Design and Performance of a Sealed CO_2 Laser

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The construction of a sealed, CO_2 gas discharge laser was undertaken as an independent study project. Glass laser tube design as well as clear acrylic housing makes this an excellent demonstrational tool. Sealed operation was characterized in mode, power, warm-up and stability over the period of weeks. Novel design approaches are used for expediency and cost savings and an anomalus turn-on behavior is also discussed.

1. Introduction

The construction of a sealed CO_2 laser was undertaken for several reasons. The CO_2 laser provides an impressive and graphic demonstration of quantum mechanical processes. The laser was constructed out of glass and is contained in an acrylic casing so that all of its functioning components can be observed. The laser simply plugs into a standard A/C outlet and more than 20 Watts of coherent, monochromatic laser radiation is produced, enough to burn paper and wood. Another reason why this was undertaken was because all the supplies, equipment and lab space were readily available; It only took time and inclination to exploit these resources to arrive at a useful device. It was also an achievable project as evidenced by the author's demonstration of a smaller, less complicated flown gas CO_2 laser the previous semester in a junior physics lab course. Most importantly, the author simply wanted to have a relatively compact, portable laser for future work, which did not require bulky vacuum equipment or gas cylinders.

2. The CO_2 Laser

2.1 The Resonator

The resonator used in confocal-confocal. Since the optics used in this project were donated from a company, the author did not have a choice of mirror curvature. Also, since the higher power and not best quality mode was desirable, particular attention was not paid to resonator optimization. With the High Reflectance mirror radius of curvature of 2.685 m and the Output Coupler radius of curvature of 5.072 m, the resonator is in the stable regime at .66 as determined by the stability relation

$$0 \le (1 - \frac{L}{R_1}) - (1 - \frac{L}{R_2}) \le 1$$

Where L is the cavity length, here 65 cm, and R is the radius of curvature of the mirror.

2.2 Energy Transfer in the Discharge

The most commonly observed lasing transitions in the CO_2 molecule, barring the use of any frequency tuning mechanisms, are the from the CO_2 asymmetric stretch transition from the (00° 1) to the (10° 0) symmetric state at 10.6, μ and to the (02° 0) bending state at 9.6 μ, using the notation (V_1V_2 V_3) where V_1 refers to the symmetric stretch quantum number, V_2 refers to the bending quantum number and V_3 refers to the asymmetric stretch quantum number.

There are literally dozens of other laser transitions [6] which can be exploited by employing and intracavity grating. In a CO_2 laser, lasing of one vibrational transition precludes efficient lasing of another so that lasing lines 'hop' from one to another, depending on instantaneous gain medium conditions. Any singly possible laser line can be forced though the use of an intracavity grating. Rotational structure, having energies clustered very close to one another, may exist at any time.

Nonradiative decay to short-lived lower lying states followed by nonradiative decay to the ground state follows. N_2 is added to the laser gas to more efficiently transfer energy from electron impact to the CO_2 upper vibrational laser level. The glow discharge is very effective at vibrationally exciting the N_2 molecule with up to 50% of the population being vibrationally excited [7], most of the species excited to a useful collisional energy. Since N_2 is a homonuclear molecule, dipole radiative dexcitation is forbidden which allows for long lived vibrational states, and therefore, higher probability for collisional interaction with CO_2. Dexcitation is only accomplished collisionally with the wall or other gas constituents, the most beneficial of which is the CO_2 molecule. The N_2 V=1 state is only 18 cm^{-1} (2.2×10^{-3} eV) from the upper laser level of the CO_2 molecule. Note that N_2 has only two atoms, and therefore can have only one vibrational mode. This makes resonant energy transfer between N_2 and CO_2 likely. This energy is much smaller than average kinetic energy of the molecules so vibrational energy can easily be supplied to the CO_2 molecules. Energy transfer occurs from vibrational values up to V=4 in N_2 because the ensuing anharmonicity of these states due to bond stretching is still well below the average molecular kinetic energy [7]. CO is isoeletronic with N_2 and also has vibrational levels easily excited in the glow discharge.

