RESEARCH STUDY OF A CO_2 LASER RADAR TRANSMITTER

SEMIANNUAL TECHNICAL SUMMARY REPORT

June 1967

AD 653725

Prepared by

Perry A. Miles
Frank A. Horrigan

Raytheon Research Division
Waltham, Massachusetts 02154

Reproduction in whole or in part is permitted for any purpose of the United States Government.

(This research is part of Project DEFENDER under the joint sponsorship of the Advanced Research Project Agency, the Office of Naval Research, and the Department of Defense.)

ARCHIVE COPY

RECEIVED
JUN 27 1967

55

S-970

RESEARCH STUDY OF A CO_2 LASER RADAR TRANSMITTER

Semiannual Technical Summary Report
1 November 1966 through 1 May 1967

Prepared by

Perry A. Miles
Frank A. Horrigan

Raytheon Research Division
Waltham, Massachusetts 02154

ARPA Order No. 306
Project No. NR 015-714
Contract No. N00014-67-C0264

Distribution of this document is unlimited. It may be released to the Clearinghouse, Department of Commerce, for sale to the general public.

TABLE OF CONTENTS

		Page
I.	INTRODUCTION	1
II.	REVIEW	4
	A. Molecular Level Populations and Dynamics	4
	B. Energy Storage and Gain Characteristics	9
	C. Conversion Efficiency in Oscillators and Amplifiers	15
III	GAIN AND SATURATION MEASUREMENTS IN DC-EXCITED AMPLIFIERS	17
	A. Spurious Oscillations	24
	B. Super Radiance Effects	27
IV.	PULSE AMPLIFICATION IN DC-EXCITED AMPLIFIERS	28
V.	PULSE FORMATION AND AMPLIFICATION IN PULSE-EXCITED AMPLIFIERS	35
VI.	REFRACTIVE AND DISTORTION EFFECTS IN AMPLIFIERS	41
VII.	OPTICAL MATERIALS	44
VIII.	PRESENT STATE OF THE TRANSMITTER DEVELOPMENT	46
IX.	SUMMARY	48
	REFERENCES	49

LIST OF ILLUSTRATIONS

Figure	Title	Page
1	Vibrational-Rotational Energy Levels of CO_2 Involved in Laser Emission	5
2	Effect of the Addition of Helium on the Frequency Distribution of Laser Output	6
3	Molecular Level Dynamics in the CO_2 Laser	8
4	Peak Gain vs Tube Diameter for N_2-CO_2 and N_2-CO_2-He Mixes.	11
5	Radial Profile of Single-Pass Gain of a One-Meter Long, Two-Inch Diameter Laser Tube with 15 cfm Pump for Various Currents.	13
6	Experimental Arrangement for High-Power Amplification Measurements.	18
7	Plots of ln (G-1) vs Input Power for Various Values of a_oL.	21
8	Experimental Data for a 3-Meter Amplifier Plotted as ln G vs P_{in} (G-1)	22
9	Experimental Data from Kogelnik and Bridges for a 5-Meter Amplifier Plotted as ln G vs P_{in} (G-1)	23
10	Spurious Oscillation Pulse in a dc-Excited Amplifier. .	26
11	Self-Oscillation Signal Produced by Reflections from the Chopper Blade	26
12	Pulse Distortion Produced on Amplification	29
13	Time-Dependent Amplification in a Discharge Excited by 60 cps Current	29
14	Large Signal Gain Observed as a Function of Time for a Single Input Pulse	31
15	Experimental Results on Pulse Amplification	33
16	Gain Enhancement Under Pulse Excitation	36
17	Deterioration of Gain in Pulse-Excited Amplifiers . . .	36
18	Pulse Emission Profiles Generated when a cw Signal Is Passed Through a Pulse-Excited Amplifier	38

BLANK PAGE

I. INTRODUCTION

The object of this work is twofold; first, to investigate the physical properties of laser amplifiers using electrically excited mixtures of CO_2, N_2, and He with a view to producing high-power pulse emission with well-controlled temporal and spatial form; second, to design and build such a source with an average power of 1 kW in a form suitable for use as a laser radar transmitter.

Our approach to the project, recognizing the limited time available, has been to anticipate the final transmitter design and perform experiments on components of this design, pushing to high powers as quickly as possible. In this way, operational problems which arise would be relevant in the actual engineering design, while investigation of the processes which will finally determine the gain, saturation, and optical properties of the gaseous discharges would take place in a geometrical form very closely related to that of the finished transmitter.

That we have been able to do this with some degree of success depended on a considerable foreknowledge of the physical processes which dominate the excitation and energy transfer processes in CO_2-N_2-He discharges derived from the work of M. Weber and T. Deutsch[1] and from the high power oscillator work of D. Whitehouse,[2] all of this laboratory. This work has provided us with measurements both of excited-state lifetimes of CO_2 levels in collision with their neighbors CO_2, N_2, and He, and of the resultant gain, gain profiles, and energy storage capabilities of discharges as functions of temperature, tube diameter, current density, and gas mix.

The problem of producing a compact and efficient power amplifier is essentially a matter of identifying the energy source which a specific input signal can draw upon, and controlling the excitation and decay processes which relate directly to that energy source. From this standpoint, it was clear that the dominant energy source depended on the time scale chosen for the input signal.

In the present case we considered input pulse lengths that varied from the Q-switched variety of 10^{-7} sec to pulses longer than 10^{-4} sec, where the system behavior approximates that of a steady-state cw amplifier. Because we require the output signal to be at a stable frequency it has to be generated from a stabilized oscillator, preferably a cw source. We would anticipate the output for such a source to lie in the range of 5-50 W; after modulation, an amplification into the range of 5-50 kW would be necessary depending on the duty cycle chosen. At the outset we decided that a dc-excited system could have an advantage of stability over a pulse-excited one, both in pulse-to-pulse gain and in the spatial form of its output. Consideration of the energy level dynamics then indicated that an efficient extraction of energy could take place by using a sequence of input pulses of length between 10 and 30 μsec, at repetition rates in excess of 3000 cps. Discussion with our radar engineering collegues indicated that for the proposed radar system, pulse lengths in the range of 5-30 μsec would indeed be acceptable.

The experimental program has evolved from this as a starting point, and has been directed primarily (but not exclusively) at gain and power measurements on dc-excited amplifiers subjected to input pulses of 10 and 20 μsec at repetition rates up to 12 kc. Measurements have also been made in pulse-excited discharges and will continue throughout the program.

From our experience in the first six months of this study, we have developed designs for both dc- and pulse-excited amplifiers, and believe that we understand the physical limitations of each well enough to produce the required output of 1 kW. The physical quantities of importance in these designs have been measured, notably the signal intensity required to drive an amplifier to saturation, together with information on the refractive properties of the discharge, the time constant determining maximum pulse repetition rates, both for the input pulse trace and for the pulse excitation process, and the practical gain levels that can lead to self-oscillation in the amplifier. We believe that the original concept of a completely dc-excited system amplifying a train of 10 - 15 μsec pulses at a repetition rate of 10-12 kc leads to the simplest and most flexible type of radar source. A more efficient source, in terms of the useful output per unit primary electric power, can be built, but at the expense of cumbersome lengths of amplifiers and of stability.

II. REVIEW

A. Molecular Level Populations and Dynamics

The 10.6μ CO_2 emission comes from a population inversion established between rotational sublevels of the (00°1) vibration level as compared to the corresponding rotational sublevels of the (10°0) vibrational level (Fig. 1). This inversion is produced by collisional transfer of energy from vibrationally excited N_2 or CO molecules formed in an electrical discharge which may be operated with dc, ac, or pulsed currents. A detailed analysis of the dynamics of these molecular levels has been carried out in our research laboratories by Deutsch and Weber.[1] Due to the near equality of the energies of CO_2 molecules in (00n) vibration states with those for excited nitrogen, this transfer is more likely than is usual in most vibration-vibration transfers, and takes (on the average) some 500 classical collisions. For pressures of N_2 and CO_2 each at 1 torr, this transfer time is of the order of 100 μsec.

A second requirement for population inversion to exist has to do with the distribution of population among the rotational sublevels of the CO_2 vibration levels. The close spacing of these levels (for 1 to 50 cm^{-1}) makes energy transfer between them and kinetic states of the molecules a more probable process than vibration-vibration transfer. Thus the rotational levels tend to come quickly into thermal equilibrium with the kinetic temperature of the ambient gas. This process is further accelerated by the introduction of helium gas into the discharge, and typically takes ≃0.1 μsec. The lower the rotational temperature, the more is the amplifier gain concentrated in a single emission line (see Fig. 2). These emission lines are usually associated with the P branch of the CO_2 spectrum, with J values in the range of 17 to 25. The introduction of helium also assists in the transfer of excitation in CO_2 from the lower laser levels of the (10°0) vibrational state to nearby levels in the (020) vibrational state. From there, a very rapid de-excitation to the ground states can take place.

