A PARAMETRIC STUDY OF A TRANSVERSE GAS FLOW
TEA CO₂ LASER

by

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The University of British Columbia
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ABSTRACT

A transverse gas flow TEA CO₂ laser has been constructed and the use of a perforated hollow rod to serve simultaneously as the cathode of the discharge and the gas inlet vessel was successfully demonstrated.

The electrical efficiency of the laser is typically 3% with peak powers of 40 kw being emitted on the P(20), P(18) and P(16) lines of the CO₂ spectrum. A parametric study of peak power, gas pressure, gas composition, time delay of the laser pulse and the interdependence of these quantities was undertaken.
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Chapter 1

INTRODUCTION

This thesis describes a parametric study of a CO₂ laser carried out to acquire knowledge and experience in the operation of molecular lasers and infrared detectors, not previously studied in this laboratory. In order to obtain the highest flexibility in the application of such lasers for future use, it was the aim to design a laser cavity which would allow the study of electrical as well as chemical activation and approach with modest means as high average laser powers as possible.

1.1 Properties of CO₂ Lasers

Infrared lasers have attracted strong interest in communications, plasma physics and spectroscopy for several reasons: The efficiency is high (theoretical maximum of 41%*) because the energy of the upper laser

*Quantum efficiency of 00°1-02°0 transition is 41%.
level is only ~ 1/3 ev above the ground level. The energy
difference between the upper laser level (00°1) and the
lower laser level (02°0) is also rather small so the wave-
length (10.6μ) falls in the 8-13μ region where there is
an atmospheric window making the CO₂ laser attractive for
communications purposes. The long wavelength of infrared
radiation is also desirable and beneficial for inter-
erferometry in laser scattering experiments and the produc-
tion of plasmas.

Laser emission from CO₂ has been obtained in
both continuous wave (cw) and pulsed operation. The popu-
lation inversion necessary for laser action can be obtained
by electron impact (electrical discharges), supersonic
expansion (Laval nozzles) and resonant energy transfer
(N₂ or DF).

For the case of electron impact the parameter
E/N governs the efficiency of the laser [1,2]. E/N is
proportional to the energy electrons acquire, on the
average, between two collisions in an electric field E,
with neutral particle density N. In theory E/N may be
optimized for any electrically excited CO₂ laser but in
practice this has only been achieved in TEA (Transversely
Exited at Atmospheric Pressures) lasers. Such a TEA laser
configuration consists of a multispark discharge at right
angles to the laser resonator axis, as will be described later in more detail. This type of laser has been used to obtain laser action in various chemicals by chemical reactions [4]-[7]. The TEA laser stands in another respect at the end of the present development of CO₂ lasers.

The first CO₂ lasers operated at pressures of several torr and used r.f. or a.c. excitation between electrodes at opposite ends of a glow discharge tube. If the laser had a flowing gas system the input and exhaust ports were invariably at opposite ends of the tube so the gas flow was longitudinal, Figure 1 (a). For low capacity pumping systems this arrangement had two definite disadvantages: Dissociation products formed in the discharge were not removed quickly enough [8,9] and the heating of the gas itself reduces the gain of the laser [10].

TEA arrangements combine simplicity in construction and operation and the flexibility of being able to obtain electrical as well as chemical activation. However, in most devices with longitudinal flow the gas exchange rate is not very high and one cannot expect a high repetition rate or high average powers, Figure 1 (b). A device by Ahlborn et al. [7] with transverse gas flow through the ground electrode improves this situation, but only at the cost of a rather complicated construction, Figure 1 (c).
Figure 1. Gas Flow in CO₂ Lasers.

(a) longitudinal flow, longitudinal discharge
(b) longitudinal flow, transverse discharge
(c) transverse flow, transverse discharge
(d) simplified version of (c) tested in this thesis
The aim of this thesis was to design a TEA laser with transverse gas flow but with a greatly simplified construction: eliminating the 200 gas inlet tubes of reference [7] and replacing them by a hollow ground bar with very small gas inlet holes opposite the pin electrodes, Figure 1 (d), the contention being that the exciting or activating transverse sparks would issue exactly from the holes in the ground electrode and hence guarantee that the replacement gas was flowing exactly into the region where it was needed.

1.2 Arrangement of Thesis

The organization of this thesis reflects the purpose of the work: Test a new electrode configuration, design a laser and study its performance.

Chapter 2 discusses preliminary experiments with hollow ground electrodes and gives the laser design derived from these initial experiments.

In order to appreciate the performance of this newly designed laser, we have summarized in Chapter 3 some of the standard knowledge about CO₂ lasers, which may be useful for someone just getting interested in this field and we try to show the limits of the present understanding of this laser.
Chapter 4 begins with typical experimental "tricks of the trade" and procedures to operate the laser and then gives the parametric study of the device operated as a transversely pulsed CO$_2$ laser.

Chapter 5 describes attempts to obtain chemical reactions in the cavity and Chapter 6 discusses conclusions and suggestions for the possible improvement of the device.

Many experimental details* are contained in the appendices in order not to load the main body of the thesis with too much detail.

*which are standard knowledge but may save a future investigator much time.
Chapter 2

ELECTRODE DESIGN AND LASER CONSTRUCTION

2.1 Electrode Design

It is attempted in this work to construct a TEA laser with transverse gas flow using the idea of injecting the gas through holes in a hollow ground bar directly into the spark channels. To ascertain the feasibility of this idea a study of the behaviour of spark channels created by a discharge between a chain of resistor pins and a hollow ground rod with many holes was undertaken in a small scale experiment. For this purpose the test chamber shown in Figure 2 was constructed.

The chamber was made entirely of lucite and enclosed an evacuated cylindrical region 7 cm high and 12 cm in diameter. On the top plate of the chamber in two staggered rows of 10 were place 20, 1 kΩ each, resistors. The interelectrode distance, Δ (see Figure 2), was fixed at 0.5 cm for each ground rod constructed and the resistors were vacuum sealed using Apezion Q-compound.
Figure 2. Cross-Section Through Cylindrical Test Chamber and Schematic View of Discharge Circuit.
The hollow ground bar to be tested was placed inside the chamber affixed to the bottom plate and aligned parallel to the resistor pins. The cathode-anode separation, $d$, was fixed at 2.54 cm for each ground rod tested. Twenty small holes were made in the top of the ground bar, one opposite each resistor pin. The purpose of these holes was two-fold: to localize the arcs and inject the gas flow. Since a sharp edge has a small radius of curvature, large electric field strengths are preferentially created at the lip of the holes and thus the discharge from the legs of the resistors would strike the edges of the holes, as shown in Figure 2. At the same time it is possible to have a flow of gas, in this case air, from the atmosphere, through the holes in the hollow ground bar, into the spark channels after which it is evacuated from the chamber through a hole in the top plate by a mechanical forepump.

Photographs of the discharge were taken using a polaroid Land camera with a close-up lens and polaroid film type 47, 3000 speed. The photos were qualitatively analyzed for uniformity and reproducibility of the discharge pattern. In addition the repetition rate was measured using a Rogowski coil and a type 551 Tektronix dual-beam oscilloscope. A photograph of a typical discharge pattern is shown in Figure 3.
Two different hollow grounding rods were tested. The first was constructed of 1/32" thick copper sheet, 10 cm long, which was bent and soldered into a triangular cross-section. The holes to serve as gas inlets were made by simply puncturing the copper sheet with a nail, from the inside, so that the resulting sharp edges were directed towards the resistor pins. The second rod was a cylindrical copper pipe (3/4" i.d., 7/8" o.d.), also 10 cm long, with 20 holes made with #65 drill bit (0.035").