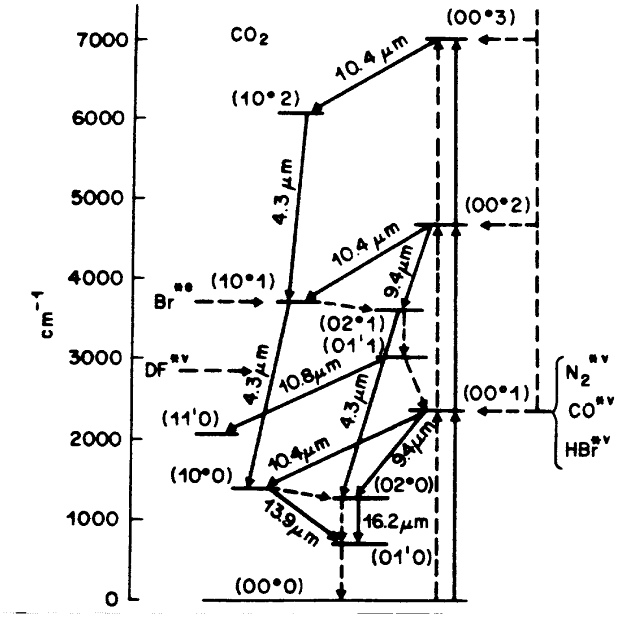

Fig. 1. Highly simplified energy level diagram of the CO_2 laser showing most common lasing transitions and vibrational energy transfer modes.

Figure 1. details the more common energy transfer routes in the CO_2 laser. Excited N_2 and CO transfer vibrational energy though collision to CO_2 exciting any of a number of asymmetric stretch modes. Thermal poisoning can occur, which is a build up of lower lasing level populations in CO_2. This results in a reduction in laser power due to a “clogging” of the path from upper lasing level to ground state, where the CO_2 upper lasing level is most efficiently populated through collisions with N_2. These lower levels are cooled by the addition of He to the gas mix. He energy levels are relatively high, about 20 eV, so that for typical electron energies in the glow discharge of 1 to 3 eV, the discharge is not significantly affected by the existence of He [7]. Only a small amount of energy is lost from the discharge due to inelastic collisions with He and subsequent collisions with the walls. Thermal conductivity in gases is independent of pressure and since thermal conductivity of He is roughly six times that of CO_2 and N_2, He makes an efficient transporter of waste heat to the walls of the discharge tube. The efficiency of heat transfer resulting from the addition of he to the mixture allow for a higher discharge current before radiation saturation [7].

CO may also be added to the laser mix to improve efficiency, but does not transfer vibrational energy as efficiently as N_2 due to a difference between the CO V=1 level and CO_2 upper lasing level of 170 cm^{-1}. CO also has a dipole moment which allows for radiative decay. CO is a component in the dissociation equilibrium so when using added CO with CO oxidation catalysts, larger concentrations of CO may affect CO_2 concentrations. Even with these drawbacks, CO still adds to more efficient CO_2 vibrational excitation than electron impact alone.

H_2O can be added as a heat transfer enhancer but is less efficient at cooling than He. H_2O, in small concentrations, also has the beneficial side effect of homogeneous catalytic effects and effectively depopulates the upper lasing levels of CO_2. The optimum concentration of H_2O in the laser gas has been shown to be a function of the laser bore diameter[7].

