EFFECTS OF A HEAVY PARTICLE EXTERNAL IONIZATION
SOURCE ON CARBON DIOXIDE LASER DISCHARGES

BY

JAMES TERRENCE GANLEY

B.S., University of Illinois, 1967
M.S., University of Illinois, 1968

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Electrical Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 1972

Urbana, Illinois

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

peg

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

EFFECTS OF A HEAVY PARTICLE EXTERNAL IONIZATION
SOURCE ON CARBON DIOXIDE LASER DISCHARGES

James Terrence Ganley, Ph.D.

Department of Electrical Engineering

University of Illinois at Urbana-Champaign, 1972

Experiments are described which explore the effects of a heavy particle external ionization source on electrically excited CO_2 laser plasmas. Effects on both longitudinal and transverse discharges have been investigated.

High energy nuclear particles produced by the reaction of thermal neutrons with boron-10 served as an ionization source which was completely independent of any applied electric fields. The presence of the external ionization decoupled the electron production process from the electron heating process. The result was a pronounced change in the electrical characteristics of the discharge.

In low pressure (<50 torr), longitudinal discharges, the external ionization has made it possible to control the discharge current and E/N independently. Conditions have thus been produced which are more favorable for laser operation than the conditions which can be produced with only an applied electric field. Under these conditions, increased laser output and efficiency have been obtained.

Increases in laser power output and efficiency have also been obtained from irradiated high pressure (100 to 760 torr) transverse discharges. Also, for any given pressure, there is a decrease in the voltage required to produce breakdown and lasing. Correspondingly, for a given value of voltage, there is an increase in the maximum pressure at which lasing can be achieved.

The collision frequency for excitation of the upper laser level has been measured on a per electron basis as a function of E/N . For the particular gas mix involved, the peak in the curve corresponds to the electrical operating conditions which produce the most efficient laser pumping.

In addition to changing the electrical characteristics of the discharge, the external ionization also appears to have a pronounced effect on the shape of the

MASTER

electron energy distribution function. It is believed that this phenomenon is important in affecting laser performance. The results of experiments with electrostatic probes imply that the external ionization produces important changes in the high energy tail of the electron distribution function.

ACKNOWLEDGEMENTS

The author wishes to thank the Atomic Energy Commission, Research Division for providing funds to support his research.

Also, he would like to express his sincere gratitude to the many people who have assisted in various stages of this work. Of particular importance were the members of the reactor operating staff: Harry Keiser, Howard Palmer, Orville Whipple, Paul Hesselman, and Gerald Beck. Their cooperation and assistance have been invaluable throughout the course of these experiments. Credit for excellent work in machining certain parts of the experimental equipment should be given to Barney Marshall and John Goldman. Their prompt and conscientious workmanship is greatly appreciated. Also, the author would like to express his gratitude to Jean Guyot and to his colleagues in the Gaseous Electronics Lab, who have given so freely of their advice and equipment. Special thanks go to Don Meeker and David Swanson, whose activities have provided the author with much needed comic relief.

Of great help in the design and maintenance of experimental equipment were the members of the Electrical Engineering Special Processes Lab: Keith Kuehl, Ed Boose, and Al Wilson. The author would like to thank them for their unfailing technical assistance, and also for their dubious political and financial advice.

The assistance of Carol Lee and Marilena Stone, who typed the manuscript, and Dave Talbert, who made the drawings, is gratefully acknowledged.

A number of faculty members have indirectly played a role in determining the content of this thesis. Of particular significance have been the many helpful comments and suggestions provided by Prof. Blake Cherrington, Prof. Ladislav Goldstein, Prof. Bernard Wehring, and Prof. George Miley.

The author would like to express his sincerest gratitude to his advisor, Prof. Joseph Verdeyen, for his patience as a teacher. His unique contributions to this effort, both personal and technical, will never be forgotten.

In addition, the author would like to thank the members of his family, especially his parents, for their confidence and encouragement over the years.

Finally, the author wishes to thank his wife, Ann, for her tolerance and uncomplaining love in the face of many annoying circumstances.

TABLE OF CONTENTS

	Page
I. INTRODUCTION.....	1
II. PRELIMINARY DISCUSSION.....	7
A. CO ₂ Molecular Physics.....	7
B. CO ₂ Laser Physics.....	9
C. Historical Development of the CO ₂ Laser.....	13
D. Basic Problems of CO ₂ Lasers.....	18
E. Present CO ₂ Laser Research.....	20
III. EXPERIMENTS AND OBSERVATIONS.....	22
A. Low Pressure Experiments.....	22
1. Description of Experiment.....	22
2. Characteristics of Irradiated Discharges.....	26
3. Laser Output Measurements.....	36
4. Laser Gain Measurements.....	46
5. Electrical Probe Studies.....	50
B. High Pressure Laser Work.....	55
1. Description of Experimental Equipment.....	55
2. Experimental Procedure and Results.....	55
IV. CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK.....	60
APPENDIX A - Calculations of Nuclear Ionization Rate.....	62
APPENDIX B - Electrical Probe Theory.....	65
REFERENCES.....	71
VITA.....	75

I. INTRODUCTION

The population inversion in electrically excited gas lasers is produced, either directly or indirectly by electron collisions with the atoms or molecules of the gas. Thus, the pumping process depends on the electron density and, because of the energy dependent collision cross sections, on the electron energy distribution function.

In the case of CO₂ laser discharges, a great deal of theoretical and experimental work has been devoted to the problem of translating these microscopic plasma parameters into the macroscopic discharge variables of current and E/N.* Several reports have been made of measurements of the electron density,¹ the average electron energy,^{2,3} and the electron energy distribution^{4,5,6} for various discharge conditions. In addition, theoretical attempts^{7,8} have been made to predict the energy distribution in various gas mixes from a knowledge of E/N. The fact that cross sections^{9,10,11,12} are known for the important collision processes in CO₂ laser discharges has made these theoretical efforts useful and the results have given a great deal of insight to the problem of choosing discharge conditions which optimize laser performance.

Laser performance can be judged in terms of two important parameters: small signal gain and saturation intensity.

Small Signal Gain (α): When a light signal of the proper frequency passes through a medium with an inverted population, it is amplified or intensified by stimulated emission. If the light signal is small enough that the stimulated emission does not significantly affect the population inversion, the signal's amplification is given by:

* E/N, the ratio of the electric field in the discharge to the number density of gas particles, is a rough measure of the energy gained by an electron between collisions. The reader may be more familiar with the convention of describing discharge conditions in terms of current and voltage. However, E/N is a more generalized parameter than voltage since it is normalized with respect to the gas pressure and the physical length of the discharge ($E=V/l$).

$$\frac{I_{\ell}(\nu) - I_0(\nu)}{I_0(\nu)} = e^{\gamma(\nu)\ell} - 1$$

where $I_0(\nu)$ = intensity of incident light

$I_{\ell}(\nu)$ = intensity of signal after traversing a distance ℓ
through the medium.

$\gamma(\nu)$ = gain coefficient of the medium, a quantity which depends
on the population inversion.

If ℓ is taken to be a unit length, for instance, one centimeter, then
the small signal gain, $\alpha(\nu)$ is defined by:

$$\alpha(\nu) = \frac{1}{\ell} [e^{\gamma(\nu)\ell} - 1]$$

$\alpha(\nu)$ is usually expressed as a percent per unit length. For high power
 CO_2 lasers, a typical small signal gain would be about 4% per centimeter.

Saturation Intensity (I_s) When a high intensity light signal is passed
through a medium with population inversion, the process of stimulated
emission can become strong enough to destroy a large fraction of the
inverted population. Because of this, large signal gain is less than a
small signal gain. A quantity called the saturation intensity is
defined as that intensity of light for which the gain of the medium
falls to one-half of its small signal value. It can be seen that I_s is
a rough measure of the density of energy stored in the upper laser
level. Typical values of I_s for high powered CO_2 lasers are several
hundreds of watts per square centimeter.

The importance of these two parameters becomes obvious when it is realized
that the product of the small signal gain and the saturation intensity is a
measure of the maximum specific power (watts per c.c.) which can be obtained
from the lasing medium. Thus, when $\alpha(\nu)$ and I_s are known, it is possible to

estimate the maximum power output and efficiency of a laser.

A number of investigations^{13,14} have been performed to determine the effects of various discharge conditions on $\alpha(v)$ and I_s for CO_2 laser discharges. In particular, the conditions necessary for high power operation have been explored. The following general conclusions have been formed as a result of these investigations.

1. High pressure operation is necessary to produce large values of $\alpha(v)$ and I_s . The reason for this is simple. In order to extract large quantities of optical power, it is necessary to have a great number of molecules pumped into the upper laser state. When the pressure is high, more molecules are available for pumping.
2. Both $\alpha(v)$ and I_s are increasing functions of electron density. Thus high power output is favored by a large electron density. The reason is similar to that given above. To produce high power output, it is necessary to pump many molecules into the upper state. Since the pumping is done by electrons, high electron densities are required.
3. The gain $\alpha(v)$, is a sharply decreasing function of gas temperature, while I_s is an increasing function of gas temperature. However, the specific power ($\alpha(v) \times I_s$) is a decreasing function of gas temperature. Thus, high power operation is favored by low gas temperature. The reasoning behind these statements is based on the detailed physics of the CO_2 laser system. A discussion of these matters is presented in the next chapter.
4. For any given gas mix, there is a particular value of E/N which leads to the most efficient laser pumping. This is the value of E/N which produces the most electrons with energies in the regions where the laser pumping cross sections peak.

As attempts have been made to produce higher and higher power CO_2 lasers, problems have been encountered in producing the desired values of E/N , electron density (or current), and gas temperature. There are a great many problems associated with high pressure, high current electrical discharges: instabilities, inhomogeneities, self-constriction (arcing), to mention only a few.

