displacement of the pinhole. For a system with only one pinhole, Berger et al calculated the dependence of diffraction loss factor V on the pinhole displacement (Δ). A first-order perturbation theory for the TEM_{00} mode delivers:

$$V = 1 - \left[1 + 2\left(\Delta/w\right)^2 \left(a/w\right)^2\right] \exp\left[-2\left(a/w\right)^2\right] \tag{15}$$

Where

a = pinhole radius,
w = beam diameter of the TEM_{00} field pattern at the pinhole, and
V = loss factor per resonator bounce.

Generally a resonator has limiting apertures on both mirrors. Then the loss factor by tilting mirror S_i is given by:

$$V_i = \left(V_{ii} . V_{ji}\right)^{1/2} \qquad i \neq j \tag{16}$$

$$V_{ji} = 1 - \left[1 + 2\left(\frac{\Delta_{ji}}{w_j}\right)^2 \left(\frac{a_j}{w_j}\right)^2\right] . \exp\left[-2\left(\frac{a_j}{w_j}\right)^2\right] \tag{17}$$

For small losses (1-V_{ji}, 1-V_{ii} << 1), Eq. (16) combined with Eq. (17) can be approximated by

$$V_i \cong V_o - \left\{ \left[\left(\frac{\Delta_{ji}}{w_j}\right)\left(\frac{a_j}{w_j}\right)\right]^2 \exp\left[-2\left(\frac{a_j}{w_j}\right)^2\right] + \left[\left(\frac{\Delta_{ii}}{w_i}\right)\left(\frac{a_i}{w_i}\right)\right]^2 \exp\left[-2\left(\frac{a_i}{w_i}\right)^2\right] \right\} \tag{18}$$

V_o is the loss factor of the aligned system with

$$V_o = 1 - \frac{1}{2}\left\{ \exp\left[-2\left(\frac{a_i}{w_i}\right)^2\right] + \exp\left[-2\left(\frac{a_j}{w_j}\right)^2\right] \right\} \tag{19}$$

For minimizing diffraction losses on the one hand and preventing multimode oscillation on the other hand, it is reasonable to use pinhole radii a bit larger than the beam radii. Combining the above equations, we finally get

$$V_i = V_o\left(1 - \alpha_i^2 \frac{S^2}{\exp 2S^2 - 1} D_i^2\right) \tag{20}$$

$$V_o = 1 - \exp\left(-2S^2\right) \tag{21}$$

$$D_i^2 = \frac{\pi L^*}{\lambda}\left(\frac{g_j}{g_i}\right)^{1/2} \frac{1 + g_1 g_2}{\left(1 - g_1 g_2\right)^{3/2}} \tag{22}$$

Equation (20) represents the diffraction loss factor V_i per resonator bounce, if mirror S_i is tilted by α_i. Misalignment sensitivity D_i, which according to Eq. (22) depends on the resonator length L^* and the g_i parameters. If a mirror is tilted by an angle $\alpha = 1/D_i$, additional losses of 10% are caused. This gives a clear idea of the meaning of the misalignment sensitivity D_i. However, the low-gain lasers are affected much more by an additional loss of 10% than the high-gain lasers. Thus, misalignment sensitivities of different resonator configurations may be compared if their gains are the same. If both mirrors are misaligned, the losses proportional to D_i^2 are summed up. Therefore, the misalignment of the complete system is defined as $D = \left(D_1^2 + D_2^2\right)^{1/2}$ and is given by:

$$D = \left[\left(\frac{\pi L^*}{\lambda}\right)\frac{1+g_1g_2}{\left(1-g_1g_2\right)^{3/2}}\frac{\left|g_1+g_2\right|}{\left(g_1g_2\right)^{1/2}}\right]^{1/2} \tag{23}$$

Where, 'D' is a number characterizing any spherical resonator with respect to its sensitivity against mirror tilting. High value of *D* means high misalignment sensitivity. The most insensitive resonator is the symmetric con-focal one with $g_1=g_2=0$.

$$D_0 = \left(\frac{2\pi L^*}{\lambda}\right)^{1/2} \tag{24}$$

But, from the stability diagram, we learn that $g_1=g_2=0$ represents a discontinuity. Small deviations from symmetry may cause high losses and high misalignment sensitivity.