The spark channels produced with these electrodes did indeed preferentially strike the lips of the holes in the ground bar but the spark channels had some tendency to interfere with one another. This was probably due to some irregularities in the spacing of the resistor pins and the small inter-electrode distance, \( \Delta \), used. Since this interference was more noticeable with the more complicated triangularly shaped ground bar, all further observations made here were carried out with the cylindrically shaped ground bar, which is shown in Figure 2.
The spark channels were photographed at pressures of .2, 60 and 100 torr, as measured by the Speedivac vacuum gauge, with and without the air flowing. There appeared to be no differences in the symmetry of the spark channels with the air static and flowing at the pressures used. The effect of air pressure though was quite pronounced. At pressures of .2 torr the entire region between the cathode and anode is ionized and there are no distinct spark channels. For pressures of 60 and 100 torr individual sparks are evident with those of 100 torr being more uniform. At higher pressures the number of spark channels decreases until there is a single arc and finally no air breakdown at all.

For these experiments we used the breakdown voltages of 14, 17 and 24 kv. The larger the voltage the higher the pressure attainable before the air ceases to break down. At 24 kv the highest pressure measured was 160 torr. The negative d.c. potential used to break down the air was applied to the resistor chain and also to the hollow ground rod. However, this only affected the discharge pattern at low pressures. When the high voltage was applied to the resistor chain each resistor leg developed a corona whereas when the hollow rod was connected to the high voltage it exhibited 3 to 4 hot spots on its surface.
The values of $R$ and $C$ used in the discharging circuit were also varied. Resistances of 10 and 20 $\text{M}\Omega$ and capacitances of 5 and 0.5 $\text{nF}$ were used. These variations of $R$ and $C$ did not affect the spark channel patterns but changed the discharge repetition rate. Since the spark gap was not externally triggered and the discharge time $<<$ the charging time, the repetition rate is given by:

$$f = 1 \left\{ \frac{RC}{\ln \left( 1 - \frac{V_{S.G.}}{V_0} \right)} \right\}^{-1}, \quad (2.1)$$

where: $V_{S.G.} = \text{breakdown voltage of spark gap.}$

$V_0 = \text{power supply voltage.}$

The maximum repetition obtained was 260 pulses/sec. The reproducibility of the discharge up to the highest repetition rate was verified by rotating the camera quickly with the shutter open. This is a rather primitive smear camera technique but adequate for our purposes. The photograph shown in Figure 4 was obtained in this fashion.
2.2 Laser Construction

The preliminary studies of multi-spark discharges led to the following conclusions:

1. Holes in the hollow ground bar localized the spark channels quite well, with and without transverse gas flow.

2. The hollow ground rod may be used as cathode or anode at pressures above 60 torr. At lower pressures the bar develops only a few spots if operated as the anode.

3. The discharge pattern is reproducible at repetition rates of at least 260 Hz.

Encouraged by these results we designed a TEA laser with a perforated hollow bar electrode in an otherwise standard arrangement.

2.2.1 Reaction tube.

A lucite tube (2.5" i.d., 3.0" o.d.) 1.2 m long was used to contain the laser's active medium. Flanges,
also made of lucite, were cemented to each end of the tube. Potassium chloride \((\text{KCl})\) windows \((2" \phi)\) were placed on Brewster angle mounted supports at each end of the tube and were O-ring sealed by the pressure differential between the atmosphere and the gas mixture in the tube. To feed gas into the tube a brass coupling was attached to one end (see Figure 5).

To ensure mechanical stability the reaction tube was secured to a 2.13 m long steel I-beam which was bolted to a 2.5 m long steel frame. This arrangement proved to be quite adequate.

2.2.2 Electrodes.

The anode of the discharge is composed of 200-1\(\Omega\)-1\(w\) Allan Bradley resistors (they last longer!) connected in parallel and mounted in two staggered rows of 100 on the top of the reaction tube. The resistor legs protrude into the reaction tube through holes \((\#53 \text{ drill bit})\) spaced 5 mm apart and are vacuum sealed with Silastic TRV cement and Apezion Q-compound.

Using the results of our preliminary studies a copper rod \((3/4" \text{ i.d.}, 7/8" \text{ o.d.})\) 1.14 m long with 200 holes \((0.01" \phi)\) at intervals of 5 mm was used as the cathode. The rod was aligned parallel to the resistors pins and adjusted so the resistor legs were opposite the holes in
Figure 5. Brewester Angle Mount and Gas Inlet Coupling.
the copper rod. The rod is electrically connected to ground through the brass coupling used to feed gas into the reaction tube.

The cathode-anode separation was fixed at \( d = 1.8 \) cm. A cross-sectional view of the reaction tube is shown in Figure 6.

**Figure 6. Cross-Sectional View of Reaction Tube.**
The circuit used to initiate the discharge is similar to the one used in our feasibility studies and is shown in Figure 7. No external trigger is used for firing the spark gap.

![Electrical System Diagram](image)

**Figure 7. Electrical System**

### 2.2.3 Gas supply and extraction.

The flow rate of each gas that enters the reaction tube is found by making use of the Poiseuille effect. From its storage cylinder the gas flows through a capillary tube, 5 cm long, with the resulting pressure drop across the tube being measured by a U-shaped manometer with 76 cm long arms. Using capillary tubes of radii 0.5, 1.0, 2.0 and 3.0 mm with n-butyl phathlate (ρ = 1.047 gm/cc) it is possible to obtain flow rates from $10^{-4}$ l/sec to $10^2$ l/sec.
The flowmeter board constructed was comprised of four such manometers.

From the flowmeter board the gases enter a mixing tank and then enters the reaction tube through the aforementioned brass coupling. A small piece of 1/2" polyfio connects the brass coupling to the copper tube used as cathode.

The used gas is extracted through 20 exhaust ports (3/8" i.d.) spaced at intervals of 4.8 cm along the topside of the lucite tube (see Figure 6) by a mechanical forepump. An overall view of the vacuum system is shown in Figure 8.

2.2.4 Laser cavity.

The 2 m long laser cavity, discussed in more detail in Section 4.1 (see Figure 12), consists of a gold coated concave mirror (100%, R = 10 m) and a Germanium flat with an experimentally measured transmissivity of 8% at 10.6\mu. Both mirrors forming the resonator cavity are held in Lansing mounts (3 min of arc adjustments) and have apertures of 2.5 cm. Beam waist calculations indicate that more than 99% of the radiation incident on the Germanium flat falls within its aperature.
Figure 8. Vacuum System.
Before going into details of the characteristics of our laser it is useful to summarize some of the standard knowledge of CO₂ lasers. A reader who is already familiar with this background information can skip the next chapter and turn to Chapter 4 where the experimental results of the transverse flow transverse discharge laser are presented and discussed.
3.1 Vibrational Energy Levels of CO₂

Carbon dioxide is a linear, symmetric, triatomic molecule, which can vibrate in three different modes: the longitudinal symmetric stretch mode ($ν_1$) (Figure 9 (a)), the bending or deformational mode ($ν_2$) (Figure 9 (b)), and the asymmetric stretch mode ($ν_3$) (Figure 9 (c)). The

![Figure 9. Vibrational Modes of CO₂.](image-url)
molecule can vibrate in more than one mode at the same time and possess more than one quantum of vibrational energy in each mode. The vibrational levels are normally designated by four numbers representing the number of vibrational quanta of each mode associated with that level and written in the order \((v_1, v_2, v_3, \ell)\), where \(\ell\) represents the number of quanta of angular momentum associated with the bending mode.

The \(\text{CO}_2\) energy levels of prime importance in laser action are shown in Figure 10 with their spectroscopic classifications. Rotation-vibration transitions from the \((00^01)\) vibrational level to the \((10^00)\) level form the \(9.6\mu^*\) band and those from \((00^01)\) to \((02^00)\) the \(10.6\mu\) band, using the notation of [21].

