OPERATING CHARACTERISTICS OF A TEA LASER WITH BRASS ELECTRODES

by

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B.Sc., Simon Fraser University, 1969

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
in the Department of

Physics

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SIMON FRASER UNIVERSITY

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ABSTRACT

A four electrode design for a transversely excited atmospheric pressure (TEA) carbon dioxide laser has been investigated. The laser is operated by discharging a 0.002 or 0.005 F capacitor charged to voltages as high as 60 kV between two brass bars a meter long. Two flat copper electrodes are mounted parallel to the plane of the main electrodes and are held at the same potential as the anode. The side electrodes are necessary to obtain a uniform discharge and consequent laser operation. The laser operation has been investigated as a function of gas mixture and electrode separation and with various circuit parameters. The results are compared to those obtained with the more usual two electrode TEA laser in which one of the electrodes consists of a row of resistors. It is found that the new design gives a higher energy output and an output pulse of shorter duration than the conventional design. Also deterioration of the resistors limits the lifetime of the conventional design but is not a factor in the new design.
ACKNOWLEDGEMENTS

I am indebted to Dr. J.C. Irwin for his valuable help and guidance throughout the course of this investigation. Also, I wish to thank my friends and colleagues, particularly Jim LaCombe and Frank Wick, for their helpful encouragement.

A great debt of gratitude is due to my wife Moray, who has inspired me when times were bad and has helped me to appreciate the good times.

Financial support in the form of a NRC scholarship is gratefully acknowledged.
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CHAPTER I

INTRODUCTION

After the discovery of the ruby laser in 1960, it was assumed that solid state lasers would be the most powerful lasers ever built simply because of the greater density of "lasing" particles in a solid than in a gas. Nevertheless, solid state lasers have their disadvantages. They rate rather poorly in two important criteria of laser performance—spectral purity and spatial coherence of the output radiation. In addition, most high power solid state lasers are a source of short intense bursts of light rather than of a continuous beam of light. In contrast, the atomic gas lasers produce continuous beams with excellent spectral purity and spatial coherence, but their power output was very low compared with the power output from the solid state lasers.

The situation has changed entirely with the advent of the molecular gas lasers. The outstanding example of this new class of lasers is the carbon dioxide laser, which can produce a continuous laser beam with a power output of several kilowatts while at the same time maintaining the high degree of spatial coherence and spectral purity characteristic of the lower power atomic gas lasers.

Whereas the most widely employed type of continuous gas
laser, the helium-neon laser, can be characterized by efficiencies on the order of \(10^{-5}\) to \(10^{-4}\) and a power 5-50 mW, and argon ion lasers by values \(10^{-3}-10^{-2}\) and 1-20 watts, respectively, the efficiencies of CO\(_2\) lasers reach \(10^{-1}\) at powers on the order of hundreds of watts.

A conventional CO\(_2\) laser (Patel, 1968a; Sobolev and Sokovikov, 1967) operates on a low pressure (10 torr) mixture of CO\(_2\), helium, and nitrogen. The discharge of approximately 10 kilovolts and 100 milliamperes is longitudinal; that is, parallel to the laser axis as defined by the mirrors. With the discharge tube being cooled, a power output of fifty to seventy watts per meter of length can be expected from such a laser. Furthermore, such a laser can be Q-switched. Lasing action is prevented by blocking the beam path; this allows the population of the upper laser level to build up. When the laser is allowed to oscillate, the energy is extracted in a pulse lasting about 100 nanoseconds of about 10 kilowatts. Q-switching a CO\(_2\) laser is most often done with a rotating mirror.

The transversely excited atmospheric pressure carbon dioxide laser, or TEA laser, is capable of producing megawatt pulses (Beaulieu, 1970). The obvious advantage of an atmospheric pressure laser is easy construction and maintenance,
as vacuum pumps and vacuum seals are of no concern. The increase in power results from the greater density of molecules that contribute, assuming no change in the excitation efficiency. Also the pulse repetition rate is limited by the lifetime of the energy level to which the lower laser level decays; this lifetime is determined primarily by collisions and is inversely proportional to operating pressure. Thus increasing the pressure makes the laser easier to build, gives a higher energy per pulse, and allows an increase in the pulse repetition rate.

An abnormally large voltage would be required if the discharge at atmospheric pressure was longitudinal. The electrodes therefore are long and narrow and are arranged parallel to the cavity axis. A reasonably regular discharge between these electrodes is required for laser action as irregularities cause local heating and variations in the index of refraction of the gas which give rise to severe losses. Consequently much effort has been expended in an effort to achieve uniform discharge conditions and a variety of electrode structures have been investigated.

The most common electrode design employs a row of 1000 ohm resistors as one electrode and a brass bar as the other, or rows of resistors for both electrodes (Beaulieu, 1970;
Fortin, 1971). One lead of each resistor points toward the opposite electrode, the other lead is connected to a common terminal. The interelectrode separation is about 2 cm. Gas mixes used are 5 to 10% each of CO\textsubscript{2} and N\textsubscript{2}, and the remainder helium. For a meter long laser, a capacitor of up to 0.02 microfarads charged to about 30 kV is discharged across the two electrodes, producing output pulses of several hundreds of millijoules lasting a fraction of a microsecond. The resistive loading of the pins provides a uniform discharge as there is a long time constant for a discharge through a single pin, but not for a discharge through 100 to 200 pins in parallel.

With more careful circuit design reducing the inductance, a uniform discharge can be obtained with electrodes consisting of pins that are not resistively loaded (Laurie and Hale, 1970, 1971). Higher voltages (up to 60 kV) and a smaller capacitance are used than with the resistor electrode laser. A meter-long laser of this kind has produced two joule pulses with 17% efficiency. It is believed that this system provides a uniform discharge because the rise time of the current pulse is shorter than the characteristic time associated with the breakdown of the gas. All the pins will therefore begin to pass current simultaneously. Another system which does not use resistively loaded electrodes is
one in which each pin is connected to its own capacitor (Johnson, 1971; Smith and DeMaria, 1970). This system has not operated with the efficiency of that of Laurie and Hale.

This thesis describes a new electrode arrangement for the TEA laser. The main electrodes are two brass rods about a meter long parallel to the cavity axis; a good discharge is obtained with both round and square rods. In addition there are two flat side electrodes parallel to the plane of the two main electrodes and one on each side of this plane. The auxiliary electrodes are electrically connected to the anode. A reliable, uniform discharge and high output power are obtained when a capacitor charged to voltages as high as 60 kV is discharged between the main electrodes.

The results obtained with this laser are compared to those obtained with the more established type of TEA laser in which one electrode is a brass bar and the other electrode consists of a row of pins, each pin connected to a common terminal through a thousand ohm resistor.

The organization of the thesis is as follows. Chapter II contains a discussion of the vibrational-rotational energy levels and transitions involved in the CO₂ laser, and the role of the different gases in achieving a population inversion.
The next chapter discusses the collision reactions important in the excitation processes in a TEA laser. Following this is a description of the laser investigated and the auxiliary apparatus used in this work. Chapter V presents the results of the investigation of the properties of the laser, and discusses the discharge characteristics and the power output. Suggested improvements and possible avenues for future work are discussed in the final chapter.
CHAPTER II

EXCITATION MECHANISMS IN CARBON DIOXIDE LASERS

This chapter contains a discussion of the properties of the CO₂ molecule and the processes that lead to a population inversion in the carbon dioxide laser. The role of the different gases in the discharge is considered and a brief analysis of the collision reactions that result in a population inversion is given.

II-1. The CO₂ Molecule

The carbon dioxide molecule in its equilibrium configuration is linear and symmetric and has nine degrees of freedom: three translational, two rotational, and four vibrational. There are four independent normal modes of vibration as shown in figure 1; two of these are degenerate and are considered as one doubly degenerate mode. The two degenerate modes combine with appropriate phase difference to form a mode with a net angular momentum. However if two quanta are excited, they may have equal or opposite angular momenta, so the total vibrational angular momentum is 0 or 2. The vibrational energy levels (figure 2) are denoted \((v_1v_2^Lv_3)\) where \(v_1\) is the number of quanta of mode 1 that are excited and \(L\) is the net angular momentum of the degenerate level. In the harmonic approximation the energy (in cm⁻¹) of the \((v_1v_2^Lv_3)\) level is given by (Herzberg, 1964, pg 210)
Figure 1. Vibrations of Carbon Dioxide Molecule. 
a. Normal modes of vibration. b. Combination of degenerate modes to form a mode with net angular momentum.
Figure 2. Low-Lying Vibrational Levels of Carbon Dioxide

Numbers in parenthesis indicate energy of the levels in \( \text{cm}^{-1} \). The laser transitions are indicated by dashed lines. Other allowed transitions involving the laser levels are shown as dotted lines.
Where \( d_i \) indicates the degeneracy of the \( i \text{th} \) mode and is equal to unity for the nondegenerate modes.

The separation between the \( 10^00 \) level and the \( 02^{L0} \) levels is very small \((16 \text{ cm}^{-1})\). Anharmonicities perturb the \( 10^00 \) and the \( 02^00 \) levels, forming new levels \( 10^3 \text{ cm}^{-1} \) apart, each a combination of the two original levels. The \( 10^00 \) level does not interact with the \( 02^20 \) level because they have different angular momenta. This is the only anharmonic effect large enough to be considered in this work.

If a molecule is in a given vibrational state and a given electronic state, it may be in any one of a number of rotational states. That is, on each of the vibrational states of figure 2, there are superimposed a number of rotational states, as shown in figure 3. The energy levels in \( \text{cm}^{-1} \) due to rotation are given by (Herzberg, 1964, pg 14)

\[
E_T(J) = BJ(J+1) - DJ^2(J+1)^2
\]

Where \( J \) is the rotational quantum number and the rotational constant \( B \) associated with a particular vibrational state is given by

\[
B = \frac{\hbar}{8\pi^2cI}, \quad I = \sum_j m_j r_j^2.
\]

The \( DJ^2(J+1)^2 \) term arises because of the non-rigidity of
Figure 3. Partial energy level diagram of rotational-vibrational levels. Relative population densities $N(J)$ of rotational levels in the same vibrational state indicated on horizontal axis.
the molecule and for our purposes can be considered negligible. The energy of the $J$ rotational level of the $(v_1 v_2 L v_3)$ vibrational state is given by the sum of equations 1 and 2.

Since the nuclear spins of $^{12}C$ and $^16O$ are zero, a CO$_2$ molecule obeys Bose statistics, and the total wavefunction must be symmetric with respect to a simultaneous exchange of the identical nuclei. The even $J$ rotational levels of the $10^00$ and $02^00$ vibrational states and the odd $J$ rotational levels of the $00^01$ vibrational state are symmetric. Antisymmetric rotational-vibrational levels do not exist in CO$_2$ and therefore only those levels mentioned above are shown in figure 3.