However, in spite of the many difficulties involved, a number of noteworthy advances have been made in the quest for higher powers. Innovative developments in electrode design have produced the transversally excited atmospheric (TEA) laser^{15,16,17,18} which is capable of multi-megawatt pulses of microsecond duration. The TEA design has been modified and advanced in a number of ways. The most successful version is generally referred to as the double discharge laser,^{19,20,21} a design which utilizes a pre-ionizing discharge in advance of the main laser discharge. The result has been the production of narrower laser pulses with higher peak powers.

A number of authors have reported success in attempts to extend the capabilities of CO_2 lasers by using external ionization sources to supplement the applied electric fields. Andriakhin,²² et.al., have utilized a beam of high energy protons to increase the power output and efficiency of a D.C. excited, low pressure CO_2 laser. A volume source of high energy protons has been used by Allario,²³ et.al., to produce similar results.

More recently, beams of high energy electrons have been used as auxiliary ionization sources in CO_2 laser discharges.^{24,25,26} This technique seems to be particularly well suited to the task of pumping large volumes of high pressure gas.

The present work gives the results of a study of the effects of an alpha particle ionization source on both low pressure longitudinal and high pressure transverse CO_2 laser discharges. Previously, Ganley,²⁷ et.al., have reported very significant increases in laser output power and efficiency as a result of

this nuclear induced ionization. This work includes discussions of more recent experiments and also more extensive analysis of the results.

In work with low pressure (<50 torr) longitudinal discharges, the laser characteristics (output power and gain) have been monitored in conjunction with the changes in current and E/N which were produced by the nuclear radiation. The effects of the external ionization on the steady-state current-E/N characteristics of the discharge are discussed and a semiquantitative explanation of the changes is presented. This discussion is not extended to include laser performance data because steady state operation produces gas heating and dissociation effects which tend to obscure the meaning of the observed results. These problems have been bypassed in experiments with pulsed discharges. These experiments are discussed in the light of information which they supply on the characteristics of CO₂ laser operation. In particular, the effective excitation frequency of the upper laser levels by electrons has been measured as a function of E/N.

In some situations, the external ionization has produced increases in laser output and efficiency without producing any noticeable change in the discharge voltage or current. A detailed exploration of this phenomenon has been made by observing the nuclear induced changes in laser gain and by studying the irradiated discharge with double electrostatic probes.

Results of work with transversely excited discharges are also presented. Discharges at pressures up to one atmosphere have been irradiated. Increased laser output has been observed and there has been a lowering of the voltage required to produce lasing.

The details of the interaction of the external ionization source with the laser discharge are not completely understood. However, there appear to be three important phenomenon involved:

1. Increased control over the electrical conditions within the discharge

2. Increased uniformity and stability of the discharge
3. A change in the shape of the electron energy distribution function.

II. PRELIMINARY DISCUSSION

In 1964, C. K. N. Patel²⁸ first obtained coherent output from the vibrational-rotational transitions of the CO_2 molecule. Since that time, the CO_2 laser has become one of the most extensively investigated and widely used of all laser systems. The high gain of the laser and the relatively long wavelengths of the output radiation make it possible to use rugged, inexpensive optical materials in constructing the resonant cavity. High efficiency and high power output make the CO_2 laser a natural choice for a tremendously broad range of scientific and industrial applications.

A review of the development of the laser leads naturally to a discussion of the problems which are encountered in its operation. Since the main purpose of the present work is the gathering of information which might lead to more effective methods of solving or circumventing these problems, such a review seems appropriate.

A. CO_2 Molecular Physics

CO_2 is a linear, triatomic molecule, and as such, it possesses four vibrational degrees of freedom. However, due to the symmetry of the molecule, two of the modes are degenerate. Thus, the vibrational energy levels can be expressed in terms of three independent modes: symmetric stretch ($10^\circ 0$), bending ($01^\circ 0$) and asymmetric stretch ($00^\circ 1$).

A simplified energy diagram²⁹ of some of the vibrational levels and the radiative transitions connecting them is shown in Figure 1. The laser transitions are indicated by wavy lines. The strengths of the different transitions are also shown. However, for conditions typical of CO_2 laser discharges, radiative transitions are not the dominant destruction mechanisms for the various levels. Of far greater importance are processes of collisional decay. The details of these interactions are extremely complicated and at the present time there are still many unanswered questions concerning the important processes. The survey

Fig. 1 Energy levels directly involved in the CO₂ laser.

by Taylor and Bitterman³⁰ provides a good starting point for an examination of the tremendous amount of literature which has been produced in this area.

Each of the vibrational states shown in Figure 1 is split into a number of rotational sublevels. Thus, for a molecule in the ground electronic state, vibrational transitions actually occur between the rotational sublevels. This gives rise to a band structure in the radiation observed for any given vibrational transition.

The population of a vibrational level consists of molecules allotted to the various rotational sublevels in accordance with a Boltzmann energy distribution. Thus, a rotational temperature describes the population distribution within a vibrational level. In most cases, the rotational temperatures of all the vibrational levels are roughly the same, and are approximately equal to the translational temperature of the gas.

Some of the detailed band structure of the more important laser transitions is shown in Figure 2. The selection rule for the transitions is $\Delta J = \pm 1$, where J is the rotational quantum number. The group of transitions for which $\Delta J = +1$ is called the P branch, while the group for which $\Delta J = -1$ are called R branch. A particular line is unambiguously identified by stating its branch and the J value of the lower state. Thus, the transition from $J = 19$ to $J = 20$ is labeled P(20). The particular band (i.e., $00^{\circ}1 \rightarrow 10^{\circ}0$) is identified separately.

B. CO₂ Laser Physics

A very important point concerning the energy level diagram of Figure 1 is that the vibrational levels important to lasing are in the ground electronic state of the molecule. With the laser levels situated in this manner, a high quantum efficiency (approximately 40%) is available for laser operation. This efficiency has never been realized experimentally, but efficiencies of about 33% have been obtained.³¹

Fig. 2 Rotational band structure of the $00^{\circ}1 \rightarrow 10^{\circ}0$ and $00^{\circ}1 \rightarrow 02^{\circ}0$ vibrational transitions

Part of the reason for the high efficiency of the CO_2 laser is the way in which the population inversion is established. The phenomenon involved is called a partial inversion and it arises from the fact that vibrational radiative transitions actually take place between rotational sublevels. When speaking of any particular transition, a population inversion exists when more molecules are in the upper rotational level than in the lower rotational level. When one considers the Boltzmann distribution of rotational levels, it becomes apparent that this requirement can be satisfied even if the upper vibrational level has fewer molecules than the lower vibrational level. This situation is called a partial inversion and it can be achieved much more easily than a total inversion between the vibrational levels.

Level populations typical of a partial inversion are shown in Figure 3-A. The laser output obtained from a partial inversion arises from P branch transitions ($\Delta J = +1$). The reason is that, with the rotational levels of both vibrational states distributed in accordance with the same temperature, the J^{th} level of the upper vibrational state is not as far out in the Boltzmann tail as the $J + 1$ level of the lower vibrational state. This gives rise to a partial inversion for the P branch transitions. However, for the R branch transitions ($\Delta J = -1$) the opposite situation exists and no gain is possible unless the upper vibrational state has more molecules than the lower vibrational state.

Since rotational temperatures are strongly coupled to the gas temperature, a partial inversion is very sensitive to gas heating. Figure 3-B shows the effect of increasing gas temperature on a partial inversion. As the temperature increases, the high energy tail of the distribution becomes flatter and the partial inversion disappears. Thus, an increase in gas temperature of a relatively few degrees can have a very serious detrimental effect on the population inversion and thus on small signal gain. Basically this is the reasoning behind the statement in the previous chapter that rising gas temperature causes a serious decrease in small signal gain.

$\Delta N_J = \text{Population Inversion}$

$\Delta N_J(T_1) > \Delta N_J(T_2)$ if $T_1 < T_2$

Fig. 3 (A) Level populations typical of a partial inversion.
 (B) Effect of increasing temperature on a partial inversion.
 Note decrease in ΔN_J .

The other important characteristic of the CO_2 laser system is the large power output which can be obtained. The saturation intensity is an important parameter in this respect. The variation of I_s with discharge conditions cannot be easily explained without resorting to a rather involved analysis. However, it should be mentioned that I_s increases with increasing loss rates from the upper laser levels. These loss processes are enhanced by high temperatures, so I_s increases with gas temperature. Bullis,³² et.al., and Fowler³³ have calculated the effects of gas temperature and electron density on the small signal gain, the saturation intensity, and on their product, the available specific power. Their results are shown in Figure 4.

It should be noted that all three parameters are favorably affected by increases in electron density. However, since the laser levels lie in the neutral CO_2 molecule, the fractional ionization must be kept small. Thus, to derive advantage from an increased electron density, it is necessary to increase the gas pressure accordingly.

C. Historical Development of the CO_2 Laser

Patel's first CO_2 laser was produced by passing direct current through pure CO_2 gas at pressures of a few tenths of a torr. The efficiency of the laser was very low and the output power was only a few milliwatts. The output radiation consisted of transitions between a large number of vibrational-rotational levels. The lines observed were identified to be transitions ranging from P(12) to P(38) for the 00^0_1 to 10^0_0 vibrational band and from P(22) to P(34) for the 00^0_1 to 02^0_0 vibrational band. R-branch transitions were obtained in this early work.

Patel successfully explained these results by calculating the gain of the various transitions for different values of population inversion. The results of his calculations are shown in Figure 5. These curves show quite clearly the importance of a partial inversion, since for some of the P branch transitions a

Fig. 4 Variation of small signal gain, saturation intensity, and specific power with gas temperature and electron density (after Bullis, ref. 32).

Fig. 5 Variation of optical gain with J-value for P-branch and R-branch transitions of the $00^{\circ}1 \rightarrow 10^{\circ}0$ band (after Patel, ref. 28).

substantial gain exists even when there is not a total vibrational population inversion.