3.9.2 Experimental investigation

The power and stability of a laser system is mainly governed by the misalignment sensitivity of optical resonator. To ensure stable and high power from laser system misalignment sensitivity has to be known. The effect of reflector and output coupler misalignment for concave -concave & Plano-concave resonators in single and double limbs of V-fold laser are investigated experimentally and compared to first-order perturbation theory. Eq.23 is used to quantify the misalignment sensitivity of the V-fold laser resonator. It is proved experimentally that this misalignment sensitivity depends on the effective resonator length *L** and the *gi* parameters only. High value of *D* means high misalignment sensitivity. The influence of mirror misalignment on laser output and field distribution was investigated by various authors. Experiment was carried out for four different arrangements.

a. Single limb with concave-concave resonator
b. Single limb with Plano-concave resonator
c. Double limbs with concave-concave resonator and
d. Double limbs with Plano-concave resonator.

Laser was operated with all these arrangements and then misaligned with the help of micrometer screw fitted on the backside of the optics. These four arrangements gave the misalignment characteristics for the single and double limb as well as Plano-concave and concave-concave resonator. Power was measured in the best-aligned condition then graphs were plotted for laser power v/s misalignment (Fig.20). The experimental results are verified by theoretical calculation of the misalignment sensitivity parameter '*D*' (Table-6).

Misalignment sensitivity increases with L* i.e. no. of limbs. It is also observed that the plano-concave resonator is more sensitive to misalignment then the concave-concave resonator (Fig.20 & 22). It is also interesting to observe that the output coupler is less sensitive to misalignment compare to the rear concave reflector (Fig.21 & 23). This is due to very high

S.No.	Type of Resonator	Active Medium Length (cm)	D (mrad)
1	Concave-Concave	150	1.687
2	Concave-Concave	300	2.378
3	Plano-Concave	150	2.286
4	Plano-Concave	300	3.223

Table 6. Theoretical Value of Misalignment Sensitivity Parameter '*D*'

coupling loss of resonator & long gain length. The radiation, which begins from the output coupler-end, sees the round trip gain while the radiation which begins from the rear mirror; sees only single trip, and the starting intensity of radiation in the first case is relatively smaller than that in the second case. Therefore the misalignment in first case (output coupler) has relatively less effect on the laser power build up compared to the misalignment of the second case (rear reflector). Furthermore, the experimental results indicate that sensitivity parameter '*D*' is a suitable parameter to describe the alignment stability of a resonator.

SL – Single limb, DL – Double limb, CC – Concave-Concave resonator, PC – Plano-Concave resonator, M1 – Micrometer1, M2 – Micrometer2
Note: Micro-meters are numbered 1 & 2 in anticlockwise direction.