II-2. Rotational-Vibrational Transitions

The matrix element for the dipole moment are evaluated to determine the allowed transitions between rotational-vibrational levels. The matrix elements are given by

$$\overline{\mu}_{12} = \sum_i q_i \int \Phi_i^{*} \Phi_j \Phi_2 d\tau$$

where the wave function, neglecting rotational-vibrational interactions, is

$$\Phi = \Phi_{\text{vib}}(v) \Phi_{\text{rot}}(J)$$

and $\vec{r}_i$ is the coordinate of the $i^{th}$ particle with respect to coordinate axis fixed in space. A tensor $\overline{T}_{ij}$ relates the
coordinates $\bar{\mathbf{r}}_i$ to another set of coordinates $\bar{\mathbf{r}}'_i$ which are fixed in the molecule and rotate with it. $\bar{T}_J$ depends on the axis and frequency of rotation but is independent of the vibration. In this approximation the matrix elements for the dipole moment are given by

$$\bar{K}_{VV',JJ'} = \int \Phi_{\text{rot}}^* (J) \bar{T} \Phi_{\text{rot}} (J') d\tau_{\text{ret}} \sum_i \int \Phi_{\nu_i}^* (\nu) \bar{\Phi}_{\nu_i} (\nu) d\omega$$

$$= \bar{T}_{JJ'} \bar{K}_{VV'}$$

That is, the matrix elements are to a good approximation the product of the matrix elements $T_{JJ'}$ and $K_{VV'}$ for the rotational and vibrational transitions individually.

For linear molecules such as $\text{CO}_2$ the rotational matrix elements are non-zero only for transitions that satisfy the condition

$$\Delta J = \pm 1.$$ 

For these cases (Herzberg, 1967, pg 127)

$$T_{J', J+1}^2 = J$$  \hspace{1cm} 4a.

and

$$T_{J', J-1}^2 = J+1$$  \hspace{1cm} 4b.

There is no dipole moment associated with symmetric vibrations, as can be seen from figure 1. Therefore transitions are not allowed between the $10^00$ and the $00^00$ states.
The 01^0_0 and 00^0_1 vibrational states are however connected to the ground state. Also, the transitions 00^0_1 to 10^0_0 (10.6 microns wavelength) and 00^0_1 to 02^0_0 (9.6 microns) are allowed. Lasing action in CO_2 takes place on these transitions.

In the allowed transitions the J value of the final state can be one more or one less than the J value of the initial state. P branch transitions are absorptions (\Delta J = -1) or emissions (\Delta J = 1) connecting the J rotational level of the lower vibrational state to the J-1 rotational level of the upper vibrational state. R branch transitions are between the J and the J + 1 rotational levels of the lower and upper vibrational states respectively. The transitions are indicated by P(J) and R(J) where J traditionally refers to the rotational quantum number of the lower state. Two such transitions are indicated on figure 3.

The relative strengths of different spectral lines are influenced by the populations of the initial states. If a vibrational level \( \nu_1 \nu_2 \nu_3 \) has total population \( N(\nu_1 \nu_2 \nu_3) \), then the distribution of population among the rotational levels in equilibrium is given by

\[
N(\nu_1 \nu_2 \nu_3, J) = C N(\nu_1 \nu_2 \nu_3) g_J e^{-\frac{hc}{kT} E^*_J} , \quad C \approx \frac{2hcB}{kT} \tag{5}
\]

where \( E^*_J \) is the energy in cm\(^{-1}\) given by equation 2, and \( g_J \), the statistical weight of the level is given by

\[
g_J = 2J + 1.
\]
This population distribution is illustrated in figure 3.

II-3. **Gain in Carbon Dioxide Lasers**

Lasing action—the excess of stimulated emission over absorption processes—can take place from the rotational levels of the 0001 level to those of the 1000 level that satisfy the condition \( \Delta J = \pm 1 \). A population inversion is of course required for lasing action. The following arguments consider the gain as a function of the specific transition.

If \( N(v',J') \) is the population of the upper laser level (0001,J') and \( N(v,J) \) is the population of the lower laser level (1000,J), then the gain per unit length on the transition is given by

\[
G(J) = B_{VV'}JJ' \left[ N(v',J') - \frac{g_J'}{g_J} N(v,J) \right] \frac{h\nu}{c}
\]

Here \( h \) is Planck's constant, \( c \) is the velocity of light, and \( \nu \) is the frequency of the transition. \( B_{VV'}JJ' \) the stimulated emission probability is given by

\[
B_{VV'}JJ' = \frac{2\pi^2e^2}{3\hbar^2c} \frac{1}{g_J'} \left| M_{VV'}JJ' \right|^2
\]

where \( e \) is the electronic charge and \( \varepsilon ' \) the dielectric constant of free space. The matrix element for the transition can be separated into two parts \( K_{VV'} \) and \( T_{JJ'} \), where \( T_{JJ'} \) is given by equation 4. If the total populations of the upper and lower vibrational levels are \( N(v') \) and \( N(v) \) respectively,
then the population of their $J$th rotational levels are given by equation 5. $B'$ and $B$ are the rotational constants in the upper and lower vibrational states respectively. Combining these equations, the gain on the P($J$) transition is

$$G(J) = \frac{4\pi e^2}{3\varepsilon_0 kT} |K_{\nu\nu}|^2 \left[ N(\nu) B' e^{-\frac{\hbar c E_{\nu}(J+1)}{kT}} - N(\nu) B e^{-\frac{\hbar c E_{\nu}(J)}{kT}} \right]$$

and the gain on the R($J$) transition is

$$G(J) = \frac{4\pi e^2}{3\varepsilon_0 kT} |K_{\nu\nu}|^2 (J+1) \left[ N(\nu) B' e^{-\frac{\hbar c E_{\nu}(J+1)}{kT}} - N(\nu) B e^{-\frac{\hbar c E_{\nu}(J)}{kT}} \right]$$

The gain as a function of $J$ for these transitions is plotted in figure 4, taking the rotational constants for the upper and lower vibrational states to be 0.3866 cm$^{-1}$ and 0.3897 cm$^{-1}$ respectively (Patel, 1964a). For convenience, the constants in the equations 6 are taken equal to unity; that is,

$$\frac{4\pi e^2}{3\varepsilon_0 kT} |K_{\nu\nu}|^2 N(\nu) = 1$$

Some noticeable features of the gain curve are as follows. P-branch transitions can show gain even when there is no net population inversion. R branch transitions need a considerable inversion to show gain, and when they do the gain is less than that on the corresponding P branch. The P branch transitions will therefore dominate. There is power output on the R branch only when there is a wavelength discriminating device such as a grating in the cavity introducing
FIG. 4  Normalized gain as a function of upper-level \( J \) for \( P \) and \( R \) branches (for \( T = 400^\circ K \) and \( N_0 \ 0^0_1/N_1 \ 0^0_0 = 0.95, 1, 1.05, \) and 1.1).
a loss in the P branch transitions so that the net gain on the R branch is higher.

A similar treatment may be applied to transitions from the rotational levels of the 00\textsuperscript{0}1 vibrational state to the rotational levels of the 02\textsuperscript{0}0 vibrational state. The gain on these transitions around 9.6 microns or 1060 cm\textsuperscript{-1} is however lower than that on the 00\textsuperscript{0}1 to 10\textsuperscript{0}0 transitions, and consequently the power output at 9.6 microns will be lower than that at 10.6 microns. In cases where there is strong competition between the two transitions, all the output will be at 10.6 microns.

II-4. Excitation Mechanisms in a Carbon Dioxide Discharge

Laser action in a low pressure CO\textsubscript{2} discharge was first observed (Patel, 1964b) on the P branch rotational transitions of the 00\textsuperscript{0}1-10\textsuperscript{0}0 and 00\textsuperscript{0}1-02\textsuperscript{0}0 vibrational bands. Several possible excitation mechanisms have been proposed for a laser operation on CO\textsubscript{2} alone.

Direct electron impact excitation is a possible mechanism that would result in a population inversion and hence laser action. For incident electrons with energy between 0.3 and 3 eV the cross-section for excitation to the 00\textsuperscript{0}1 level is much larger than that for excitation to the 10\textsuperscript{0}0 level. At larger electron energies, there is less difference between the cross-sections, as shown in figure 5. For electron
Figure 5. Electron impact excitation cross-sections in Carbon Dioxide and Nitrogen. In CO₂:

a) measured (Bones and Schulz, 1968)

b) calculated from known transport properties (Hade & Phelps, 1967)

Note that 10₁₀₀, 01₁₀₀ and 00₁₀₁ levels occur at 0.17 eV, 0.08 eV, and 0.29 eV respectively. In N₂:

c) cross sections to individual levels and d) total vibrational excitation cross section (Schulz, 1964)
energies lower than 0.3 eV, the cross-section for excitation to the $10^00$ level is largest. Therefore for a wide range of electron energies, the rate of pumping to the $00^10$ level is greater than the rate to the $10^00$ level.

It is by no means agreed that direct electron excitation is the only cause of the population inversion in a laser operated on CO$_2$ alone. Another suggestion (Patel, 1964b) is that carbon monoxide and oxygen from the dissociation of CO$_2$ recombine to form carbon dioxide in vibrationally excited states, which then lose their energy in near resonant collisions with other CO$_2$ molecules in the ground state:

$$\text{CO}_2(00^0v_3) + \text{CO}_2(00^00) \rightleftharpoons \text{CO}_2(00^01) + \text{CO}_2(00^0v_3-1) + \Delta E$$

where $\Delta E$ is much less than $kT$. Characteristic carbon monoxide spectra were observed in the carbon dioxide discharge.

Sobolev and Sokovikov (1967) suggested another excitation mechanism in which a near resonant transfer of energy takes place from the vibrationally excited states of CO formed in the discharge to the $00^01$ level of CO$_2$, similar to that in the CO$_2$-N$_2$ laser (see next section). The energy difference between the lowest excited state of CO and the upper laser level is approximately one half of $kT$, the thermal energy.

The above possibilities appear to be the most important mechanisms for populating the upper laser level. Their
relative importance is however a matter of controversy and further investigations are required to establish the dominant mechanism. Of course, it is not necessarily the same mechanism that dominates under different experimental conditions.