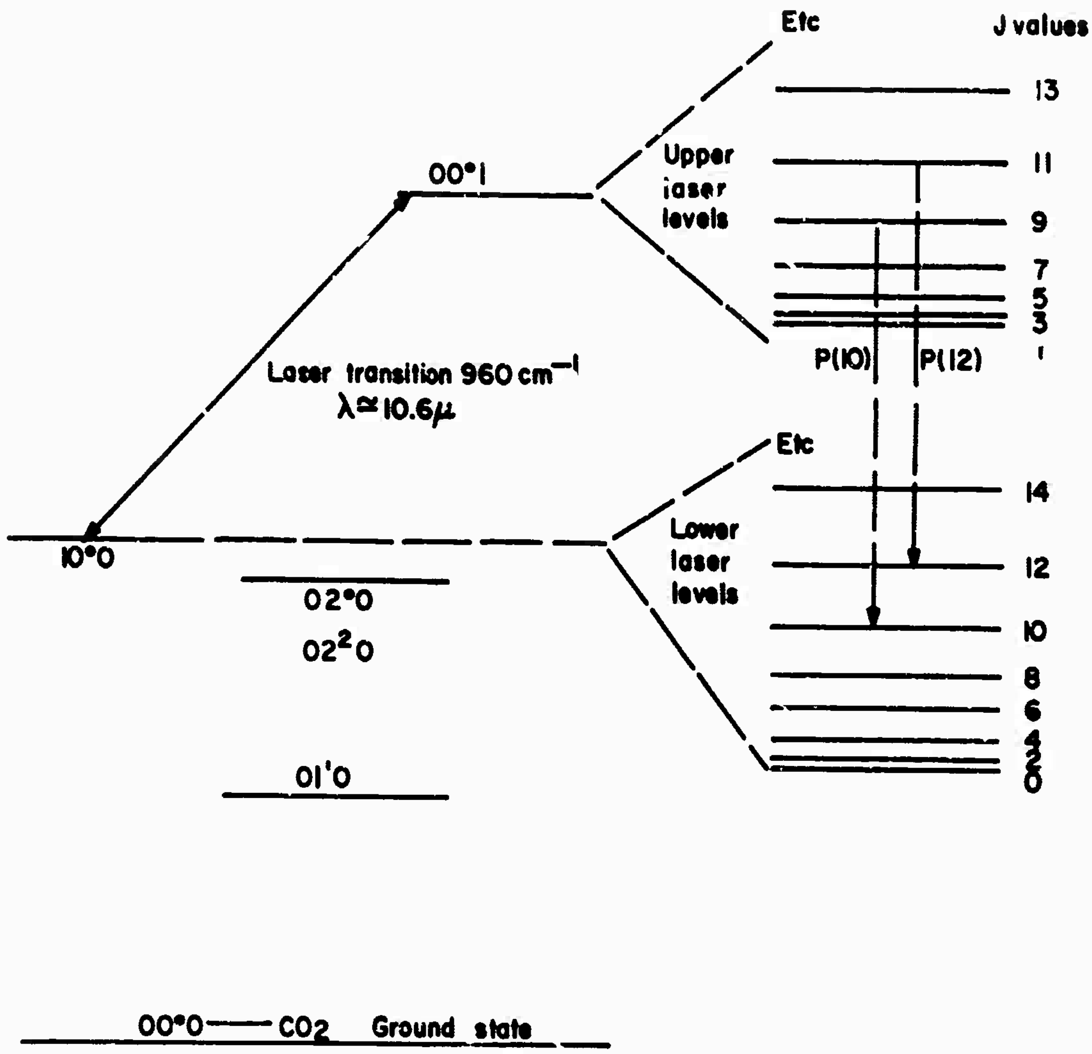


Fig. 1 Vibrational-Rotational Energy Levels of CO_2 Involved in Laser Emission

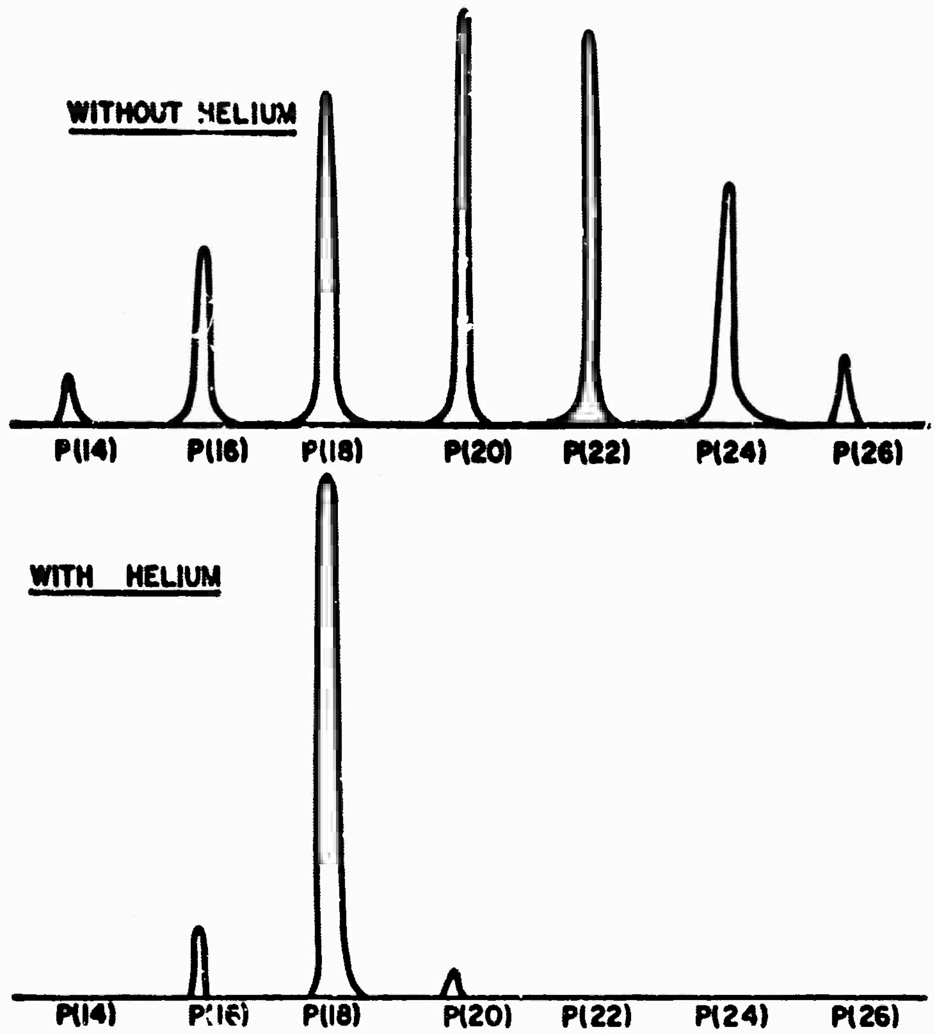


Fig. 2 Effect of the Addition of Helium on the Frequency Distribution of Laser Output

A high inversion requires, therefore, an efficient excitation of nitrogen molecules in a medium with as low a gas kinetic temperature as possible. The dynamics of this system are represented in Fig. 3, albeit in a simplified form.

In examining this figure, we see that the discharge dynamics, having to do with the degree of ionization of CO_2, N_2, CO, O_2 and their constituent atomic ions and the related electron energy distribution, will depend on the gas mixture, pressure, and tube diameter. They will result in excited nitrogen molecules which can come into equilibrium with CO_2 upper vibration levels at a rate governed by a time constant of the order of 100 P_{N_2} μsec where P_{N_2} is the partial pressure of nitrogen in torr. Vibrational transfer among the (00n) vibrational levels can be expected to be of the order of 10 μsec. This last vibration-vibration interchange is possible because of the resonant nature of the transfer, the vibrational levels being essentially equally spaced. Effective temperatures of the order of 5000°K are established for the population distributions in the upper CO_2 and N_2 vibrational levels, corresponding to the energies found in the electrons of the discharge.

As discussed above, the helium-assisted transfer between rotational levels, and between these and the gas kinetic ambient, takes place in approximately 0.1 μsec, while the transfer out of the lower laser vibrational states, also assisted by helium, takes place in approximately 10 μsec.

Finally, the gas kinetic temperature will relax back to the tube wall temperature at a rate governed by the heat diffusion from the axis to the walls, by excited molecular migrations, both governed by the degree of macroscopic fluid flow and gas mixing going on in the tube. These rates will depend on tube diameter and flow rate, and typically give time constants of between 2 and 20 msec for tube diameters between 2 and 5 cms.

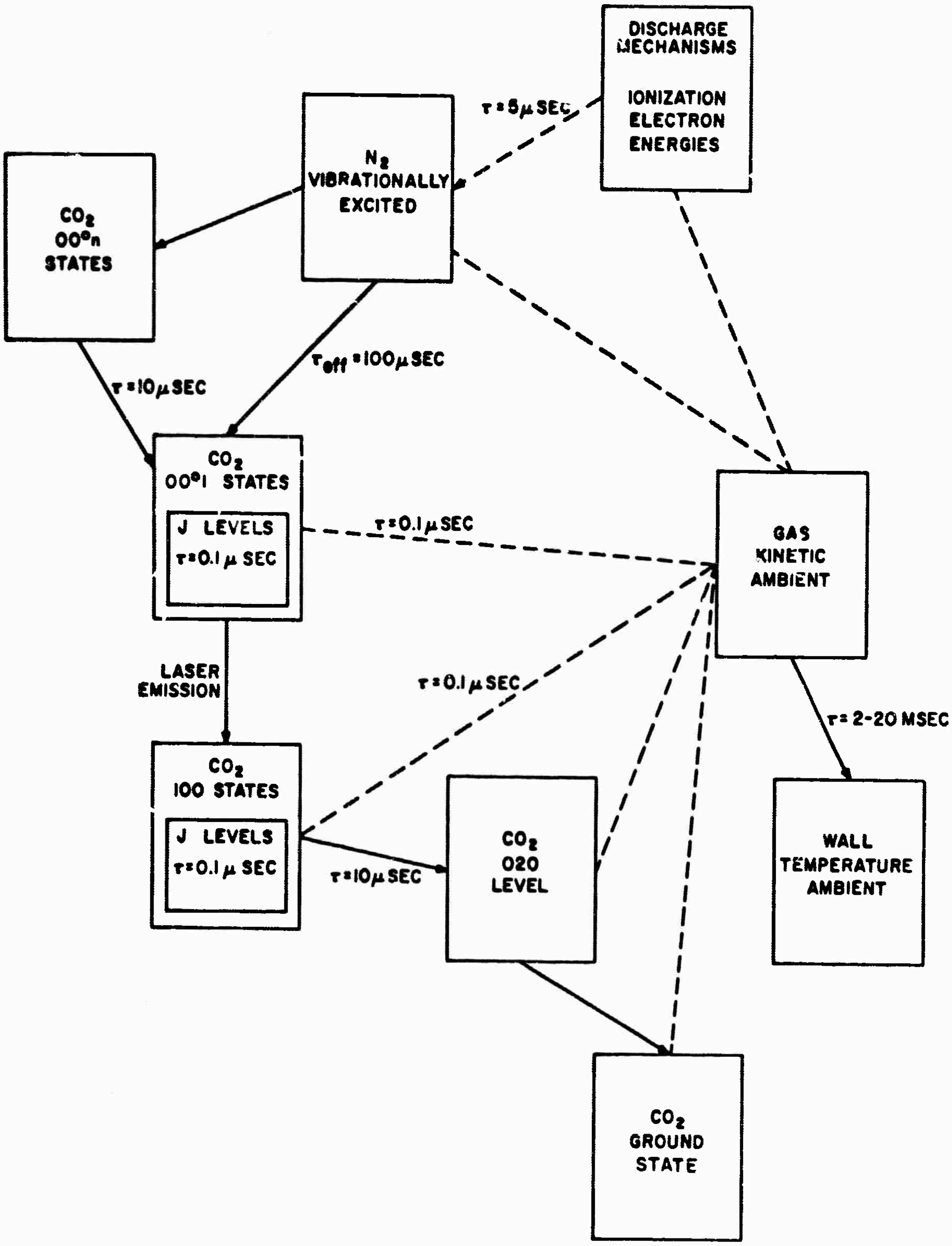


Fig. 3 Molecular Level Dynamics in the CO_2 Laser (Schematic)

B. Energy Storage and Gain Characteristics

In considering the extraction of energy from an excited system of CO_2 and N_2 molecules, we have to take into account the sequence of transfer processes that are going on, illustrated in the previous section. The aspects of the pulse wave train which are relevant in this connection are the pulse length and pulse repetition rate, as well as the pulse height, of course.

As to the individual pulse lengths, there are clearly four time regimes. A pulse input of duration less than 10^{-7} sec can draw on the population inversion of a single pair of rotational levels which exists before the pulse is applied. There will be insufficient time for any transfer to take place from nearby rotational levels. At a maximum, such a pulse could extract energy equivalent to one-half of that initial inversion, after which the level populations would be equal (under special conditions, this limit may be exceeded and approach unity, but these conditions are unlikely to be met in the type of amplifier we are contemplating). Whether the factor of one-half is reached depends also on the type of spectral line-broadening present. For a homogeneously (e. g., collision) broadened line, the input radiation may be considered to attract with all excited molecules at all times. For an inhomogeneously broadened line, e. g., for Doppler broadening, the radiation interacts only with those molecules whose characteristic frequencies lie within the larger of the intervals $\Delta\nu = 1/2\pi\ T_{coll}$, $\Delta\nu = \mu E/h$, or $\Delta\nu = 1/2\pi\ T_{sp}$, where T_{coll} is the collision lifetime, T_{sp}, the radiative life, μ is the dipole moment associated with the molecular transition, E is the electric field strength associated with the applied radiation, and h is Planck's constant.

In the present context, the total linewidth is typically 80 Mc wide, made up from approximately 50 Mc to 60 Mc for Doppler broadening, the rest from collision broadening. Thus we expect an essentially homogeneously broadened response, taking into account both the actual collision width and the fact that individual molecules will change their position under the Doppler envelope in a time of the order of 10^{-7} sec.

Input pulses with lengths between 0.1 and 10 μsec can affect all rotational levels with (001) vibrational state, while the population of this state should be replenished from others of the (00n) series in a time of the order of 10 μsec. In fact the work of T. Bridges at Bell Laboratories indicated a typical recovery time of the order of 30 μsec in an oscillator delivering 1 μsec pulses.[3] This time sets an upper limit on the useful repetitive rate which can be achieved, of the order of 30 kc.

Pulses of 10 to 100 μsec last long enough for population transfer between CO_2 vibrational levels to take place, but with little chance for transfer from the main energy reservoir, the excited nitrogen molecules. Such pulses, then, can draw on a greater excited-state population, but the system will take longer to recover, namely ≃100 μsec, indicating an upper limit of repetition rate of 10 kc. As we will see later, our experiments confirm this prediction. Pulses longer than 100 μsec can draw on the full energy storage in the excited nitrogen molecules, and upon the continual replenishment of these levels from the electron bath itself. The behavior of the amplifier to such long pulses should tend progressively to that for the amplification of a cw signal.

The instantaneous inversions which can be established can be inferred from measurements of the gain as seen by weak input signals. The relationship between gain coefficient, α, and inversion, Δn, per c.c. is given by

$$\alpha = \Delta n \times 2 \times 10^{-16}\ \mathrm{cm}^{-1}$$

for a spectral linewidth of 80 Mc and using the dipole moments computed by Statz, et al.[4] Experimentally, we find that α depends on gas mixture, current density, gas flow rate, wall temperature, and tube diameter. Further, the highest value of gain obtainable in a tube of given diameter d tends to vary inversely with d (Fig. 4). The value for a 2 cm (3/4 in.) diameter tube is $\alpha = 0.007\ \mathrm{cm}^{-1}$ corresponding to a gain of approximately 3 dB/meter.