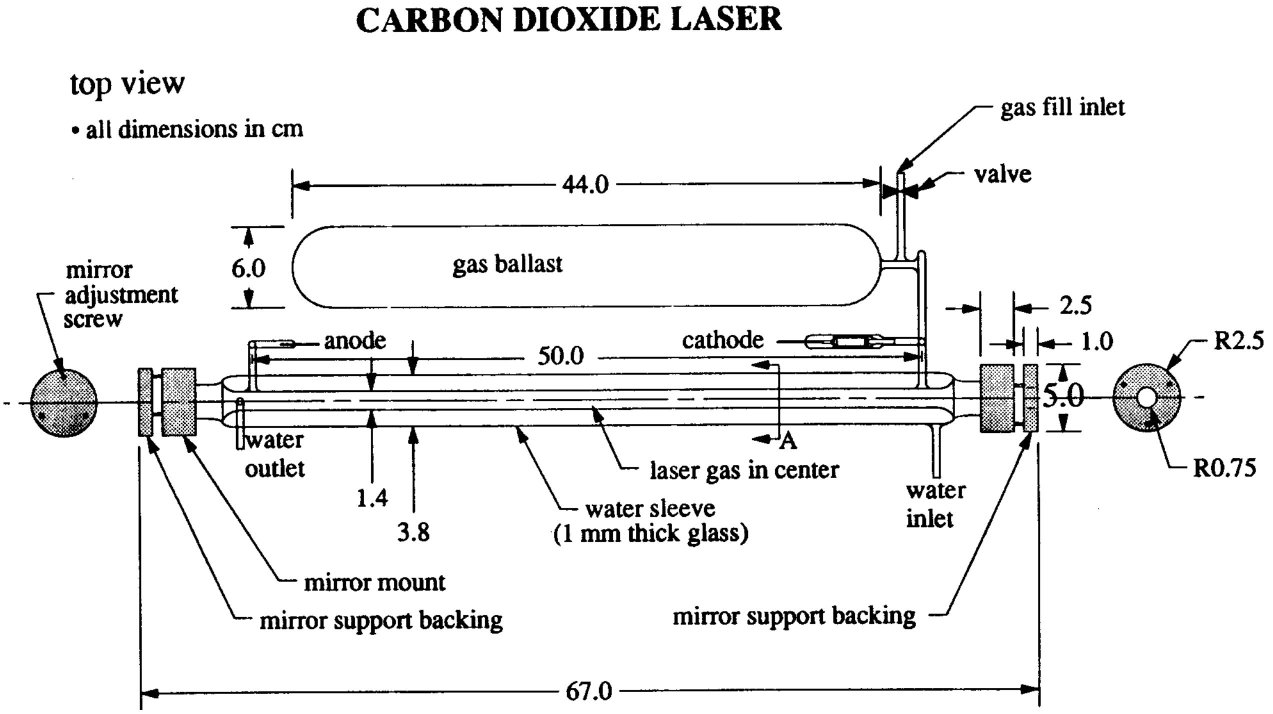

Fig. 2. Laser design.

Xe may also be added to a laser mixture to effectively cool the electron temperature of the discharge at a given current, thereby reducing the amount of electron impact dissociation of CO_2. The prohibitive cost of laboratory grade Xe prevented the investigator from utilizing it.

3. Construction

3.1 The Laser Tube

The laser is a sealed, DC discharge type with attached ballast tank for long life. The silver-copper cathode design was used to reduce the amount of gas consumption by sputter pumping. Construction of the laser was kept simple to reduce expense and excessive consumption of time. The laser is constructed of Pyrex, fabricated on the Boulder Campus by the chemistry department's glass blower. See Fig. 2.

The design incorporates a laser bore nested in a water cooling jacket, with a feed through the water jacket so that the discharge can go to an external cathode and anode. having the external electrodes lower than the axis of the laser bore reduces the possibility that sputtering or oxidation products at the electrodes will contaminate the optics. This becomes an important consideration when working with CO_2 lasers as intracavity power densities, even in a resonator of this design, can easily exceed 100 Watts/cm^2, readily causing thermal damage on the surface of an optic should a small piece of contaminant land on it.

A glass vacuum valve is attached for evacuation and filling. Water inlet and outlets are positioned so that air bubbles which from inside the water jacket are ejected as they rise to the top of the tube. Without this design, air buildup inside the jacket would create a radial temperature differential, detuning the resonator and/or thermally poisoning the gain medium.

3.2 Mirror mounts

Mirror mounts were tuned out of scrap rolled aluminum from the Physics Instrument Shop. The mounts are of a simple set versatile design incorporating an O-ring which provides both the vacuum seal and the restoring force for the mirror adjustment. The finished pieces were sanded with a very fine grained sand paper and then polished to reduce surface area in the vacuum, thereby reducing the potential of laser gas poisoning due to adsorbed contaminants. See Fig. 3. Since the travel on the mirror for optical adjustments is small, motion of the mirror on the O-ring for mirror adjustment doesn't break the vacuum seal.