In continuous CO$_2$ lasers, in addition to populating the upper state, it is important that the lower laser level decay rapidly to the ground state to preserve the population inversion. This is accomplished mainly through the collision reactions (Sharma, 1968)

$$\text{CO}_2(1^00) + \text{CO}_2(00^0) \rightleftharpoons \text{CO}_2(02^2) + \text{CO}_2(00^0) + 53 \text{ cm}^{-1}$$  \hspace{1cm} 8a.$$

$$\text{CO}_2(02^2) + \text{CO}_2(00^0) \rightleftharpoons 2\text{CO}_2(01^0) + 1\text{ cm}^{-1}$$  \hspace{1cm} 8b.$$

The molecules in the $01^10$ state decay to the ground state mainly through inelastic collisions with other molecules and the container walls.

II-5. The CO$_2$-N$_2$ Laser: Resonant Energy Transfer

Operating a CO$_2$ laser with nitrogen added to the gas mix results in an increase in power output: a factor of three increase has been reported by Bridges and Patel (1965). This increase is due to the resonant transfer of energy from excited vibrational states of nitrogen to the upper laser level.

The nitrogen molecule has two rotational degrees of
freedom and one vibrational degree of freedom. The first excited vibrational level is 2330.72 cm\(^{-1}\) above the ground state (Herzberg, 1967, pg 553). This is only 18 cm\(^{-1}\) from the \(00^01\) vibrational excited state of carbon dioxide, much less than the average thermal energy of the molecules (210 cm\(^{-1}\)). Therefore the reactions

\[
N_2(1) + CO_2(00^00) \rightleftharpoons N_2(0) + CO_2(00^01) - 18 cm^{-1}
\]

and

\[
N_2(v) + CO_2(00^00) \rightleftharpoons N_2(v-1) + CO_2(00^01) - \Delta E
\]

have large cross sections, and are very likely to occur upon collision.

The cross-sections for electron impact excitation of the states \(N_2(v)\), \(v=1\) to 8, have been measured (Schulz, 1962, 1964) and found to be large. The peak value of the excitation cross section is \(3 \times 10^{-16} \text{ cm}^2\). Dipole radiation transitions from \(N_2(1)\) to \(N_2(0)\) are forbidden as the nitrogen molecule is symmetric and has no dipole moment. Thus a large proportion of the nitrogen molecules in an electrical discharge are in the excited vibrational levels. The addition of nitrogen to the discharge provides an efficient means of selectively exciting the upper laser level, resulting in a power increase.

Nitrogen also increases the lifetime of the lower laser level (Cheo, 1967), an effect detrimental to laser action.
but more than compensated for by the selective excitation of the upper laser level. The increase in lifetime is thought to be due to collision processes with the vibrationally excited states of a metastable electronic state of nitrogen:

\[ N_2(A^3\Sigma_u^+, v=1) + CO_2(00^00) \rightleftharpoons N_2(A^3\Sigma_u^+, v=0) + CO_2(10^00) + 44.8 \text{ cm}^{-1} \]

II-6. The CO$_2$-N$_2$-He Laser

Further increases in power output are obtained from carbon dioxide lasers operating with both nitrogen and helium added to the CO$_2$ discharge. A conventional laser operated with 1.2 torr of N$_2$ and 0.33 torr of CO$_2$ shows an increase in output from 12 watts to 106.5 watts upon addition of 7 torr of helium (Patel et al., 1965). The effect of the helium is twofold (Patel, 1968b, pg 106). Firstly it helps deexcite the 01$^10$ level of CO$_2$ and prevents a buildup of population in that state, through the reaction

\[ CO_2(01^10) + He \rightarrow CO_2(00^00) + He + 667 \text{ cm}^{-1} \]

Secondly, it is thought to aid in the excitation of CO$_2$ molecules to the 00$^01$ level, either directly or through interactions with nitrogen. One suggested interaction (Patel et al., 1965) is the collision of metastable $2^3S_1$ helium atoms produced in the discharge with nitrogen molecules,
resulting in their dissociation:

\[
\text{He}(2^3S_1) + N_2 \rightarrow \text{He} + 2N + 84,000 \text{ cm}^{-1}
\]

The nitrogen atoms recombine to form molecules in highly excited vibrational states, which then decay via the reactions 9, 10, and

\[
N_2(v) + N_2(0) \rightarrow N_2(v-1) + N_2(1) + \Delta E; \quad \Delta E \ll kT.
\]

The molecules so produced can then aid in filling the upper laser level (equation 9).
In a pulsed laser the power output may be several orders of magnitude higher than in a continuous laser, but lasts for only a short time. The three principle types of pulsed CO\(_2\) lasers are the current pulsed and the Q-switched conventional laser and the TEA laser.

III-1. **Current Pulsed CO\(_2\) Lasers**

Simply pulsing the current supply on a low pressure longitudinally excited laser results in a factor of 10 increase in "peak power output over that in a DC excited laser". The increase in peak power arises because of two effects. The first is that the gas remains cooler under pulsed excitation because the total energy dissipated in the gas is much smaller than under DC excitation, and there is sufficient time between pulses for appreciable cooling. Equation 6 shows the gain to be approximately inversely proportional to the temperature, so cooler operation will result in higher gains. The second reason for the increase in peak power is that the lower laser level is very nearly empty at the beginning of each excitation pulse, so a higher population inversion is achieved.
The second effect mentioned above limits the maximum useful pulse repetition rate to one such that the time between pulses is somewhat longer than the lifetime of the lower laser level. At faster pulse repetition rates, the lower laser level is no longer empty at the beginning of the pulse; thus the gain and the power output are decreased.

With pulsed excitation, the CO$_2$-N$_2$-He laser produces pulses with a duration of the order of 1 millisecond which occur several hundred microseconds after the current pulse (Patel, 1968b, pg 110).

III-2. The Q-switched CO$_2$ Laser

The Q-switched technique gives power outputs of 10 kW from a laser which would give 50 watts if run continuously and about 500 watts if current pulsed (Patel, 1968b, pg 112). When the laser is not allowed to oscillate energy is stored in the upper laser level for a time of the order of the level lifetime, about 1 millisecond at 2 torr of CO$_2$. When the laser is allowed to oscillate, the energy is extracted in a pulse of about 100 nanoseconds and hence there is a large increase in peak power. The Q-switched laser does not however take full advantage of the energy in the molecules CO$_2$(00$^0$0) and N$_2$(v) as the operating time of the laser is short compared to the relaxation time for the transfer of excitation to the upper laser level (equations 7, 9, 10 and 12).
at low pressure.

III-3. The TEA Laser

The TEA laser differs from the conventional gas lasers in that the gas mixture is at atmospheric pressure and the discharge is transverse to the cavity axis. It is excited by a capacitive discharge resulting in a high current lasting a short time (typically 100-800 amperes with a width at half maximum of 0.5 microseconds). As a result of the greater density of molecules at atmospheric pressure, the rate of transfer of excitation to the upper laser level (equations 7, 10 and 12) is much increased over the rate in low pressure lasers. Consequently, the output occurs after a shorter delay following the current pulse and is of considerably shorter duration, or the order of one microsecond. Another consequence of the increased molecular density is that the power outputs obtained (about one half megawatt) are significantly larger than those from a Q-switched conventional laser.

The remainder of this chapter is devoted to a discussion of the energy transfer processes resulting in the gain in a TEA laser. The discussion is also applicable to the current pulsed laser, but the time scales involved are considerably different.
The capacitive discharge results in the excitation of carbon dioxide and nitrogen molecules to all their vibrational levels. Transfer of excitation between molecules in these various levels takes place in collision reactions of two main types. Vibrational-translational (V-T) collisions change vibrational energy into translational energy:

\[ A^* + M \rightarrow A + M + K.E. \]

M may be a container wall, another molecule of the same kind, or a molecule of a different kind. Equation 11 is an example of such a reaction. Helium is very effective as a de-exciting agent through V-T collisions because of its light mass. Vibrational-vibrational (V-V) collisions result in the transfer of excitation from one species to another:

\[ A^* + B \rightarrow A + B^* \pm \Delta E. \]

These collisions are reversible; that is, they can proceed in either direction, but the exothermic reaction is faster than the endothermic. If \( \Delta E = 0 \), the reaction is said to be resonant. Generally speaking, they are two orders of magnitude faster than V-T collision reactions (Taylor and
Bitterman, 1969). Equations 9, 10, and 12 are examples of V-V reactions.

Some information about the relaxation rates and relaxation times for these processes is available (Taylor and Bitterman, 1969) from experiments with CO₂ gas or with gas mixes used in conventional CO₂ lasers, and from ultrasonic attenuation measurements. No information that is pertinent to the gas mixes commonly used in TEA lasers is available at the present time. The lifetimes of the levels and the reaction rates are determined primarily by collisions and are therefore very dependent on the pressure and the temperature, the surface-to-volume ratio of the container, the gas mix, and impurity concentrations. A value for a level lifetime found in one experimental situation is by no means valid in another situation. Nevertheless, these measurements can be considered a basis for estimating values for the level lifetimes in atmospheric pressure gas mixtures. These "calculated" values are given only as a temporary substitute for values found by direct measurements. Because of the great interest in the TEA laser it is expected that measured values of the level lifetimes will be available in the near future.

The lower level lifetime is influenced by three different processes. If the population of the 10⁰⁰ level is increased by some means above its equilibrium value, the excess energy
is rapidly redistributed amongst the $0^2_0$, $0^2_2$ levels by near-resonant V-V collisions between the molecules. Secondly, there is a near-resonant transfer of energy from these levels to the $0^1_0$ level. The reaction (equation 8b) involving the $0^2_2$ level is known to be two orders of magnitude faster than the reactions with the other levels (Sharma, 1968). This reaction results in an equilibrium distribution of population between the $0^2_2$, $0^1_1$, and $0^0_0$ levels at some vibrational temperature $T_v$. Decay from the $0^1_1$ level to the ground state which proceeds mainly through a V-T collision with helium (equation 11) disturbs this equilibrium and results in a further transfer of energy from the $1^0_0$ level to the $0^2_2$ level and thence to the $0^1_1$ level. The time scales for these processes were estimated to be approximately $10^{-9}$ seconds, 0.05 μsec., and 0.2 μsecs respectively, assuming 5% CO$_2$, 5% N$_2$, and 90% He in a gas mix at atmospheric pressure, with 5% of the CO$_2$ initially excited to the lower laser level and 50% remaining in the ground state. The population of the lower laser level does not decay in a simple exponential, but as the sum of several exponentials. The decay constants and the relative influence of each exponential depend on the population in each excited level.