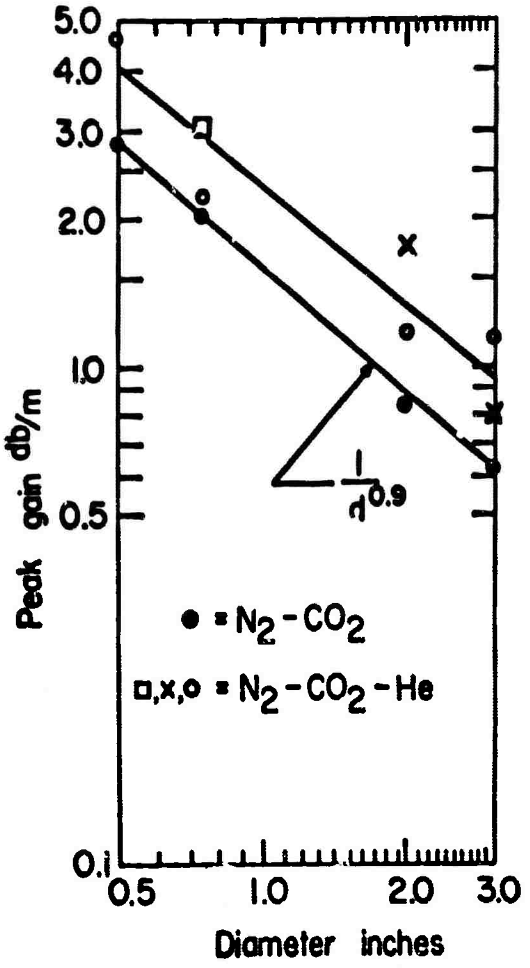


Fig. 4 Peak Gain vs. Tube Diameter for N_2-CO_2 and N_2-CO_2-He Mixes

For the projected radar application, the appropriate pulse length is of the order of 10 μsec. The added requirement for as much energy as possible per pulse brings up the question of the best way of exciting the discharge so as to maximize the output-pulse height. The choice lies between a dc-excited tube, and a pulse-excited tube. To avoid confusion in treating the subject, we will deal here with energy storage for dc-excited amplifiers, and consider the pulse excited case in the context of our measurements. In this discussion, we will continually refer to tubes of 2 in. diameter. This is because: (1) we have data on such tubes; and (2) we believe that this is the most manageable diameter, both from the point of view of providing uniform discharges, of handling the optical diffraction of the beam over lengths of the order of 40 meters, and of maintaining acceptable gas flow rates.

In choosing a tube diameter, we have to further bear in mind that the low-signal gain (and, therefore, the energy storage available to 10 μsec pulses) depends on the radial position to the tube (Fig. 5). Thus the conditions which give the largest low-signal gain as measured along the tube axis usually do not correspond to the condition giving the highest power output in a cw oscillator. The reason is simply that as the current increases, the radial gain profile saturates and then decreases along the axis, while the off-axis gain keeps increasing before saturating at a higher current level. The output power depends on an integration of the low-signal gain across the tube cross section, and this will be a maximum for current values greater than for optimum gain measured on axis. In choosing amplifier cross sections for our present program, we wish to obtain the highest gain in initial amplification stages, the largest total power in later stages, and overall, an output intensity distribution either: (a) as uniform as possible across the output plane; or (b) as close to gaussian as possible. Choice (a) maximizes the use of the amplifier tube cross section, and at the same time minimizes the angle of the central lobe of the transmitter pattern (at the expense of introducing a side lobe structure) whereas choice (b) eliminates the transmitter side lobes at the expense of less efficient use of the tube cross section. In either case it seems that constant gain off-axis would be helpful in the preamplifying section to preserve the input intensity distribution. In the power amplifier sections, either a uniform gain or one peaked up off-axis is called for. These conditions are closer to those appropriate to maximum power output than to those chosen for maximum axial gain.

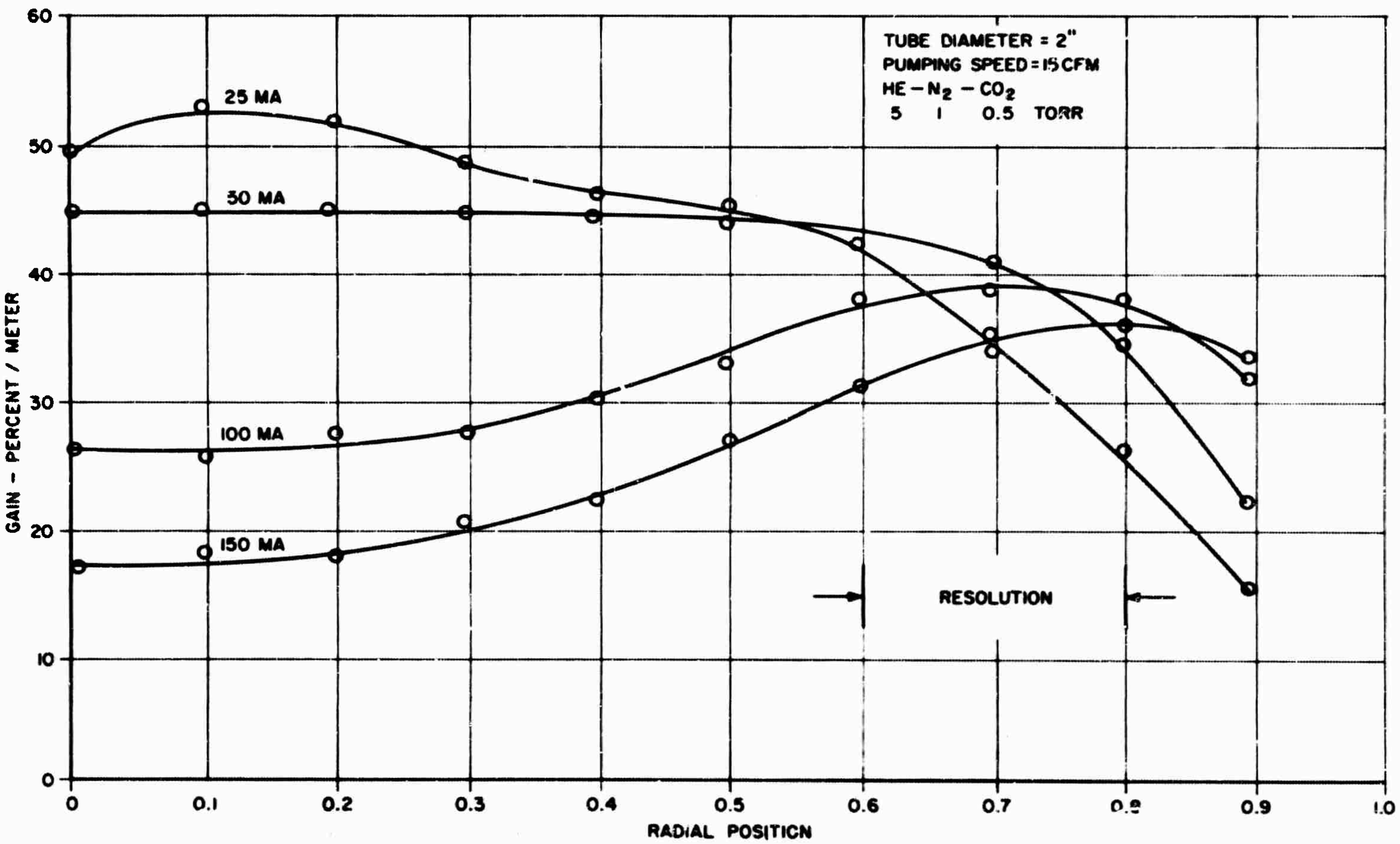


Fig. 5 Radial Profile of Single-Pass Gain of a One-Meter Long, Two-Inch Diameter Laser Tube with Fifteen CFM Pump for Various Currents

With this preface, let us consider the energy storage accessible to a 10 μsec input pulse, passed through a dc-excited tube of 2 in. diam. with a typical low-signal gain of 1 dB/meter ($\alpha = 0.0023\ cm^{-1}$). From this data, the excited state density is 1.1×10^{13}/cc, and at a photon energy of 1.7×10^{-20} J/photon, the stored energy is $W = 1.85 \times 10^{-4}$ J/liter of discharge.

On this basis some 7 mJ would be available from a single rotational level in a 20-meter length of 2 in. discharge. This number sets a lower limit to the available energy, and will be added to by transfer from other rotational and upper vibrational states.

A second estimate of the available energy can be derived by considering the power output from a 2 in. tube operated as an oscillator. Such a tube delivers 60 W per meter (at a gas flow rate of approximately 2.5 meters/sec).

Thus in any 100 μsec interval, an energy of $60 \times 10^{-4} \times \frac{1}{1.8}$ J/liter is delivered. We can draw the inference that 3 mJ/liter would be accessible to a 100 μsec pulse. In terms of length, a 20-meter discharge would have approximately 120 mJ accessible to a 100 μsec pulse.

The fraction of this available to a 10 μsec pulse would depend on the relative populations of excited CO_2 to excited N_2. The ratio of these populations will be the ratio of gas pressures, modified by a factor depending on the relative number of ava. ..e rotational-vibrational states in the same energy range. The ratio is of the order $N_2/CO_2 = 4{:}3$ for equal pressures of N_2 and CO_2. As a result we expect approximately 1.5 mJ/liter to be available to a 10 μsec pulse under dc excitation (or 60 mJ/pulse for a 20-meter, 2 in. tube). These two estimates set upper and lower limits to the energy available per 10 μsec pulse; i.e., 20 meters of dc-excited tube should give between 7 and 60 mJ per pulse when driven as a saturated amplifier.

C. Conversion Efficiency in Oscillators and Amplifiers

The efficiency with which energy from the primary power source is converted into useful output radiation depends in part on the excitation and collision processes going on in the electrical discharge, in part on geometrical factors which determine the fraction of the total excited volume accessible to the radiation field of the device, on the efficiency with which radiant energy is coupled out from the active region, and finally on the temporal aspects of the excitation and emission processes.

The most complicated of these determinants are the multiple ionization, collision, and excitation effects which go on to establish the inversion between the emitting molecular levels. These depend on gas mixture, current density, temperature, and gas flow rate. Despite the complexity of the details, we can state overall experimental results for oscillators.

Experiments have been performed in which at least 80 percent of the available energy generated as a molecular inversion has been extracted in the output beam. Under these conditions, and using laser mirrors which maintain a radiation field filling the active region of the discharge, efficiencies of 15-20 percent have been achieved. That is, 15-20 percent of the energy dissipated in the discharge itself has been converted to an output beam which, although belonging to a single P line, usually contains a number of separate modes. Under these conditions, some 75 watts per meter of discharge is obtainable. The number depends on the gas flow rate, and at higher flow rates, 100 watts/meter has been quoted. We believe that the 20 percent figure can be used as the basis of an oscillator design.

On the other hand, the need to produce a single-mode output forces a restriction of the radiation field to a size smaller than that of the actual active discharge region. As a result, we can expect the output efficiency to decrease, roughly by a factor of two. While this figure may be improved by more sophisticated designs of discharge tubes, we will consider our own transmitter designs to be based on a 10 percent efficiency for power extraction in a single mode.

The efficiency with which one extracts energy from a single-mode amplifier will depend on the level at which it is driven. In the limit of large input signals where the amplifier becomes nonlinear, and is driven into saturation, its efficiency should approach the cw oscillator figure, namely 20 percent multimode, 10 percent single mode. As indicated in the next section, our experiments indicate that strong saturation takes place when the input intensity is of the order of 60 watts/cm^2. For an efficient amplifier, then, one should arrange to reach this level of radiation density as soon as possible.

In an amplifier where the input is a sequence of pulses, with a duty cycle of 1/10 or less, the power extraction problem is more involved, as indicated previously. If we are concerned with extraction of energy in 10 μsec pulses, the repetition rate of these pulses should be increased until the pulse spacing is of the order of the time for energy transfer from the reservoir of excited N_2 to the upper laser level, a time which we estimated to be of the order of 100 μsec. For repetition rates greatly in excess of 10 kc, the output efficiency should again be comparable to that of a saturated amplifier driven by a cw signal.