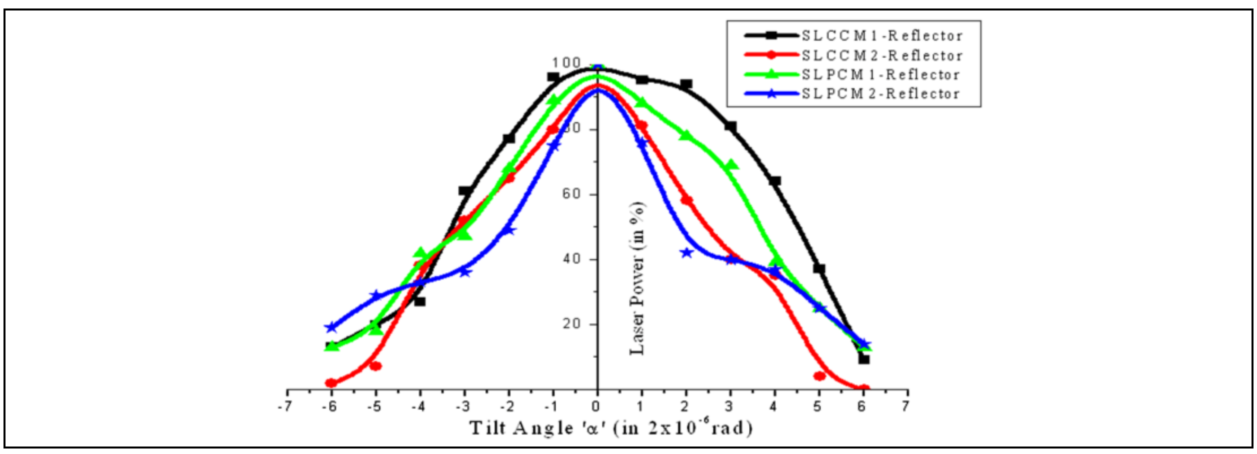

Fig. 20. Misalignment in Single Limb for Reflector

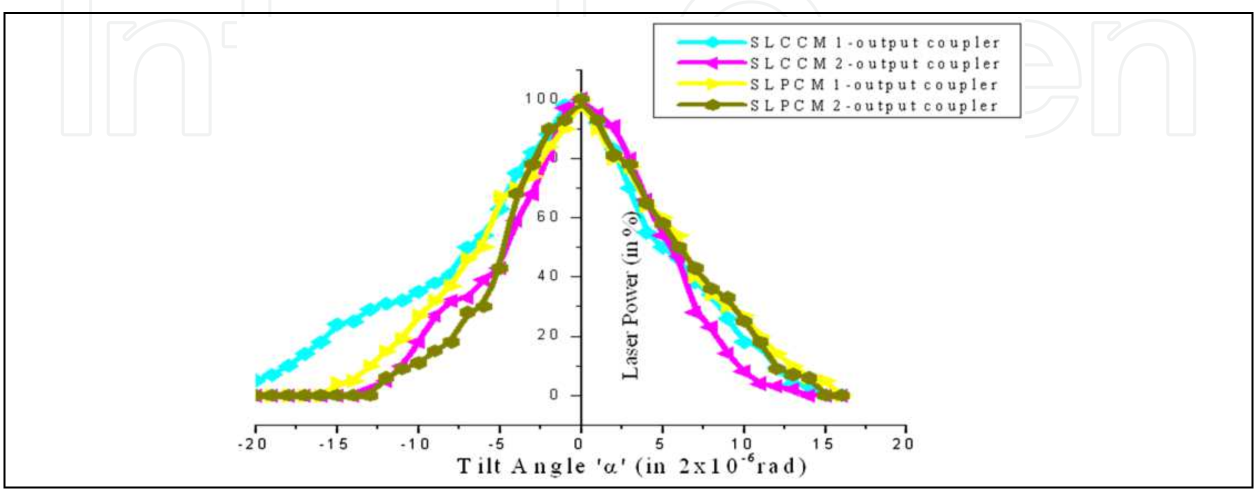

Fig. 21. Misalignment in Single Limb for Output Coupler

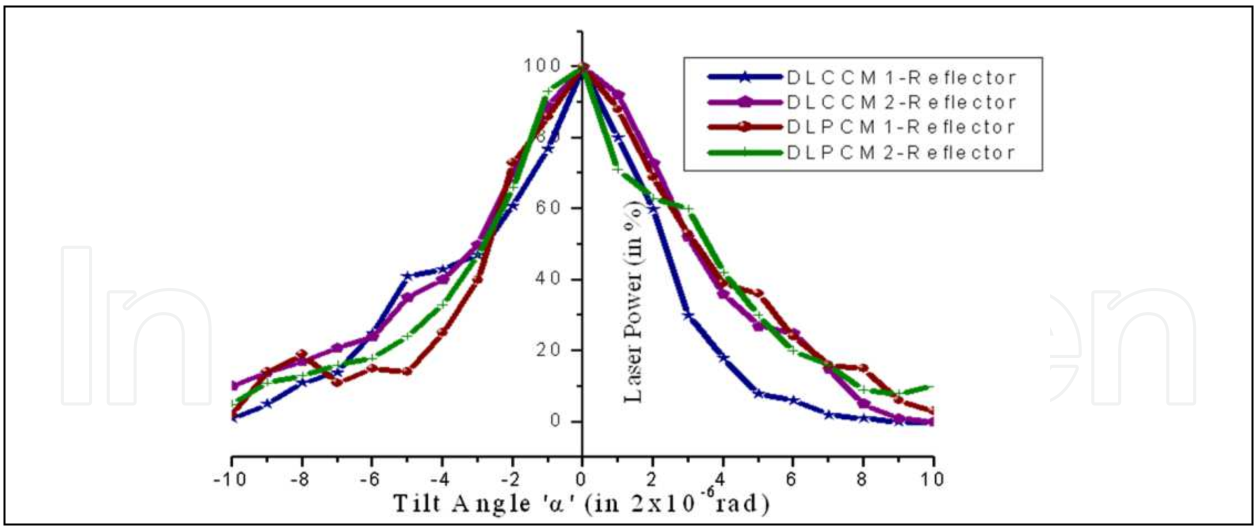

Fig. 22. Misalignment in Double Limb for Reflector

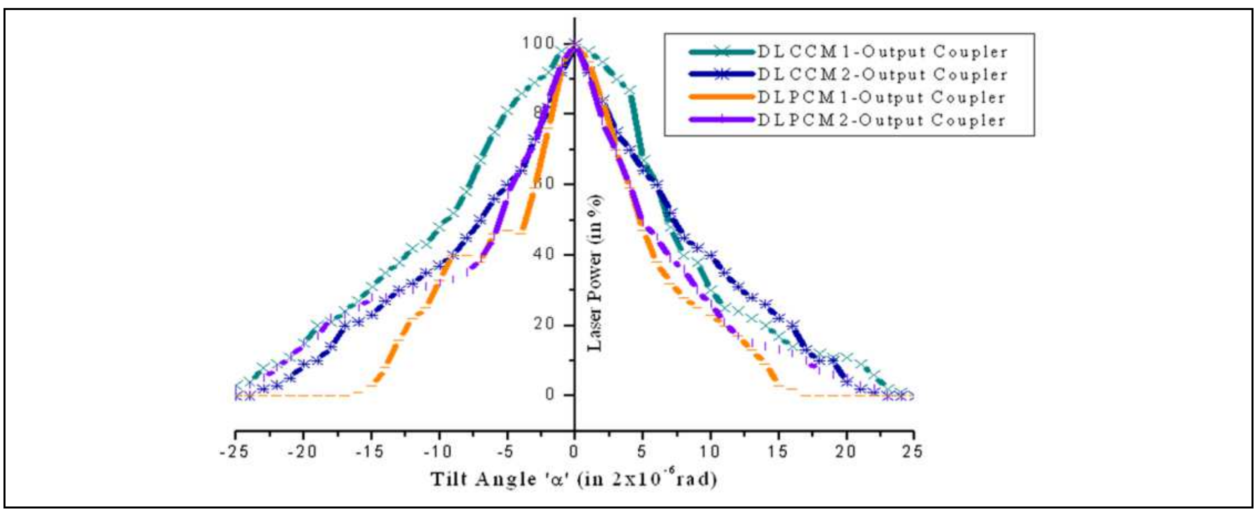

Fig. 23. Misalignment in Double Limb for Output Coupler

3.10 Optimum reflectivity of output coupler of V-fold laser

In V-fold type of resonator since there are more number of limbs and each limb has different output coupling reflectivity. So the output power of a laser that can be extracted depends on the reflectivity/transmission of the output coupler (Eq.25).

$$P_{out} = A_b I_s \frac{1-R}{1-R+\sqrt{R}\left(1/a - a\right)}\left[g_0 l - \ln\sqrt{R\times a^2}\right] \quad (25)$$

Where

A_b = Cross section area of medium,
R = Reflectivity,
a = cavity losses,
I_s = Saturation Intensity and
$g_0 l$ = Small signal gain.