The lifetime of the upper laser level does not appear to be as strongly affected by the presence of helium as is
the lower level lifetime (Cheo, 1967). Collisions with other \( \text{CO}_2 \) molecules and \( \text{N}_2 \) molecules determine the lifetime through the collision reaction

\[
\text{CO}_2(00^0 1) + M \rightarrow \text{CO}_2(V_1V_2^L 0) + M + \text{KE}.
\]

where the state excited as a result of the collision is one of \((03^L 0), (04^L 0), \) or \((11^L 0)\). The reaction rate is \(5 \times 10^{-14}, 8 \times 10^{-14}, \) and \(10^{-15} \text{ cm}^3/\text{sec}\) for collisions with \( \text{CO}_2, \text{N}_2, \) and \( \text{He} \) respectively (Taylor and Bitterman, 1969). The inverse lifetime with a specific gas mix and gas pressure is the sum of the products of the reaction rates and the density of the respective molecules. Based on these figures an estimate of the upper level lifetime is 5 \( \mu \text{secs} \) in a 5\% \( \text{CO}_2, \) 5\% \( \text{N}_2, \) and 90\% \( \text{He} \) gas mix at atmospheric pressure. The lifetime is however dependent on the relative proportions of the different gases in the gas mix.

The lifetime of the lowest vibrationally excited state in nitrogen is determined by V-T collisions with helium. In an atmospheric pressure gaseous mixture consisting mostly of helium the lifetime is 40 microseconds (from data of Taylor and Bitterman, 1969). Thus energy can be stored in the vibrational energy levels of nitrogen for a time long compared with the upper laser level lifetime.

The population of the upper laser level is greatly influenced by the transfer of excitation from nitrogen
(equation 10) and from higher excited states of CO₂ 
(equation 7). The rate equation for the population $N_c(l)$ 
of the upper laser level, considering these equations and 
equation 13, is

$$\frac{dN_c(l)}{dt} = -\frac{N_c(l)}{\tau_u} + \sum_{\nu \neq 1} \left[ k_{nv} N_n(v) N_c(\nu) - k'_{nv} N_n(v-1) N_c(l) \right] + \sum_{\nu \neq 2} \left[ k_{cv} N_c(v) N_c(\nu) - k'_{cv} N_c(v-1) N_c(l) \right]$$

$N_c(v)$ is the population density of CO₂ molecules in the $(00^0v)$ states and $N_n(v)$ the population density of $N_2(v)$ molecules. $\tau_u$ is the lifetime of the upper laser level determined by 
equation 13, $k_{nv}$ and $k_{cv}$ the reaction rates for equation 10 
and 7 respectively, and $k_{nv}'$ and $k_{cv}'$ the reaction rates 
for the reactions in the reverse direction. Since $\Delta E \ll kT$ 
in all cases, $k_{nv} \approx k_{nv}'$ and $k_{cv} \approx k_{cv}'$. From the rate 
equation it is obvious that the rate of transfer of energy 
to the upper laser level will depend on the density of 
molecules in each excited level and in the ground states.

III-5. Gain in a TEA Laser

An attempt can be made to describe qualitatively the 
temporal behavior of the gain in the absence of stimulated 
emission following a short current pulse. For simplicity,
the populations of all the rotational levels of a given vibrational state are considered as a whole. The current excites nitrogen and carbon dioxide molecules to the various vibrational states. The transfer of excitation from nitrogen molecules and from more highly excited CO₂ molecules increases the population of the upper laser level, until the transfer reactions reach equilibrium. The rate of transfer of energy depends on the initial distribution of the energy among the excited levels, and the number of molecules in the ground states. Molecules in the upper laser level lose their energy in a collision reaction (equation 13) with a time constant that depends strongly on the proportion of gases in the gas mix. Because of the transfer of energy and decay processes tending to increase and to decrease the population of the upper laser level, it decreases initially, goes through a maximum, and finally decreases. The time of the maximum depends on the density of molecules in each excited state and in the ground states, and on the proportion of the gases in the gas mix. The initial population of the lower laser level decays faster than does that of the upper laser level. The gain, proportional to the difference between the populations, increases at first, goes through a maximum close to the maximum of the upper laser level population, and decreases. Gain measurements indicate a temporal behavior of this general shape (Robinson, 1970)
with the time of the maximum varying between 1.5 and 5.5 microseconds after the current pulse and depending on the gas mix.

The threshold for lasing action occurs when the gain (equation 6) is equal to the losses in the cavity. The laser will not oscillate until the gain increases to the point that this condition is satisfied. There is therefore a delay between the current pulse and the start of the lasing action. The delay, the time it takes for the gain to increase to its threshold value, depends on the losses in the cavity and those factors that influence the temporal behavior of the gain. Abrupt spatial fluctuations of the index of refraction due to heating of the gas in the rather narrow discharge channels are probably the most important cause of loss in a TEA laser. Discharge conditions greatly affect the loss in the laser cavity, and hence affect the delay time. As mentioned in the previous paragraph, the temporal behavior of the gain, and hence the delay time, is affected by the density of population immediately following the discharge in each excited state and in the ground states of CO$_2$ and N$_2$, and by the relative proportions of the gases in the gas mix.
CHAPTER IV

DESCRIPTION OF THE LASER AND ANCILLARY APPARATUS

Two lasers were used in this work, or rather, one laser with two different cathodes. One was the four electrode laser which was the main subject of the investigation. The operating characteristics are compared to those of a TEA laser with a resistor cathode, similar to that used by other investigators (Beaulieu, 1970; Fortin, 1971). For the remainder of this thesis, the laser when operated with the brass bar cathode and with the side electrodes connected to the anode, shall be referred to as laser A, and when operated with the resistor cathode shall be referred to as laser B. Both lasers were used with the same laser chamber, mirrors, gas supply system, and electrical circuit.

IV-1. Laser Box and Mirror Mounts

One predominant feature of the laser is that it is made from ordinary and unsophisticated materials. The laser box itself was constructed of plexiglass (lucite), with inside dimensions 7.6 x 7.6 x 102 centimeters. The individual pieces of lucite were screwed and glued together with the exception of the top plate which is removable. A three centimeter length of five centimeter diameter lucite tubing
protruded from each endpiece, to make a connection to the mirror housing.

The mirror housings were machined out of aluminum, and consist of a cylindrical box 7.6 cm. in inside diameter and five cm. long. The mirrors themselves were mounted to the rear plate, which could be raised or lowered with a total movement of 2.5 cm. to adjust the relative position of the cavity axis. A polyethylene sheet taped to the lucite tubing on the laser box and to the mirror housings ensured that the mirrors were in the same gaseous atmosphere as the laser chamber, but was not a rigid connection. With this arrangement Brewster-angle windows were not needed, but a rock salt exit window 2.5 cm. in diameter, 0.3 cm. thick was used in the back plate of the mirror housing at the output end.

The laser box was bolted onto two labjacks which in turn were bolted to an inverted U-beam. The mirror housings were mounted on the same U-beam, which was rigidly attached to a heavy table.

IV-2. Electrodes

Brass bars, either round with 1.3 cm. diameter or square with a 1.3 cm. side, were used for the anode. When a square bar was used an edge rather than a face pointed towards the cathode. The square bar was 97 cm. long, the round bar was 99 cm. long. The ends of both were rounded off and smoothed
down. The two anode mounts served a dual purpose; because of a lock-nut arrangement they were rigid enough to be used to raise and lower the anode; and they provided an electrical connection with the discharge circuit.

As mentioned previously and shown in figure 6, two distinctly different kinds of cathode have been employed. One kind, used in laser A, utilized brass bars similar to those in the anode. Either a round or a square bar was used. The second kind was the row of resistively loaded pins used by Beaulieu and others. The pins were the leads of the 1000 ohm one watt resistors; both carbon composition and film resistors were tried. To construct one such cathode, a series of 121 holes, each 0.6 cm. in diameter were drilled in the center line of the removeable top plate of the laser box; the resistors were glued in these holes and their top leads soldered to a thick (3 mm.) copper wire. The bottom leads projected through the bottom of the piece of lucite forming a row of pins; these were cut off to a length of 1.3 cm. A second cathode of this type in which there was two rows of resistors with the bottom leads bent towards each other had twice as many pins. Aligning the pins was more of a problem here, but was accomplished by squeezing the pins between two strips of lucite, as in figure 6. All the measurements with laser B were taken with the cathode consisting of the double row of resistors.
Figure 6. Construction of the laser.
a) cross section of the laser chamber and of different cathodes used. 3/4 scale.
Shading indicates lucite material.
Figure 6. (cont). b) Cross-section of mirror housing and connection to laser chamber.
The side electrodes consisted of strips of copper tape 1.9 cm. wide, running almost the length of the laser box. They were covered with two and in some places three layers of mylar each 60 micrometers thick. Each side electrode was electrically connected to the anode by two thin copper wires soldered to the copper strip, passed through a small hole in the lucite, and around the outside of the box to brass plates screwed into the bottom of the box and in contact with the anode mounts. The side electrodes could easily be disconnected from the anode, and were disconnected when the laser was operated with a resistor cathode. The presence of the side electrodes in the chamber did not affect the discharge characteristics of the energy output of laser B, as compared to the characteristics before the side electrodes were installed in the chamber.

IV-3. Mirrors

The mirrors used in this work were a brass mirror, five cm. in diameter, with a hole of diameter 3.5 mm. through the center, polished to be optically flat, and a silver coated glass mirror 2.5 cm. in diameter with a two meter radius of curvature. There was a SiO protective coat on the silver mirror. The mirrors were mounted on the removeable backs of the mirror housings with three springs and screws each, ¼/20 screws for the flat mirror, 8/32 for the concave. The
mounting was such that the alignment could be adjusted while the laser was in operation. The cavity length was 1.4 meter.

The beam diameter of the fundamental mode at the flat mirror is 3.5 mm, which is equal in diameter to the hole in the mirror (Kogelnik and Li, 1966).

IV-b. Gas Supply System

The CO₂ source was a pressurized tank with a standard regulator to reduce pressure to 20 p.s.i. Nitrogen and helium were obtained from a wall supply pressurized at 14 to 18 p.s.i. Precision needle valves controlled the flow of the gases; the flow was subsequently measured on gas flowmeters: #13 Gilmont Compact Flowmeters supplied by Kontes Glass Company. The gas was mixed in a mixing chamber and passed from there into the laser chamber. Although no pains had been taken to make the box air-tight, two 0.6 cm. holes, one at each end, were provided to allow the gas to escape from the box into the atmosphere.

As the flowmeters had a scale reading of liters per minute of air at atmospheric pressure and room temperature, it was necessary to calibrate the flowmeters for use with carbon dioxide, helium, and nitrogen. The absolute accuracy of the calibration is limited to 0.85 l/min for CO₂ and N₂ and to 2.5 l/min for He, as compared to the total gas flow
usually used of about 30 l/min. The relative accuracy was somewhat better, about 1% of the total flow for CO₂ and N₂ and 3% for He.