III. GAIN AND SATURATION MEASUREMENTS IN DC-EXCITED AMPLIFIERS

While experiments carried out for this project have varied in their detailed form over the 6-month period covered by this report, Fig. 6 indicates the general form taken by the equipment. This consisted of an oscillator emitting between 15 and 35 W single mode, whose output was focused either by mirrors or NaCl lenses to permit a focal plane shutter to form the primary pulse train signal. After recollimation, the beam passed through two 3-meter lengths of 2 cm i.d. amplifier and, at times, a further section of 20 meters of a 5 cm i.d. amplifier. The small-bore amplifier could be excited with ac, dc, or pulsed current; the large-bore amplifier was always driven from a dc supply. NaCl windows have been used throughout this system.

The mirrors on the oscillator were usually a 10-meter radius, gold-coated silica reflector set in opposition to a 1/4 in. thick germanium optical flat, mounted in a water-cooled holder. The open structure of the oscillator allowed the introduction of irises to produce a single-mode output. Due to air currents in the open sections, however, the output tended to fluctuate with time. The mirror surfaces exposed to high powers in the latter stages of the amplifier were made of stainless steel or sapphire, both gold plated.

Signals were detected using a gold-doped germanium photoconductor, operated at 77°K. Average powers were measured using an anodized aluminum, conical absorber cooled by a known flow of water. Measurement of the increase of water temperature, usually of the order of several degrees, gave a direct calorimetric determination.

The exact chronological order of the various measurements was rather involved and depended on the availability of the various amplifier components and power supplies. These measurements will be grouped under the

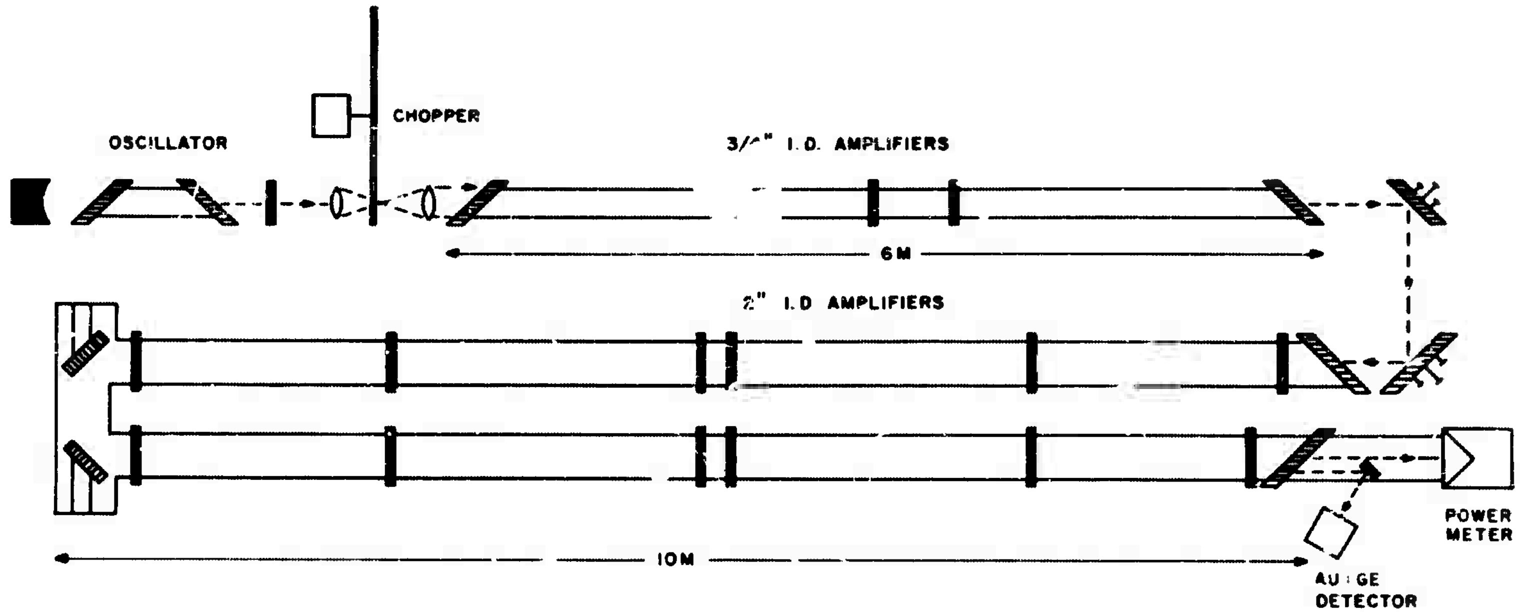


Fig. 6 Experimental Arrangement for High Power Amplification Measurements

following topics for the purpose of discussion: straight cw amplification, amplification of a cw signal by current-pulsed amplifier, and of pulse trains by dc and pulse-excited amplifiers. We will first treat the cw case. The simplest form this could take would be for a beam of uniform intensity to be amplified by a medium of uniform gain and saturation parameter. By contrast, our measurements have been taken on a more complicated system, where a roughly gaussian beam has been amplified by a medium where there is likely to be a strong radial dependence of gain. At this point of time, however, we have analyzed the data on the basis of a uniform propagation model only.

In this, we assume that a cw signal of intensity $I_{in}(W/cm^2)$ passes through an amplifier whose exponential gain coefficient $\alpha = \alpha_o(I/I_{sat})^{-1}$. For this case, assuming a uniform input wave and uniform excitation, the power gain is:

$$\frac{dP(x)}{P(x)} = \frac{\alpha_o dx}{1 + \frac{P}{P_{sat}}}$$

where

$$P = I_{sat}A$$

$$P_{sat} = I_{sat}A$$

Hence

$$\ln \frac{P_{out}}{P_{in}} + \frac{P_{in}}{P_{sat}} \left(\frac{P_{out}}{P_{in}} - 1\right) = \alpha_o$$

or

$$\ln G + \beta(G-1) = \alpha_o L$$

where

$$G = \frac{P_{out}}{P_{in}}$$

$$\beta = \frac{P_{in}}{P_{sat}}$$

Figure 7 shows the solution to this equation plotted as ln (G-1) vs β for various values of $\alpha_o L$. The quantity $(G-1) P_{in}$ is the additional power contributed by the amplifier. Alternatively, we may plot ln G vs $P_{in}(G-1)$. This should give a straight line plot with intercept $\alpha_o L$ at $P_{in} = 0$ and a slope of $-1/P_{sat}$. We have carried out such experiments on cw gain in dc-excited amplifier tubes of i. d. = 2 cms (3/4 in.). Figure 8 shows the results of two sets of experiments, one with a convergent beam, the second with a uniform beam. From both sets of data, we obtain $d^{\alpha_o L} = e^{2.2} = 10^{0.95}$ for a length of 3 meters (α_o = 0.73 nepers = 3.2 dB/m). The uniform cross-section beam gave an effective saturation power of 13 W, an average saturation intensity of 28 W/cm^2. The corresponding intensity at the center of the beam was ≈ 56 W/cm^2. A similar experiment has been performed by Kogelnik and Bridges[5] who also obtain a gain of 3.2 dB/meter for a 2 cm tube. They quote a central intensity of 100 W/cm for I_{sat}, but on reanalyzing their data in the manner indicated above, we obtain a value of 65 W/cm^2 (Fig. 9). This number allows us to predict the behavior of various amplifiers by reuse of Eq. 4 or of Fig. 4.

A second way to estimate the saturation parameter is to use the figure for the power output per unit length of an oscillator. In conditions where the resonator losses are dominated by the output coupling, we can use the limiting case of Eq. 4 for high P_{in}/P_{sat}, to give: $P_{out} \rightarrow P_{sat}\, \alpha_o L$.