Because there is competition between the various transitions for a common upper state population, the high gain P-branch transitions persist while the R-branch transitions are suppressed. By using a frequency selective device in the laser cavity, such as a prism or a grating, it is possible to suppress all the transitions except for a particular one. In this way, laser oscillations on R-branch transitions have been obtained.

Patel³⁴ obtained information concerning the pumping mechanisms of his first CO₂ laser by operating the discharge in the pulsed mode. It was found that the laser output pulse followed the discharge current pulse by some 300 microseconds. This time delay was interpreted by Patel as strong evidence against direct excitation of the upper laser levels by electron collisions. Instead, he postulated that the pumping was due either to cascading from higher lying levels or to the recombination of dissociation products into excited states:

Recently, quantitative measurements have been performed³⁵ which show that the latter process is indeed an important pumping mechanism in pure CO₂ discharges. Evidence of direct pumping by electron collisions has also been published,³⁶ but this process is probably not as important as recombination. Both processes are surely involved in all CO₂ lasers, and the relative importance of each probably depends upon the particular discharge conditions involved.

The pumping mechanism which Patel observed in his first CO₂ laser was extremely inefficient. The majority of the pumping was done by cascade or dissociation-recombination processes. Since these processes are produced by relatively large expenditures of energy, the low-lying laser levels were not being efficiently used. A number of workers³⁷ suggested the possibility of

improved laser performance by the addition of N_2 to the CO_2 . Since N_2 is a diatomic molecule, it has only one series of vibrational levels. The lowest of these levels, N_2 ($v = 1$) is separated by only 18 cm^{-1} from the CO_2 ($00^{\circ}1$) state. This means that the excitation energy of the N_2 ($v = 1$) state can be resonantly (large cross section) transferred to the CO_2 upper laser level. Also, since N_2 is a homonuclear molecule, it has no permanent dipole moment, and therefore radiative transitions from vibrational levels in the ground electronic state are forbidden. Thus, the N_2 ($v = 1$) state is metastable, and since it has a very large cross section for formation by direct electron impact, it presents an efficient means of storing energy and then transferring it to the upper laser levels in the CO_2 molecule.

Patel³⁸ demonstrated experimentally that excited nitrogen could indeed be used to pump a CO_2 laser. Later workers used this technique to improve both the power output and efficiency of the CO_2 laser system.³⁹

A short time later, it was discovered⁴⁰ that the addition of helium to CO_2 laser discharges resulted in substantial improvements in laser performance. Helium plays no direct role in the electronics of the laser plasma because its lowest excitation potential is nearly 20 eV. Since the average energy of the electrons in the laser plasma is only a few electron volts, excitation of the high lying helium levels is very rare. Thus, the helium atom interacts with the other species in the discharge mainly by billiard ball type collisions.

In these collisions, vibrational energy of the lower-lying CO_2 levels (the lower laser levels) is efficiently converted to translational energy of the helium atom. Therefore, helium provides an efficient means of depopulating the lower laser state. De-excitation of the higher-lying CO_2 levels is not such an efficient process because the energy exchange is greater.

Helium collisions are also an efficient way of coupling the gas temperature to the rotational temperature of the CO_2 molecules. This cross relaxation of

the CO_2 rotational levels has the same effect as increasing the population inversion. As laser action attempts to destroy the population inversion on the high gain transitions, helium collisions repopulate the rotational levels involved by continuously redistributing the energy of the entire band. In this way, all the molecules in the 00^0_1 vibrational level can be made available for lasing.

With the use of helium, it became possible to construct CO_2 lasers with efficiencies of a few per cent and output powers of several watts. Even at this early stage of development, the CO_2 laser was far more efficient than any other laser system and it offered the promise of extremely high powers in both pulsed and continuous wave operations. This situation led to a great deal of research into the problems limiting the performance of the laser. A number of basic difficulties were identified and solved in one manner or another.

D. Basic Problems of CO_2 Lasers

A fundamental problem involved with electrical pumping of a CO_2 laser is dissociation of the CO_2 molecule:

In sealed-off systems, this reaction can completely remove the CO_2 constituent from the discharge and thus destroy laser operation. Some of the oxygen produced in this way combines chemically with gas impurities and with the metal of the electrodes before it can recombine with CO to replenish the CO_2 supply. Sealed-off CO_2 lasers systems have been built⁴¹ with lifetimes in excess of 10,000 hours by making the electrode surfaces very small and by using very pure gases.

Such systems are successful because of the extreme care used in their production. A more common solution to the dissociation problem is to use flowing gas. In this type of system, the dissociated gas is continuously pumped out and

replaced by fresh gas. The advantages of the flowing gas system are that moderate amounts of gas impurities are tolerable and that the electrodes may be constructed in any desired shape or size. Disadvantages are the requirements of a gas supply and a vacuum pump.

One additional advantage of a flowing gas system is that gas which has been heated in the discharge is pumped out and replaced by cool gas. If the gas flow rate is very rapid, extremely high currents can be used without significantly heating (or dissociating) the gas. This fact is the basis for experiments⁴² which have shown that CO_2 laser power can be scaled directly with gas flow rates. Fast flow, or aerodynamic, techniques have been used to produce a laser-amplifier system with a continuous power output in excess of 20 kilowatts.⁴³

Another parameter which is important in the operation of CO_2 lasers (especially small bore, low pressure CO_2 lasers) is the temperature of the walls of the discharge container. The walls of the discharge tube are important in conducting heat away from the gas. But of even greater importance is the fact that wall collisions are an important process in destroying the lower laser level population. As the wall temperature increases, the probability that a wall collision will de-excite a molecule in the lower laser level decreases. For these reasons, the walls of CO_2 laser discharges are usually cooled by passing a fluid (air, water, liquid nitrogen, etc.) over them. It should be mentioned that the problems of wall heating are not important in fast-flow lasers, where the gas removal time may be much less than the time required for diffusion to the wall.

The difficulties just discussed (gas dissociation, gas heating, wall heating, etc.) are problems which result from passing an electrical discharge through a volume of gas. There are other problems which are met in attempting to produce the electrical discharge. The discharge must be stable and uniform and it must possess plasma properties which are consistent with reasonably efficient laser

pumping. The achievement of all these conditions simultaneously involves the solution of a number of difficult problems. Several attempts have been made to circumvent these problems by using pumping techniques which do not require the use of an electrical discharge. Thermal pumping,^{44,45} optical pumping,⁴⁶ and pumping by chemical reactions^{47,48} have all been employed with some success. However, electrical pumping is still the most versatile and efficient technique. Currently, the great majority of work being done with CO₂ lasers involves schemes attempting to take full advantage of the versatility of electrical pumping.

E. Present CO₂ Laser Research

The goal being sought in present work with CO₂ lasers is to produce stable, uniform electrical discharges with high current densities and E/N values consistent with efficient laser pumping. The main problems being encountered are gas heating, gas dissociation, and discharge instabilities which occur at high pressures and high currents.

In steady state or long-pulse discharges, problems of gas heating and gas dissociation are solved by using rapidly flowing gas. Aerodynamic techniques are used to maintain the desired stability and uniformity of the discharge. The pressures and currents utilized are limited only by the rate at which gas can be removed from the system.

When extremely high laser power is desired, short pulse discharges are used. In this situation the total energy input to the gas from a single discharge pulse is not sufficient to cause significant gas heating or dissociation. Gas flow is not important except that the gas in the discharge volume is changed between pulses. Electrode geometries have been developed which produce short, high current pulses in high pressure gases. An even more promising scheme is to use a source of external ionization to obtain uniform breakdown of a large volume of high pressure gas. This approach has the advantage that relatively simple electrode geometries can be used to produce very uniform discharges with high

current densities in gases at very high pressures. In addition, the external ionization gives an independent means of controlling E/N within the discharge. This leads to improved laser efficiency.

III. EXPERIMENTS AND OBSERVATIONS

The experiments to be described have involved investigations of both longitudinal and transverse electrical discharges. Work with longitudinal discharges was done at relatively low pressures (less than 50 torr). Both pulsed and steady state experiments were performed. The electrical characteristics of these low pressure plasmas have been studied, as well as the laser output and small signal gain. In addition, electrical probe studies of the plasmas have been performed.

The transversely excited discharge tube was designed for pulsed operation with high pressure gas. Because of experimental difficulties, it was only possible to monitor the laser output power in these experiments. The large amounts of electrical noise produced by the pulsing circuitry made it impossible to follow the temporal variations of the discharge voltage and current.

A. Low Pressure Experiments

1. Description of Experiment

Figure 6 shows the details of an electrical discharge tube which was used to study the effects of a nuclear ionization source on the operation of low pressure CO₂ lasers. The important feature of this tube was the boron-10 coating which was placed on the inside surface. When the tube was exposed to a flux of thermal neutrons, high energy ions were produced in the coating by the following nuclear reaction:

The particles produced in this way passed into the gas creating ionization which was independent of the electric field applied by the electrodes.

The boron coating covered the entire inner surface of the discharge tube with the exception of the regions less than one centimeter from the electrodes. The

Fig. 6 Discharge tube used to study low pressure irradiated plasmas.

thickness of the coating was rather non-uniform and for this reason, it was difficult to calculate exactly the amount of ionization created by the nuclear source.

Quartz tubing was used in the construction of the tube in order to minimize the absorption of neutrons in the walls and thus maximize the ionization produced in the gas by a given level of neutron flux. Most commercially available glasses contain impurities which are strong absorbers of neutrons.

Flowing gas was used in all experiments but the flow velocities were quite modest. Typical values were five to ten centimeters per second. Thus, the lifetime of a given sample of gas in the discharge was between five and ten seconds. These flow velocities were adequate to eliminate serious problems arising from long term gas heating and dissociation. However, when larger discharge currents were used, such problems became quite bothersome. The usual technique used for high current operation is to quickly pump out the warm, dissociated gas and replace it with fresh gas. Lifetimes for gas samples in such discharges are typically a few milliseconds. This option of fast flow rates was not available in the present work. The small amount of space available made it necessary to connect the vacuum pump and the gas supply bottles to the discharge tube with small diameter hoses. This was the important factor in limiting the gas flow velocities. Since it was not possible to use fast flow, the problems of gas heating and dissociation were solved by pulsing the discharge. The electrical pulses to the discharge were kept short enough that the energy input to the gas from a single pulse was not enough to cause significant heating or dissociation. The time between pulses was long enough to permit gas cooling and recombination to occur.