IV-5. **Electrical Circuit**

The electrical circuit used is shown in figure 7. A 60 kilovolt power supply model no. R60A-N made by Hipotronics Inc. is used. The charging resistors were IRC 20 megohm 50 watt resistors; two of these in parallel were used for R’. A variety of capacitors were available with capacities from 0.001 to 0.02 microfarads and voltage rated up to 80 kilovolts; they were phenolin-cased high voltage capacitors from Film Capacitors, Inc.

The spark gap was made of lucite tubing with 11.4 cm. inside diameter, 10.2 cm. long, with a lucite bottom holding one electrode and a brass top holding the other. The electrodes were 1.3 cm. brass bolts with hemispherical heads; one has a hole drilled down the bolt and through the head. The trigger pin consisted of a tungsten wire inside a glass capillary. The glass capillary was inserted in the electrode hole and insulated the trigger pin from the spark gap electrode.

The trigger unit was of the Theophanus type (Theophanus, 1960). A high voltage source charges up a six foot length of RG8A/U transmission line. A switch at the source end
Figure 7. Electrical circuit used to excite the laser. C: Capacitor, sg: spark gap, R and R' charging resistors, sw represents switching circuit of Figure 8.
shorts out the transmission line, launching two travelling waves in the line, one in each line. The capacitor and the resistor terminating the line, effectively an infinite termination, reflect the incident pulse with a reflection coefficient of unity, instantaneously doubling the voltage across the termination. Simultaneously the 500 pF capacitor discharges. The sum of the voltages across the resistor is sufficient to break down the gap between the trigger pin and the spark gap electrode, producing a small spark.

The high voltage for the trigger unit was produced by a standard television circuit using a flip-flop oscillator, a tetrode amplifier, and a flyback transformer. Varying the voltage on the screen grid of the tetrode varied the high voltage between 5 and 15 kilovolts.

The switch itself was a hydrogen thyratron 5C22. The switching circuit is shown in figure 8. The B+ (300V) and A- (-100V) voltages were obtained from a regulated power supply. Shorting input B or applying a positive pulse to input A caused the thyratron 2D21 to conduct electricity which fired the larger thyratron. To trigger the laser at regular intervals, either a pulse generator or the +gate signal from a free running time base of a dual beam oscilloscope was used to provide a positive pulse to input A.
Figure 8. Switching circuit of the trigger unit.
IV-6. **Detectors**

A pyroelectric energy meter was used to measure the energy of the laser output, and a photon drag detector was used to observe the pulse shape. The mechanisms operative in these detectors are discussed in the appendix.

The pyroelectric energy meter was made from lead zirconate titanate ceramic HST-41 purchased from Gulton Industries Ltd. The ceramic was disc shaped, 2.5 cm. in diameter, 0.25 mm. thick, and has silver evaporated on both faces. Its physical properties are as follows (Lachambre, 1971):

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε  dielectric constant</td>
<td>1800</td>
</tr>
<tr>
<td>T₀  Curie temperature</td>
<td>270°C</td>
</tr>
<tr>
<td>ρ  density</td>
<td>7.6 gr/cc.</td>
</tr>
<tr>
<td>S  specific heat</td>
<td>0.4 j/gr-°C</td>
</tr>
<tr>
<td>K  thermal conductivity</td>
<td>1 watt/m-°C</td>
</tr>
<tr>
<td>λ  pyroelectric constant</td>
<td>0.02 microcoul/cm²-°C</td>
</tr>
</tbody>
</table>

The ceramic was mounted with one face against a brass rod which formed the heat sink and one electrode. The other electrode consisted of two strips of brass which bent to exert pressure on the silvered face of the ceramic, holding it against the heat sink. The assembly was mounted in a 5 cm. copper can with a 2.5 cm. copper pipe protruding
as shown in figure 9; the copper can and the front facing surface of the ceramic were grounded to minimize radiative pickup. The front face of the detecting element was blackened with an air-drying graphite solution.

The detector was calibrated using a ruby laser, a beam splitter, a Hadron Model 108 thermopile and a microvoltmeter, as shown in figure 10. The ruby laser was not Q-switched; the output as monitored on a 925 photodiode was a series of irregular pulses lasting 0.7 milliseconds. The reflectivity of the beam splitter was determined with a helium neon laser and a conventional power meter to be 9.1%. Changing the neutral density filters varied the energy incident upon the pyroelectric energy meter from one to 130 millijoules. The results of the calibration for 0.69 micron wavelength is shown in figure 11; the average responsivity of the detector was $11.8 \pm 1.13$ volts/joule. Taking into account the different reflectivity of carbon at 0.69 microns (Taft and Philipp, 1965) and at 10 microns (Sato, 1968) and assuming all the light energy not reflected was absorbed and turned into heat, the calibration at 10 microns wavelength was $7.05$ volts/joule.

The voltage output of the energy meter was displayed on an oscilloscope. Successive shots of the laser were recorded by using an open shutter on a polaroid camera mounted on the oscilloscope; twenty shots or more were recorded on
Figure 9. Sketch of pyroelectric energy meter.
Figure 10. Apparatus for calibrating pyroelectric energy meter.
Figure 11. Response of pyroelectric energy meter to incident radiation at 0.69 μm.
one frame by using a slow trace. The pulse heights recorded in this way are averaged and the root mean square deviation from the average is quoted as the error of measurement. It is actually an indication of the shot-to-shot reproducibility of the laser output energy.

To measure the rapid variation of the output with time, a photon drag detector was used. It consisted of a piece of p-type germanium 13 x 1.3 x 1.3 mm, with resistivity measured to be 3.75 ohm-cm. One end was soldered to the metallic center conductor of a BNC male connector. The crystal was then epoxied in position and an electrical connection was made to the exposed end. The detector was connected by RG58C/U cable directly to a Tektronix 555 oscilloscope. The response time of the detector was limited by the resistance of the crystal and the capacitance of the cable to be 50 nanoseconds.
CHAPTER V

EXPERIMENTAL RESULTS AND DISCUSSION

V-1. Discharge Characteristics

A reproducible discharge uniform along the length of the electrodes is a prerequisite for laser action from a TEA laser. Such a discharge with both laser A and laser B consisted of a series of narrow channels originating at the cathode and spreading out towards the anode. The discharge characteristics depended critically on the voltage, capacitance, interelectrode spacing, and gas composition. There was a distinct range of values of these parameters beyond which the discharge became irregular, with most of the discharge passing through one or several points. A bright arc discharge was the result, most of the gas remained unexcited, and as a consequence the laser output was drastically reduced.

With laser B, voltages up to 30 kV were used with a 0.01 μF capacitor. The discharge channels originate at the resistor pins and spread out to a diameter of 2 or 3 mm. With the proper choice of the parameters mentioned above a uniform discharge was obtained although even under the best possible conditions some discharge channels appeared somewhat
brighter than others. With more than about 8% each of CO2 and N2 in the gas mix, the irregularities became more severe and bright arc discharges became much more frequent.

A bright arc discharge with the resistor cathode resulted in the burning out of resistors. In particular, the use of a larger capacitor resulted in their rapid deterioration. The resistors in the cathode have had to be replaced several times in the course of this work. Both carbon composition and film resistors have been tried, and both are susceptible to being burnt out, although the carbon composition resistors are perhaps more durable.

A bright arc discharge would often result when the discharge between certain resistors and the anode did not occur directly, but via adjacent resistor pins. In other words, the current through several adjacent resistors flowed in one discharge channel. It is well known that the resistance of a gas discharge decreases with increasing current; this effect will cause an increase in the current of the joint channel at the expense of the normal discharge channels.

Two different cathodes were used with laser B. They were the same length, but one contained twice as many resistors as the other. In one cathode the pins were 8 mm. apart, in the other they were 4 mm. apart. It was hoped that the cathode with the larger number of pins could be used with a capacitor twice as large, hence injecting twice
as much energy into the cavity. The current per pin would be the same as when using the smaller cathode and the smaller capacitor. Some improvement in energy output was noticed under these conditions. However, interactions between discharge channels resulting in bright arc discharges, as discussed above, greatly restricted the CO$_2$ and N$_2$ content of the gas mix used with the cathode with the smaller distance between pins and the larger capacitor. Consequently, the improvement was not as great as expected. This indicates that a greater range of values for the operating parameters would have resulted if the second cathode had been constructed with the same separation between pins as the smaller cathode, but twice as long.

With laser A, voltages up to 60 kV were used with capacitances as high as 0.005 microfarads. The voltage was higher and the capacitance lower than with laser B. The discharge consisted of a series of channels along the length of the bars, each channel presumably originating from an irregularity on the cathode. The channels varied somewhat in size, position, and appearance from shot to shot. The appearance depended very much on the helium concentration in the gas mix. The discharge channels in pure helium were 2 to 3 millimeters apart but some were considerably brighter than others. The bright channels, about 1 cm. apart, spread out from a point on the cathode to a diameter of about 5 mm.
at the anode. The excited gas was a distinct pink colour. Bright arc discharges never occurred in pure helium. When 7.5% CO$_2$ was added to the gas mixture, the discharge became whiter in colour, less bright, and the discharge sounded like a muffled explosion. With a higher concentration of CO$_2$ (11%), the discharge became brighter but remained white in colour. The channels were about 3 mm. wide. When nitrogen was added, the discharge became pink again, and the channels narrower, about 2 mm. wide (7% CO$_2$, 8% N$_2$). When the N$_2$ and CO$_2$ concentrations approached 15% each, the discharge deteriorated in that arcing occurred in about half the shots. At higher concentrations of CO$_2$ and N$_2$, a good discharge was impossible. Thus a large proportion of helium is a prerequisite for a reliable discharge at atmospheric pressure with both the resistor cathode and the brass bar cathode.

A good discharge was not obtained with laser A when the side electrodes were disconnected from the anode. Every discharge was a bright arc, even in a gas mix consisting of helium alone. It would thus appear that the side electrodes perform somewhat the same function as the resistors in reducing the current density below that characteristic of a bright arc discharge, and thus providing a uniform discharge. It is believed that this function is performed by the action of the side electrodes in spreading out the discharge laterally. In this way the current density is reduced.
V-2. **Optimization of Output Energy**

An attempt was made to find the best operating conditions for a specific voltage and capacitance. First the interelectrode spacing was varied keeping all other parameters unchanged. For these measurements the location of the cavity axis as determined by the mirror positions remained centered between the electrodes. As can be seen from figure 12, the energy output is at a maximum when the interelectrode spacing is about 3 cm. The discharge became irregular with smaller interelectrode spacings, resulting in decreased energy output. The root mean square deviation from the average energy output increased at small electrode spacings due to the deterioration of the discharge. When using a 0.005 microfarad capacitor, a reliable discharge could not be obtained at interelectrode spacings less than 2.8 cm.