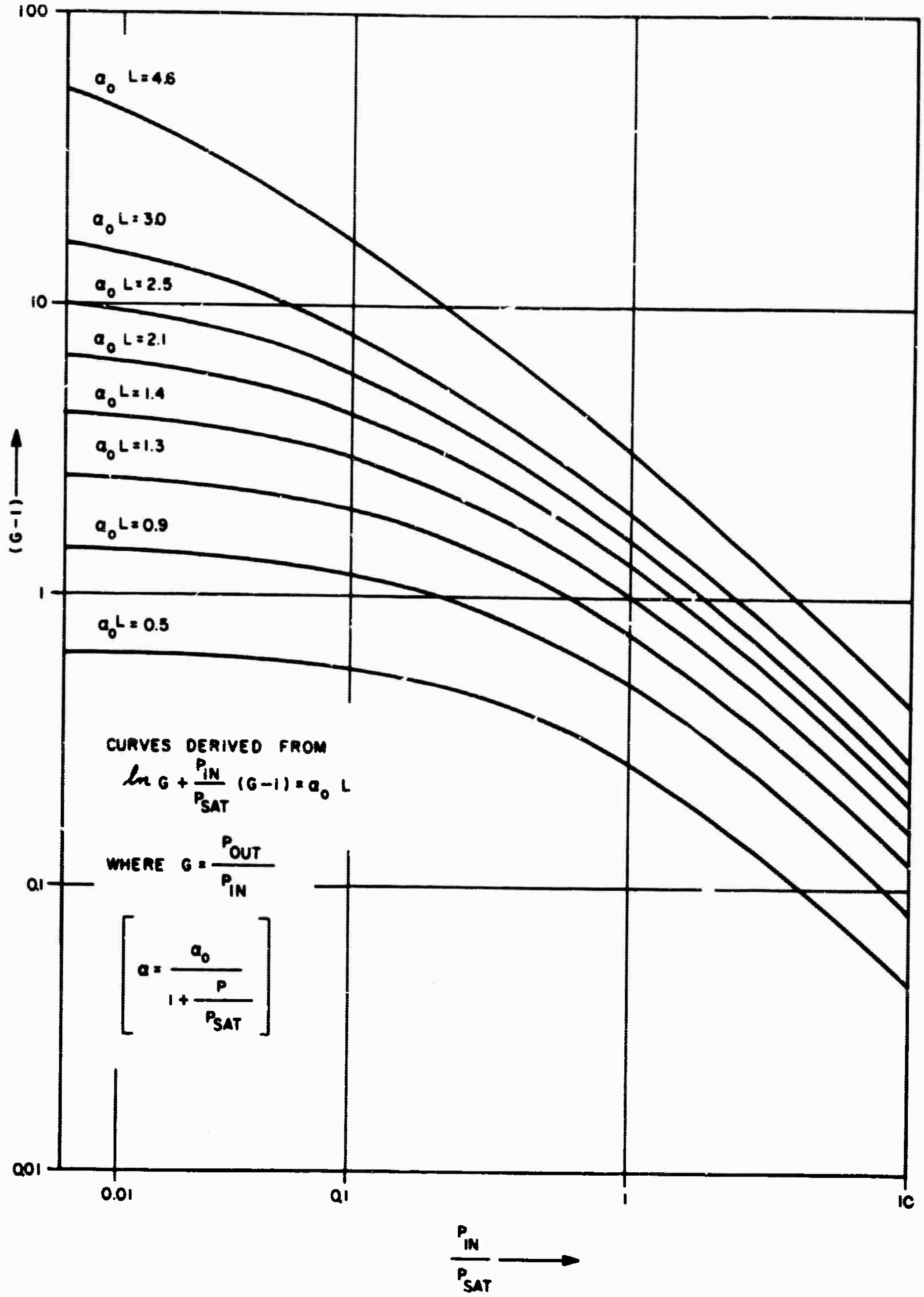


Fig. 7 Plots of ln (G-1) vs. Input Power for Various Values of $a_o L$

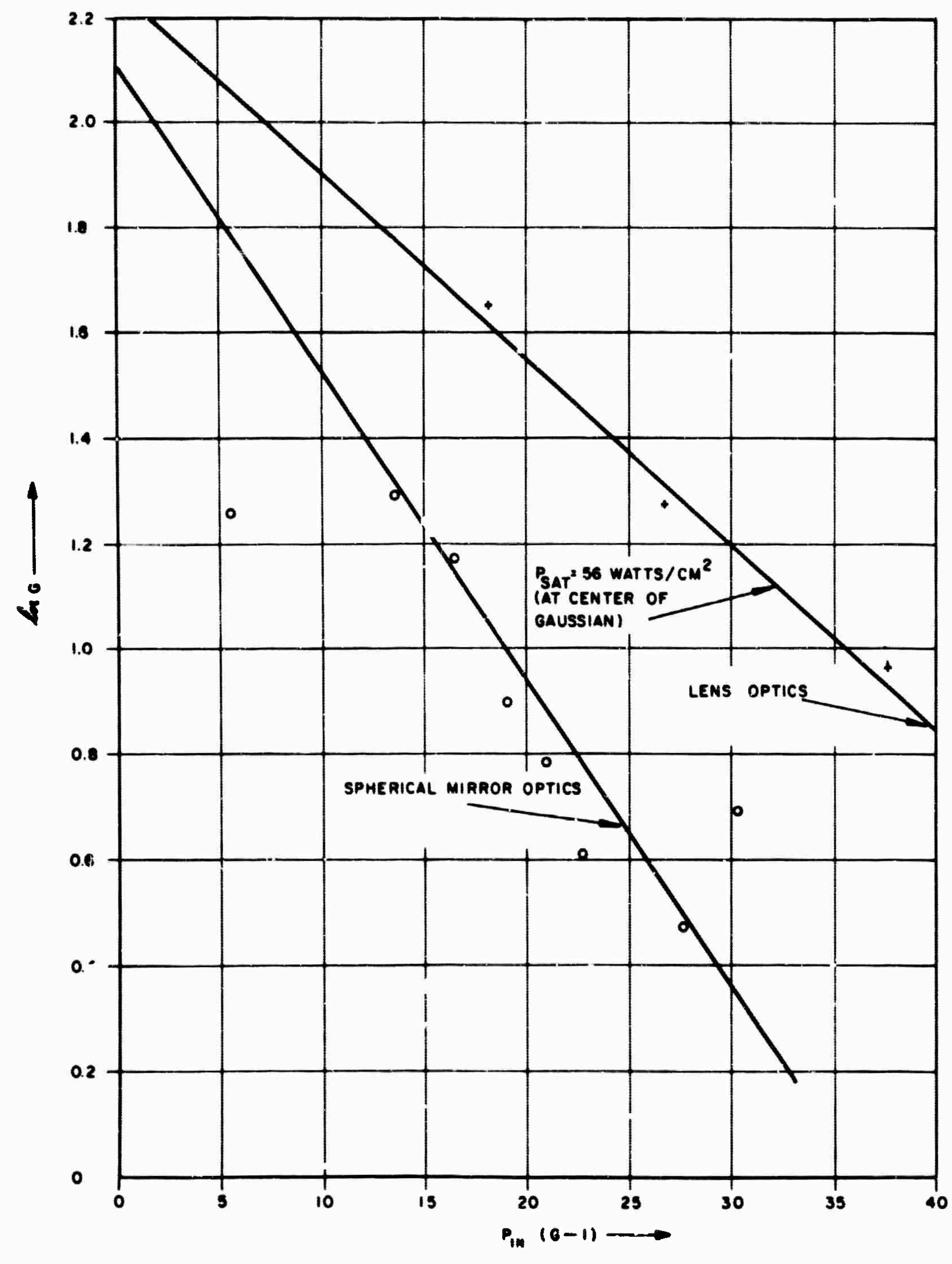


Fig. 8 Experimental Data for a 3-Meter Amplifier Plotted as ln G vs. P_{in} (G-1)

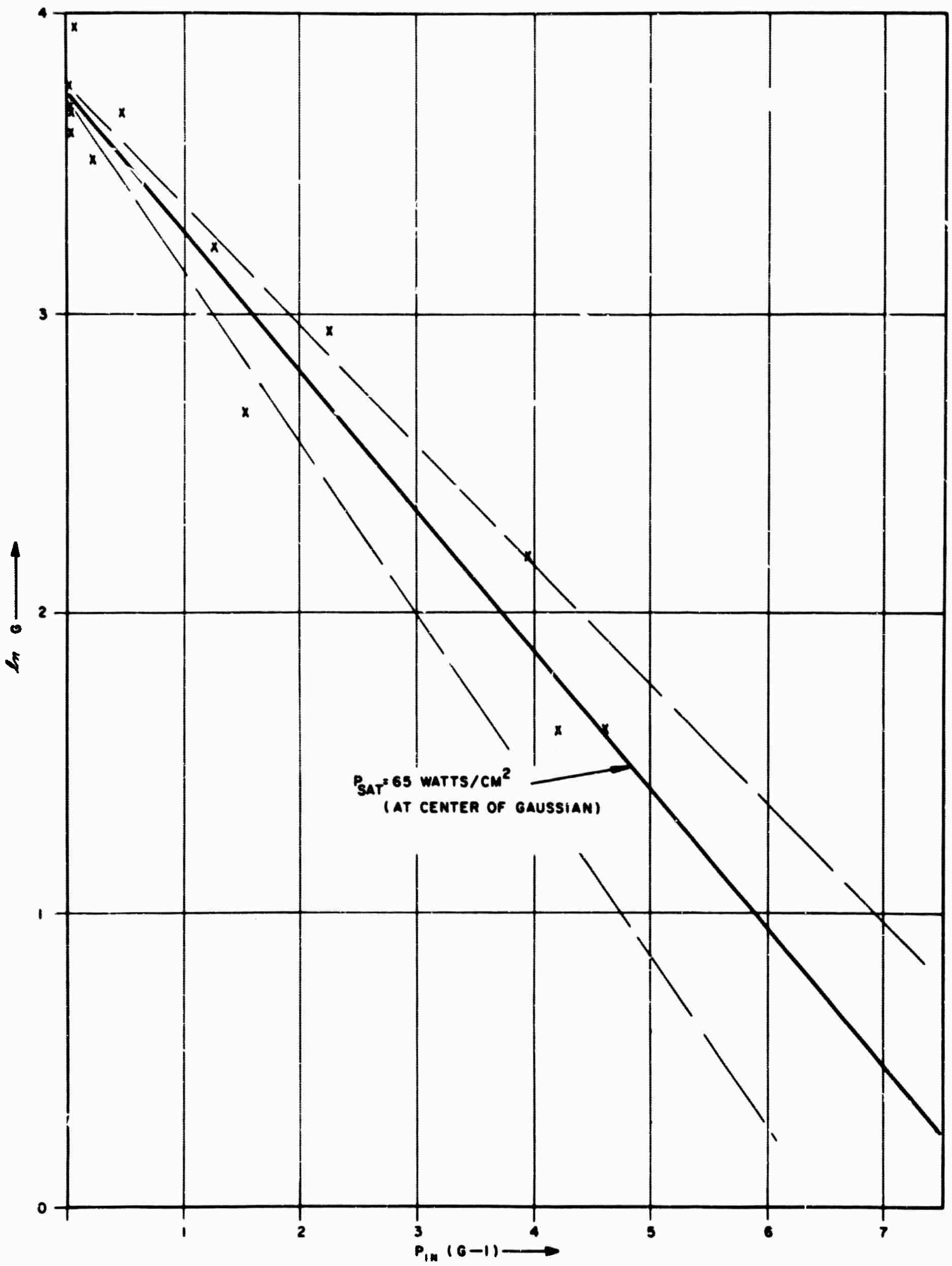


Fig. 9 Experimental Data from Kogelnik and Bridges[5] for a 5-Meter Amplifier Plotted as ln G vs. P_{in} (G-1)

For a 2 cm tube, $P_{out} \simeq 50$ W/meter, $\alpha_o \simeq 0.7\ m^{-1}$

to give $$P_{sat} \simeq \frac{50}{0.7} = 70\,W \quad ,$$

and $$I_{sat} \simeq \frac{70}{3} = 23\,W/cm^2 \quad .$$

This result is in fair agreement with our direct gain measurement, since the actual effective area is somewhat less than the full 3 cm^2 assumed in this calculation. For a 2 in. tube, on the other hand, $P_{out} \simeq 75$ W per meter of discharge and $\alpha_o \simeq 0.23,\ m^{-1}$ whence

$$P_{sat} = \frac{75}{0.23} = 330\ W,$$

or

$$I_{sat} = \frac{330}{18} = 19\,W/cm^2$$

Again, allowing for a somewhat reduced effective area, we would estimate the actual figure to be closer to 25 W/cm^2 for the 2 in. tube. In either case, the saturation parameter would appear to be a slow function of tube diameter.

A. Spurious Oscillations

One of the major problems in handling high gain optical amplifiers, as in rf amplifiers, is the suppression of spurious oscillations which draw the power into unwanted output beams. An overall power gain of 100 is contemplated in the production of 1 kW output power. With a duty cycle of 1/10, this corresponds to a pulse average gain of 1000 under saturated conditions, and a small signal gain of at least 10^4. In fact, as we will describe later, we contemplate a design with a large bore tube length of 40 to 50 meters preceded by 13 meters of small bore tube. The total small signal gain of this assembly would be approximately $50 \times 1 + 13 \times 2.5 = 82.5$ dB. Considering the fact that one end of this system faces a resonant cavity (the oscillator) with a high reflectance coefficient, a double-pass gain of 10^{16} must be contemplated!

In our experiments, we have detected self oscillations of the amplifier at a single-pass gain of 10^4 using 20 meters of 2 in. diameter, and 6 meters of 3/4 in. diameter tube with a NaCl slab on one end, giving $\simeq 10$ percent Fresnel reflection, and a NaCl flat set at Brewster's angle at the other end. The effective double pass gain was $10^4 \times 1/10 \times 10^4$, or 10^7. Reduction of the single-pass gain by a factor of 5 suppressed this effect. Apparently, there is sufficient surface backscatter from the NaCl Brewster window to cause oscillation at an effective total gain of approximately 10^6. That is, the Brewster window has an effective reflectivity of 10^{-6}. The oscillations appear as a steady output in the absence of any signal from the oscillator. With the chopper blade removed, the output can be as much as 200 W, in a spatial pattern showing the circular fringes characteristic of reflections from the tube walls. With the chopper in place, the oscillations appear as noisy spikes of the order of 2 μsec on base, with a delay of 1 - 3 μsec after the opening of the chopper (Fig. 10). The average power of these pulses can be as much as 30 W. In addition to these pulses, a noisy spectrum can occur when the amplifiers are running at maximum gain, produced by reflections from the chopper blade itself which is not entirely plane (Fig. 11). The latter noisy oscillations can give average powers of up to 100 W.

When the primary oscillator is turned on, the spatial form of the output changes abruptly, and becomes dominated by a pattern similar to that observed in the absence of any amplification. At the same time, the spurious oscillation pulses which occurred while the chopper was open are completely suppressed by the incoming signal.

Fig. 10 Spurious Oscillation Pulse in a dc-Excited Amplifier. (Time scale: 1 division = 1 μsec)

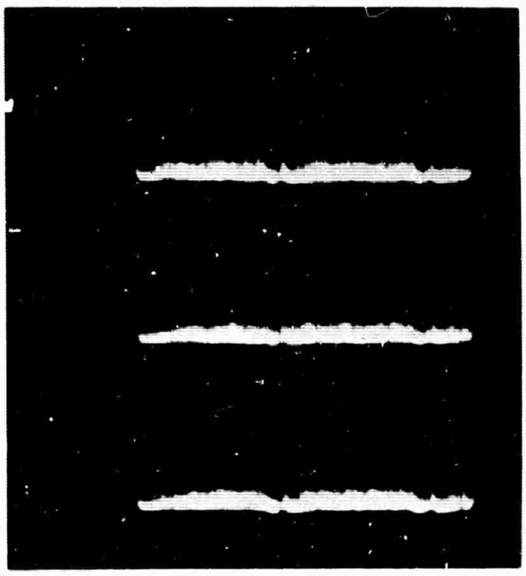


Fig. 11 Self-Oscillation Signal Produced by Reflections from the Chopper Blade. (Time scale: 1 division = 20 μsec)

The lesson to be learned here is that for stable operation of an amplifier one should either drive it into saturation with a cw signal, or isolate sections (each of which has a small-signal gain of less than 10^6) using reflective optics and well-made Brewster (or at least angled) windows. The separation could be achieved either with multiple shutters or by beam division and subsequent amplification in parallel elements.

B. Super Radiance Effects

A problem related to spurious oscillations is the loss of energy due to amplification of the natural spontaneous emission at 10.6μ. While this is of low intensity and emitted isotropically, it will finally set a limit on the length of amplifier which can be kept excited continuously.