Both the high reflectance mirror and the output coupler have mirror mount backings with depression in them to hold the mirror near the center of the optical axis during assembly. With extra room between the glass end of the laser and the mirror mount shoulder, the mount can be aligned coaxially to the laser bore during assembly and the glass blowing need not obey strict tolerances. The mirror mounts need not be mounted exactly perpendicular to the laser bore since even relatively gross alignments can be accomplished with the O-ring backing plate design.

3.3 Assembly

The mirror mounts were attached to the glass laser tube with the aid of a mandrel which aligned the mirror mount coaxially with the optical axis. The mandrel was simply a piece of Delrin turned so that one end fit snug into the center of the mirror mount and the other end fit snug into the laser bore. This alignment procedure was necessary as tight tolerances were not requested for the glass work in order to avoid excessive cost.

The laser tube was tipped on end and the mirror mount brought up from beneath with a simple lab jacket to meet the laser tube end. After the mandrel had aligned the axis correctly, it was removed for the next step. Apiezon W vacuum sealing wax was broken into small chips and dropped along the inside edge of the mirror mount, between the glass and the aluminum shoulder. See figure A. A heat gun was used to warm the mirror mount so that the sealing was melted and flowed to form a positive vacuum seal between the mount and tube. While Apiezon W makes a suitable clean vacuum seal, it does not have adequate structural strength for this application so common five minute epoxy was added on top of the wax to enhance mechanical integrity of the mount.

Alignment of the laser using a Helium neon (HeNe) laser required the mounting of the laser on an optical bench. Since the laser itself had been built into an acrylic box to protect it from breakage, and the user from electrical hazards, the entire box was mounted on an optical rail. The laser was secured in an acrylic box, on acrylic mounts lined with Sorbithane shock absorbing material. Aluminum strips were use to secure the ballast tank to its mounts while acrylic pieces screwed into the laser mounts secure the laser tube. For alignment of the laser resonator, two alignment mandrels were again made each fitting snug in the ends of the laser bore, but easily passing though the mirror mount. Each had a 1 mm hole drilled in the center so that coaxial alignment of the HeNe alignment laser with the CO_2 resonator was assured.

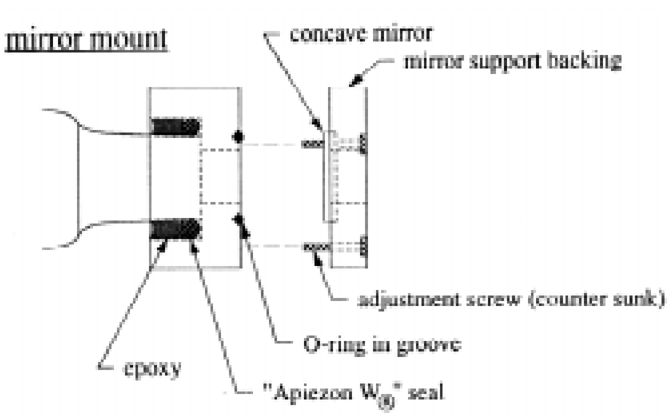

Fig. 3 Mirror mount detail.

After the HeNe beam was aligned with the CO_2 laser bore, the mandrels were removed and the rear high reflector (HR) mirror was mounted and aligned so that the beam was reflected back into the HeNe aperture. The output coupler (OC) was then mounted then aligned to the HR by eye, since trying to make sense of the multiple reflections of the HeNe beam was futile. A bright, quartz halogen light was directed into the OC so that the image of the light was visible on the HR when looking down the bore thought the OC. The OC was then adjusted so that the light source created a "hall of mirrors" effect between the HR and OC. With a concave-concave resonator and such a high gain medium as CO_2, this type alignment procedure is more than adequate. A simple evacuation and fill system was assembled using polyflo tubing and swagelock fitting using plastic ferrules. Industry standard CO_2 laser gas mix consisting of 4.5% CO_2, 14% N_2 and balance He was used for the fill.

