NRL Report 6536

Helium-Neon Laser Discharge Parameter Study

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June 21, 1967

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Washington, D.C.

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ABSTRACT

An experimental study is made to determine which energy level is dominant in limiting the output power of the helium-neon laser. This is done by comparing laser power versus discharge current data for the three main laser transitions, with the temperature and pressure as parameters. Such a comparison is informative because two of the laser transitions (0.6328 and 3.39 microns) share a common upper level ($3s_2$); and two (0.6328 and 1.15 microns) share a common lower level ($2p_4$). Relative saturation behavior indicates that at low pressures the upper level population rate controls the output power of all three laser lines; and at high pressure (above 1 torr) the lower level depopulation rate is more important for the 0.63 and 1.15 μ lasers. The optimum pressure for maximum output of the 0.6328 μ laser occurs at an intermediate pressure (0.7 torr) where both effects are important. All of the data were taken on the same tube, (8 mm. i.d.), utilizing ultra high vacuum techniques to maintain gas purity. It has been found that an increase in the laser tube wall temperature will produce an increase in laser power at high pressures (as much as 500% for 1.15 μ); but will decrease the power at low pressures. Also of interest in the data is the fact that the 1.15 μ line can be made to oscillate at total pressures at least as high as 20 torr.

Note: This report consists of a thesis submitted to the faculty of the Graduate School of the University of Maryland in partial fulfillment of the requirements for the degree of Master of Science, 1967. The thesis and abstract was approved by Dr. Carroll O. Alley, Associate Professor, Department of Physics and Astronomy, University of Maryland, on October 11, 1966. The thesis was submitted to be an NRL Report on December 23, 1966, as an interim report on NRL Problem R08-45, Project RR 008-03-46-5674.

CHAPTER I

INTRODUCTION

Besides being the first continuous wave laser and the first gas discharge laser, the helium-neon laser is the one most in use, and will probably maintain this position for some time to come. The helium-neon laser has become a standard laboratory source for highly directional, monochromatic, coherent light which is used for many diverse purposes.

The three main laser transitions in the helium-neon system are the 0.6328 μ, 1.1523 μ, and the 3.3913 μ lines. The first oscillations were obtained by Javan, Bennett, and Herriott[1] in 1960, at five different wavelengths in the near infrared including the 1.1523 μ line. In 1962, oscillation at 0.6328 μ was obtained by White and Rigden;[2] and late in 1962, oscillation at 3.3913 μ was obtained by Bloom, Bell and Rempel.[3] Since then many other laser lines in both the visible and infrared have been obtained in the helium-neon system.[4]

The gas discharge mechanisms which produce the population inversion necessary for oscillation have been studied in detail,[5,6] and are fairly well established. However, the quantitative details of mechanisms which limit the

output power and efficiency are not known, although much work has been done on the problem.[4-17] To improve power output and efficiency it is necessary to know where the power limitations occur. An efficiency improvement is desirable since the efficiency of a typical helium-neon laser is less than 0.1%.

It is well known that there is an optimum discharge current for obtaining maximum laser output. This optimum current varies with the partial pressures of helium and neon, and with the tube geometry. In general, as the discharge current is increased, the laser power first increases, reaches a maximum (saturation), then decreases to zero (quenching). Therefore, one cannot obtain more output power simply by feeding more power into the discharge. The decrease in output at higher currents is of course caused by a decrease in available population inversion; and the purpose of the present study is to determine if the dominant saturation effect is in the excitation rate of the upper level or in the depopulation rate of the lower level. A secondary purpose is to obtain experimental data, under clean gas conditions, on the behavior of the laser power as a function of various gas discharge parameters.