We have made a calculation for a 2 in. diameter tube, assuming non-reflecting tube walls and find that for a single pass gain of 10^7, some 10 percent of the available power is being depleted by superradiance. While this figure could be reduced by the use of focussing optics and apertures, we believe that these are impractical. Furthermore, considering the likelihood of the onset of spurious oscillations at gains of 10^6, we do not believe that population depletion by superradiance will be a problem in practice.

IV. PULSE AMPLIFICATION IN DC-EXCITED AMPLIFIERS

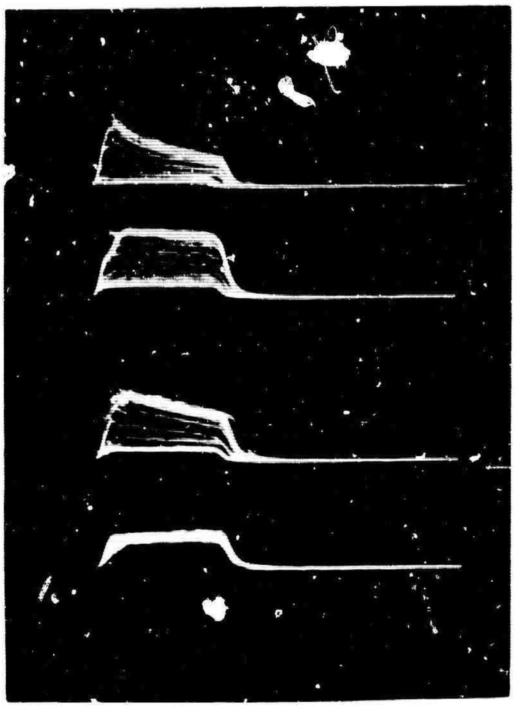
Figure 12 shows an early result of the amplification of 20 μsec pulses in the small bore (2 cm i. d.) amplifiers excited by a 60 cps current. The multiple traces indicate the variation of pulse profile with time during the current cycle. Figure 13 gives a better sense of this variation. The original flat-topped pulse becomes progressively distorted by depletion of the molecular inversion by the leading edge of the pulse. In dc-excited discharges, the saturation behavior is the same, although the peak gain observed is somewhat lower in the dc case as compared to the peak gain for ac excitation. For a steady input signal of 15 W, ratio of peak gain was approximately 2 to 1.

We have not developed the theory of saturation for pulsed inputs in any sophisticated way. However, if we assume that the 10 and 20 μsec pulses used draw on all the inversion present in the levels of CO_2, but are sufficiently short to prevent any population redistribution between CO_2 and N_2 molecules, we can define a saturation input intensity, $I_{sat,p}$ such that:

$$A \cdot I_{sat,\,p} \cdot \tau \cdot e^{\frac{1}{2}\alpha_o L} = W$$

wher τ is the pulse length, W is the total available energy, and A is the cross-sectional area of the tube.

The simplification here is that we assume that the power level is constant throughout the pulse, and is of such a magnitude as to reduce the instantaneous population inversion by a factor of 2. A more precise treatment would take into account the time and space dependence of both radiation intensity and gain parameter.



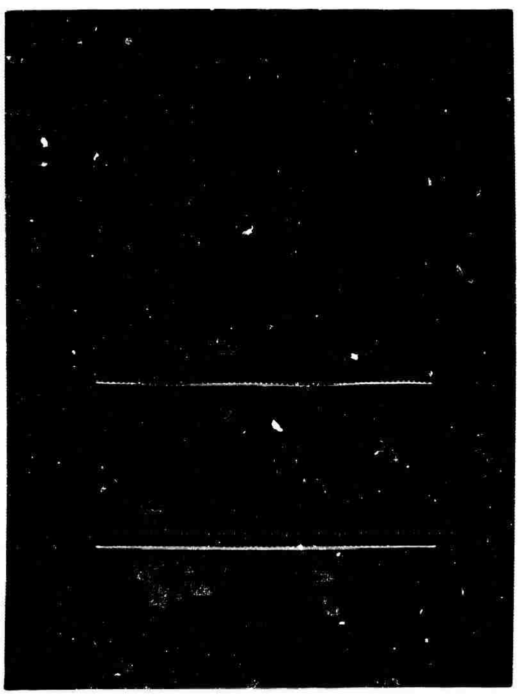
(a) Output pulse after amplification sequentially by Amplifiers A and B

(b) Output pulse from Amplifier B in which there was uniform propagation

(c) Output pulse from Amplifier A in which severe beam constriction took place

(d) Input pulse (Length 20 μsec)

Fig. 12 Pulse Distortion Produced on Amplification



(a) Amplifier output

(b) Input - a train of 20 μsec pulses

Fig. 13 Time-Dependent Amplification in a Discharge Excited by 60 cps Current

For a 2 cm diameter tube with α_o = 3.2 dB/m, and a 3-meter length, assuming a total stored energy of eight times the calculated energy for a single rotational level, then:

$$W = 8 \times \frac{7.3 \times 10^{-3}}{2 \times 10^{-16}} \times 1.7 / 10^{-20} \times 300 \times \pi \text{ joules}$$

$$\approx 5 \text{ millijoules}$$

From this we calculate for a 10 μsec pulse

$$P_{sat\ p} = \frac{5 \times 10^{-3}}{10^{-5}} \times \frac{1}{3}$$

$$= 170 \text{ W}$$

that is,

$$I_{sat\ p} = 60 \text{ W/cm}^2$$

In early experiments of this type, we found that input intensities of the order of 200 W/cm^2 were required to reduce the gain of a 3-meter length of such a tube by a factor of 2 from the low-signal value. Clearly, our model will have to be made more elaborate. As an experimental fact, however, it is clear that the effective saturation parameter for short pulses is considerably larger than the corresponding cw case.

An alternate way to present the data is to plot the observed gain level as a function of time after turning on a long pulse input signal. Figure 14 shows the result of such an experiment, contrasting the pulse results with data taken using a cw input of identical geometric form. Drawing the dashed curve appropriate for the cw analysis through the 8 μsec point is admittedly done on shaky grounds, but it indicates a displacement of some 7 times to higher powers and would then give 7 × 28 or approximately 200 W/cm^2 for a spatial average saturation power density.

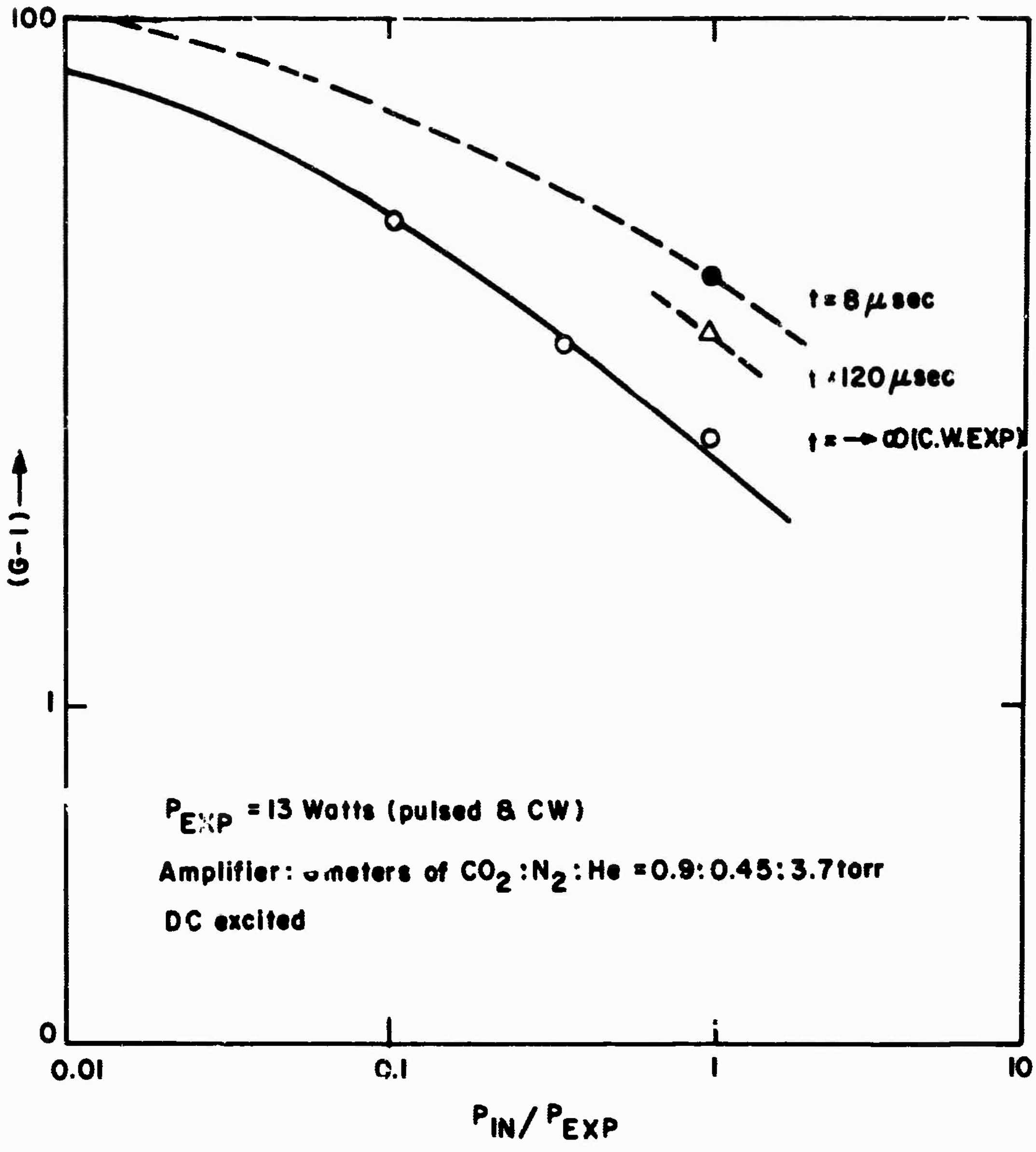


Fig. 14 Large Signal Gain Observed as a Function of Time for a Single Input Pulse

It is clear that as a design parameter, an input power density of this order (200 watts/cm^2) is required to efficiently extract the energy stored in the excited CO_2 molecules. The efficient extraction of energy for the reservoir of excited N_2 molecules now requires a repetitive application of the 10μsec pulses. We have taken data on the complete system of 3/4 and 2 in. diam amplifiers shown in Fig. 6. Due to the limitation of our recollimating optics at the time of the experiment, the full cross section of the large bore amplifiers was not used. As a result, we estimate that only one-half of the available volume of excited gas molecules was influenced by the injected signal. The data is shown in Fig. 15. For the 10 μsec pulses, the initial slope is 25 mJ/pulse with a progressive falling away from the line with increasing repetition rate. If we interpret this data on the basis of a model with single time constant τ connecting the N_2 and CO_2 states, τ is the reciprocal of the frequency at which the curve drops away from the initial straight line by 1/e. In our case τ = 100 μsec. In this experiment we used a standard gas mix of 0.5 torr CO_2, 1.0 torr N_2, 5.5 torr of He in the larger bore amplifier, 0.45 torr CO_2, 0.9 torr N_2, and 3.7 torr He in the small bore section. At these pressures, and a gas temperature of, say, 500°K, a time of 100 μsec would imply that approximately 200 collisions are required per quantum transfer.