3.4 The Cathode

Cathode material selection in a sealed DC laser is crucial. The abundance of free, ionized oxygen in the discharge rules out any material which readily oxidize like tungsten, nickel, aluminum and stainless steels. The abundance of CO in the discharge also limits many otherwise suitable materials since many materials from gaseous carbonyls, removing CO_2, exposing fresh cathode surfaces for oxidation, and transporting metal compounds onto the optics. The "Hochuli cathode" was found though a literature search on cathode materials conducted earlier by the author. Professor Urs Hochuli generously donated cathodes to the project. The Hochuli cathode was designed specifically for long life sealed CO_2 lasers but was only tested at much lower currents, of about 5 mA. [3] The Hochuli cathode is made of Ag and Cu in a matrix which is internally oxidized. This oxygen equilibrium within the cathode allows for the Ag and Cu to not consume any oxygen from the discharge, thereby eliminating the cathode as a chemical sink of oxygen. The materials in the cathode are not readily transported in the discharge, so mirror contamination is no a problem. The cathode is in the familiar hollow cathode design so sputter pumping of gas through physisorption is less of a problem, although this may be the ultimate source of gas consumption by the cathode.

A glass plasma limiting sheath is incorporated in the cathode design to prevent the glow from forming on the outside of the cathode which would render the hollow cathode design useless. The discharge is physically channeled to the inside of the cathode. The simple tungsten anode pin used as the anode does not suffer from high momentum impacting ions and does not have glow forming over its surface so oxidation and sputtering is not a major issue there. It is the cathode which experiences severe ion bombardment in the process of secondary electron emission, which is the mechanism whereby the cold cathode liberates electrons. [4]

3.5 Power Supply

The power supply for the laser of the simplest design. A 15 kV, 60mA neon sign transformer is used to obtain the high voltage. The output of this is connected to a high voltage bridge rectifier. Since high voltage bridge rectifiers are expensive and often difficult to find, the bridge used here was assembled out of several high voltage diodes in series, on each leg of the bridge. The output of the bridge is connected to a high voltage filtering capacitor which has a 10 MΩ bleeder resistor across its terminals. Since the output of the transformer is center tap grounded, neither end can be tied to ground. Consequently, while in operation, all components of the high voltage end of the power supply are floating with respect to building ground. 200 kΩ of high power ballast resistance is placed in series with the discharge to limit tube current. The tube current is varied rather crudely, by simply using a variac to adjust input voltage to the transformer.

4. Laser Operation

After the laser was assembled and aligned, it was connected to a sink and drain for cooling water. A closed circuit heat exchanger will be built to make the laser self contained. The laser head and power supply had been mounted in separate acrylic boxes for safety purposes. An open-ended mercury manometer was use to measure the pressure of the gas fill. Due to daily fluctuations of atmospheric pressure, the manometer had to be set to the days' pressure. The laser and fill system was roughed out until it settled to a lowest value. This lowest value was take to be 0 Torr since a good mechanical pump can pump down to at least .1 Torr [5]. Due to this approximation, the laser tube pressure is taken to be within one Torr of measured value.

After evacuation, a leak-proof system was verified to first order by simply closing off the system to the pump and watching the pressure gauge. After several days no appreciable leaks were detected. The system was filled to a nominal pressure of 30 Torr to attempt lasing. Lasing was obtained but lasted for less than a second. This anomaly is believed to now be understood and will be discussed later. Lasing action is now repeatably attainable. Output power data were taken at varying pressures and currents.

Mode burns (laser burn patterns in cardboard) were taken in various alignments of the resonator and a burn for the best power alignment was also taken. Due to laser powers exceeding the capabilities of the commercial meter available, power was measured by a simple thermocouple pair. Laser light is absorbed by a small piece of black anodized aluminum which absorbs 10 μ photons very well. This small piece is mounted against a larger heat sink to dissipate the laser power. One junction is placed on the target piece and another reference junction is placed on the heat sink. The millivolt output of the thermocouple junctions in series is monitored as an indicator of input laser power. This meter was calibrated using a commercial laser power meter.

4.1 Performance

The data in Table 1. were taken over tube current and gas pressure before the laser tube had come to complete equilibrium from the turn-on phenomenon and without optimizing the resonator each time. Therefore, the peak power obtained in the data does not correspond to the highest power obtained of 22 Watts. It is quite clear from the data, however, that an optimum pressure and current does exist for maximum power and efficiency. The optimum pressure was arrived at empirically to be 30 Torr. The optimum current was 9.2 mA.