In a further attempt to cut down on the detrimental effects of gas heating, the walls of the discharge tube were water cooled. For a small diameter tube such as the one being used, and for the low gas flow rates involved, removal of heat

by the walls is an important process. The mode structure observed in the laser output beam verified this fact. In most cases, warm gas at the center of the tube suppressed the dominant TEM_{00} mode* of the laser, by destroying the partial inversion. In cooler gas near the walls, a partial inversion was present and higher order modes (TEM_{10} and TEM_{01}) were able to oscillate. This situation produced an output beam with an annular shape.

The electrodes were constructed of aluminum in order to minimize the formation of radioactive products with long lifetimes. A tubular design was adopted so that the electrodes could be placed inside the optical cavity without interfering with laser operation. This made possible a compact, stable optical cavity and led to a more uniform discharge.

Connections for hoses from the gas supply bottles and from the vacuum pump were made through the mirror supports in order to save space. A vacuum gauge was connected to the discharge tube through an auxiliary line in which there was no flow of gas. Since there was no flow in the line, there was no pressure drop between the discharge tube and the vacuum gauge, and the pressure read at the gauge was equal to the pressure in the discharge.

The experiments were performed with the discharge tube in the beamport of a Triga reactor, adjacent to the reactor core. Four distinct sets of experiments were performed. Studies were made to determine the effects of the external ionization on: (1) macroscopic electrical properties of the discharge (current, E/N), (2) coherent output power of the laser, (3) small signal gain of the plasma, and (4) microscopic plasma properties within the discharge. All the experiments were performed over a relatively broad range of pressures and currents.

* For a medium in which the gain is spatially uniform, the dominant mode (mode with the lowest losses) of an optical cavity made of circular mirrors is the TEM_{00} mode. In this mode, the profile of the intensity of optical radiation is radially symmetric, with the maximum intensity appearing on the axis of the cavity. The variation of intensity with radius is Gaussian.

2. Characteristics of Irradiated Discharges

The electrical behavior of the irradiated discharges was important for the basic physical information which it supplied and also because it provided a means of correlating the data of the other experiments. Figure 7 shows the electrical circuit which was used in this part of the work. The voltage across the discharge tube was measured with a high voltage probe. This measurement, together with the pressure reading, yielded the E/N within the discharge. The current through the discharge was monitored by recording the voltage across a ten ohm series resistor. A capacitor was used to improve the short term regulation of the power supply. The purpose of the load resistor was to stabilize the discharge along a specific load line in the voltage-current plane. By varying the value of R_L , it was possible to map the various operating points for the discharge with different values of flux.

The voltage was adjusted to a value which was well below the breakdown value for the particular pressure in the tube. Initially, there was no current in the circuit, but when the reactor power was increased, the nuclear ionization allowed a current to flow through the gas. As the current in the circuit increased, the voltage applied to the discharge decreased because of the increasing voltage across R_L . In this way, R_L controlled the discharge without suppressing information on its electrical properties.

Figure 8 shows the results of a typical reactor pulse. The reactor power range of 0 to 30 megawatts was studied during this pulse. However, a much larger pulse (200 megawatt peak) was used because it was desired to sweep through the flux range of interest as fast as possible. By shortening the time scales involved, the voltage regulation of the capacitor supply was improved and it was possible to go to higher discharge currents. For the particular pulse shown in Figure 8 the gas pressure was 9 torr and the gas mix was 8:1:1 (He , N_2 , CO_2). Similar results were obtained for other pressures and gas mixes.

Fig. 7 Circuit used to study the effects of nuclear ionization on the electrical behavior of the longitudinal discharge.

$V_0 = 2700\text{V}$ $P = 9\text{ Torr}$
 $R_L = 10\text{ K}\Omega$ $(8:1:1 \text{ He, N}_2, \text{CO}_2)$

Fig. 8 Changes in discharge parameters during a reactor pulse.
 (Zero voltage is on bottom of scale, zero current is one
 division up, zero flux is at top of scale.)

Figure 9 shows the variation of discharge current with E/N for a number of different flux levels. There are several important points concerning the data of this figure which should be mentioned before proceeding with a discussion of the detailed processes occurring in the discharge. First, the nuclear radiation made possible the production of stable, high current discharges at pressures above those which could be sustained in the normal way with the available power supply. All the curves in Figure 9, except the curve for zero reactor power, have positive slopes. This corresponds to a positive dynamic resistance for the discharge and accounts for the stability produced by the nuclear radiation. The most important point to note is that, for any given pressure, operation is not limited to a single curve in the current- E/N plane. Instead, since the reactor flux is a continuously variable parameter, operation is possible anywhere to the left of the curve for zero reactor power. This fact allows an independent choice of current and E/N , merely by properly selecting the neutron flux level.

The general features of the curves just discussed can be explained by considering the details of the ionization and loss processes occurring within the discharge. If these processes are known it is possible to solve a balance equation for the electron density. When the electron density is multiplied by the drift velocity and integrated over the cross section of the discharge, an implicit relation is obtained between the current and E/N .

For a plasma in the steady state, the following equation governs the electron density:

$$I(\phi) + v_i(E/N) n_e = \alpha_R n_e^2 - D_a \nabla^2 n_e$$

where $I(\phi)$ is the nuclear ionization source rate
(electron ion pairs per c.c. per second)

ϕ is the thermal neutron flux (# per square centimeter per second)

$v(E/N)$ is the electron ionization frequency

n_e is the electron density

Fig. 9 Relation of discharge current and E/N for various reactor power levels.

α_R is the electron-ion recombination coefficient

$D_a(E/N)$ is the ambipolar diffusion coefficient

∇^2 is the Laplacian operator

An attempt will now be made to calculate the form and the relative importance of the various terms.

The rate at which ionization is produced by the nuclear radiation can be roughly estimated from the known slowing down cross sections^{49,50,51} of alpha particles and lithium ions. When this is done, (see Appendix A) the result is:

$$I(\phi) = 7\phi[p_{He} + 6.6p_{N_2} + 9.6p_{CO_2}] \frac{\text{ions}}{\text{c.c.-sec}}$$

where p_x is the partial pressure of the x^{th} component gas in Torr. ($x = H_e, N_2, \text{ or } CO_2$)

When no voltage is applied to the discharge tube, the electrons and ions produced recombine or diffuse to the walls. However, if a voltage is applied, a directed velocity is superimposed on the random thermal motion of the charges and a current is produced. As the E/N within the tube is increased, the discharge current becomes larger because of the increased drift velocity of the electrons. When the E/N within the tube becomes large enough, some of the electrons gain sufficient energy between collisions to produce more electron ion pairs. The next question which arises concerns the importance of the electron multiplication process. In other words, is the value of E/N used in the experiments ever large enough that the term $v_1(E/N) n_e$ represents a significant source rate?

For the E/N regime involved in the data of Figure 9, electron multiplication is an important process in determining the functional variation of current with E/N . If electron heating were the only important factor, the variation of current with E/N would be the same as the variation of electron drift velocity with E/N . Experiments^{52,53} have shown that the electron drift velocity is roughly a linear

function of E/N for He, N_2 , and CO_2 . Thus changes in drift velocity are not sufficient to explain the sharply rising current curves of Figure 9. However, in the electron multiplication region, the current varies roughly as $e^{k\alpha}$, where k is a constant depending on the discharge geometry and α is Townsend's first ionization coefficient. The variation of α with E/N over the narrow E/N range involved may be represented by a linear function. Thus, in the electron multiplication region, one would expect an exponential relationship between current and E/N .^{*} A semilogarithmic plot of the data is shown in Figure 10. The linearity of the curves implies that the general arguments presented above are applicable and that electron multiplication is an important production process in the discharge.

Having considered the electron source terms, we turn now to the problem of determining the important loss processes. If recombination is the dominant process, the balance equation becomes:

$$I(\phi) + v_i(E/N) n_e = \alpha_R n_e^2$$

The solution is:

$$n_e = \frac{v_i(E/N) + \sqrt{v_i^2(E/N) + 4 \alpha_R I(\phi)}}{2 \alpha_R}$$

$$I_D = ev_D \int n_e dA = \pi R^2 ev_D \left[\frac{v_i(E/N) + \sqrt{v_i^2(E/N) + 4 \alpha_R I(\phi)}}{2 \alpha_R} \right]$$

where

I_D = discharge current

v_D = drift velocity of electrons

R = radius of discharge

e = electron charge and the integration is over the cross section of the discharge.

If diffusion is the important loss process the balance equation becomes:

* The arguments presented here are very qualitative and do not take into account all the important processes involved. The agreement of this elementary theory with experimental data is not proof of the validity of the theory, but it is evidence of the usefulness of the ideas in considering this rather narrow range of parameters.

Fig. 10 Semilogarithmic plot of current vs E/N for various reactor power levels.

$$I(\phi) + v_i(E/N)n_e = -D_a \nabla^2 n_e.$$

The solution is:

$$n_e = \frac{I(\phi)}{v_i(E/N) J_0\left(\frac{v_i(E/N)}{D_a} R\right)} \left[J_0\left(\frac{v_i(E/N)}{D_a} r\right) - J_0\left(\frac{v_i(E/N)}{D_a} R\right) \right]$$

where J_0 and J_1 are zero and first order Bessel functions and r is the radius variable in the discharge.

$$I_D = \frac{2 e v_D I(\phi)}{v_i(E/N) J_0\left(\frac{v_i(E/N)}{D_a} R\right)} \left[\frac{D_a}{v_i(E/N)} R J_1\left(\frac{v_i(E/N)}{D_a} R\right) - \frac{R^2}{2} J_0\left(\frac{v_i(E/N)}{D_a} R\right) \right]$$

From the above equations, it can be seen that for a recombination dominated plasma there will be a square root relationship between current and flux especially at low values of E/N where v_i is negligible. On the other hand, when diffusion is the dominant loss process, there will be a linear relationship between current and flux. The experimental data presented in Figure 11 implies that diffusion is the dominant process for the particular pressure range used here. At higher pressures and higher currents, recombination becomes more important.