CHAPTER II

GAS LASER THEORY BACKGROUND

A. Interaction of Matter with Radiation

Let us consider just two non-degenerate energy levels of an atom, E_k and E_m, where E_k is greater than E_m. If the energy state E_k is initially occupied, there is a certain probability that the electron will jump to level E_m, causing the atom to emit a photon of energy

$$E_k - E_m = \hbar\omega_{km}, \tag{1}$$

where $\hbar$ is Planck's constant divided by 2π, and ω_{km} is the angular frequency of the radiation. For a group of atoms, the number of emission acts per second is

$$[A_{mk} + B_{mk}\rho(\omega_{km})]N_k, \tag{2}$$

where A_{mk} and B_{mk} are the Einstein coefficients for spontaneous and stimulated emission respectively, and N_k is the number of atoms with an electron in the energy state E_k. The coefficients A and B are fundamental measures of the interaction of the atoms with the radiation field. Their ratio, which is independent of whether or not the system is in thermal equilibrium, is given by

$$A_{mk}/B_{mk} = 2\hbar\omega_{km}^3/\pi c^3. \tag{3}$$

The radiation density is given by Planck's law:

$$\rho(\omega_{km}) = 2\hbar\omega_{km}^3/\pi c^3[\exp(\hbar\omega/kT) - 1]. \tag{4}$$

Now if the state E_m is occupied, there is a certain probability that a photon will be absorbed from the radiation field causing the electron to jump to state E_k. The number of absorption acts per second is given by

$$B_{km}N_m\rho(\omega_{km}), \tag{5}$$

where B_{km} is the Einstein coefficient for absorption, and N_m is the number of atoms with electrons in energy state E_m. It can be shown simply that

$$B_{km} = B_{mk}. \tag{6}$$

Thus the net rate of loss of radiation (assuming some external pumping mechanism) is

$$A_{mk}N_k + B_{mk}\rho(\omega_{km})[N_k - N_m]. \tag{7}$$

In an ordinary gas discharge in thermal equilibrium, the relative numbers of atoms in different levels are given by the Boltzmann law

$$N_k/N_m = \exp[(E_m - E_k)/kT]. \tag{8}$$

Since E_k is greater than E_m, then N_m is greater than N_k. Therefore in an ordinary gas discharge, absorption predominates over stimulated emission.

However, because of preferential pumping mechanisms in a gas laser discharge, more atoms are pumped to the energy

state E_k, so that N_k is greater than N_m. In this case stimulated emission predominates over absorption, so that a net gain exists in the system.

Since the spontaneous emission is independent of the radiation density, we can increase the stimulated emission rate relative to the spontaneous rate by increasing the radiation density in the system. This is done by enclosing the system in a resonant cavity.

Thus in a laser, stimulated emission predominates over absorption because of a population inversion, and over spontaneous emission by the increase of the radiation density due to the resonant cavity.

B. The Helium-Neon Laser

The complexity of the mechanisms active in a helium-neon laser discharge is well described in Bennett's review articles.[4,5] Only the main features will be presented here. A partial energy level diagram of helium and neon is given in Fig. 1. The reactions mainly responsible for populating the upper laser levels are:

$$\mathrm{He}\ (2^1S) + \mathrm{Ne} \rightarrow \mathrm{Ne}\ (3s_2) + \mathrm{He}, \tag{9}$$

$$e + \mathrm{Ne} \rightarrow \mathrm{Ne}\ (3s_2) + e, \tag{10}$$

$$\mathrm{He}\ (2^3S) + \mathrm{Ne} \rightarrow \mathrm{Ne}\ (2s_2) + \mathrm{He}, \tag{11}$$