Current *(ma)*	*Voltage* *(kV)*	*Power* *(W)*	*Efficiency*
20 Torr			
5.3	9.76	1.1	.021
5.7	9.59	.93	.017
6.1	9.55	.22	.004
6.5	9.36	.99	.016
24 Torr			
6.9	10.46	1.42	.020
6.5	10.44	1.75	.026
7.0	10.29	2.07	.029
7.6	10.15	1.26	.016
7.8	10.12	.99	.012
8.1	10.03	.17	.002
26 Torr			
7.4	10.57	2.94	.037
7.7	10.78	3.49	.044
8.2	10.45	2.62	.031
8.6	10.35	2.18	.024
8.9	10.71	1.75	.018
28 Torr			
8.4	11.13	9.80	.015
8.8	11.03	7.62	.079
30 Torr			
9.2	11.40	11.43	.109
8.9	11.37	10.34	.102
8.8	11.28	9.53	.096
9.1	11.25	5.45	.053
9.4	11.08	.99	.009
32 Torr			
9.0	11.41	3.75	.037
9.1	11.31	3.43	.033
9.3	11.17	1.64	.016
9.7	11.08	.55	.005

After cycling the laser power and allowing for mixing as described earlier, output power was measured as a function of time. Power fluctuations at turn on were found to be due to mode changes. It appears that as the laser warms up, the resonator alignment changes. This was verified by simply tweaking the mirrors for the lowest order mode while it is warming up, then watching that mode be detuned. The mode could be brought back by simply adjusting the resonator again. Thermal detuning appears to be a plausible explanation since the glass tubes which feed the discharge out the laser bore go through the walls of the tube which make up the laser resonator. As these feeds heat up on the outside due to no water cooling over them, they expand and create a wedging in the resonator structure. The laser can be tuned for best mode after stabilizing. If the laser is allowed to cool, then is turned back and allowed to restabilize, the good mode that was achieved previously will come back. The supports the idea of thermal detuning. Power performance as a function of time after turn on is given in Figure 4. Monitoring the mode periodically during the first few minutes at turn on indicates that the power fluctuations are due to the cavity tuning through different modes. In the data shown, the power fluctuations settle down after about 25 minutes and settle to something other than the best power mode.

Further measurement has shown this settling behavior to consistently be the case. The spikes in the data are artifacts of a noisy chart recorder. The thermal inertia of the meter does not allow for such a fast response so the spikes cannot be real. The ordinate is one minute per division. Initial variation of 22% of the peak power is seen as the cavity tunes through different modes and the highest power attained is 16.5 Watts. The resonator does not settle to the highest power mode. Vertical sensitivity is 1.17 Watts/division.