The lines in a rotational-vibrational spectrum are designated by \(P(J), Q(J)\) and \(R(J)\), where \(J\) is the rotational quantum number of the lower level of the transition. The \(P, Q\) and \(R\) branches are distinguished from each other by the rotational transition selection rule \(\Delta J = -1, 0\) and \(+1\) respectively (see Figure 11). For a linear, symmetric molecule like \(\text{CO}_2\) the rotation-vibration spectrum is greatly simplified. There are no

\*This band arises due to mixing of the \((10^00)\) and \((02^00)\) states caused by Fermi resonance.
Figure 10. Energy Level Diagram for $\text{CO}_2$ and $\text{N}_2$ (showing only those vibrational levels important for $\text{CO}_2$ lasers).
Q-branch transitions since both the upper and lower laser levels have $\ell' = 0$ (i.e. $\sum \equiv \ell' = 0$), where $\ell'$ is the component of electronic orbital angular momentum along the internuclear axis. Alternate lines in the spectrum of the $\Sigma^+_u - \Sigma^+_g$ bands of CO$_2$ are also missing because of CO$_2$'s symmetry [11].

3.2 **Excitation and Inversion in CO$_2$**

A great deal of the early history of CO$_2$ lasers can be attributed to C.K.N. Patel. He was the first to
observe laser emission from CO$_2$ (1964 [12], from CO$_2$-N$_2$ mixtures (1964 [13] and CO$_2$-N$_2$-He mixtures (1965) [14]. The last result was simultaneously obtained by Moeller and Rigden [15].

Patel originally believed [16] that CO$_2$ was dissociated into CO and O$_2$ with the subsequent recombination leaving CO$_2$ vibrationally excited. Sovolev and Sobovnikov [17] disagreed with Patel and suggested that the CO formed by the dissociation of CO$_2$ was electronically excited and transferred this energy to CO$_2$ by collisions. However it has since been shown by Boness and Schulz (1968) [18] and verified in laser experiments by Cheo (1967) [19] and McKnight (1969) [20] that the dominant excitation mechanism is direct electron impact, symbolized by:

$$\text{fast } e^- + \text{CO}_2 \rightarrow \text{slow } e^- + \text{CO}_2^+ .$$

Direct electron impact is a rapid process which inverts the population densities because the electron impact excitation cross-section is larger for the upper (optically allowed) laser level than the lower (optically forbidden) one [20].

The increase in efficiency and larger powers obtained by adding different gases to CO$_2$ can, in part,
be qualitatively explained by the data shown in Table I. In the

Table I
Induced Vibrational Relaxation Rates of the CO₂
ν³ and ν₂ Modes in the Presence of Other
Gases at 300°K [21]

<table>
<thead>
<tr>
<th>Gas</th>
<th>ν³ - ν₂ (sec⁻¹ - torr⁻¹)</th>
<th>ν₂ + ground state (sec⁻¹ - torr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>365 ± 15</td>
<td>200 ± 10</td>
</tr>
<tr>
<td>N₂</td>
<td>110 ± 5</td>
<td>~ 40</td>
</tr>
<tr>
<td>He</td>
<td>≤ 85</td>
<td>4 ± 0.8 x 10³</td>
</tr>
<tr>
<td>H₂O</td>
<td>3.3 ± 0.9 x 10⁴</td>
<td>10⁵ - 10⁶</td>
</tr>
<tr>
<td>Dissociation</td>
<td>CO</td>
<td>193</td>
</tr>
<tr>
<td>Products</td>
<td>O₂</td>
<td>110 ± 5</td>
</tr>
</tbody>
</table>

presence of other gases the populations of the upper (ν³) and lower (ν₂) laser levels are modified by collision induced vibrational relaxation. The main effect of these collisions is to depopulate the ν₂ level more rapidly than the ν³ level, thus aiding the formation of the population inversion necessary for laser emission. However the effects of N₂ and He, the two main gas additives, are not limited to collisional relaxation alone.
Nitrogen is a homonuclear molecule and therefore has a zero dipole moment in the ground state. Thus radiative rotation-vibration transitions are strictly forbidden and the vibrationally excited levels of $N_2$ are very long lived (ns) [11]. The total electron impact excitation cross-section for $N_2$ is very large ($3.8 \times 10^{-16}$ cm$^2$) [21] and since the $00^01$ level of $CO_2$ is only 20 cm$^{-1}$ above the $v = 1$ level of $N$, there is an efficient near resonant transfer of energy from the vibrationally excited $N_2$ to $CO_2$ by collisions. Cw $CO_2$ lasers are more efficient because of this $N_2$ storage mechanism while in pulsed $CO_2$ lasers the presence of $N_2$ usually creates a long tail in the laser pulse shape by repopulating the depleted $00^01$ level of $CO_2$.

He, on the other hand, besides profoundly affecting the population of the $v_2$ level also lowers the mean gas kinetic temperature of the discharge because of its high thermal conductivity. Thus the gain of the laser is increased [10] and the electron energy distribution is also affected.

The importance of the electron energy distribution was theoretically demonstrated by Nighan and Bennett (1969) [1]. Using experimentally obtained cross-sections and computer solutions of the electron energy distribution
from the Boltzman equation for spatially uniform steady states [2] they solved the electron kinetic equation numerically as a function of E/N. Their results show that the electron energy distribution is non-Maxwellian. Of even more importance are their results for the fractional power transferred from the electrons to the vibrational and electronic levels of CO\(_2\) and N\(_2\), as a function of E/N and \(\overline{u}\) (the average electron energy: \(\overline{u} = \frac{2}{3} \int_0^\infty u^{3/2} f(u)du\)).

For an E/N value of 10\(^{-16}\)v-cm\(^2\) up to 65% of the electron energy goes directly into the (00°1) level of CO\(_2\)*. But for an E/N of 10\(^{-15}\)v-cm\(^2\) this figure is only about 20% with most of the electron energy being used to excite the electronic levels of CO\(_2\) and N\(_2\). The more efficient the energy transfer is the more non-Maxwellian the electron energy distribution becomes, falling off faster at higher energies than the Druyvesteyn distribution.

3.3 Present State of the Art

In spite of this basic understanding of the molecular processes in CO\(_2\) lasers it is however not possible to

*For a TEA laser at atmospheric pressure with a cathode-anode separation of 2.54 cm and an applied voltage of 20 kv, E/N = 3.2 \(\times\) 10\(^{-16}\)v-cm\(^2\).
predict the quantitative performance of a CO₂ laser. A quantitative analysis would require a knowledge of: 1) what is precisely the electron energy distribution in a pulsed discharge as a function of pressure, gas composition and current density, 2) how energy is transferred from electrons in a pulsed discharge to the vibrational levels of CO₂ and N₂, 3) how this vibrational energy relaxes because of collisions of the gas particles and, 4) how coherent radiation interacts with the excited population of CO₂.

To-date no experimental measurement of the electron energy distribution exists and its non-Maxwellian form makes the use of the concept of mean electron "temperature" questionable.

The narrow amplification bandwidth of the CO₂ lasers (see Section 4.3.3) does not make it suitable for mode-locking because of the small number of longitudinal modes that can be fitted within the gain curve. Nevertheless, mode-locking has been attempted and achieved with active and passive optical elements. Pulse widths as short as 1 nsec with peak power of ~ 1 Mw have been reported (1972) [22].

To increase the laser output one has to increase the number of electrons, nₑ, in the discharge. The most obvious way to do this, namely to increase the current,
does not work, since increased current density will lead to a higher gas temperature in the discharge, which increases the deactivation processes. Two other methods for increasing $n_e$ however have been successful. Firstly, Richardson et al. (1973) [23] at NRC have used elaborate techniques to preionize the gases and have obtained an output of 300 joules at several gigawatts. Daugherty (1973) [24] has used electron beams to inject electrons into the active medium and obtained 2000 joules with almost 100 Mw's of power.