and

$$e + \mathrm{Ne} \rightarrow \mathrm{Ne}\ (2s_2) + e. \tag{12}$$

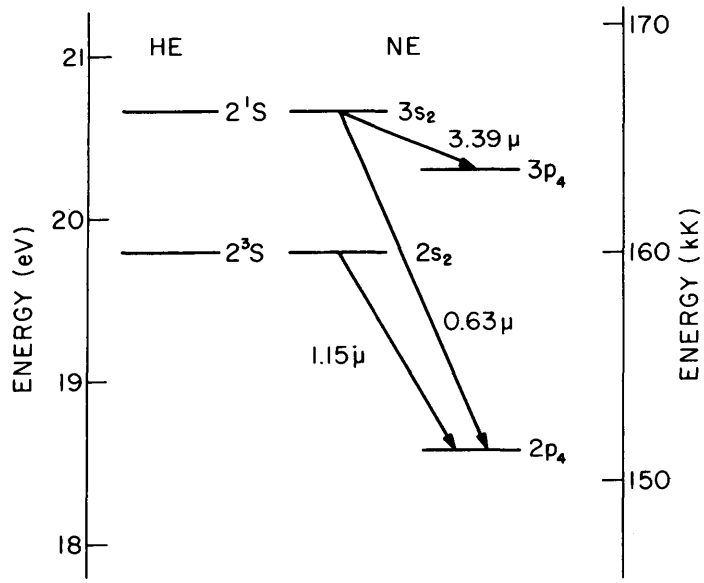


Fig. 1 - Energy levels pertinent to the helium-neon laser

Reaction (9) is more important than reaction (10) according to White and Gordon.[6] Reactions (11) and (12) are of about equal importance according to Bennett,[5] with reaction (12) being enhanced by the presence of helium. The lower laser levels decay by spontaneous emission:

$$\text{Ne } (3p_4) \rightarrow \text{Ne } (2s,1s) + h\nu, \tag{13}$$

$$\text{Ne } (2p_4) \rightarrow \text{Ne } (1s) + h\nu. \tag{14}$$

However, two of the neon (1s) levels are metastable and the other two are quasimetastable by virtue of radiation trapping with the ground state. These 1s levels are sources for deleterious population of the lower laser level $2p_4$ by radiation trapping and by electron impact excitation:

$$\text{Ne } (1s) + h\nu \rightarrow \text{Ne } (2p_4), \tag{15}$$

$$\text{Ne } (1s) + e \rightarrow \text{Ne } (2p_4) + e. \tag{16}$$

Bennett[4] suggests that radiation trapping (15) is dominant at the large diameter extreme, and electron collision (16) more important at small diameters. Another reaction which is harmful to laser action is de-excitation of helium metastables by electrons:

$$\text{He } (2S) + e \rightarrow \text{He}(1S) + e. \tag{17}$$

The data of White and Gordon[6] indicate that at high currents reaction (17) is the dominant loss mechanism for helium (2^1S)

metastables. However, Wada and Heil[9] state definitely that de-excitation of helium metastables by electrons is negligible in a helium-neon laser discharge.

CHAPTER III

EXPERIMENTAL APPROACH

In the He-Ne system, the three main laser transitions are 0.6328 μ ($3s_2$-$2p_4$), 1.1523 μ ($2s_2$-$2p_4$), and 3.3913 μ ($3s_2$-$3p_4$). The 0.63 μ line shares a common upper level with the 3.39 μ line and a common lower level with the 1.15 μ line (Fig. 1). If the population inversion limitation occurs in the excitation rate of the $3s_2$ level, the effect should be common to both the 0.63 μ laser and the 3.39 μ laser. Similarly if the limitation occurs in the depopulation rate of the $2p_4$ level, the effect should be common to both the 0.63 μ laser and the 1.15 μ laser.

Data have been taken under high gas purity conditions of laser power versus discharge current for each of the three main transitions at various partial pressures of helium and neon. A comparison of the laser power versus discharge current curves reveals similarities which indicate the level responsible for the output power saturation. Laser power versus tube wall temperature data have also been recorded. These data for the three main laser transitions also reveal similarities which give another indication

of the energy level responsible for the output power saturation.

The spontaneous light emission from the upper and lower laser levels, both with the tube lasing and not lasing, has been monitored. The spontaneous emission in the limit of zero optical thickness gives a direct indication of the relative population of a particular energy level. This information is correlated with the two previously mentioned sources of information to determine the energy level responsible for saturation.