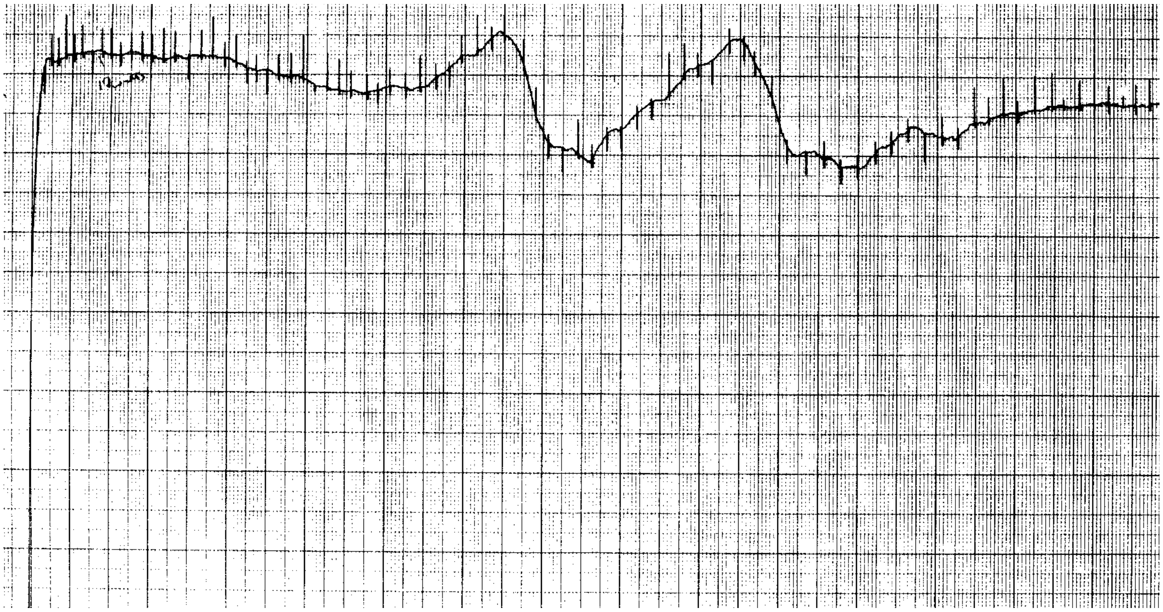

Fig. 4. Output power as a function of time. Vertical axis is 1.17W/div, horizontal is 1min/div.

Typical best power ‘donut’ or ‘bulls eye’ laser modes, (TEM_{01}* or TEM_{10}) are shown as contrast enhanced burns in thermally sensitive fax paper and plain white cardboard.

Other mode burns in cardboard, taken during cycling of the laser during warm up, over the period of about one minutes, shown evolving symmetries corresponding to lower power.

5. Discussion

The anomaly mentioned earlier, whereupon a fresh fill, measurable laser power lasted less than a second, is believed to be due to oxygen specie migration between the laser bore and the ballast tank. This mechanism is believed to occur as follows: Upon initial filling, the gas in the laser bore and ballast tank is uniformly a laser mix of 18.7:2.4:1 ($He:N_2:CO_2$). When the discharge is turned on, many other species are formed due to dissociation of CO_2 and CO and O and the subsequent formation of NO_x and other compounds. At this point, the laser bore has an abundance of NO_x and other species and the ballast tank does not. Diffusive processes drive these byproducts from the laser bore to the ballast tank. Indeed, the characteristic green glow of NO_x + O combination fluorescence can be seen streaming out of the cathode section towards the ballast tank. Also, a characteristic white discharge in the laser bore indicates a CO rich medium, which would be the case if free atomic oxygen were leaving the bore. In low current discharges of CO_2 laser mix, the pinkish emission bands of the N_2 fourth positive system are seen which are due to $D^3\Sigma_u^+ - B^3\Pi_g$ transitions [2]. If a white discharge is seen, dissociation is dominating the discharge. The length and brightness of the exiting fluorescence stream was observed to be proportional to the discharge current.

A rapid migration of oxygen containing species out of the laser bore makes for a sink of CO_2 in the ballast tank and the laser then becomes lean in its lasing medium. If this migration hypothesis is correct, we would expect that the laser power should last longer upon initial turn on if dissociation products are allowed to come to an equilibrium between laser bore and ballast tank. This is indeed the case. After repeatedly turning on the laser then allowing diffusion time, performed over a period of a couple days, power does begin to remain consistent at turn on. The maximum power attainable does improve after several days of turning the laser on and off and allowing it to sit. Ultimately, a laser power of 22 Watts (44 Watts/meter) has been achieve this way, with relatively stable output power lasting for over and hours worth of operation.

6. Conclusion

The original objective of building a sealed, DC CO_2 laser was accomplished with satisfactory laser performance. The anomalous turn-on effect delayed progress since many other possible problems were investigated first such as a leaky system, water contamination, dirty optics etc. but is now believed to be understood. The laser has yielded powers up to 22 Watts and has repeatable power performance, on a single fill, on the order of several weeks. The best mode attainable for this resonator design is a donut mode or a $TEM_{01}*$ mode.

7. Further Investigations

It is recommended that, should further research be possible on this laser design, the oxygen transportation phenomenon be more thoroughly studied. More detailed analysis will most likely require the use of a mass spectrometer for time resolved characterization of the gases in the laser bore and the ballast tank after initial turn-on. Improvements on the resonator design with respect to thermal stability and warm up cycles is desirable. Recent work in Au intracavity catalysts has been said to improve laser performance to powers in excess of 100W/m. Further studies in intracavity catalysts such as Pt/Pd on SnO_2 or Rh on SnO_2 may prove fruitful.

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Sputtered Au catalyst was added to the bore several years after construction, allowing higher tube currents, and output powers exceeding 50 Watts.

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