Decreasing reflectivity to extract more power increases the overall loss of the system, requiring greater pumping power to reach threshold. Increasing the output coupler reflectivity increases the cavity photon life time, thereby increasing the photon loss and resulting in decrease of laser output power (Fig.24).

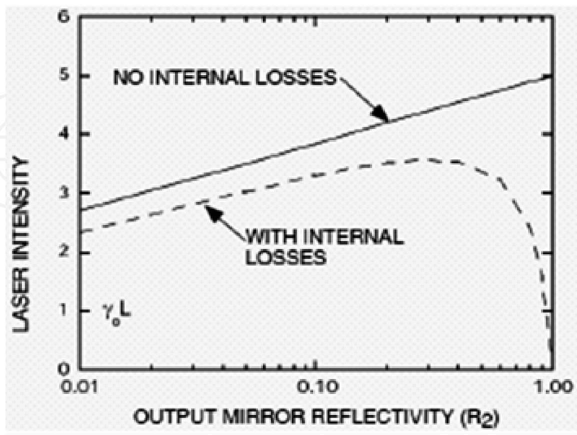

Fig. 24. Theoretical Curve for Output Coupling Reflectance

There must be an optimum reflectivity of an output coupler at which the radiant output power will be a maximum. This part reports the variation of output power as a function of output coupler reflectivity and active medium length for a V-fold diffusion cooled CO_2 gas laser. A relationship (Eq.26) is used for optimum transmission coefficient of the output couplers to verify experimental measurements.

$$T_{opt} = \left(g_0 La\right)^{1/2}\left[1-\left(\frac{a}{g_0 L}\right)^{1/2}\right] \tag{26}$$

In the development of a high-power CW CO_2 laser; it is a design challenge to reach high output power simultaneously with good beam quality. The problem becomes stringent in multi-fold diffusion cooled CO_2 lasers that uses a stable resonator configuration, where many meters of resonator length are required to generate a few kilowatts of energy, owing to the low aspect ratio between the discharge diameter and the discharge length necessary to obtain a mono mode beam. A laser will operate satisfactorily with many possible combinations of output coupler reflectivity, provided that the gain in a single pass through the amplifier is sufficiently large to equal or exceed the mirror transmission losses (or other losses).

Experiment is carried out to test the performance of the laser for different reflectivity of output couplers and different active medium length. We used a concave-concave resonator; consist of gold coated copper mirror and a concave ZnSe output coupler of 5 meter radius of curvature each. In our experimental set-up, we have taken five different output couplers of reflectivity 5, 10, 17, 50 and 60% and corresponding output power was measured for 1.5, 3.0, 4.5 and 6.0 meter active medium length. These results are plotted for active medium length v/s output power for different output couplers (Fig.25) & reflectivity v/s output power for above stated active medium lengths (Fig.26). Output power of diffusion cooled laser is proportional to active medium length but we can see (Fig.25) that as the length increases power increases but the rate of increase of output power decreases. This is because of diffraction losses increases with increase of length. For theoretical calculation, in order to estimate g_0 and a in our laser, we have used the Eq.25 of laser power in a V-fold CO_2 laser. Substituting the value of laser power for three different reflectivity of the output coupler, the three unknowns i.e. $g_0, a \& I_s$ are calculated theoretically. Thus using these values in expression (Eq.26), the T_{opt} is estimated to be 66% for 6 meter active medium length theoretically. Experimentally also we have observed that laser output power is 209 watts for 83% transmissivity and 150 watts for 50% transmissivity. From the above data we can predict that the optimum value of transmissivity lies somewhere between 50 & 83%.