Since diffusion is the dominant loss process in the discharge, the last equation above gives the desired relation between current, neutron flux, and E/N . However, the current is expressed as an implicit function of E/N , and the exact form to be expected in the current - E/N curves is not immediately obvious. However, in the E/N regime being considered, certain simplifying assumptions can be made and the use of a few empirical formulas is certainly justified. For instance, if E/N is not too small, elementary arguments lead to the following approximations:

$$v_D(E/N) \propto E/N$$

$$D_a(E/N) \propto E/N$$

$$v_i(E/N) \propto (E/N)^{1/2} \exp\left[-\frac{k_1}{E/N}\right]$$

Fig. 11 Discharge current vs reactor power for different E/N levels.

where k_1 is a constant.

Substitution of these relations into the current equation produces an explicit relation between the current and E/N :

$$I_D(E/N) = k_2 \frac{I(\phi)}{x} \left[x \frac{J_1(x)}{J_0(x)} - \frac{x^2}{2} \right] \quad 0 \leq x \leq 2.405$$

where k_2 is a constant and $x = \frac{v_1(E/N)}{D_a(E/N)} \propto (E/N)^{-1/2} \exp(-\frac{k_1}{E/N})$.

A plot of $I_D(E/N)$ as a function of normalized E/N is shown on linear coordinates in Figure 12 and on semilogarithmic coordinates in Figure 13.

When one considers the effect of normalizing the E/N scales of Figure 9 and 10 with respect to the positive column saturation value ($E/N = 2.3 \times 10^{-16}$), it becomes apparent that the experimental data corresponds to the lower and central portions of the theoretical curves. By properly choosing current scaling constants, it is possible to fit the experimental curves to the theoretical curves. The fit is especially good for the 2 and 5 Mw curves.

3. Laser Output Measurements

Figure 14 shows the setup which was used in studying radiation effects on laser output power. The laser power was monitored by directing the output beam first to a focussing mirror and then onto a gold-doped germanium detector. It was impossible to collect all the beam because of the large distance from the laser to the detector. Therefore, laser power levels and changes in power levels were measured in arbitrary or relative units. The absolute power measured at the laser output mirror was typically a few tenths of a watt and thus one can roughly convert these arbitrary units to absolute values if desired.

It was mentioned earlier that in studying the effects of external ionization on laser operation, complications arise from problems of gas heating and gas dissociation. Figure 15 illustrates the problem. The discharge was

Fig. 12 Calculated relation of relative discharge current and E/N (linear scale). E/N normalized to pos. column saturation value.

Fig. 13 Calculated relation of relative discharge current and E/N (semilogarithmic scale). E/N normalized to pos. column saturation value.

Fig. 14 Experimental setup for studying effects of nuclear radiation on laser power output.

Fig. 15 Effects of gas heating and dissociation on laser output power.

subjected to a long current pulse (~500 μ sec) which produced lasing. The laser power increased at first, and then began to decrease as the gas heated. When the current pulse was terminated, the gas started to cool and laser pumping continued via the nitrogen vibrational levels and/or the recombination of carbon monoxide and oxygen. As a result, the laser power increased for quite some time (about 50 microseconds) after the current was turned off. Experiments of this type seem to imply that the time constant involved for recombination and cooling are on the order of 50 microseconds (for this pressure, gas mix and tube bore). This time is consistent with calculations of the wall thermal decay time and scaling laws derived from the heat equation for the gas within the discharge.⁴² The heat equation for gas in the discharge is:

$$K_o \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) = \rho C_v \frac{\partial T}{\partial t}$$

where

K_o is the thermal conductivity

T is the gas temperature

ρ is the gas density

C_v is the specific heat of the gas

t is the time variable

If the gas is at an initial temperature of T_i and is allowed to cool by conduction to a wall at temperature T_w , the solution for the gas temperature is:

$$T = T_w + (T_i - T_w) J_o \left(\frac{2.405}{R} \right) \cdot \exp \left[- \frac{K_o}{\rho C_v} \left(\frac{2.405}{R} \right)^2 t \right]$$

where R is the radius of the tube. This solution predicts a decay time for the gas which is proportional to $\frac{\rho C_v R^2}{K_o}$. Elementary arguments can be made to show that K_o is proportional to $\rho \bar{\lambda} \bar{c}$, where $\bar{\lambda}$ is the mean free path of the diffusing particles and $\bar{c}$ is their mean thermal velocity. Thus, the decay

time scales as $R^2/\lambda c$. When Hill's⁴² results are scaled to the tube radius, gas pressure, and gas mix being used in the present work, it seems that thermal decay times of about 50 microseconds are to be expected.

Other explanations are possible, such as a relaxation time for the lower laser state. For example, if the electrons were pumping the lower laser state during the active discharge, the end of the current pulse would be followed by a decay of the population in this state. It is possible that the decay time for this process could be as long as 50 microseconds but experimental evidence seems to imply that lower state relaxation times for the conditions being studied are probably less than 20 or 30 microseconds.

By using very short current pulses, such as the one shown in Figure 16, it is possible to use the relaxation time to eliminate some of the effects of heating and dissociation on laser output. The laser output pulse follows the current pulse by some 50 to 100 microseconds. This delay is the time required to transfer energy to the upper lasing levels and build up the population inversion required for the onset of lasing. During this time the gas cools, molecular recombination occurs, and the lower state population decays away. As a result, by the time lasing begins, these problems have become much less important. Of course, during the delay time, some molecules in the upper laser states are lost by collisions and diffusion.

In these experiments, a hard tube pulser was used to apply voltage pulses of variable magnitude and duration to the discharge tube at various levels of neutron flux. As can be seen from the scope traces in Figure 16, the voltage was constant during each pulse, and thus E/N was also constant. Therefore, it was possible to study the laser performance with E/N as a running parameter. The laser performance data will be presented by defining an effective excitation frequency for electrons, $\frac{\nu_{ex}}{n}$.

Fig. 16 Laser output resulting from a short current pulse in the presence of nuclear radiation. Note difference in time scales.

$$\frac{\nu_{\text{ex}}}{n} = \frac{\frac{1}{Vh\nu} \int_0^{\infty} P_L(t) dt}{\frac{1}{Ae\bar{v}} \int_0^T i(t) dt}$$

where

T = duration of current pulse

V = volume of discharge

h = Plank's constant

ν = frequency of laser radiation

$P_L(t)$ = instantaneous laser power

A = cross sectional area of discharge

e = electron charge

$\bar{v}$ = drift velocity of electrons^{11,12}

$i(t)$ = instantaneous discharge current

The quantity $\frac{\nu_{\text{ex}}}{n}$ as defined above may be interpreted as the collision frequency for a single electron to produce molecules which are excited into an upper laser level. It is a measure of the efficiency with which electrons pump CO_2 molecules, by any process, direct or indirect, to upper laser states. A plot of the experimental $\frac{\nu_{\text{ex}}}{n}$ versus E/N is shown in Figure 17 for a pressure of 10 torr and a gas mix of 8:1:1 (He , N_2 , CO_2). Similar results have been obtained at other pressures. The peak in the curve corresponds to an E/N value which is most favorable for laser pumping in this particular gas mix. Calculations by Nighan⁷ predict that the peak in the curve occurs at an E/N of about 3×10^{-16} volt cm^2 . This is very close to the value obtained experimentally. Unfortunately, it is not possible to obtain absolute numbers for the experimentally determined values of $\frac{\nu_{\text{ex}}}{n}$, because there are mechanisms other than stimulated emission which cause the loss of molecules in the upper laser levels. These processes have been ignored and this prohibits absolute measurements of $\frac{\nu_{\text{ex}}}{n}$ by this technique.

Fig. 17 Effective excitation frequency of upper laser levels by electrons as a function of E/N .

4. Laser Gain Measurements

An interesting feature of the laser output data is shown in Figure 18. Here the laser output and E/N are plotted as functions of current for zero flux and a reactor power of about 1 MW. These curves were produced by passing different values of direct current through the discharge and measuring both laser output and E/N for reactor power levels of zero watts and one megawatt.

According to Nighan's⁷ calculations, once the gas mix, current, and E/N are chosen, both the electron density and energy distribution are fixed and thus the laser pumping rate is determined. However, it can be seen that for a range of currents, there is an increase in laser output even when the external ionization produces no noticeable change in the value of E/N . In order to study this situation more carefully, a series of experiments was performed to measure changes in the small signal gain coefficient, γ . The experimental setup is shown in Figure 19. The discharge tube used in these experiments was the same one used in the laser power measurements. The only difference was that the output mirror of the laser was replaced by a sodium chloride window. In performing the experiments, the output beam of a reference laser was directed onto a sodium chloride beam splitter which reflected part of the light into a reference detector. The rest of the light passed through the beam splitter, made a double pass through the discharge tube, returned to the beam splitter, and was reflected onto an output detector. By comparing the signals from the two detectors, it was possible to calculate the change in gain which was produced in the discharge by the external ionization.

Figure 20 shows plots of $\Delta\gamma$, the increase in gain coefficient, and changes in E/N for a number of different pressures. The maximum increase in gain is produced when E/N is slightly less than the positive column value. However, there is no change in gain at currents above the points where the E/N curves merge together. Thus, the gain experiments seem to contradict the

Fig. 18 Variation of E/N and laser power output with current and reactor power.

Fig. 19 Experimental setup used to study the effects of nuclear ionization on 10.6μ gain.

Fig. 20 Change in 10.6μ gain and E/N produced by the nuclear ionization.