The lack of a comprehensive theory necessitates the extensive investigation of any new CO$_2$ laser with different features. To this end one should vary as many parameters as possible in order to understand the properties of the new device. The experimental studies of our laser are presented in the next chapter.
4.1 Aligning CO\(_2\) Laser

Any laser work starts with the frustrating operation of alignment. Since the wavelength of radiation emitted by a CO\(_2\) laser is in the infrared some of the optical components used are opaque to radiation in the visible spectrum. Thus to align the laser cavity it is necessary to introduce the alignment beam used in a roundabout way. The set-up is shown in Figure 12.

*Removed after initial alignment.*
One should not be surprised if, after careful alignment, no laser action is observed. This is due to the change in the refractive index of the laser medium because of the heating of the gas and the pulsed discharge. Such an effect has been observed in low pressure CO₂ lasers, He-Ne lasers and most recently by Fortin et al. (1971) [25] in a helical TEA CO₂ laser where a diverging lens effect was attributed to each pitch of the helix. This effect causes the alignment beam to "jump" on the surface of the mirrors ~ 0.5 cm each time the discharge occurs. Thus for alignment purposes it is better to note the position of the beam while the discharge is on.*

Once the laser has been aligned the KCl plate is removed because it is a source of loss in the cavity and affects the pulse shape and delay time. Quite frequently multiple pulsing occurs with some pulses being emitted over 20 μsec after the initiation of the discharge (see Figure 13). This behaviour is in general the case if the round trip gain is small, which may be caused by operating at low gas pressures, a slight misalignment of cavity mirrors or losses in the cavity. These points are discussed further in Section 4.3.3.

*Different beam displacements due to difference in index of refraction for 10.6μ (CO₂) and 6328Å (He-Ne) may be neglected.
The mechanical rigidity of the laser was such that once the laser was aligned only slight adjustments were necessary for successful operation on a day-to-day basis.

The usual CO₂ pulse shape obtained is shown in Figure 14 with the pulse shape parameter measured in this

![CO₂ Pulse Shape Parameters](image)

**Figure 14.** CO₂ Pulse Shape Parameters.
chapter as indicated. Since no external trigger was used to fire the spark gap no great effort was made to eliminate the electrical noise. On the contrary, the noise was used to trigger the oscilloscope so that $\tau_d$ measures the elapsed time between the start of the current pulse and the beginning of the laser pulse.

4.2 Operating Conditions

4.2.1 The electrical system.

Of course the first question to be asked is: Does the hollow ground rod actually work? The answer, found after several weeks of fruitless adjustment, is yes. How well it works though depends upon the interelectrode distance, $\Delta$, used, as can be seen in Figure 15.

Using all 200 resistors creates a discharge pattern that shows the sparks channels interfering and coupling with one another. By disconnecting one chain of resistor pins the interelectrode distance is doubled and the discharge pattern is quite uniform.

However, the power from the 200 resistors is larger than that with only 100 resistors. Also significant is the reduced height of the tail of the CO$_2$ pulse. This means the energy of the pulse is less (but not by a factor
of 2) because less $N_2$ is being excited. With all 200 resistors in use more volume of the gas is excited and thus the energy content of the pulse is larger. For this reason the laser was operated using 200 resistors.
Throughout the experiment repetition rates of 1 pulse/sec were used. By varying the spark gap setting and the power supply voltage it was verified that the repetition rate agreed with equation 2.1 (Section 2.1). The choice of 1 Hz was necessitated by the need to apply a reasonable voltage to the discharge and avoid excessive overheating of the 1 watt resistors used as the anode. In addition there was the very human problem of electrical noise from the discharge and spark gap which brought frequent (1 Hz ?) complaints from fellow students and was eventually solved by simply setting the spark gap at a lower voltage, namely 16 kv.

4.2.2 Effect of gases and pressure.

As explained in Section 3.2, the presence of other gases alters the power and energy output of a CO₂ laser. The oscillograms shown in Figure 16 verify these statements. With no gas additives (Figure 16(a)) the laser pulse shows a very fast rise and decay time. The rapid risetime is attributed by Beaulieu (1970) [3] to the fast excitation caused by the short current pulse. This causes a rapid build up in gain which creates a gain-switching situation giving rise to a giant pulse.
The addition of N₂ does not alter the peak power too much but increases the energy of the pulse as evident by the tail in the CO₂ pulse (Figure 16(b)). When He is added to CO₂ (Figure 16(c)) the peak power is almost doubled but the pulse shape is the same as with only CO₂ present. Oscillograms with all three gases present are shown in Figure 15 and exhibit the same pulse shape as that of CO₂ and N₂ alone but with the peak powers of CO₂ and He.
The volume ratio of gases used throughout most of the experiment were 10 parts He:1 part \(N_2\):2 parts \(CO_2\). This ratio is typical of the values cited in the literature for \(CO_2\) lasers. Some work was done on the effect of increasing the He content in the gas mixture and it was found that for ratios up to 25:1:2 the peak power was increased ~ 30%. This larger gas ratio was used when obtaining the spectrum of the laser (see Appendix B). Although more He gives more power, He is expensive! Enough said about that!

The variation of peak power with gas pressure is shown in Figure 17. In this graph, as in all others, the error bars represent the rms error of five shots each. The curve has an approximate parabolic shape which is due to several effects. The initial increase in power with pressure is created by an increase in the energy per unit volume. If no other effects were important the power would increase linearly with pressure. However, de-excitation mechanisms in the gas mixture are due to collisions and the collisional relaxation rates also increase linearly with pressure [26]. Thus the inversion itself is reduced by de-activating collisions at high pressures. Also above 5.2 torr the line width of \(CO_2\) is collision broadened [26] and this homogeneous broadening increases the threshold for lasing and thereby reduces the extractable laser power.
Figure 17. Peak Power vs. Total Pressure.
A similar graph was also obtained with gas ratios of 15:1:2. This graph had the same parabolic shape but the optimum pressure occurred at 150 torr instead of the 140 torr with the 10:1:2 gas mixture. This is reasonable since He clears out the lower laser level by collisions (see Table 1) and thus increases the population inversion even though the threshold increases with the increasing band width.

Using these results the laser was operated at a pressure of 140 torr (10:1:2 gas mixture) when studying other properties of the laser.

4.3 Properties of System

4.3.1 Power decay in a closed system.

The most important component in the vacuum system is the laser reaction tube which is made of lucite. Since this vessel had over 200 holes drilled in it for the resistor pins, exhaust ports, etc., it was not too surprising that the lowest vacuum (?) obtainable was 200 microns as measured with a McLeod gauge. To see what effect the vacuum leaks had upon the laser output the vacuum pump was closed from the reaction tube and no fresh gas was supplied to the tube. Thus the graph shown in
Figure 18. Power decay in closed system.

MAXIMUM $P = 41 \text{ kW}$

20kW

$\text{NE: CO}_2$

$\text{He: NE: CO}_2$
Figure 18 was obtained. Since the vacuum leak was at a rate of 5 torr/min some gas was periodically evacuated from the system to maintain a constant pressure of 140 torr. At a leak rate of 5 torr/min, after 50 min some 250 torr of air will have leaked into the reaction tube making the partial pressure of air some 60% of the total pressure in the tube. Even with this large amount of impurities in the reaction tube the laser still lases but only at 30% of the power it started with initially.

4.3.2 Electrical efficiency.

The electrical efficiency of a laser is defined as the ratio of the energy of the laser pulse to the electrical energy input. In a resistively loaded TEA laser the efficiency is typically 5% [28].