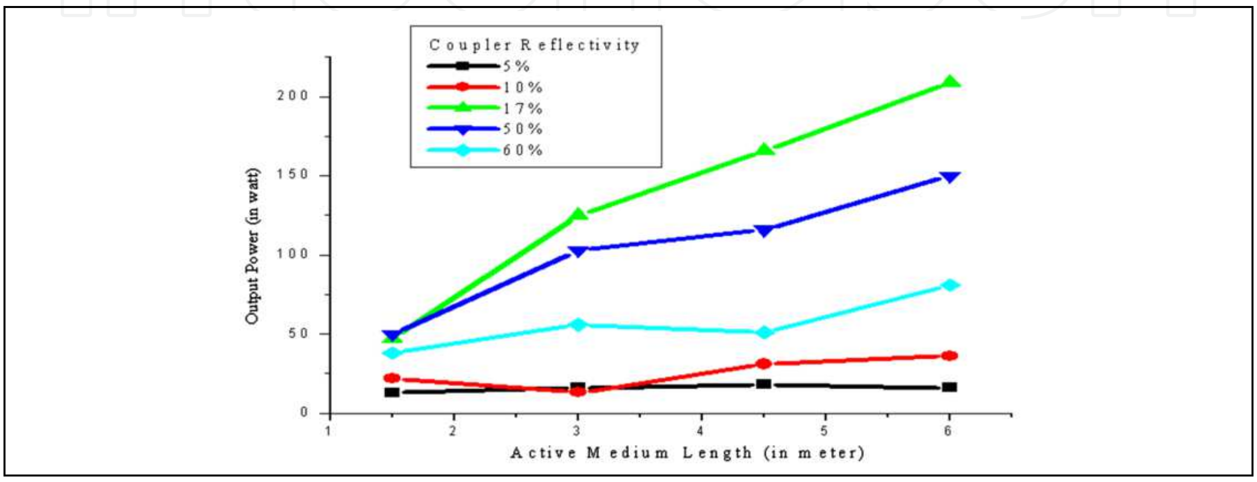

Fig. 25. Experimental Curve: Output Power v/s Active Medium Length

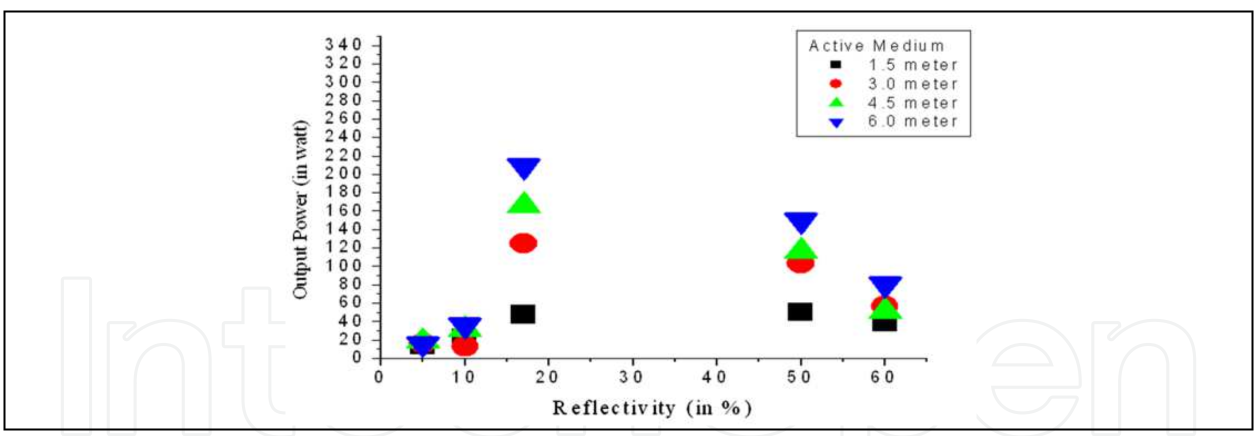

Fig. 26. Experimental Curve: Output Power v/s Reflectivity

4. Safety precautions

Some general considerations when working with V-fold CO_2 lasers are as follows:

- Provide a beam stop capable of safely absorbing this power on a continuous basis.
- Clearly mark and if possible, block off access to the path of the beam.
- Reflected beams may have nearly as much power as the original and are just as dangerous. Although many common materials will block 10.6 µm, specular surfaces will reflect it quite well.