Horizontal scale is discharge current in milliamperes.

laser data shown in Figure 18. This conclusion is not well founded because the power output also depends on the saturation intensity, a parameter which was not studied in these experiments. Another problem is that the gain measurements are only sensitive to conditions along the discharge axis. At high currents, this portion of the tube contains hot gas and the optical gain is very small. This makes changes in gain very difficult to detect. Experiments which would sense the off-axis gain could supply more useful information about changes in laser output in the high current regions because the laser output power is sensitive to off-axis conditions when the laser is operating in the doughnut mode. Unfortunately, the particular geometry of the experiment made such measurements impossible.

In short, the gain experiments do not provide a final answer to all the questions, but they do prove that the changes in laser power are produced by changes in the population inversion within the gas, and not by nuclear induced changes in the cavity optics or the laser mode structure.

5. Electrical Probe Experiments

One possible explanation for the data of Figure 18 is a nuclear induced change in the shape of the electron energy distribution function. With the primary ionization created by high energy particles, it is possible that the molecular and atomic ionic species present are different from those in the normal positive column. These new species could produce a change in shape of the distribution function, especially if they are involved in the charge-transport processes. If the new distribution function overlapped more effectively the cross sections for formation of upper laser levels, there would be an increased laser output. Dolgov-Savelev, et al²⁴ have proposed an explanation similar to this for data which they obtained in work with an electron beam ionization source.

In order to test these ideas experimentally, a series of experiments was performed with electrical probes. An explanation of the theory necessary for interpretation of experimental probe data is available in a number of texts.⁵⁴ In addition, a brief discussion of the more important features of the theory is given in Appendix B.

Figure 21 shows a discharge tube which was constructed in order to make electrical probe measurements of the irradiated plasmas. The tube was similar to the one discussed previously except that it was not water cooled and it had no optical mounts at the ends. These differences were not important, however, because they did not greatly affect the electrical characteristics which the probes were measuring. It is true that the neutral gas temperature and the presence or absence of lasing do affect the shape of the electron energy distribution function, but these effects are much too small to be seen using the techniques described here.

Attempts were made to trace out the electron energy distribution function by electronically taking the second derivative of single probe current-voltage curves. These experiments failed because of a large amount of noise in the discharge and also because of the limited amount of time (integrating time) available for doing the experiments. Irradiation times had to be kept as short as possible in order to prevent excessive activation of the experimental equipment.

Experiments with identical double probes were much more successful, primarily because it was not necessary to differentiate the double probe characteristics. However, the amount of information gained from the double probes was not enough to decide whether or not the ideas about a shifting energy distribution function were correct. Nevertheless, the results are very intriguing.

Fig. 21 Double probe discharge tube and associated circuitry.

Figure 22 shows the effects of various radiation levels on the double probe characteristics. The sharply rising portion of the curve is caused by current carried to the probes by high energy electrons. The saturation regions result from the slowly varying ion current to the probes. Note that the curves are symmetric about the zero current point, which is located approximately at the center of the pictures. This is consistent with the theory of Appendix B. Since the probes are spaced downstream from one another in the discharge, the probe to plasma potential is not the same at the probe surfaces. This results in a shifting of the characteristics to the left or right as the voltage drop between the probes changes. This is the reason that the zero current points of the three characteristics shown do not line up vertically. For the different discharge currents involved, there are differences in the voltage drop between the probes.

As the radiation level is increased, the ion saturation current decreases, and the electron current portion of the curves becomes less important. There are a number of phenomena which could be responsible for these changes. Probably, a combination of effects is involved. It is possible that there is a decrease in the number of high energy electrons and a shift in the distribution function toward lower energies where more efficient laser pumping could be achieved. Another possibility is a change in the dominant ion species within the plasma. Such a change would result in a change of probe-to-plasma potential and a change in the ion saturation current. Thus, it can be seen that although the probe results are quite interesting, the interpretation of the data involves considerable guesswork. One logical explanation of the data would be to say that the nuclear ionization produced a change in the ion species of the plasma. This change could bring about both a shift in the electron energy distribution function and a change in the probe-to-plasma potential. These effects would produce the observed changes in the probe characteristics.

2

Fig. 22 Effects of external ionization on double probe current-voltage characteristics. Power levels of 0 and 150 k.w. Zero current at center of picture.

In closing, it must be admitted that the original goal being sought in performing the probe experiments was not successful, but some very interesting and previously unreported results were obtained. Although these results cannot be explained at the present time, future experiments may provide the necessary data.

B. High Pressure Laser Work

Experiments with transverse discharges were not as extensive as those with longitudinal discharges. Only the gas pressure, initial voltage, and laser output were monitored.

1. Description of Experimental Equipment

The laser tube used in this part of the work is shown in Figure 23. The anode consisted of a half-inch diameter aluminum rod which was covered with a thin coating of boron-10. The cathode was made up of a row of metal pins which were just the copper leads extending from a row of carbon resistors (10k Ω , 1/2 watt). The resistors were spaced 1/4 inch apart and the tips of the leads were about 3/4 inch from the anode. The electrodes were supported in a three-inch diameter plexiglass tube which served as a gas containment vessel. The mirrors were supported by O-rings which were fitted in grooves in the end plates. Slowly flowing gas was used (8:1:1, He, N₂, CO₂) at pressures from 100 to 760 torr. The electrical circuit used to pulse the tube is shown in Figure 24.

2. Experimental Procedure and Results

A typical experiment consisted of pulsing the laser at intervals of about one second as the reactor power was slowly increased. The results of such an experiment are shown in Figure 25. For clarity of presentation, each pulse was offset both horizontally and vertically from its predecessor by a rastered scope display. The picture gives a record of the pulsing operation

Fig. 23 High pressure transverse discharge tube with boron-10 coated anode.

Fig. 24 Electrical circuit used to pulse high pressure transverse discharge tube.

Fig. 25 Effects of increasing reactor power on high pressure laser.

in the presence of an increasing neutron flux. The external ionization enhances laser output by as much as a factor of two. Due to the large amount of noise picked up from the thyatron discharge circuit, it was not possible to monitor the time variation of the narrow voltage and current pulses. The particular circumstances of the experiment made it almost impossible to do any diagnostic work on the high pressure plasmas. Therefore, one can only guess at the detailed effects produced by the nuclear ionization. One obvious effect is a lowering of the breakdown voltage required for any given pressure. Also, it appears that there is an increase in the stability of the discharge (less tendency to go into an arc). Other effects may be involved, such as an increase in the uniformity of the lasing volume, a change in E/N and electron density, or changes in the shape of the electron energy distribution function.

This study of the effects of heavy particle ionization on a high pressure laser is quite closely related to work being done with electron beam ionization. Both techniques have been used to significant advantage in producing uniform breakdown of high pressure gases, and when closely analyzed, the two methods are seen to be very similar. The heavy particle ionization may possess one inherent advantage, and that is the possibility of extremely uniform breakdown - a characteristic of extreme importance in high power, long pulse lasers.

IV. CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

It has been shown that a heavy particle external ionization source produces several desirable effects on CO_2 laser discharges.

1. The external ionization leads to a uniform breakdown of the gas at lower voltages and higher pressures than with the applied electric field acting alone.
2. Discharges produced in the presence of the external ionization have a positive dynamic resistance for all values of voltage and are thus very stable at relatively high currents and pressures (currents of several hundred milliamperes and pressures up to 50 torr for the longitudinal discharge tube studied).
3. Within the limits set by available equipment, it has been possible to create discharges in which the current and E/N were chosen independently to have any desired values. This has made laser operation possible at the E/N values which produce optimum laser pumping.
4. The laser output power and 10.6 micron gain have been increased by the external ionization. At low currents, these increases are caused by an increase in the number of electrons which have the proper energy for pumping the upper laser levels. In the high current region, the exact mechanism producing the improved laser performance is not well understood. It has been postulated that there is a change in the shape of the electron energy distribution function which favors more efficient laser pumping. Probe experiments to test this theory show a pronounced effect on the high energy tail of the energy distribution. However, an exact interpretation of the results is not possible at this time.
5. Nuclear irradiation of a transversely excited laser has led to increased power output, possibly because of increased volume and uniformity of the

discharge within the optical cavity.

When one considers the additional versatility which results from the use of a nuclear ionization source, there are a number of possible experiments which come to mind. Perhaps the most obvious experiment is to study effects on other lasing gases. With positive control over both discharge current and E/N , it should be possible to improve the performance of a number of other laser systems. A few interesting choices would be CO and Xe, both of which offer the possibility of high efficiency.

The usefulness of the external ionization source could certainly be improved by obtaining a better understanding of the detailed processes involved. Discharge geometries might be designed which are amenable to more sophisticated diagnostic techniques.

If a more complete picture of the interaction processes involved were available, it might be possible to find ways to use irradiated discharges for such things as improving the rate and yield of chemical reactions. Along these lines, one could trigger chemical reactions whose products were in excited states. These excited states might then serve as upper laser levels. Thus, the nuclear induced chemical reaction could pump a laser.

APPENDIX A

CALCULATION OF NUCLEAR IONIZATION RATE

The nuclear reaction involved with producing the high energy ionizing particles is:

The entire energy of the reaction is not available as kinetic energy of the products because 92% of the lithium ions are produced in a state 0.44 MeV above the ground state. Thus, the average kinetic energies of the particles are:

$$E_{\text{av}}(\alpha) = 1.52 \text{ MeV}$$

$$E_{\text{av}}(\text{Li}) = 0.87 \text{ MeV}$$

The slowing down cross sections for α particles are well known, but the cross sections for lithium ions have not been studied so extensively.

$$F_{\text{He}}(\alpha) = \alpha \text{ energy loss rate in pure He} = 500 \text{ ev/cm-torr}$$

$$F_{\text{He}}(\text{Li}) = \text{Li energy loss rate in pure He} = 660 \text{ ev/cm-torr}$$

$$F_{\text{N}_2}(\alpha) = \alpha \text{ energy loss rate in pure N}_2 = 3325 \text{ ev/cm-torr}$$

$$F_{\text{CO}_2}(\alpha) = \alpha \text{ energy loss rate in pure CO}_2 = 4865 \text{ ev/cm-torr}$$

At low pressure, the heavy particle path length is determined by geometry and not by pressure. Also, the energy of the particles is essentially unchanged as they pass through the gas, so the slowing down cross sections are also constant.