To obtain this measurement it is necessary to know the voltage, $V$, applied to the resistor chain from the spark gap. The electrical energy input is the energy stored by the capacitors which is $(\frac{1}{2})CV^2$. The $I^2R$ losses due to the resistively loaded anode are usually neglected. The voltage across the capacitor bank can be obtained by calibrating either the spark gap or, because there is no externally applied trigger pulse to the spark gap, the power supply. Since the electrodes of the spark gap
deteriorate with use the latter of the two methods was used. The power supply was calibrated using a compensated Tektronix high voltage probe (30 kv max.).

The energy content of the laser pulse was found by measuring the area under the curve of the power pulse shapes from the Au:Ge detector (see Appendix A).

The efficiency curve obtained is shown in Figure 19. To interpret this graph it is necessary to look at the work of Nighan and Bennett (1969) [1] and Nighan (1970) [2]. They found that the fractional transfer of power to the electronic and vibrational levels of CO₂ and N₂ are dependent upon the value of E/N, where E is the electric field strength and N the total neutral particle density. The fractional ionization of the gases is quite small, typically 10⁻⁸ - 10⁻⁶, and may be ignored. To find E (i.e. \( E = \frac{v'}{d} \)) it is necessary to know the net voltage, \( v' \), applied to the gas mixture. This is the voltage applied across the electrodes by the power supply minus the cathode fall and voltage drop across the anode resistors. These potential drops have been estimated by Lyon (1973) [26] to be less than 2 kv in a laser with a gas mixture similar to that used here. Thus for a cathode-anode separation \( d = 1.8 \text{ cm} \) at a pressure of 140 torr the values of the input energy used represents E/N values in the range \( 9.2 \times 10^{-16} \text{v-cm}^2 \) to \( 22.5 \times 10^{-16} \text{v-cm}^2 \). From these considerations the
Figure 19. Electrical Efficiency Curve.
increase in efficiency is not explainable since the values of E/N used indicate that the average electron energy (3.5 - 4.5 e.v.) is so high that most of the CO₂ and N₂ is electronically excited. With increasing applied voltage (i.e. energy) less CO₂ and N₂ is directly excited vibrationally and therefore it would be reasonable to assume the efficiency was decreased.

These results illustrate that one still does not fully understand all facets of CO₂ lasers.

4.3.3 Time delay of pulse.

The time delay, τ_d, between the beginning of the laser pulse and the start of the current pulse is governed by losses in the laser cavity and the gain [30]. This was already mentioned in Section 4.1 in connection with the multiple pulsing caused by the KCl plate used during alignment and operating the laser at low pressures (< 30 torr). The graph in Figure 20 shows this time delay as a function of total gas pressure.

If the time delay was due to collision effect we would expect the delay to decrease with increasing pressure because the collisional relaxation rates are directly proportional to the total pressure. The influence
Figure 20. Time Delay vs. Total Pressure.
of losses may be excluded also since the only additional losses introduced by increasing the pressure as absorption losses which are negligible. This leaves only the effect of the gain. It has been found by Gerry et al. (1966) [27] that above 5.2 torr CO\textsubscript{2} is collision broadened with a bandwidth increase of 6.5 MHz/torr. Therefore, as the pressure increases the gain curve gets larger and broader thus increasing the threshold for lasing. With a cavity length of 2 m the frequency separation between axial modes is 75 MHz (i.e. \( \Delta f = c/2L \)). Thus, at a pressure of 20 torr there are at most two axial modes within the gain curve whereas at 240 torr there are 21 modes present. The increase in the time delay may be caused by coupling between these modes with one mode saying to the other "After you" and the other mode replying "No, after you!"

It is also known by those more familiar with CO\textsubscript{2} lasers* that the current pulse plays quite an important role with CO\textsubscript{2} lasers and is affected by the discharge which in turn is partially determined by the pressure.

Another interesting observation is that up to pressures 100 and 120 torr the CO\textsubscript{2} pulse is modulated. This modulation was much more pronounced in mixtures of just CO\textsubscript{2} and N\textsubscript{2} and is shown in Figure 21. By referring

*Private communications with Dr. A.A. Offenberger.
to Figure 20 one will note that it is around these pressures that the delay time no longer remains constant but starts to increase with pressure. This suggests that these two phenomena are related. This modulation, with period $T \sim 70$ nsec, is not caused by mode-locking effects and attempts to explain it as laser spiking by the Statz-De Mars equation have proven futile [14]. Once again we return to the effects of the current pulse. For a circuit containing non-negligible inductance the current pulse will ring and thus pump the laser level possibly causing this effect. However, the ringing frequency of the discharge which can also be seen in Figure 21 appears to be too slow to provide the possible explanation.

Measurements of the half-width of the laser pulse, $\tau$, show no variation with pressure.

4.3.4 Spectral analysis.

The spectrum of the laser was investigated with a Jarrel-Ash 0.5 m spectrometer equipped with a 148 $\lambda$/mm
grating. The alignment of this instrument caused some difficulties which were finally overcome by using a small piece of untreated steel which was sufficiently heated by the laser pulses to evaporate the grease on its surface and emitting a faint, visible light flash. *

The procedure used and difficulties involved in obtaining the infrared spectrum are described in Appendix B. Only three P branch transitions were observed: the P(20), P(18) and P(16) lines. These lines did not shift and other lines did not appear when the pressure was varied from 40 to 200 torr and spark gap settings of 17.4 and 15 kv were used.

The P(20) line was by far the most intense line and using Patel's [10] analysis of the gain coefficients for P-branch transitions it is possible to determine the population ratio \( \frac{N_{001}}{N_{020}} \). This was done by maximizing the gain coefficient with respect to \( J \) and solving for \( \frac{N_{001}}{N_{020}} \) with \( J + 1 = 20 \). The result obtained was \( \frac{N_{001}}{N_{020}} = 1.11 \), for a kinetic temperature of 300°K.

Having successfully operated the laser configuration as a transversely pulse-initiated CO₂ laser we moved on to the more difficult task of obtaining laser emission by means of chemical pumping. The gas mixtures used and results obtained are discussed in the next chapter.

*Alcohol cleaned surfaces did not show the same effect.
Laser emission by means of chemical pumping was first successfully accomplished by Kasper and Pimentel (1965) [30] in a flash photolytically initiated hydrogen/chlorine explosion. In the past three years transversely spark-initiated chemical lasers have been operated using CO [4], [7] and HF [5], [31,33], produced in chemical reactions up to pressures of one atmosphere. During this time gas mixtures containing hydrocarbons [33-35] have also produced laser action but only at very low pressures in discharge tubes.

Attempts to obtain laser emission from molecules produced in chemical reactions were not successful. The gas mixtures and operating conditions used are shown in Table II.

To obtain maximum sensitivity with the Au:Ge detector a KCl lens (f = 9.4 cm) was used to ensure all radiation was focused on the detector element and no 50Ω
<table>
<thead>
<tr>
<th>Gas Mixture</th>
<th>Gas Ratios by Volume</th>
<th>$P_{\text{TOTAL}}$ (torr)</th>
<th>Laser Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 $C_2H_2 + CO_2 + N_2 + He$</td>
<td>4.5:2:1:10</td>
<td>30-50</td>
<td>Yes</td>
</tr>
<tr>
<td>#2 $C_2H_2 N_2 + He$</td>
<td>1:25:60</td>
<td>5-25</td>
<td>No</td>
</tr>
<tr>
<td>#3 $C_2H_2 + He + Air^+$</td>
<td>1:4.2:1.7</td>
<td>5-75</td>
<td>No</td>
</tr>
<tr>
<td>#4 $C_2H_2 + CO_2 + O_2$</td>
<td>$&lt;1:5:40^*$</td>
<td>45</td>
<td>No</td>
</tr>
<tr>
<td>#5 $C_2H_2 + He + O_2$</td>
<td>$&lt;1:1:5^*$</td>
<td>5</td>
<td>No</td>
</tr>
<tr>
<td>#6 $C_2H_2 + O_2^+$</td>
<td>1:2*</td>
<td>5-60</td>
<td>No</td>
</tr>
<tr>
<td>#7 $SF_6 + C_2H_2 + He$</td>
<td>12:1:233</td>
<td>15-40</td>
<td>No</td>
</tr>
<tr>
<td>#8 $SF_6 + H_2^+$</td>
<td>1.7:1</td>
<td>10-40</td>
<td>No</td>
</tr>
<tr>
<td>#9 $H_2 + CO_2 + He$</td>
<td>1:1.7:8.6</td>
<td>50-80</td>
<td>Yes</td>
</tr>
<tr>
<td>#10 $SF_6 + CO_2 + He$</td>
<td>1:2:10</td>
<td>40</td>
<td>No</td>
</tr>
</tbody>
</table>

^ Laser emission has been reported in these mixtures.