- Make sure that everyone in the vicinity of the laser or anywhere the beam (or its reflection) may be is fully aware of the safety issues and has proper eyewear.
- Provide visible and unambiguous indications that the laser is powered and the beam is on.
- A kill switch is essential and should be located far enough from the laser tube so that it is accessible in an emergency even if a total meltdown is in progress.
- For flowing gas lasers, provide adequate ventilation. While the lasing gasses (helium, nitrogen, and carbon dioxide) are not toxic, and not very much is involved for laser operation, a leak in the gas delivery system could go undetected. CO_2 in particular is heavier than air so it will displace air in an enclosed space which may result in various symptoms from nausea to asphyxiation.
- Where maintenance or repair is involved, be aware of the properties of the specific materials used for the optics and elsewhere. For example, the biohazards of zinc selenide and beryllia.

5. Conclusion

In the present laser, power of 380 Watts from 7.5 m discharge length and maximum 420 W from seven limbs (10.5 meter discharge length) has been achieved. The maximum average power of 50 W/m is obtained from this laser, which is comparable to other diffusion-cooled laser developed till now. Studies have shown that dissociation of CO_2 molecules increases with the increase of no of tube or discharge length. Care has been taken to have a low gas residence time to reduce the deleterious effect of CO_2 dissociation. The electro-optic efficiency of the laser is about 13%.

The power and stability of a laser system is mainly governed by the misalignment sensitivity of the optical resonator. To ensure stable and high power from a laser system misalignment sensitivity has to be known. The experimental results indicate that sensitivity parameter D is a suitable parameter to describe the alignment stability of a resonator.

The output power of a laser that can be extracted depends on the reflectivity/transmission of the output coupler. There must be an optimum reflectivity of an output coupler at which the radiant output power will be a maximum.

According to Rigrod's formula if length increases power reduces, as there are many other parameters, which are not optimized. So power goes on decreases when length increases. Beam size also affects the output power.

6. Acknowledgement

Author is thankful to Sh. Mukesh Jewariya, Sh. Firoz Koser, Sh. D.D. Saha, Sh. M.B. Pote, Sh. S.V. Deshmukh, Sh. A.K. Nath, Sh. Dinesh Nagpure, Sh. Abrat Verma and all other colleagues of Laser and Material Processing Division, RRCAT, who directly or indirectly involve in design and development of this laser. Author is also thankful to Sh. Abhay Kumar (IMA Section) and Sh. Arup Ratan Jana (Accelerator and Beam Physics Lab.).

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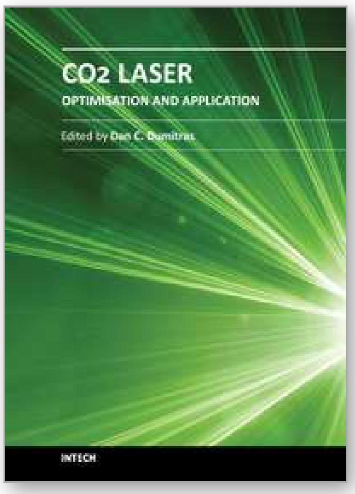

CO2 Laser - Optimisation and Application
Edited by Dr. Dan C. Dumitras

ISBN 978-953-51-0351-6
Hard cover, 436 pages
Publisher InTech
Published online 21, March, 2012
Published in print edition March, 2012

The present book includes several contributions aiming a deeper understanding of the basic processes in the operation of CO2 lasers (lasing on non-traditional bands, frequency stabilization, photoacoustic spectroscopy) and achievement of new systems (CO2 lasers generating ultrashort pulses or high average power, lasers based on diffusion cooled V-fold geometry, transmission of IR radiation through hollow core microstructured fibers). The second part of the book is dedicated to applications in material processing (heat treatment, welding, synthesis of new materials, micro fluidics) and in medicine (clinical applications, dentistry, non-ablative therapy, acceleration of protons for cancer treatment).