With these assumptions, geometrical arguments can be made⁵⁵ to show that one-fourth of all the particles produced in the coating enter the gas and they enter with an energy equal to three-fourths of their energy at birth.

The particles have an average path length in the gas which is approximately equal to the tube diameter.

Let N represent the number of alpha particles produced per unit length of the tube per unit time:

$$N = \phi \sigma \frac{N_o \rho}{A_B} t \pi d$$

where ϕ = thermal neutron flux

σ = cross section for boron-10 to absorb

a thermal neutron = 4000 barns

N_o = Avogadro's number = 6.02×10^{23} atoms/gr-mole

ρ = density of boron-10 coating = 2.3 gr/cc

A_B = atomic number of boron-10 = 10

t = thickness of coating $\approx 5 \times 10^{-4}$ cm (estimated)

d = diameter of tube ≈ 2 cm

$$N = 1.7 \phi \text{ particles/cm-sec}$$

Let E_α represent the energy deposited by an average α particle:

$$E_\alpha = \sum_i F_i(\alpha) p_i d$$

$$E_\alpha = 2[500p_{\text{He}} + 3325p_{\text{N}_2} + 4865p_{\text{CO}_2}] \text{ ev}$$

$$E_\alpha = 10^3[p_{\text{He}} + 6.6p_{\text{N}_2} + 9.6p_{\text{CO}_2}] \text{ ev}$$

where p is the partial pressure in torr of the various gas components.

The volume per unit length of the tube is 3.14 cm^2 . Thus, the rate at which energy is supplied to a unit volume of the gas by the alpha particles is given by:

$$P_g(\alpha) \approx \left[\frac{N}{4}\right][E_\alpha]\left[\frac{1}{3.14}\right] \frac{\text{ev}}{\text{cc} - \text{sec}}$$

$$P_g(\alpha) \approx 130 \phi [p_{\text{He}} + 6.6p_{\text{N}_2} + 9.6p_{\text{CO}_2}] \frac{\text{ev}}{\text{cc} - \text{sec}}$$

Assuming that the lithium ions deposit as much energy in the gas as the α particles, the total power input to the gas is given by:

$$P_t \approx 260 \phi [p_{\text{He}} + 6.6p_{\text{N}_2} + 9.6p_{\text{CO}_2}] \frac{\text{ev}}{\text{cc} - \text{sec}}$$

Roughly speaking, the heavy particles must deposit about 35 eV in the gas for each electron-ion pair which is created. Thus, the ionization rate is:

$$I \approx 7 \phi [p_{\text{He}} + 6.6p_{\text{N}_2} + 9.6p_{\text{CO}_2}] \frac{\text{ions}}{\text{cc} - \text{sec}}$$

APPENDIX B

ELECTRICAL PROBE THEORY

When an isolated probe is inserted into a plasma, it assumes a potential relative to the plasma such that the electron current to the probe is equal to the ion current. Since the electrons are more mobile than the ions, the probe will be at a potential below the plasma potential in order to repel electrons and attract ions. In this way, the two currents are equalized in spite of the differing mobilities. The potential assumed by an isolated probe is called the floating potential.

Consider two identical probes inserted in a plasma and connected to an external circuit as shown in Figure B1. If no voltage is applied between the probes, both will assume the floating potential. The electron and ion currents to each probe will be equal and there is no current in the external circuit (assuming that the plasma potential is the same in the region of both probes).

With the probes in this "electron retarding" region, the variation of ion current with the probe to plasma potential, V_p , is very weak. Ideally, the ion current in this region is constant. The electron current, however, is a very rapidly varying function of V_p . If the electron energy distribution function is Maxwellian, the electron current is an exponential function of V_p . If a constant ion current and a Maxwellian electron distribution are assumed, it is possible to derive the "double probe voltage-current characteristic." This ideal characteristic is very similar to the actual characteristics obtained in experiments described in Chapter III. The currents and voltages involved in the derivation are:

I_{ext} = current measured in external circuit

V_a = voltage applied externally

$I_{p1,2}$ = ion currents to probes 1 and 2

Fig. B-1 Double probe circuit.

$V_{p1,2}$ = probe to plasma potentials for probes 1 and 2

$I_{e1,2}$ = electron currents to probes 1 and 2

From Figure B1 it is obvious that

$$I_{\text{ext}} = I_{e1} - I_{p1} = I_{p2} - I_{e2}$$

Assuming that the probes always repel electrons and that the electron energy distribution function is a Maxwellian described by a temperature T , we have that

$$I_{e1} = A_{p1} n_o e \sqrt{\frac{kT}{m}} \pi \exp\left[-\frac{eV_{p1}}{kT}\right] \quad (V_{p1} < 0)$$

$$I_{e2} = A_{p2} n_o e \sqrt{\frac{kT}{m}} \pi \exp\left[-\frac{eV_{p2}}{kT}\right] \quad (V_{p2} < 0)$$

where $A_{p1,2}$ = area of probes 1 and 2

n_o = electron density in undisturbed plasma

e = electron charge

k = Boltzmann's constant

m = mass of electron

The ion current to each probe is assumed to be constant

$$I_{p1} = I_{p2} = I_o$$

The potential diagram of Figure B1 shows that

$$V_a = V_{p1} - V_{p2}$$

The experimentally observable quantities are V_a and I_{ext} . When the other currents and voltages are eliminated by algebraic manipulation of the above equations, the result is:

$$I_{\text{ext}} = I_o \tanh\left(\frac{eV_a}{2kT}\right)$$

This characteristic has two distinct regions: a flat portion called the ion saturation region and a sharply breaking portion in which the current carried by high energy electrons is very important. The saturation current depends primarily on the type of ion species present. In the real case, where the ion current is not constant as V_p changes, the saturation current also depends on V_p , which in turn depends on the number of electrons in the high energy tail of the distribution. Unfortunately, in work with double probes, it is not possible to measure V_p for either probe. This leads to confusion in interpreting the results. The only parameter which can be obtained unambiguously from double probe data is the slope of the high energy tail of the electron energy distribution. For a Maxwellian distribution, this slope may be interpreted as an electron temperature. In CO_2 laser plasmas, however, the electron energy distribution is not Maxwellian.

Figure B2 shows a probe arrangement which is potentially much more useful than the double probe setup. This arrangement is called a single probe and the current-voltage curves for the circuit are called single probe characteristics.

One advantage of the single probe circuit is that changes in the applied voltage, V_a , are equal to changes in the probe to plasma potential, V_p . Another advantage is that, for probe currents which are much smaller than the discharge current, the ion current to the anode can always match the electron current to the probe, thus maintaining charge neutrality in the plasma even when the probe to plasma potential is near zero. Therefore, the single probe characteristics result from a sampling of electrons of all energies. When V_a is such that the electron current to the probe is much larger than the ion current, geometrical arguments can be made to approximate the current in the external circuit as:⁵⁴

$$I_D \gg I_{ext}$$

$$I_e \gg I_p$$

$$I_{ext} \approx I_e$$

Fig. B-2 Single probe circuit.

$$I_{\text{ext}} \approx I_e = - \frac{2\pi A_e}{m^2} \int_{-eV_p}^{\infty} dE (E + eV_p) f(E)$$

where I_e = electron current to probe

V_p = probe to plasma potential ($V_p < 0$)

$f(E)$ = electron velocity distribution function, normalized to n_0 ,
the undisturbed electron density.

Differentiating the above equation twice with respect to V_p , we obtain:

$$\frac{\partial^2 I_{\text{ext}}}{\partial V_p^2} \approx \frac{\partial^2 I_e}{\partial V_p^2} = - 2e\pi A_p \left(\frac{e}{m}\right)^2 f(E) \Big|_{E = -eV_p}$$

Thus, the velocity distribution function can be obtained from the second derivative of the single probe characteristic.

REFERENCES

1. Novgorodov, M. Z., Sviridov, A.G., and Sobolev, N.N., "Electron Concentrations in CO₂ Laser Discharges," J. Tech. Phys., 41, 752 (1971).
2. Polman, J., Wittman, W.J., "Electron-Radiation Temperature Measurements in a Sealed-off CO₂ Laser System," I.E.E.E. J. of Q.E., 6, 154 (1971).
3. Carswell, A.I., and Wood, J.I., "Plasma Properties of a CO₂ Laser Discharge," J. of Appl. Phys., 38, 3028 (1967).
4. Bletzinger, P., and Garscadden, A., "Burning in the Electron Energy Distribution by Lasing Action in the CO₂-N₂-He Discharge," Phys. Lett., 29A, 265 (1969).
5. Novgorodov, M.Z., Sviridov, A.G., and Sobolev, N.N., "Electron Energy Distribution in CO₂ Laser Discharges," I.E.E.E. J. of Q.E., 7, 508 (1971).
6. Avivi, P., Dothan-Deutsch, F., Keren, H., "Influences of Lasing on the Electron Energy Distribution in CO₂ Mixtures," J. of Appl. Phys., 42, 5551 (1971).
7. Nighan, W.L., "Electron Energy Distributions and Collision Rates in Electrically Excited N₂, CO, and CO₂," Phys. Rev., 2A, 1989 (1970).
8. Mills, C.B., Los Alamos Scientific Laboratory, Private Communication.
9. Schulz, G.J., "Vibrational Excitation of Nitrogen by Electron Impact," Phys. Rev., 125, 229 (1962).
10. Schulz, G.J., "Vibrational Excitation of N₂, CO and H₂ by Electron Impact," Phys. Rev., 135, A988 (1964).
11. Englehardt, A.G., Phelps, A.V., Risk, C.G., "Determination of Momentum Transfer and Inelastic Collision Cross Sections for Electrons in Nitrogen Using Transport Coefficients," Phys. Rev., 135 A1566 (1964).
12. Hake, R.D., and Phelps, A.V., "Momentum-Transfer and Inelastic-Collision Cross Sections for Electrons in O₂, and CO and CO₂," Phys. Rev., 158, 70 (1967).
13. Fowler, M.C., "Quantitative Analysis of the Dependence of CO₂ Laser Performance on Electric Discharge Properties," Appl. Phys. Lett., 18, 175 (1971).
14. Sobolev, N.N., and Sokovikov, V.V., "CO₂ Lasers," Sov. Phys. Usp., 10, 153 (1967).
15. Beaulieu, A.J., "Transversely Excited Atmospheric Pressure CO₂ Lasers," Appl. Phys. Lett., 16, 504 (1970).
16. Freiberg, R.J., and Clark, P.O., "CO₂ Transverse Discharge Lasers," I.E.E.E. J. of Q.E., 6, 105 (1970).