* Gas ratios by partial pressures.
terminator was used with the detector. These two steps would enable detection of powers as low as 50 mw although distorting the power pulse shape because of the integration due to the large RC time constant of the BNC cable-oscilloscope input impedance network (see Figure A-4). When attempting to detect laser emission from HF (mixtures #7 and #8) electrical noise was a problem. The HF laser pulse is created ~100 nsec after the initiation of the discharge which would bury it amid the electrical noise from the discharge. After unsatisfactory attempts to reduce the noise a delay cable (3 μsec) was used to delay the signal from the detector thus sidestepping the noise problem.

The gas mixtures of primary interest are #3, #6 and #8. These mixtures have previously been reported to produce laser emissions from CO and CO₂, CO and HF molecules respectively. The other gas mixtures were used to study what effect the gases of the primary mixtures (i.e. #'s 3, 6 and 8) had on a laser mixture which is known to work in our laser. In short, the conclusions and observations of these studies are:

The violent nature of C₂H₂ + O₂ reactions requires the use of low operating pressures. The C₂H₂ + O₂ mixture produced flame-like reactions, which are known to
suppress laser action, at pressures in excess of 50 torr. Using low pressures, however, is detrimental to a transversely spark-initiated laser because of the resulting non-uniformity of the discharge pattern.

Laser action in the mixtures \( C_2H_2 + CO_2 + N_2 + He \) and \( H_2 + CO_2 + He \) can be attributed to electrically excited \( CO_2 \). These mixtures produced multiple pulses as soon as \( H_2 \) and \( C_2H_2 \) were introduced into the active medium. This type of behaviour has already been discussed in Chapter 4 (see Figure 13) and indicates that \( C_2H_2 \) and \( H_2 \) decrease the gain of the laser.

Laser emission from \( CO_2 \) stopped immediately when \( SF_6 \) and \( O_2 \) entered the reaction tube. This isn't too surprising since \( SF_6 \) quenches electrons available for \( CO_2 \) and \( N_2 \) excitation and then adds "insult to injury" by readily absorbing what \( CO_2 \) radiation is emitted. For these reasons \( SF_6 \) has been used to quench arcs in circuit breakers and as a saturable absorber for Q-switching of \( CO_2 \) lasers. Studies on the dissociation products of \( CO_2 \) indicate that \( O_2 \) is deleterious to laser emission because it destroys the population inversion by depleting the upper laser level (see Table I).
Although laser emission by chemical pumping was not detected this does not necessarily mean that the laser reaction tube is inadequate for the task. In Chapter 6 improvements that may help to achieve an operating chemical laser are described and possible experiments for the future are discussed.
A transverse gas flow, transversely pulsed laser has been constructed and operated as an electrically excited CO$_2$ laser. The innovation of using a hollow ground rod for transverse gas flow and discharge cathode was successfully demonstrated.

The efficiency of the laser is comparable to other resistively loaded TEA CO$_2$ lasers although the powers obtained are not as large. Some measurements of the characteristics of the laser pulse and laser system were not explainable by present theories of CO$_2$ lasers.

To improve the performance of the laser the interelectrode separation, $A$, should be fixed between 0.5 cm and 1.0 cm, large enough to prevent coupling of the spark channels and thus maximizing the excitation volume used. The efficiency and power output may be improved by optimizing $E/N$ according to Nighan and Bennett's criteria. This would require larger voltages but would
also increase the optimum pressure thus reducing problems with the vacuum system.

Experimental results by Mikoshiba and Ahlborn (1973) [36] indicate that the power may be increased by optimizing the laser cavity using a variable focal length gold-coated mirror. Some rule of thumb guides for optimizing the transmissivity of the output mirror are given in an analysis by Meneely (1965) [37] for high power CO₂ lasers.

For operation as an electrically excited CO₂ laser the Brewster angle mounted KCl windows should be removed and the mirrors forming the resonator cavity mounted directly on the reaction tube. These KCl windows are a source of loss in the cavity but should be used for chemical laser operation because of the possible damage to good quality mirrors by the chemicals formed.

Another small item of possible value is a mixing tank with facilities for pre-cooling of the gas mixture. This would lower the gas kinetic temperature and thus increase the laser's gain.

Failing to find laser action with chemical pumping, gain measurements would be useful to ascertain if any vibrationally excited molecules are produced in the discharge.
The use of transverse gas flow makes this laser design suitable for studying the effect of gas replacement rates on the power output. This would require improving the vacuum system (i.e. place anode resistors inside reaction tube) to eliminate impurities and constructing a fast repetition rate high voltage supply.

In conclusion this laser vessel has lived up to some but not all our expectations. Although no laser emissions were detected from chemical pumping processes the arrangement did produce adequate transverse discharges to allow operation as an electrically excited $\text{CO}_2$ laser, under various conditions of flow, pressure and gas mixture it helped to establish in this lab, for the first time, the techniques of detection and measurement of $\text{CO}_2$ lasers and infrared radiation.
REFERENCES


APPENDIX A

INFRARED DETECTORS

The detection of radiation in the intermediate infrared range 1.5μ to 30μ [38,39] is limited by background noise, since at room temperature the peak of the black body radiation curve falls near 10μ. For intense laser radiation this limitation may be bypassed but this also limits the number of useful detectors.

There are three main types of infrared detectors: thermal, photoelectric and pyroelectric.

Thermal Detectors

Thermal detectors depend upon the heating properties of the radiation to produce a temperature rise and hence involves a change in the bulk properties of the detector element. Although these detectors have a very wide spectral range they also have very slow response times and low power absorption capabilities. Thermocouples, thermopiles, Golay cells and calorimeters have been used
to measure the power output of low power cw CO$_2$ lasers but are too slow for pulsed CO$_2$ lasers. Thermal detectors are normally operated at room temperature.

**Photoelectric Detectors**

Photoelectric detectors are exclusively based on semiconductor materials and rely on a quantum interaction between the radiation and the detector. The radiation creates a voltage signal by either a photovoltaic or photoconductive effect.

In detectors based on the photovoltaic effect the radiation modifies the junction barrier potential between differentially-doped semiconductor materials.

Two types of photoconductive detectors are in use:

*Intrinsic Photoconductive Detectors*

With these undoped semiconductor materials the radiation is detected by the alteration of the electrical conductivity by direct excitation of electrons across the band gap, $E_g$ (see Figure A-1(a)). Radiation of energy less than $E_g$ does not cause intrinsic absorption but since $E_g$ is a function of temperature it is possible to decrease
Figure A-1. Photoconductive Detectors.
Eg by cooling the detector element thus increasing the detector's spectral range. PbS and InSb are two examples of photoconductive detector materials. Both are operated at room temperature with the latter also being used at 77°K (liquid N₂).