CHAPTER IV

APPARATUS

A. Vacuum System

It was essential in this study to prevent the possibility of any gas contamination, which certainly would have hindered a correct interpretation of the results. This meant that the gas manifold and the laser tube had to be thoroughly evacuated and baked. Since the laser tube was to oscillate at 3.39 μ, the Brewster angle windows had to be transmitting in this region of the infrared. Thus, the laser tube was constructed of fused quartz (except for the electrode bulbs) with fused quartz windows sealed on without the use of any adhesive. The tube was bakeable to 600°C.

A block diagram of the vacuum system is shown in Fig. 2. The diffusion pump and the manometer contain Octoil-S diffusion pump oil. The laser tube was rf outgassed with helium and the tube filaments were outgassed and activated before the system was baked. The system was then baked for 28 hours up to 450°C, during which time the oil manometer[18] was outgassed. Liquid nitrogen was applied to the diffusion pump cold trap while the rest of the system was still at 450°C. After the bake-out, liquid nitrogen was applied to

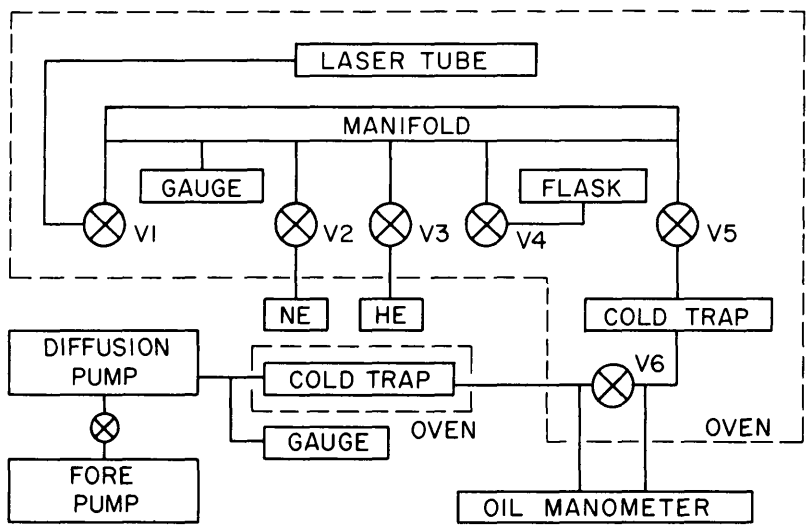


Fig. 2 - Block diagram of vacuum and gas filling system

the manometer cold trap and further outgassing of the tube filaments and the ion gauges was continued. The system reached a base pressure of $2x10^{-9}$ Torr before laser measurements were begun. Both helium and neon discharges were spectrographically examined with a Bausch and Lomb Medium Quartz Spectrograph used with Kodak type IIa O plate. Various exposures up to fifteen minutes in duration were made with a 50 micron slit width looking down the bore of the laser tube. The only impurity found was a trace of silicon which is a constituent of the tube walls.

During the course of the study, precise mixtures of helium and neon were prepared and stored in the reservoir flask. To avoid backstreaming across a valve, gas was never admitted to the manifold unless it was first thoroughly evacuated. In preparing a mixture (cf. appendix A) care was taken to avoid not only errors in the mixture ratio due to the manometer cold trap being at a much lower temperature than the rest of the system, but also errors due to the volume displaced by movements of oil in the manometer.

The pressure measurements were made using an Octoil-S manometer in conjunction with a cathetometer having a length of 102 cm and scribed in 0.05 mm divisions. Manometer readings were converted to Torr by use of 1 mm Octoil-S equals 0.06734 Torr, yielding an accuracy of 0.004 Torr. Because

the oil adhered to the glass manometer walls, and because the cold trap was at a much lower temperature than the rest of the system, about 30 min was allowed for equilibrium to be established before a pressure reading was taken. After a mixture was prepared the system was allowed to stand for at least an hour to permit thorough mixing of the helium and neon.

The gases used in this work were naturally occurring isotopic mixtures obtained from the Linde Division of the Union Carbide Corporation. The high purity gases were contained in one liter Pyrex flasks. The principal impurity was nitrogen: less than 5 parts in 10^5 as specified by the supplier.