Investigations of the energy output as a function of the position of the cavity axis between the electrodes have been performed. The results show the energy output varies by less that 25% when the cavity axis is varied over a range of about half the interelectrode spacing. Naturally the energy output drops off when the cavity axis is near either electrode.

The gas mixture was varied to find the mixture giving
Figure 12. Dependence of energy output on interelectrode spacing. Arbitrary energy units different for each case.

- $\odot 60\text{kV}, 0.002 \mu\text{F}$, one round, one square electrode
- $\odot 60\text{kV}, 0.002 \mu\text{F}$, two square electrodes
- $\ast 60\text{kV}, 0.005 \mu\text{F}$, two square electrodes.
the highest energy output for a fixed voltage and capacitance. Figure 13 gives in detail the results of one series of measurements. As can be seen, varying the CO$_2$ or N$_2$ concentration by a factor of 25\% did not change the average energy output by more than about 5\%; that is, the optimization was not critical. The shot-to-shot variation in energy output increased with increasing CO$_2$ and N$_2$ concentration, a consequence of the discharge becoming increasingly erratic. Table I gives the results of maximization of energy output with gas composition under different operating conditions. Laser A could be used with a much higher CO$_2$ and N$_2$ concentration than could Laser B.

The effect of the helium on the discharge as reflected in the energy output is shown in figure 14. Here the average detector output and the shot-to-shot variation in output are plotted as a function of helium concentration in the gas mix. A sudden rise in the shot-to-shot variation occurred when the helium concentration was reduced to below 75\%. With 70\% helium in the gas mix, the average energy output of the laser was much lower because of the increased number of shots in which bright arc occurred resulting in a small energy output. In general the highest CO$_2$ and N$_2$ concentration consistent with a good discharge gave the highest average energy output.
Figure 13. Dependence of energy output on gas mixture. (Energy in millijoules)
Readings taken with one round bar, one square bar electrodes, at 60kV, with 0.005 microfarad capacitance and 3.8 cm. inter-electrode spacing.
# TABLE I

Optimum gas composition under various operating conditions.

<table>
<thead>
<tr>
<th>Laser description</th>
<th>Voltage (kV)</th>
<th>Capacitance (µF)</th>
<th>Optimum gas composition</th>
<th>( %CO_2 )</th>
<th>( %He )</th>
<th>( %N_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One round, one square electrode</td>
<td>45</td>
<td>0.005</td>
<td>9</td>
<td>79</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.005</td>
<td>9</td>
<td>77</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.002</td>
<td>15</td>
<td>72</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>0.005</td>
<td>10</td>
<td>82</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Two square electrodes</td>
<td>60</td>
<td>0.005</td>
<td>10</td>
<td>83</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Laser B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistor cathode</td>
<td>30</td>
<td>0.01</td>
<td>6</td>
<td>89</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
Figure 14. Dependence of shot-to-shot variation of energy output on helium concentration in the gas mix.
- ¥ Average energy output
- △ Shot-to-shot variation in energy output.
V-3. Energy Output

The results of energy output measurements are shown in figure 15. The gas mixture was optimized at some points and not at other points. As can be seen on the graph, the energy output was somewhat greater using two square electrodes than using one round and one square electrode, with laser A. The efficiency was slightly higher with laser B than with laser A, although the energy output of laser A was larger. This is a consequence of the wider range of voltages that could be used with laser A.

The efficiency of lasers A and B was approximately 1.5% as compared to 3 to 5% reported by Fortin (1971) with a laser similar to laser B. Only one set of mirrors was used in this work however and no optimization of energy output with respect to output coupling was attempted. A five-fold increase in power output from a TEA laser has been reported in changing from using an output mirror with the optimum sized hole for output coupling to the optimum partially transparent coupling mirror (Wood et al., 1971). The use of such mirrors should enable similar increases in efficiency from the laser design reported here.

In addition, the mirrors used in taking the measurements of figure 15 showed signs of deterioration during the time that the measurements were taken. The surface of the silver
Figure 15. Energy output in different operating conditions
* Resistor laser
◊ Brass bar laser with two square bars as main electrodes.
Θ Brass bar laser with one round and one square bar.
coated glass mirror became pitted where small flakes of silver had been burnt away. The damage covered an area of about 1 cm. by 0.5 cm. which is an indication of the area of the beam inside the laser. The brass mirror was also discoloured over the area heated by the beam. The condition of the mirrors however did not seem to affect the laser performance, in that the output for a given set of operating conditions remained essentially constant throughout the investigation.

V-4. Effect of Electrode Shape

With laser A, a good discharge was obtained with any combination of round and square electrodes. With one round and one square electrode the discharge appeared more spread out than with two square electrodes. With two round electrodes the discharge was even more spread out, and a higher CO₂ concentration could be used. However, the best configurations for maximum energy output were: two square electrodes, one round and one square electrode, and two round electrodes, in that order. This is presumably because the mirrors used in these experiments were most effective in coupling the energy out of the less expanded excited volume available with the square electrodes. It should also be noted that the shot-to-shot variation in energy output was somewhat smaller with the round electrodes, a fact which
could be significant in many applications.

V-5. Current and Pulse Shape Measurements

The discharge current was measured with a pulse current transformer model 1025 from Pearson Electronics, Inc. The current transformer was mounted so that the grounded lead connecting the cathode of the laser with the ground of the spark gap passed through it. The discharge however produced a great amount of high frequency noise in the oscilloscope, and it was necessary to feed the signal from the current monitor through a delay line which introduced a 0.7 microsecond delay. The properties of the delay line were investigated using a Tektronix type 109 pulse generator. It was found that the delay line attenuated a square wave pulse by 5% and distorted the shape somewhat: the risetime of a pulse, originally 20 nanoseconds, increased to 70 nanoseconds. This degree of distortion, however, could easily be tolerated in these experiments.

Figure 16 shows the results of current and pulse shape measurements with laser A and B. With laser A, at 60 kV and with a 0.005 μF capacitor, the peak current was 400 amperes with a full width at half maximum of 300 nanoseconds. With laser B, at 30 kV and with a 0.01 μF capacitor, the peak current was 320 amperes with a full width of about 400 nanoseconds. The combination of higher voltage and low
Figure 16. Current and pulse shape measurements
a) Output power and
b) Discharge current with resistor laser at 30 kV
with 0.01 microfarad capacitor
c) Output power and
d) Discharge current with brass bar laser at 60 kV
with 0.005 microfarad capacitor.
The time scale in each case is one microsecond per division. The current pulses only have been delayed 0.7 microseconds.
capacitance gave a higher current than low voltage and large capacitance, although the charge stored in the capacitances was the same in the two cases. This is the result expected in discharging a capacitor across a resistive load.

With laser A, the peak current was quite sensitive to the helium concentration. In helium alone, the peak current was 560 amperes, and the width was narrower. This has been noted also with a resistor cathode laser (Robinson, 1971). These measurements indicate that one of the roles played by helium in the high pressure discharges is to lower the impedance of the gas. Lowering the impedance results in a faster rise time for the current pulse, allowing less time for a bright arc to form, and consequently results in a more uniform discharge.

The output pulse shape for laser B consisted of an initial spike, 400 nanoseconds wide, followed by a long shoulder or tail lasting several microseconds, with about one half the total energy in the spike. The value of the peak power is estimated to be 65 kilowatts. The intensity at the output window is therefore 0.65 MW/cm², which is comparable to the power densities reported by Fortin (1971).

The size and shape of the tail in the output of laser B could be varied by adjusting the N₂ concentration in the gas mix. In particular, with no N₂ in the gas mix, the tail had disappeared.
The output from laser A consisted of a single short pulse of width 400 nanoseconds. The tail characteristic of the output of laser B was noticeably absent. By adding $N_2$ to the gas mix, the tail could be made to appear, but the discharge became more irregular and there was a large shot-to-shot variation in the energy output and pulse shape. The peak power in this case is estimated to be 250 kilowatts, considerably larger than with laser B.

The power output of laser A was delayed about 1.5 microseconds after the start of the current pulse. The delay with laser B was considerably longer, about 3 to 4 microseconds. The delay with laser B decreased with decreasing $N_2$ content. Other researchers have noted similar delays with resistor electrodes (Beaulieu, 1970). Also a shorter delay has been noticed with a resistorless pin laser (Laurie and Hale, 1970). Using a rotating mirror to sample the gain at different times after the current pulse, Laurie and Hale have found that there is insufficient gain for lasing action three microseconds after the current pulse. It has been noticed that the delay decreases with increasing exciting voltage (Laurie and Hale, 1971).

By increasing the CO$_2$ and $N_2$ content in the gas mix, the discharge with laser A could be made somewhat irregular but not to the extent that the arcing would prevent lasing action. Under these conditions, the delay varied considerably
from shot-to-shot, but averaged about 5 or 6 microseconds. The output pulse shape was very irregular, consisting of several rounded peaks.

As mentioned in section II-8, the delay of the laser output following the excitation depends on three factors:

1). the losses in the cavity, chiefly due to fluctuations of the index of refraction in the columns of hot gas produced by the discharge;

2). the lifetimes of the various excited vibrational levels; and

3). the density of molecules in each excited state.

These three factors are affected by both the gas mixture used and the parameters of the excited circuit.

The delay between the current pulse and the start of the output pulse was considerably shorter when using laser A than when using laser B. It is believed that this is due to the greater uniformity of the discharge with the brass bar electrodes reducing the losses in the cavity and consequently reducing the delay. The delay was increased on increasing the losses in the cavity by deliberately making the discharge irregular. It should be noted that with a resistor electrode laser the delay can be increased by detuning the cavity (Beaulieu, 1970).

A reduction of the delay time occurs on increase of the operating voltage with a pin electrode laser (Laurie and
Hale, 1971). This may be due to the discharge becoming increasingly uniform as the voltage is raised. It may also be due to a change in the density of molecules excited to the various vibrational levels, resulting in a change in the rate of transfer of energy to the upper laser level.

The appearance of the shoulder or tail in the output pulse of the resistor laser is also dependent on the three factors mentioned earlier. The resonant transfer of energy from excited \( \text{N}_2 \) molecules is the most likely cause of the tail. Equation 14 shows that this transfer requires a high density of molecules in the ground state and is inhibited by a high density of molecules in the upper laser level. The discussion in section II-8 indicates the population of the upper laser level will be increased by the transfer of excitation until lasing action occurs; i.e., until the inversion reaches its threshold value. After this point all the energy transferred to the upper laser level will contribute to the laser action. As a result of the initial spike of stimulated emission, many molecules enter the lower laser level, but from here they decay rapidly (0.2 microseconds) to the ground state. Thus the population of the ground state increases, allowing an increase in the transfer of energy to the upper laser level from excited \( \text{N}_2 \) molecules, and further lasing action occurs. In this explanation, the tail of the output pulse is due to the decay of excited molecules
to the ground state where they can take part in energy transfer collisions.