**Extrinsic Photoconductive Detectors**

These detectors are almost entirely made of doped Germanium. In n-type detectors (Figure A-1(b)) a conductivity change occurs with excitation of electrons from a donor level into the conduction band. When the excitation is from the valence band into an acceptor level within the band gap (Figure A-1(c)) we have a p-type detector.

Some dopants produce levels which are close to the upper limit of the valence band and as thus filled by thermal excitation at room temperature. It is therefore necessary to "freeze out" these levels to have an effective detector and reduce the background noise. Two temperatures are commonly used, 77°K (liquid N₂) and 4°K (liquid He).
Pyroelectric Detectors

The pyroelectric detector is composed of a ferro-electric material which possesses a temperature dependent permanent electric polarization. Radiation absorbed by the detector is converted into heat which alters the lattice spacing of the ferroelectric. Below the Curie temperature a change in electric polarization results from these lattice alterations.

Unlike other infrared detectors the voltage signal generated is proportional to the time rate of change of the temperature and thus the detector does not come into equilibrium with the radiation. Pyroelectric devices are also capacitive rather than resistive thus having essentially an infinite electrical frequency response.

During the course of this experiment three infrared detectors were used: a gold doped Germanium (Au:Ge) power detector, which is a p-type intrinsic photo-conductive detector, a pyroelectric power detector and a pyroelectric energy meter. Table A-I gives the pertinent data for each detector.

The detector elements with the necessary detector circuits are provided for by the manufacturers in the Gentec and Molelectron pyroelectric detectors. However, for the Au:Ge detector it is necessary to construct a
<table>
<thead>
<tr>
<th>Detector</th>
<th>Detector Area (cm$^2$)</th>
<th>Responsivity</th>
<th>Operating Temperature</th>
<th>Risetime</th>
<th>Recovery Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au:Ge</td>
<td>$3.14 \times 10^{-2}$</td>
<td>1.35 v/kw</td>
<td>77°K</td>
<td>30 nsec</td>
<td>-</td>
</tr>
<tr>
<td>Molelectron*</td>
<td>$1.0 \times 10^{-2}$</td>
<td>1.5 v/kw</td>
<td>293°K</td>
<td>50 nsec</td>
<td>-</td>
</tr>
<tr>
<td>Gentec</td>
<td>3.6</td>
<td>8.1 v/joule$^+$</td>
<td>293°K</td>
<td>5 msec</td>
<td>0.3 sec</td>
</tr>
</tbody>
</table>

*Responsivity and risetime are variable.

$^+$When terminated with 1 MΩ.
circuit for the detector (Figure A-2) and a dewar configuration for cooling the detector element, which in our design is mounted in a vacuum. A CaF$_2$ window* is used to couple radiation into the detector.

![Detector Circuit Diagram]

Figure A-2. Au:Ge Detector Circuit; Output via 50Ω Cable.

To compare the responses of the detectors to a CO$_2$ laser pulse a KCl converging lens (f = 9.7 cm, φ = 2 cm) was used to focus radiation on the detector elements and mylar sheets were used as attenuators to prevent damage to the detectors. Figure A-3 shows typical oscillograms obtained with each detector.

The energy of the pulse is found by obtaining the peak voltage from the Gentec oscillogram and knowing the resistance used to terminate the co-axial cable the

*Experimentally found to attenuate laser pulse by factor of 0.42.
Figure A-3. Response of Infrared Detectors to a CO₂ Laser Pulse
manufacturer's calibration curve gives the number of volts/joule. Terminating the cable with the 1 MΩ input impedance of the oscilloscope gives a calibration figure of 8.1 v/joule.

When using the power detectors it is necessary to terminate the cable with a 50Ω terminator. Otherwise the RC time constant of the cable and oscilloscope input impedance network is of the order of 50 μsec and the oscilloscope would display the time integration of the power detector's output, which is the energy (see Figure A-4).

![Figure A-4](image)

a) Output with 50Ω terminator. b) Output with no terminator.

Comparison of the pulse shapes obtained with the Au:Ge and Molelectron power detectors show that the pyroelectric Molelectron detector does not give as much detail of the pulse shape as the photoconductive Au:Ge detector. The fast risetime of the pulse is evident in both oscillograms but the Molelectron gives increase thus
cutting off the tail of the laser pulse. Therefore it is not possible to make estimates of the energy of the laser pulse using the Molectron detector.

The calibration of the detectors was self-consistently verified using a 2 w cw CO₂ laser. The radiation was chopped at a frequency of 50 Hz and focused on the detector elements using the KCl lens. Assuming that calibration of the Gentec energy meter was correct, the calculated responsivities of the Au:Ge and Molectron detectors agreed with the manufacturer's values to within 10%.

The detector used throughout the experiment was the liquid nitrogen cooled Au:Ge detector. Experimental results have shown that the shot-to-shot power variation is the same with and without the KCl lens. Therefore, because the KCl lens is hydroscopic and deteriorates when exposed to the atmosphere, it was decided to make power measurements without the lens. When using the lens the peak power is increased by a factor of 3.22. We are fairly certain that the lens (2 cm diameter) would cover the important parts of the cross-section of the laser tube having measured the near field radiation pattern of the laser (see Figure A-5).

Using the value of 1.35 V/kW for the responsivity and taking into account the attenuation by the CaF₂ window
Figure A-5. Near Field Radiation Pattern.
and the power increase if the lens was present a calibration figure of 5.68 kw/v was used to calculate the peak powers with the Au:Ge detector.
APPENDIX B

SPECTRAL ANALYSIS

The spectral output of the laser was analyzed using a Jarrel-Ash 0.5 m Ebert spectrometer (Model 82-010). The grating used was blazed for 5.0μ at 21.6° with a ruled area 52 x 52 mm's and had 148 λ/mm. With this grating, the linear dispersion at the exit slit was 128 Å/mm. The entrance and exit slits were both set at 400μ slit width.

The manual drive of the spectrometer was originally calibrated with a grating of 1180 λ/mm. This corresponds to a dial multiplication factor of 1.0 and a maximum dial reading of 8600 Å. With the 148 λ/mm grating, the maximum measurable wavelength was 6.85μ which falls short of the 10.6μ region necessary to study CO₂ radiation. It was therefore necessary to release the grating holder from the grating pivot mount and rotate the grating by hand. By first observing the zero order of the spectrum of the calibrating light source and counting the orders of the spectra as the grating was rotated there...
was no difficulty in positioning the grating for use in the 10.6μ region.

The spectrometer was calibrated using three sources. A He Geissler tube, a He-Ne alignment laser and a mercury (Hg) lamp. The mercury lamp contained a sodium impurity and its spectrum exhibited the sodium D doublet besides the green, yellow and violet Hg lines. When working in the infrared care must be taken when obtaining measurements of wavelength since the variation of wavelength due to the changes in the refractive index of air is non-negligible. It is of the order of 29 Å for 10.6μ. All wavelengths used with the calibration are those measured in air. Table B-I shows the lines used for calibrating the spectrometer.

A smaller version of a typical calibration curve is shown in Figure B-1. For wavelengths greater than ~ 10.6μ the graph displays a non-linearity. This is not surprising because of the unusually large angle the grating makes to the incident radiation. The procedure for correcting non-linearities of the sine bar drive was carried out but there was no noticeable change and the non-linearity remained.