17. Laurie, K.A., and Hale, M.M., "Folded Path Atmospheric Pressure CO₂ Lasers," I.E.E.E. J. of Q.E., 6, 530 (1970).
18. Fortin, R., "Preliminary Measurements of a Transversely Excited Atmospheric Pressure CO₂ Laser," Can. J. of Phys., 49, 257 (1971).
19. Dumanchin, R., and Rocca-Serra, J., "Augmentation de L'energie et de la Puissance Fournie par Unite de Volume dan un Laser a CO₂ en Regime Pulse," Compt. Rend. Acad. Sci., (B), 269, 916 (1969).
20. Laflamme, A.K., "Double Discharge Excitation for Atmospheric Pressure CO₂ Lasers," Rev. of Sci. Instr., 41, 1578 (1970).
21. Lamberton, H.M., and Person, P.R., "Improved Excitation Technique for Atmospheric Pressure CO₂ Lasers," Elect. Lett., 7, 141 (1971).
22. Andriakhin, V.M. Velikhov, E.P., Golubev, S.A., Krasil'nikov, S.S., Prokhorov, A.M., Pis'mennyi, V.P., and Rakhimov, A.T., "Increase of CO₂ Laser Power Under the Influence of a Beam of Fast Protons," Sov. Phys. JETP Lett., 8, 214 (1969).
23. Allario, F., Schneider, R.T., Lucht, R.A., and Hess, R., "Enhancement of Laser Output by Nuclear Reactions," Symp. on Uranium Plasmas, Univ. of Florida, Gainesville, Florida, N.A.S.A. Sp 236, unpublished, (1970).
24. Dolgov-Savelev, G.G., Kuznetsov, V.V., Koziminkh, Y.L., Orishich, A.M., "On the Possibility of Constructing a CO₂ Laser Pumped by an Electron Beam," Zh. Prikl. Spektroskopii, 12, 737 (1970).
25. Fenstermacher, C.A., Nutter, M.J., Leland, W.T., Boyer, K., "An Electron Beam Controlled Electrical Discharge as a Method of Pumping Large Volumes of CO₂ Laser Media at High Pressures," Appl. Phys. Lett., 20, 56 (1972).
26. Douglas-Hamilton, D.H., Avco Everett Research Laboratory, Private Communication.
27. Ganley, T., Verdeyen, J.T., Miley, G.H., "Enhancement of CO₂ Laser Power and Efficiency by Neutron Irradiation," Appl. Phys. Lett., 18, 568 (1971).
28. Patel, C.K.N., "Interpretation of CO₂ Optical Maser Experiments," Phys. Rev. Lett., 12, 588 (1964).
29. Herzberg, G., Molecular Spectra and Molecular Structure II, Infrared and Raman Spectra of Polyatomic Molecules, ff 275, D. Van Nostrand and Co., Inc., Princeton, N.J., 1945.
30. Taylor, R.L., and Bitterman, S., "Survey of Vibrational Relaxation Data for Processes Important in the CO₂-N₂ Laser Systems," Rev. Mod. Phys., 41, 26 (1969).
31. Dezenberg, G.J., and Merritt, J.A., "The Use of a Multipath Cell as A CO₂-N₂ Gas Laser Amplifier and Oscillator," Appl. Opt., 6, 1541 (1967).
32. Bullis, R.H., Nighan, W.L. Fowler, M.C., Wiegand, W.J., "Physics of CO₂ Electric Discharge Lasers," United Aircraft Report J291, presented at Ninth AIAA Aerospace Sciences Meeting, (1971).

33. Fowler, M.C., "Quantitative Analysis of the Dependence of CO₂ Laser Performance on Electric Discharge Properties," Appl. Phys. Lett., 18, 175 (1971).
34. Patel, C.K.N., "Continuous Wave Laser Action on Vibrational-Rotational Transitions of CO₂," Phys. Rev., 136, A1187 (1964).
35. Chen, C.J., "Pumping Mechanism of CO₂ Laser and Formation Rate of CO₂ from CO and O*," J. of Appl. Phys., 42, 1016 (1971).
36. Danishevskii, A.M., Fishman, I.M., and Yaroshetskii, I.D., "Investigation of the Laser Effect in CO₂ During Pulsed Excitation," Sov. Phys. J.E.T.P., 28, 421 (1969).
37. Legay, F., and Legay-Sommaire, N., Compt. Rend. Acad. Sci., Paris, 259, 99 (1964).
38. Patel, C.K.N., "Selective Excitation Through Vibrational Energy Transfer and Optical Maser Action in N₂-CO₂," Phys. Rev. Lett., 13, 617 (1964).
39. Patel, C.K.N., "C.W. High Power N₂-CO₂ Laser," Appl. Phys. Lett., 7, 15, (1965).
40. Moeller, G., and Rigden, J.D., "High Power Laser Action in CO₂-He Mixtures," Appl. Phys. Lett., 7, 274 (1965).
41. Mocker, H., Honeywell Aerospace Labs., Private communication.
42. Hill, A.E., "Role of Thermal Effects and Fast Flow Power Scaling Techniques in CO₂-N₂-He Lasers," Appl. Phys. Lett., 16, 423 (1970).
43. Hill, A.E., "Uniform Electrical Excitation of Large-Volume High-Pressure Near-Sonic CO₂-N₂-He Flowstream," Appl. Phys. Lett., 18, 194 (1971).
44. Wisniewski, E.E., Fein, M.E., Verdeyen, J.T., and Cherrington, B.E., "Thermal Production of a Population Inversion in Carbon Dioxide," Appl. Phys. Lett., 12, 257 (1968).
45. Fein, M.E., Verdeyen, J.T., and Cherrington, B.E., "A Thermally Pumped CO₂ Laser," Appl. Phys. Lett., 14, 337 (1969).
46. Eletsii, A.V., Efremenkova, L. Ya., and Smirnov, B.M., "Optically Pumped Carbon Dioxide Laser," Sov. Phys. Dokl., 15, 843 (1971).
47. Gross, R.W.J., "Chemically Pumped CO₂ Laser," J. Chem. Phys., 50, 1889 (1969).
48. Wieder, I., "Flame Pumping and Infrared Maser Action in CO₂," Phys. Lett., 24A, 759 (1967).
49. Kerr, G.D., Hairr, L.M., Underwood, N., and Waltners, A.W., "Molecular Stopping Cross Sections of Air, N₂, Kr, CO₂ and CH₄ for Alpha Particles," Health Phys., 12, 1475 (1966).
50. Bourland, P.D., Chu, W.K., and Powers, D., "Stopping Cross Sections of Gases for Alpha Particles from 0.3 to 2.0 MeV," Phys. Rev.B, 3, 3625 (1971).

51. Chu, W.K., Powers, D., "Energy Loss of Alpha Particles in Noble Gases from 0.3 to 2.0 MeV," Phys. Rev. B, 4, 10 (1971).
52. Pack, J.L., and Phelps, A.V., "Drift Velocities of Slow Electrons in Helium, Neon, Argon, Hydrogen, and Nitrogen," Phys. Rev., 121, 798 (1962).
53. Pack, J.L., Voshall, R.E., and Phelps, A.V., "Drift Velocities of Slow Electrons in Krypton, Xenon, Deuterium, Carbon Monoxide, Carbon Dioxide, Water Vapor, Nitrous Oxide, and Ammonia," Phys. Rev., 127, 2084 (1962).
54. Swift, J.D., and Schwar, M.J.R., Electrical Probes for Plasma Diagnostics, American Elsevier Publishing Company, New York, (1969).
55. Herwig, O.L., "Summary of Preliminary Studies Concerning Nuclear Pumping of Gas Laser Systems," Report C-110053-5, United Aircraft Corp., (1964).

VITA

James Terrence Ganley was born on September 17, 1945 in Urbana, Illinois. In 1963 he was graduated from Newton Community High School in Newton, Illinois. In 1967, he received a B.S. in Electrical Engineering and in 1968, he received an M.S. in Nuclear Engineering. Both degrees were from the University of Illinois in Urbana.

As an undergraduate, Mr. Ganley received scholarship aid from the Gates Radio Company and from the University of Illinois Y.M.C.A. He was supported for three years as a graduate student by a fellowship from the National Aeronautics and Space Administration and for two years by a half-time research assistantship from the Nuclear Engineering Program.

Mr. Ganley has published technical articles in Applied Physics Letters, 18, 568 (1971) and in the Transactions of the American Nuclear Society, 14, 133 (1971). In addition, he has co-authored papers delivered at the First Symposium on Uranium Plasmas (Univ. of Florida, 1970), the Second Symposium on Uranium Plasmas (Georgia Tech, 1971), Eleventh Symposium on Electron, Ion, and Laser Beam Technology, (University of Colorado, 1971), and I.E.E.E. Electron Device Conference (University of Michigan, 1971).