As a practical matter, we have been able to obtain 200 W of average power at the 12 kc repetition rate, a level which would correspond to an initial slope of 28 mJ/pulse. This implies that if the same excitation had been applied to the total active volume, some 56 mJ/pulse would be achieved. Our previous calculation of 7 mJ of energy available from a single rotational level indicates that transfer for other rotational levels takes place to give an eight-fold enhancement. At a repetition rate of 12 kcs, the output per pulse will have dropped to some 60% of the low rate value, nearly to 33 mJ/pulse. This figure is to be compared to the

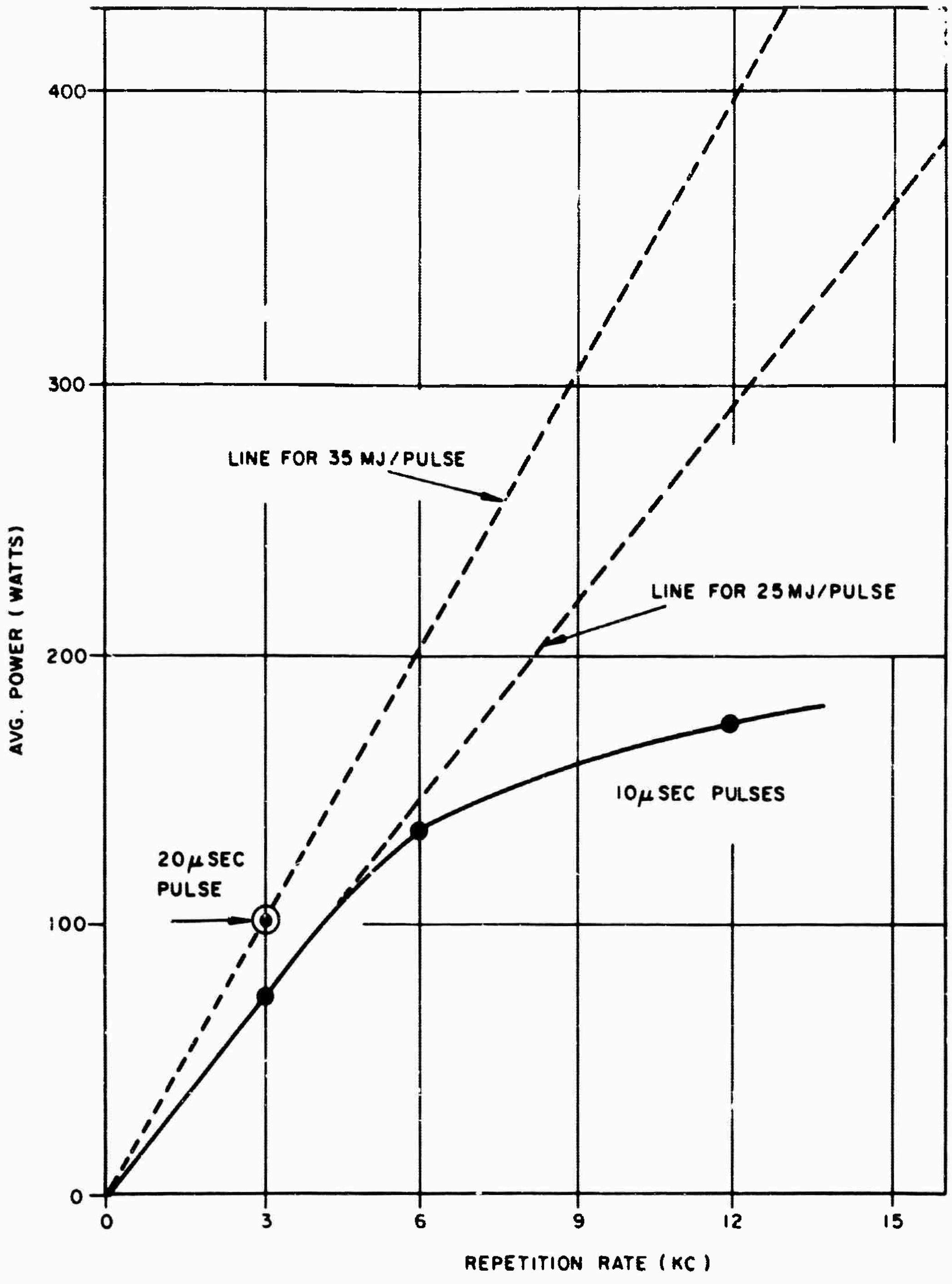


Fig. 15 Experimental Results on Pulse Amplification

estimate of 60 mJ/pulse made earlier in this report by analysis of the cw emission properties. The present results suggest that the large bore amplifier should be driven more vigorously, and in fact, the present output peak intensity is only 150 watts/cm^2 while the input is approximately 100 watts/cm^2.

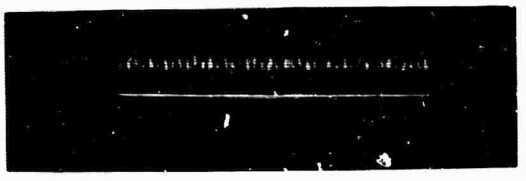
V. PULSE FORMATION AND AMPLIFICATION IN PULSE EXCITED AMPLIFIERS

The pulse trains formed by passing a uniform train of peak height approximately 15 watts through pulse-excited discharges have been studied using the small-bore amplifiers. Figure 16a shows typical traces obtained in this type of experiment. In this particular case a current pulse of 120 μsec duration was applied to the mix normally used for dc-excited tubes, namely 0.5 torr CO_1, 1 torr N_2, 3.7 torr of He. The photograph shows the superposition of many traces, in each of which the actual separation of the 10 μsec measuring pulses was 330 μsec. In this particular instance, we see that the pulse gain profile continues to rise after the termination of the 120 μsec current pulse, passes a maximum some 200 μsec later, and slowly decreases over the next millisecond.

By using 15 μsec current pulses, we can produce a situation wherein most of the increase of gain with time occurs after the current pulse. This buildup in the normal gas mix is governed by the N_2 - CO_2 energy transfer. The observed curves are again consistent with a 100 μsec transfer time.

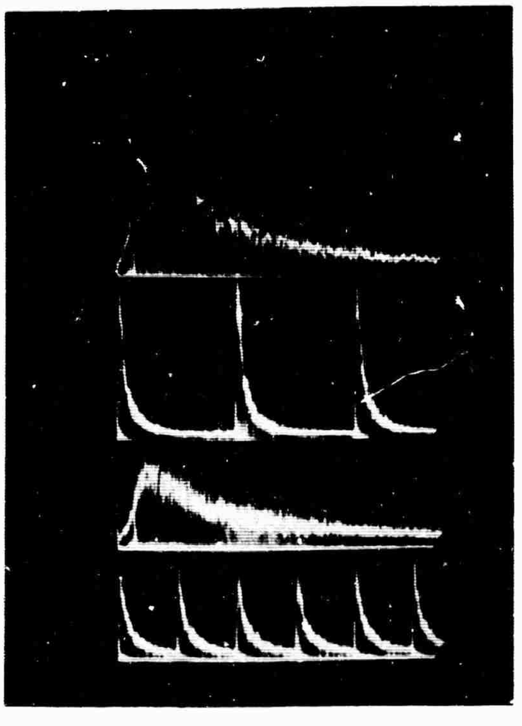
We find also that the pulse gain measured at its maximum value after the application of the current pulse has been increased by a factor of 2 over that measured in the same mixture using dc excitation (Fig. 16b). By increasing the length of the exciting current pulse to approximately 250 μsec, we have achieved a gain enhancement of three times the dc value. In interpreting this factor, it should be noted that the output pulse profiles indicated that partial saturation was occurring in the pulse amplification. Thus the small signal gain may have been increased by an even greater factor. This data implies that for a period of some 200 μsec, it is possible to at least triple the energy storage in levels accessible to a 10 μsec pulse, a result which at first sight is very attractive from the point of view of producing a compact pulse amplifier. However, if we have to provide high average powers by using high repetition rates, we would be required to

(a) Trace (a) Gain Profile measured with 10μsec pulses during and after the application of a 120μsec current pulse. (Time scale: 1 division = 200 μsec)



(b) Trace (b) A similar measurement using dc excitation

Fig. 16 Gain Enhancement Under Pulse Excitation



(a) Trace (a) Gain Profile using 120 μsec current pulses rep rate of 100 pps. (Time scale: 1 division = 200 μsec)

(b) Trace (b) as for (a) but with reduced time scale

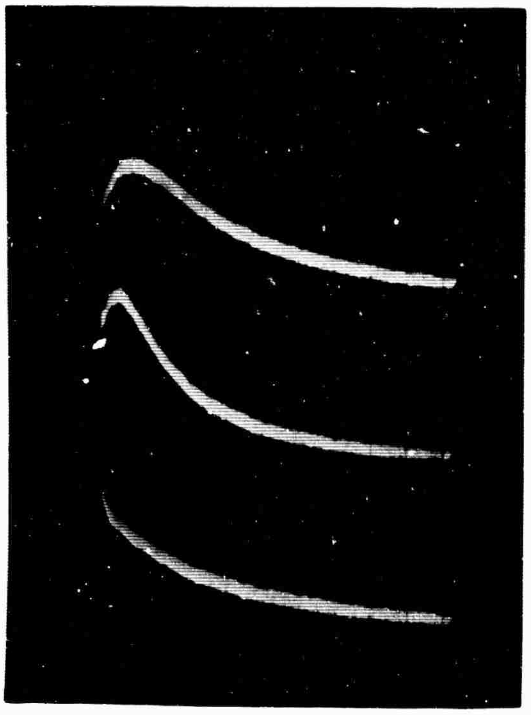
(c) Trace (c) as for (a) with 300 pps.

(d) Trace (d) as for (b) with 300 pps.

Fig. 17 Deterioration of Gain in Pulse Excited Amplifiers pulse excite at a correspondingly high rate. Unfortunately, the gain enhancement achieved with each current pulse decreases as the pulse excitation repetition rate increases. Figure 17 shows the corresponding profiles for repetition rates of 200 pps and 300 pps. The obvious drop-off in gain indicates that a process with an effective decay time of some 2 - 3 milliseconds comes into play in a 2 cm i.d. tube. Following a comparison of this data with that obtained by our companion contractors at the first quarterly review, it appears likely that the time constant is associated with the temperature of the gas mix, and depends on both the nature of this mix and on the tube diameter, becoming longer as the tube diameter increases.

In any case, it is highly unlikely that we will be able to reduce this time to the 100 μsec which would be required to handle 10 kc repetition rates, although a 1 kc rate may be practical in a 2 cm i.d. tube. It will be important to discover to what degree the response time can be reduced below 2 to 3 msec for 3/4 in. tubes, and below 20 msec for 2 in. tubes, by gas mixing and injection techniques, for example. In our own experiments on 2 in. tubes, it is clear that the gain profile follows a 120 cps current ripple, and we believe that at gas flow rates of the order of 2.5 meter/sec, the recovery time for sequential pulse excitation will be more like 10 msec, allowing a pulse repetition rate of 100 pps.

In a second set of experiments, we have studied the pulse formation which occurs when a cw signal, present at all times in the system, is amplified during and after the application of a current pulse to the second section of the amplifying chain. Figure 18 indicates the types of pulse profile that result in such cases. The profile depends on the gas mix, having its shortest decay time for pure CO_2, and increases significantly with the addition of nitrogen to the discharge. The profile becomes shorter as the gain is increased by raising the pulse current. The shortest pulse (70 μsec on base) was observed in pure CO_2, but the energy per pulse was much less than for the case of CO_2, He, N_2 mixes.



(a) Trace (a) CO_2, Ne, He gas mixtures

(b) Trace (b) CO_2, He mixtures

(c) Trace (c) Pure CO_2

Fig. 18 Pulse Emission Profiles Generated when a C. W. Signal is Passed Through a Pulse Excited Amplifier. (Time scale: 1 division = 200 μsec)

If we rely entirely on the pulse-forming characteristics of the pulse-excited discharge, it will be difficult to achieve high-power output pulses much less than 60 μsec in length. To do even this would require a pulsed preamplifier of pure CO_2 followed by a CO_2, N_2, He-filled pulsed amplifier. In fact it would be simpler to form a pulse by mechanical means, and amplify to a level required to drive the power amplifier into saturation before sending it to the pulse-excited amplifier.

As a result of these experiments, we have conceived of a system of double-modulated pulse trains which provides an attractive alternate to the dc- and single-pulse systems. Consider a system of pulses each 10 μsec long, separated by an interval of 160 μsec, which pass into a 40 meter length of 2 in. amplifier, pulse excited at 100 pps. Each exciting pulse lasts approximately 500 μsec, somewhat longer than the time required for energy transfer from excited N_2 molecules to the CO_2 upper laser levels. For a period of approximately 1 msec, the train of 10 μsec input pulses can draw on an inversion of ≈600 mJ per pulse, repeated up to three times.

In this mode of operation, three pulses, each of approximately 600 mJ/pulse would form a 0.5 msec burst repeated 100 times/sec. In this type of amplifier, we take the fullest advantage of the high energy storage in the pulse-excited mode without as large a loss of average power as occurs when only one 10 μsec pulse is used per excitation pulse. We would expect an average power of 180 W to be obtainable from a 40 meter section of 2 in. amplifier. While development of this type of excitation and operation may result in an increase of the usable repetition rate; i.e., beyond 100 pps, it is evident that in order to produce a 1 kwatt source by the means, a much longer amplifier will be necessary – approximately 200 - 250 meters.