In a gas mix containing no nitrogen the tail of the output pulse is missing. This indicates the transfer of energy from higher excited states of CO$_2$ to the upper laser level (equation ?) proceeds considerably faster than the transfer of energy from excited nitrogen. A value of less than 10 microseconds has been reported for the energy transfer at low pressures (Hocker et al., 1966). At atmospheric pressure a transfer time of about 0.1 microseconds would be expected. The energy transfer time would however strongly depend on the relative populations in the excited levels. Because of the faster transfer time the energy from CO$_2$(00$^0$1) states contributes to the main burst of lasing action and thus there is no tail in the output pulse.

The long shoulder characteristic of the output of laser B is missing in the output of laser A except at N$_2$ concentrations considerably higher than those normally used. This is possibly due to the different excitation conditions (lower capacitance, higher voltage) influencing the distribution of electron energies in the discharge. The relative rates of excitation to the excited levels are critically dependent on the electron energy. The distribution of population among the excited levels will influence the energy transfer rates. Possibly, with the excitation conditions used with laser B,
the distribution of energy amongst the excited levels will be such that all the energy can be transferred to the upper laser level rapidly and can contribute to the main burst of stimulated emission.

In this section, suggested explanations have been given for some of the phenomena observed with TEA lasers with resistor electrodes and with bar electrodes. Further information about the reaction rates and the level lifetimes in gas mixtures used with the TEA laser would support or dismiss these conjectures. For example, a knowledge of the distribution of electron energies in the discharge would enable an estimate to be made of the relative populations of the various excited levels immediately following the discharge and would provide a basis for detailed understanding of the processes involved in the transfer of energy. However, because of the high voltages and small dimensions involved in the TEA laser, a measurement of the distribution of electron energies would involve a non-trivial experiment.
CHAPTER VI

CONCLUSIONS

The fundamental problem in constructing a transversely excited atmospheric pressure laser is to obtain a uniform discharge throughout the length of the laser. It is found that there are severe limitations on the gas composition and circuit parameters such as the voltage and capacitance that can be used to obtain a uniform discharge with a TEA laser. Also irregularities in the discharge are a source of loss due to variations in the index of refraction and, in particular, a bright arc discharge heats the gas excessively, preventing laser action. The results presented here show that a new electrode design for the TEA laser provides a reasonably uniform discharge over a wider range of these parameters than previously possible.

The usual design of TEA laser employs resistors in the discharge circuit to limit the current through a single discharge channel to less than the current characteristic of a bright arc discharge. It is believed that the side electrodes of the new design serve the same purpose by spreading the discharge out and reducing the current density, in this way preventing bright arc discharges. As there are
no resistive elements in the discharge circuit, the efficiency of the laser, properly optimized, should be higher than that in the conventional laser.

Other advantages of the new design as compared to the more usual type of TEA laser, are simpler construction and greater durability. The deterioration of the resistors in the electrodes limits the useful lifetime of the conventional laser, but is not a factor in the new design where current limiting resistors are not used.

Laurie and Hale (1971) have reported 17% efficiencies using a laser with pins instead of resistors in the electrodes. A low inductance discharge circuit was necessary for uniform discharges with the pin electrode laser, but the inductance of the circuit used here was large. Robinson (1971) has noted that a low inductance discharge circuit with a resistor laser allows the use of a larger concentration of CO₂ and N₂ in the gas mix and consequently higher gains. It would be interesting to see what the effect of reducing the inductance is with the bar electrode laser. It should be possible, by reducing the inductance and by optimizing the output coupling and thus allowing more of the excited volume to contribute to the laser output, to increase the efficiency of the new design to a level near that obtained by Laurie and Hale.
There is much that remains to be learned about the excitation processes in TEA laser; how the current flow through the gas results in a population inversion and how the interactions between the vibrational levels influences the gain. When information is available about the density and energy distribution of electrons in the discharge, the density of CO$_2$ and N$_2$ molecules in each excited state can be calculated, and the subsequent decay of the levels will give the temporal shape of the gain which can be compared to the experimental gain measurements. A knowledge of the dependence of electron energy and density in the discharge would enable one to design the laser for a specific purpose, for example for maximum power or maximum energy depending on the application involved. In addition it would indicate those properties that should be looked for in other gases considered for use as the active materials in TEA lasers.

Future work on the TEA laser will also be directed towards possible applications in science and industry. It can be used as a tool in studying vibrational relaxation and energy transfer processes in gas mixes containing carbon dioxide. Second harmonic generation and parametric amplification, previously observed with Q-switched conventional CO$_2$ lasers, will be enhanced by the greater power outputs of the TEA laser. The study of the self-focussing of radiation and breakdown of solids, liquids, and gases is
another application. Also the transverse excitation principle has been applied to other gases both molecular and atomic (Wood et al., 1971). Much work is being done in developing infrared radar and range finding systems. A TEA laser operated at high repetition rates can be used for cutting, drilling, and welding metals and ceramic materials. These and other applications make the TEA laser an important development in laser technology.
A-1. Introduction

There are two major types of infra-red detectors (Smith, Jones, and Ghasmar, 1968). Thermal detectors such as the bolometer and the Golay cell rely on the heat produced by the incident radiation changing a physical property of the detecting element. They generally have a slow response time and many have to be used at low temperatures to make best use of their responsivity. The Golay cell is a room temperature thermal detector which uses the thermal expansion of a small volume of gas as the detecting property. It has a minimum detectable power of $10^{-10}$ watts and a response time of about a millisecond. In quantum or photo-detectors, a property of the detecting element changes in some way by the absorption of a photon. They have wavelength restrictions, and those which are suitable for the infrared must be used at low temperatures. In a doped germanium crystal, incident radiation excites electrons from the donor levels into the conduction band, increasing the conductivity of the crystal. The response is a maximum at 5 microns wavelength with gold doping and at 11.5 microns with mercury doping.
A gold doped germanium crystal at liquid nitrogen temperature has a minimum detectable power at 5 microns of $10^{-10}$ watts and a response time of 100 nanoseconds.

Both the pyroelectric energy meter used to measure the energy of the pulse and the photon drag detector used to observe the pulse shape were simple to construct and could be used at room temperature. They did not require an external power supply and were connected directly to the input of an oscilloscope. Pyroelectric detectors have been constructed with a response time of 30 nanoseconds and a minimum detectable power of $4 \times 10^{-9}$ watts (Glass, 1968). The detector used here, however, was used only for energy measurements and was designed to handle the high power of the laser without deterioration. The recovery time of the energy meter was about half a second.

The photon drag detector was used to measure the temporal behavior of the power output. The response time of the photon drag detector was limited by the capacitance of the connecting leads to be 50 nanoseconds. It is not as sensitive as other detectors, but this is not a disadvantage in detecting the output of a high power laser.

A-2. Pyroelectric Detectors

The pyroelectric effect is the change in the static polarization of a ferroelectric material due to a change
in temperature. In a ferroelectric, there is a net dipole moment even in the absence of an applied electric field. Several materials have been used for pyroelectric detection among which are barium titanate (Cooper, 1962a, 1962b), strontium barium niobate (Glass, 1969), and lead zirconate titanate (Lachambre, 1971). Single crystal detecting elements are preferable in applications requiring a low minimum detectable power (Stanford, 1965). Ceramic materials, although less sensitive, appear to be superior in withstanding high powers (Lachambre, 1971).

The sensitivity of a pyroelectric detector can be estimated from the following considerations. On a block of ferroelectric material there will be surface charges, the charge density being given by the normal component of the static polarization. A flow of charges in the external circuit cancels out the polarization charge. Any further change of polarization will change the surface charge and result in a current flow

\[ i = \frac{dq}{dt} = A \frac{dP_s}{dt} = A \lambda \frac{dT}{dt}. \]

Here \( q \) is the surface charge on the area \( A \) exposed to the radiation, \( P_s \) is the static polarization of the ferroelectric, \( t \) refers to the time, and \( T \) to the temperature. The pyroelectric constant is the temperature derivative of the static polarization.
\[ \lambda = \frac{dP_s}{dT}. \]

A pyroelectric detector consists of a block of ferroelectric material, electroded on the faces normal to the polar axis. The electrodes are connected to a measuring instrument with input impedance \( R \). The material electroded on two faces acts as a capacitor with capacity \( C = \frac{\varepsilon A}{l} \) and leakage resistance \( R' = \frac{l}{dA} \), where \( \varepsilon \) is the dielectric constant, \( d \) is the conductivity, and \( l \) is the distance between capacitor plates. The detecting action is that of a current generator, the current being given by equation 1. The equivalent circuit of the detector is shown in figure 17.

It follows from an analysis of the equivalent circuit that

\[ v(t) = \frac{1}{C} \int_{-\infty}^{t} i(t') \exp\left(\frac{t' - t}{\tau}\right) dt' \]

where

\[ \frac{1}{\tau} = \frac{C}{\frac{1}{R} + \frac{1}{R'}} \]

is the electrical time constant.

The thermal response of the detecting element is given by

\[ C \frac{dT}{dt} = eW - GT \]

where \( W(t) \) is the power of the incoming radiation and \( T \) is the difference between the temperature of the detector and the temperature of the surroundings. \( e \) is the emissivity,
Figure 17. Equivalent circuit of pyroelectric detector.
a constant representing the fraction of radiation absorbed. $C' = \rho SV$ is the thermal capacity of the detecting element, $\rho$ is the density, $S$ the specific heat, and $V$ the volume; $G$ is the thermal conductance which describes how the body is thermally connected to the outside world. The detecting element used here is in contact with a heat sink and the biggest contribution to the thermal conductance is from conduction to the heat sink. $G$ is thus given by

$$G = AK/l$$

where $K$ is the thermal conductivity of the detecting element.

The solution to equation 3 for the temperature derivative is

$$\frac{dT}{dt} = \frac{e}{C'} \left[ W(t) - \frac{1}{\tau_T} \int W(t') \exp \left( \frac{t'-t}{\tau_T} \right) dt' \right]$$

where

$$\tau_T = C'/G$$

is the thermal time constant. Equations 1, 2 and 4 give the response $v(t)$ of the pyroelectric detector to incoming radiation $W(t)$.

In using the pyroelectric detector to measure the energy of a short pulse of radiation, it is possible to consider the input power to be a delta function

$$W(t) = E \delta(t).$$
Then,

\[ v(t) = \frac{E}{A} \left( \frac{e \lambda}{\rho S \epsilon} \right) \left[ e^{-t/\tau} - \frac{\tau}{\tau} e^{-t/\tau} \right] \]

for \( \tau \neq \tau_\star \). The constant \( e \lambda / \rho S \epsilon \) depends only on the properties of the material. At \( t = 0 \),

\[ v(0) = \frac{E}{A} \left( \frac{e \lambda}{\rho S \epsilon} \right) \]

and the peak voltage is directly proportional to the energy of the pulse.