The calibration data was also analyzed by computer and least squares fits were obtained. A linear
Figure B-1. Spectrometer Calibration Curve.
Table B-1

Spectral Lines Used for Spectrometer Calibration

<table>
<thead>
<tr>
<th>Source</th>
<th>( \lambda ) (Å)</th>
<th>Order Used</th>
<th>( n\lambda ) (Å)</th>
<th>Colour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hg lamp</td>
<td>5461</td>
<td>19</td>
<td>103,759</td>
<td>Green</td>
</tr>
<tr>
<td>Hg lamp</td>
<td>5790</td>
<td>18</td>
<td>104,220</td>
<td>Yellow</td>
</tr>
<tr>
<td>Hg lamp</td>
<td>4358</td>
<td>24</td>
<td>104,592</td>
<td>Blue</td>
</tr>
<tr>
<td>Geissler tube</td>
<td>5875.6</td>
<td>18</td>
<td>105,761</td>
<td>Yellow</td>
</tr>
<tr>
<td>He-Ne laser</td>
<td>6328</td>
<td>17</td>
<td>107,576</td>
<td>Red</td>
</tr>
<tr>
<td>Hg lamp</td>
<td>5461</td>
<td>20</td>
<td>109,220</td>
<td>Green</td>
</tr>
</tbody>
</table>

Least squares fit was done using only the first **four** points of the calibration data, with the result shown below:

\[
Y = (86896 \pm 12) + (5.1289 \pm .003)X
\]

where,

- \( Y \) = wavelength in Å
- \( X \) = dial setting of spectrometer.

A **quadratic** least squares fit was also tried using all **six** data points, with the result being,
\[ Y = (84876 \pm 55) + (6.2414 \pm 0.029)X - (0.15 \times 10^{-4} \pm 0.000)X^2 \]

For obtaining the spectral output the apparatus was aligned as shown in Figure B-2. The spectrometer alignment was greatly facilitated by using a small piece of untreated steel which developed visible flashes of light when hit by the laser radiation. Knurled brass was also found to be effective in aligning the spectrometer.
To compensate for the loss of power due to absorption and scattering the laser power was increased by doubling the amount of helium in the gas mixture (see Section 4.2.2) so the volume ratio of He:N:CO₂ was 20:1:2.

When identifying lines the spectrometer dial was adjusted to obtain maximum peak power. All lines were measurable to an accuracy of ± 1 dial digit or ± 5 Å.

The results obtained are shown in Table B-II.

**Table B-II**

Raw Data from Spectral Analysis

<table>
<thead>
<tr>
<th>Mode of Measurement</th>
<th>Peak Voltage</th>
<th>Dial Setting</th>
<th>Width of Line (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 slits + lens</td>
<td>1.2 v</td>
<td>3706</td>
<td>45</td>
</tr>
<tr>
<td>exit slit + lens</td>
<td>1.2 v, 0.15 v</td>
<td>3706, 3669</td>
<td>45, 5</td>
</tr>
<tr>
<td>No slits + lens</td>
<td>Range of values 3545-3771, but not peaks discernible.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Width of line is range over which any power output is obtained. It is not the half power width.

The results obtained with both slits and the lens are considered valid data. The data obtained with the entrance slit removed is also considered valid because there was no noticeable increase in the peak voltage at the 3706 dial setting. This indicates that the KC₂ lens
is effectively focused on the entrance slit. Thus the lens acts as if it was the entrance slit by collimating the laser beam. The data taken with no slits gives an indication of the possible range of CO₂ lines lasing, but should be taken with a grain of salt. The exit slit in this case is effectively the diameter of the Au:Ge detector element which is 2 mm and thus the possible number of lines may be measured to within ± 256 Å (2 mm x 128 Å/mm).

The results obtained with no entrance slit are shown in Table B-III. Identification of lines is based upon comparison with standard CO₂ spectra (see Table B-IV). From the calibration graph the data taken with no slits indicates the line P(12) → P(22) are also present.

The spectrometer was also scanned in the 9.6μ region but no lines were detected.
## Table B-III

Identification of CO₂ Lines

<table>
<thead>
<tr>
<th>CO₂ Line</th>
<th>Graph</th>
<th>Linear Fit</th>
<th>Quadratic Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Y (Å)</td>
<td>Y-P(J)</td>
<td>Y (Å)</td>
</tr>
<tr>
<td>P(20)</td>
<td>105,940</td>
<td>-1</td>
<td>105,904 ± 16</td>
</tr>
<tr>
<td>P(18)</td>
<td>105,748</td>
<td>+6</td>
<td>105,714 ± 16</td>
</tr>
<tr>
<td>P(16)</td>
<td>105,555</td>
<td>+8</td>
<td>105,529 ± 16</td>
</tr>
</tbody>
</table>
Table B-IV

CO₂ Laser Transitions

Wavelengths in vacuum from Patel [16] and corrections for air calculated from C.R.C. Rubber Bible (50 Ed.), p. E-233 All wavelengths in angstroms.

<table>
<thead>
<tr>
<th>Transition</th>
<th>Wavelength in Vacuum</th>
<th>Correction Due to Air</th>
<th>Wavelength in Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(12)</td>
<td>105,135</td>
<td>28.66</td>
<td>105,163.7</td>
</tr>
<tr>
<td>P(14)</td>
<td>105,326</td>
<td>28.71</td>
<td>105,354.7</td>
</tr>
<tr>
<td>P(16)</td>
<td>105,518</td>
<td>28.77</td>
<td>105,546.7</td>
</tr>
<tr>
<td>P(18)</td>
<td>105,713</td>
<td>28.82</td>
<td>105,741.8</td>
</tr>
<tr>
<td>P(20)</td>
<td>105,912</td>
<td>28.88</td>
<td>105,940.8</td>
</tr>
<tr>
<td>P(22)</td>
<td>106,118</td>
<td>28.93</td>
<td>106,146.9</td>
</tr>
<tr>
<td>P(24)</td>
<td>106,324</td>
<td>28.99</td>
<td>106,352.9</td>
</tr>
<tr>
<td>P(26)</td>
<td>106,534</td>
<td>29.04</td>
<td>106,563.0</td>
</tr>
<tr>
<td>P(28)</td>
<td>106,748</td>
<td>29.10</td>
<td>106,777.1</td>
</tr>
<tr>
<td>P(30)</td>
<td>106,965</td>
<td>29.16</td>
<td>106,994.1</td>
</tr>
<tr>
<td>P(32)</td>
<td>107,194</td>
<td>29.22</td>
<td>107,223.2</td>
</tr>
<tr>
<td>P(34)</td>
<td>107,415</td>
<td>29.28</td>
<td>107,444.3</td>
</tr>
<tr>
<td>P(36)</td>
<td>107,648</td>
<td>29.35</td>
<td>107,677.3</td>
</tr>
<tr>
<td>P(38)</td>
<td>107,880</td>
<td>29.41</td>
<td>107,909.4</td>
</tr>
<tr>
<td>P(40)</td>
<td>108,126</td>
<td>29.48</td>
<td>108,155.4</td>
</tr>
</tbody>
</table>

00°1-02°0 Band

<table>
<thead>
<tr>
<th>Transition</th>
<th>Wavelength in Vacuum</th>
<th>Correction Due to Air</th>
<th>Wavelength in Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(22)</td>
<td>95,691</td>
<td>26.09</td>
<td>95,717.1</td>
</tr>
<tr>
<td>P(24)</td>
<td>95,862</td>
<td>26.14</td>
<td>95,888.1</td>
</tr>
<tr>
<td>P(26)</td>
<td>96,063</td>
<td>26.19</td>
<td>96,089.2</td>
</tr>
<tr>
<td>P(28)</td>
<td>96,211</td>
<td>26.23</td>
<td>96,237.2</td>
</tr>
<tr>
<td>P(30)</td>
<td>96,391</td>
<td>26.28</td>
<td>96,417.3</td>
</tr>
<tr>
<td>P(32)</td>
<td>96,576</td>
<td>26.33</td>
<td>96,602.3</td>
</tr>
<tr>
<td>P(34)</td>
<td>96,762</td>
<td>26.38</td>
<td>96,788.4</td>
</tr>
</tbody>
</table>

00°1-10°0