By comparison with a completely dc-excited, high repetition-rate source, such a pulsed type has the advantage of greater efficiency on the use of the electrical power consumed in the excitation, together with a potential advantage of high peak power. The latter is beneficial in radar applications where a low signal-to-noise ratio per pulse is to be expected. The drawbacks are the obvious one of complexity of layout and handling of the long optical paths, and the possibility of transient beam distortion effects. It is clearly important to determine the far field patterns produced in such pulsed amplifiers, and we plan to do just this.

VI. REFRACTIVE AND DISTORTION EFFECTS IN AMPLIFIERS

For the application in mind for the transmitter, accurate definition and control of the output wavefront will be important. This wavefront could be distorted by:

1. Warping of the various optical elements (particularly mirrors) due to heating produced by absorption of the incident radiation.

2. Refractive effects produced by temperature gradients and molecular dissociation within the discharge.

3. Effects of nonuniform amplifier gain across the tube diameter.

Simple heating effects will cause a time average distortion proportional to the average power level. We have observed such effects in operating a 1200 W oscillator and have devised mirrors which essentially eliminate this form of beam distortion. This is done by making the mirrors from a material with good thermal conductivity (k) and high modulus of rigidity (G), and low thermal expansion (α). Defining a figure of merit kG/α gives the following result for a number of common materials.

Material	Figure of Merit
Aluminum	0.08
Brass	0.08
Nickel	0.19
Copper	0.33
Silver	0.17
Stainless	0.026 - 0.044
Fused Silica	0.025
Sapphire (20°C)	0.33

Of these materials, either copper or gold-plated sapphire is to be preferred for this application. Our present mirrors in the large-bore amplifier are sapphire, while in the 1 kW source we will probably use copper mirrors. In either case, approximately 1.5 percent loss occurs at each reflection. The resultant heat (15 W per mirror) must be removed by conduction cooling. In addition, there are likely to be transient distortions set up by pulse heating effects. A rapid expansion occurs at the absorbing surface each time a 10 μsec pulse is reflected. When an absorptive surface is used in our present amplification experiments, a clearly audible tone is heard at 3, 6, and 12 kc, even at average power levels of a few watts.

As far as refractive effects are concerned, we have measured the effects present in a 3/4 in. discharge tube operating under the normal conditions for a maximum amplification at 10.6μ and in other gas mixtures. This was done by passing a collimated probing beam (λ = 6328 Å) along the tube axis, and also along the tube wall parallel to the axis. We have found that a refractive index gradient appears along the tube wall in discharges containing N_2, O_2, CO_2 and mixtures thereof. The introduction of helium into the discharge reduces the effect by a factor of approximately 2. The pure helium discharge shows no observable effect. A beam sent along the tube axis shows an expansion at its edges approximately 3 times less than the observed displacements for the beam along the wall. These effects are consistent with an axially symmetric negative lens effect with a parabolic dependence on radial position:

$$n(r) = n_o(1 + \gamma r^2)$$

Our measurements show that for a discharge in 1 torr of CO_2, the refractive index at the wall is greater than that along the tube axis by an amount of 3×10^{-7}. This is to be compared to the refractive index contribution of 1 torr of CO_2, namely 4×10^{-7}. Whether the cause of this effect is purely a density variation, or due to molecular excitation and dissociation is not yet clear. Nevertheless, this figure represents a difference in optical length of λ/3 for a 10.6μ beam passing through a 10 meter tube. Since we are contemplating total lengths in excess of 40 meters, it becomes an important consideration in maintaining the beam shape. Whether this effect is comparable in magnitude for radiation at 10.6μ as it is for radiation at 0.6328μ, is not yet known for sure but will soon be investigated in detail. What we have observed, however, is that the emission pattern at the output of the 20 meter, large bore amplifier is not significantly changed by the presence of the discharge, and only varies in brightness. The implication is that only minor changes, if any, are introduced by the purely refractive properties of the discharge.

The third effect, due to nonuniform gain profiles, is likely to be the most significant effect, and is yet to be experimented on. As discussed previously, we have measurements of these gain profiles as functions of gas mix and tube current on dc-excited tubes, and have considerable control over these profiles. In pulse-excited tubes, however, pulse-to-pulse instabilities may occur which distort the gain profiles to give an azimuthal variation as well as a radial variation, effects associated with streamer-like discharge patterns. These effects are still to be investigated.

VII. OPTICAL MATERIALS

While there are numerous materials which transmit radiation at 10.6μ sufficient for their use as windows and lenses in conventional optical instruments, their attenuation is usually too great for their use in the present context of a high-power transmitter.

In fact, there are four materials which we have considered:

1. Sodium chloride
2. Germanium
3. Gallium arsenide
4. Irtran-4

Of these, sodium chloride has the lowest loss coefficient ($<0.01\ cm^{-1}$) and the lowest refractive index. There are no significant heating effects in a 1/2" window for a flux below 10 watts/cm^2. We have used such windows to transmit 1200 watts over an area of $\approx 20\ cm^2$, but at this level, some deterioration is found after use for a period beyond 1 hour. This material must be handled with care, being subject to damage from moisture, slight abrasion, and mechanical and thermal shock. It is nevertheless the most widely used window material for CO_2 lasers at present.

Germanium, in its present form, has a loss coefficient of approximately $0.01\ cm^{-1}$, but this loss increases rapidly with rising temperature and is therefore subject to thermal runaway. We have used water-cooled windows to handle 100 watts per cm^2, and could probably increase this figure by a factor of at least 2. Germanium takes a good optical finish and can be obtained in large crystalline ingots. At this time it is the best material available for partially transmitting laser mirrors. Its high refractive index (4.0) requires the use of antireflection coatings when it is used as a window. Given adequate cooling, we believe that germanium is a more rugged and longer-lived material for high-power optics than is sodium chloride.

Gallium arsenide, specially doped with iron to increase its resistivity to greater than $10^6\ \Omega$ - cms, has optical properties similar to those of germanium, with the advantage that the loss should not be strongly dependent on temperature. We have used a water-cooled window of 3/4" diameter with 500 watts impinging on it with no deleterious effects, although a loss of 4 % of the incident energy was measured. If this material could be obtained in large plates, it would be somewhat superior to germanium for high-power use, although cooling would still be necessary.

Irtran-4, an aggregate of zinc selenide, tends to vary in quality from piece to piece, but the best specimens make excellent lenses and windows for medium power (less than 10 watts/cm^2) applications. Their problem is one of thermal distortion, and we believe that they would be of little use at high average power levels.

It is our intention at this time to use germanium windows, and we are setting up experiments for loss measurements on various sample pieces.

VIII. PRESENT STATE OF THE TRANSMITTER DEVELOPMENT

Based on the various observations outlined above, we have developed a design for a 1 kwatt source as follows:

We envisage a cw stabilized oscillator with a single-mode, polarized output of 30 watts. It will consist of a 2-meter length of 1/2" i.d. discharge arranged as a near semi-confocal resonator. The output window will be a water-cooled germanium flat. The beam will be collimated to form a 3/4" dia. beam and passed through a dc-excited buffer amplifier with internal diameter of 1", and total length some 12 meters. At this point the average power level will be approximately 400 watts. Using reflective optics, a focal plane chopper, carefully polished to cut down on scatter, will form the desired pulse train. After recombination and expansion of its diameter by two times, the beam will pass into 40 or perhaps 50 meters of 2" dia. power amplifier. (The window materials will all be germanium, as close to the Brewster angle as is practical.) The beam will be focused to propagate as uniformly as possible throughout the main power amplifier, which will be excited by dc current. In this design, the buffer amplifier is always driven into saturation by the incoming signal, while the power amplifier has a single pass gain of 40-50 dB, and should be stable while the chopper is closed.

We have built an experimental assembly along these lines using NaCl optics, and with only 20 meters of the final 40-50 meter power amplifier. Up to this point, the main problem has been the control of the beam coming from the primary oscillator. Using a 12 kc train of 10 μsec pulses, we have measured up to 435 watts of average power at the output window, distributed in a spatial pattern determined by the signal coming out of the buffer amplifier. In these experiments, the primary oscillator power was approximately 20 watts in a double spatial mode The cw signal at the output from the buffer amplifier was approximately 300 watts. Spurious oscillation pulses have been seen in this assembly when the chopper blade is open, but these are again suppressed by the amplified signal for the oscillator when the latter is turned on.

Work on this system is going on, of course, and we believe that with proper control of the oscillator, proper use of the two amplifiers, that an output of the order of 500 watts will be obtained from the present equipment. Even with the present results, it seems evident that a 50-meter power amplifier will produce in excess of 1 kw average power, and we intend to begin construction of such a device immediately. While this is going on, experiments will continue on the window materials, on the far-field pattern of our existing transmitter and its dependence on our optics. In a different context, the properties of the existing system will be studied using a cw source, a dc-driven buffer amplifier and pulse excitation of the main power amplifier. Pulsed power supplies adequate for these latter experiments have been built.

IX. SUMMARY

In this report we have outlined our original guiding thoughts on the achievement of a 1 kW power transmitter, our initial experiments on dc- and pulse-excited amplifiers, their interpretation in terms of the laser and discharge dynamics and their significance for the overall design of high-power amplifiers.

As a result of this work we have designed and built a prototype system which is presently being tested. The most important work yet to be done has to do with the far-field and propagation properties of the beam and investigations of the quality and stability of the optics under the action of high average powers and high pulse powers.

REFERENCES

1. M. Weber and T. Deutsch, IEEE J. Quant. Elec. QE-2, 365 (1966).

2. D. R. Whitehouse, "High Power Gas Laser Research," Final Technical Report on Contract DA-01-021-AMC-12427(Z), May 1967.

3. T. J. Bridges, Appl. Phys. Letters 9, 174 (1966).

4. H. Statz, C. L. Tang, and G. F. Koster, "Transition Probabilities between Laser States in Carbon Dioxide," J. Appl. Phys. 37, 4278 - 4284 (1966).

5. H. Kogelnik and T. J. Bridges, IEEE J. Quant. Elec. QE-3, [illegible]5 (1967).

BLANK PAGE

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Raytheon Company Research Division Waltham, Massachusetts 02154	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP N/A

3. REPORT TITLE

Research Study of a CO_2 Laser Radar Transmitter

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Semiannual Technical Summary Report 11/1/66 to 4/30/67

5. AUTHOR(S) (Last name, first name, initial)

Miles, Perry A. and Horrigan, Frank A.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June, 1967	48	5

8a. CONTRACT OR GRANT NO. N00014-67-C-0264 b. PROJECT NO. NR 015-714 c. ARPA Order No. 306 d.	9a. ORIGINATOR'S REPORT NUMBER(S) S-970 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES

Reproduction in whole or in part is permitted for any purpose of the United States Government.

11. SUPPLEMENTARY NOTES N/A	12. SPONSORING MILITARY ACTIVITY Advanced Research Projects Agency Office of Naval Research Department of Defense

13. ABSTRACT

This report concerns the investigation of physical properties of laser amplifiers, using electrically excited mixtures of CO_2, N_2, and He with a view to producing high-power pulse emission with well-controlled temporal and spatial form. The object of this investigation is to design and build such a source with an average power of 1 kW in a form suitable for use as a laser radar transmitter.

Designs have been developed for both dc- and pulse-excited amplifiers and the physical quantities of importance in these designs have been measured. The most notable of these are: the signal intensity required to drive an amplifier to saturation, information on the refractive properties of the discharge, the time constant determining maximum pulse repetition rates, both for the input pulse trace and for the pulse excitation process, and the practical gain levels that can lead to self-oscillation in the amplifier. These measurements lead to the choice of a system in which a train of 10 - 15 μsec pulses at a repetition rate of 10 - 12 kc is amplified by a 50-meter length of dc-excited power amplifier.

DD FORM 1 JAN 64 1473

Unclassified

Security Classification

Unclassified

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
CO_2 Laser Transmitter						
High Power Laser Amplifier.						
CO_2 Laser Pulse Amplification.						

INSTRUCTIONS

1. ORIGINATIN[illegible] ITY: Enter the name and address of the contractor, [illegible]ractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

Unclassified

Security Classification