To increase the absorption of the radiation, i.e. to get a value of \( e \) approximately equal to unity, a layer of absorbing black can be used on the surface exposed to the radiation.

The voltage response will be linear with increasing energy as predicted in equation 6 as long as the temperature is far from the Curie point of the ferroelectric. The spontaneous polarization drops very rapidly to zero at that temperature (Chynoweth, 1959) and \( \lambda = dp_s / dT \) becomes very large. To avoid appreciable temperature increases, the detecting element should thus be mounted against a heat sink large enough to ensure small temperature rises. The incident radiation was spread out over the detector area to reduce the power per unit area. It is not necessary for linear response that the incoming radiation be evenly distributed over the surface of the detecting element, provided
that no area is heated excessively. This can be shown by considering contributions to the total signal from a small area, and integrating over the entire face of the detector.

A pyroelectric detector can also be used to observe the pulse shape of short pulses of radiation if the length of the pulse is much less than the thermal and electrical time constants. For \( t \ll \tau, \tau_c \), equation 4 becomes

\[
\frac{dT}{dt} = eW(t)/C'
\]

and equation 2 becomes

\[
v(t) = \frac{A\lambda e}{C'C} \int_{-\infty}^{t} W(t')dt'
\]

so that differentiation of the detector voltage gives a signal proportional to \( W(t) \) (Cooper, 1962b). In this case, care should be taken in using an absorbing black because of its adverse effect on the response time.

A-3. Photon Drag Detector

The photon drag detector (Gibson et al., 1970) works on the principle of the transfer of momentum from a photon stream to free charge carriers in a semiconductor. Consider radiation of frequency \( \omega \) incident on a material of conductivity

\[
d(\omega) = \frac{\Delta}{1 + i\omega \tau} = \frac{ne^2\tau/m}{1 + i\omega \tau}
\]
and dielectric constant $\varepsilon \epsilon_0$. The conductivity will be assumed to arise from electrons of charge $-e$, mass $m$, and density $n$. $\tau$ is the scattering time of the electrons. The fields $\vec{E}$ and $\vec{H}$ and the charge velocity $\vec{v}$ inside the semiconductor will have to obey Maxwell's equations 7 to 10, the charge continuity equation (11), and the force equation for the carriers (12):

$$\text{Div } \vec{E} = \rho/\varepsilon \epsilon_0$$  
$$\text{div } \vec{B} = 0$$  
$$\text{Curl } \vec{E} = -\omega \frac{\partial \vec{H}}{\partial t}$$  
$$\text{Curl } \vec{H} = \vec{v} + \varepsilon \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$  
$$\text{Div } \vec{J} + \frac{\partial \rho}{\partial t} = 0$$  
$$\vec{F} = m \frac{d\vec{v}}{dt} = -m \frac{\partial \vec{F}}{\partial t} - e\vec{E} - e\vec{v} \times \vec{B}$$

where the current density is $\vec{J} = -ne\vec{v}$. The charge density $\rho$ is very much smaller than the average electron charge density $-en_{av}$, so $n$ can be considered a constant. It can easily be shown that a solution to these equations is given by

$$\vec{E}(\vec{r}, t) = \hat{\lambda} \ E_x \ e^{-k_{mz} t} \cos(\omega t - k_{re} z)$$  
$$+ \hat{\kappa} \left[ E_{20} - E_{32} \sin(2\omega t - 2k_{re} z - \beta) \right] e^{-2k_{mz} t}$$

$$\vec{H}(\vec{r}, t) = \hat{\lambda} \ H_y \ e^{-k_{mz} t} \cos(\omega t - k_{re} z - \theta)$$

$$\vec{v}(\vec{r}, t) = \hat{\lambda} \ v_x \ e^{-k_{mz} t} \cos(\omega t - k_{re} z + \alpha)$$  
$$- \hat{\kappa} \ v_z \ e^{-2k_{mz} t} \cos(2\omega t - 2k_{re} z - \beta)$$

where the current density is $\vec{J} = -ne\vec{v}$. The charge density $\rho$ is very much smaller than the average electron charge density $-en_{av}$, so $n$ can be considered a constant. It can easily be shown that a solution to these equations is given by
where the radiation is taken to be propagating in the z direction and \( \hat{i} \), \( \hat{j} \), and \( \hat{k} \) are unit vectors in the x, y, and z directions respectively. The components of the wave-vector are given by the familiar equation

\[
(k_{re} - ik_{im})^2 = \frac{\omega^2}{c^2} \left( \varepsilon - \frac{i \sigma(\omega)}{\varepsilon \omega} \right)
\]

16.

The following equations relate the coefficients and phases of the various terms:

\[
-nev_x = |\sigma(\omega)| E_x
\]

17.

\[
H_y/E_x = |k|/\omega \mu
\]

18.

\[
\tan \theta = k_{im}/k_{re}
\]

19.

\[
\tan \alpha = -\omega v
\]

20.

\[
\tan(\alpha + \beta - \theta) = 2\omega v - \frac{\sigma(\omega)}{2\omega \varepsilon_0}
\]

21.

\[
v_z = \frac{\varepsilon \varepsilon_0}{m} v_x H_y \cos(\alpha + \beta - \theta)
\]

22.

\[
E_{z0} = -\frac{\mu}{\varepsilon} v_x H_y \cos(\alpha + \beta) = \frac{N}{2Nc} \frac{|\sigma(\omega)|}{(1 + (\omega \mu)^2)} v_x E_x^2
\]

23.

\[
E_{z2} = \frac{ne}{2\omega \varepsilon_0} v_z
\]

24.

The field \( E_x \) inside the conductor is related to the intensity \( I \) outside, by the equation

\[
E_x^2 = \frac{2N}{c\varepsilon \varepsilon_0} (1-R) I
\]

25.

where \( N \sim \sqrt{\varepsilon} \) is the refractive index and

\[
R = \left( \frac{N - 1}{N + 1} \right)^2
\]

is the reflection coefficient.
The fields inside the semiconductor are completely determined by equations 13 to 25 if the incident intensity is known. Conversely, the fields are an indication of the incident intensity. The voltage across a length L in the direction of propagation is given by

\[ V = \int E \cdot d\mathbf{x} = \frac{E_0}{2k_{im}} \left( 1 - e^{-2k_{im}L} \right) \]

where, from equation 16,

\[ 2k_{im} \approx \frac{\omega}{c} \frac{c_0 / \epsilon_0 \omega N}{1 + (\omega \tau)^2} \]

The probes used to measure the voltage cover an area greater than one wavelength and therefore the \( \sin(2\omega t - 2k_{re}z) \) term in the longitudinal field does not contribute to the integral in equation 26. Substituting the equations for \( E_0 \) and \( 2k_{im} \) into equation 26,

\[ V = \frac{N}{ne\epsilon c} (1 - R) I (1 - e^{-2k_{im}L}) \]

If \( \exp(-2k_{im}L) \ll 1 \) and \( n = 10^{16} \text{ cm}^{-3} \), then

\[ V \approx 0.5 \times 10^{-7} \frac{\text{volts}}{\text{watt/cm}^2} \times I \]

The longitudinal voltage develops because of the transfer of momentum from the radiation to the charge carriers. This can be seen from the following argument. The rate of momentum transport through a unit area is equal to the energy density of the radiation \( u(z,t) \) which in turn is related to
the intensity incident on the material by

\[ u(z, t) = \frac{(1-R)N}{c} I(t - \frac{N}{c}) e^{-Kz} \]

where \( K = 2k_{im} \) is the absorption coefficient. The rate of momentum loss per unit volume when radiation passes through a material is given by

\[ \frac{u(z, t) - u(z + dz, t)}{dz} = - \frac{\partial u(z, t)}{\partial z} \]

The rate of momentum gain of the charge carriers is equal to the rate of momentum loss of the radiation. The equation of motion of the charge carriers is therefore

\[ \eta \frac{d^2z}{dt^2} = - \frac{\partial u(z, t)}{\partial z} - \frac{\rho m}{\varepsilon} \frac{dz}{dt} - ne E_z(z, t) \]

where \( E_z(z, t) \) is a longitudinal electric field, \( \rho m \) is the mass per unit volume and \( -ne \) the charge density. If the sample of material is open circuited, there is no net motion of charge carriers and

\[ E_z(z, t) = - \frac{1}{ne} \frac{\partial u(z, t)}{\partial t} \]

The voltage across the sample is

\[ V(t) = \int_0^L E_z(z, t) \, dz \]

\[ = \frac{1}{ne} \left[ u(0, t) - u(L, t) \right] \]

or

\[ V(t) = \frac{N(1-R)}{ne} \left[ I(t) - I(t - \frac{N}{c}) e^{-KL} \right] \]

27.

28.
If $\exp(-KL) \ll 1$, then

$$V(t) = \frac{N(1-R)}{neC} I(t)$$

as before.

There will be a contribution to the integral 26 from all $z < z_0$ where $z_0$ is the smaller of $1/K$ and $L$. The detector will not resolve time variations such that there is a different field on different parts of this region; the time response of the detector is thus limited to the smaller of $N/cK$ and $NL/c$. For germanium with $10^{16}$ free electrons per cubic centimeter, $K = 0.27$ cm$^{-1}$ at 10.6 microns wavelength (calculated from equation 16). The response time of a one centimeter long sample of this material is therefore 130 picoseconds. In practice the time response is limited by the RC time constant of the resistance of the detector and the capacitance of the cables, or the rise time of the display device.

An expression similar to equation 28 can be derived for the case when both charge carriers are present (Gibson et al., 1970), but as the effects of holes and electrons tend to cancel each other, the responsivity decreases, so this case is of little interest.

Any material in which the absorption of radiation is predominately by free charge carriers can be used as a photon drag detector. Absorption in n-type germanium is
approximately proportional to wavelength squared in the wavelength interval 5 to 12 microns (Moss, 1961, pg 131) as would be expected from equation 16 with \( \omega t \gg 1 \). The process in \( p \)-type germanium is more complicated although the net result is the same. The valence band is split and as a result there is strong intraband absorption at 3.4, 4.7, and 15 microns. The absorption at 10 microns is due to an intraband transition. The heavy holes that are mainly responsible for the DC conductivity are annihilated and light, highly mobile holes in the lower band are formed. The responsivity is however independent of the nature of the holes and depends only on the total number, as shown in equation 28. The number of holes is conserved during intraband absorptions and therefore \( p \)-type as well as \( n \)-type germanium may be used in a photon drag detector.
LIST OF REFERENCES

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