B. Experimental Setup

A diagram of the experimental setup is shown in Fig. 3. The laser tube was 8 mm i.d. and the discharge length inside the cavity was 56.5 cm. Directly heated oxide coated filaments, identical to those used in fluorescent light tubes, were used for both electrodes so that the polarity could be reversed to check the effect of cataphoresis.[19] The 2 m radius of curvature mirrors were separated by 1 m; this cavity configuration not only yields a large mode density, but also efficiently utilizes a large portion of the tube

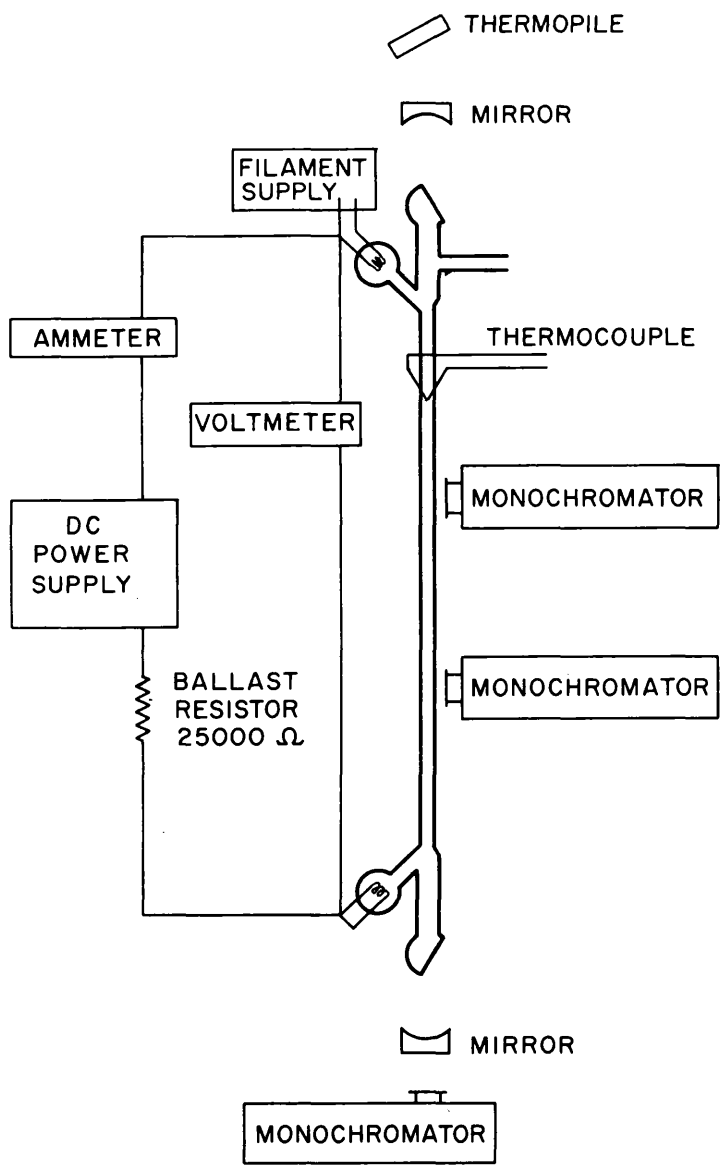


Fig. 3 - Diagram of experimental setup

volume.[20]

The mirrors were mounted in holders that could be readily interchanged in the mirror mount (Fig. 4) without losing alignment. The mirror mounts had independent orthogonal adjustments, with fine control provided by a micrometer driven weak spring acting against a hinge rod. Moving the micrometer 1/40 mm corresponded to rotating the mirror through approximately 6 sec of arc.

The output laser beam was monitored with a Jarrell-Ash 0.5 m grating monochromator using an RCA 7102 photomultiplier tube as the detector. The side light was monitored with two small Bausch and Lomb grating monochromators, one using an RCA 1P28 photomultiplier tube, the other using alternately RCA 7102 and RCA 6199 tubes.

In order to monitor 1.1523 μ spontaneous light, it was necessary to refrigerate the RCA 7102 tube with the simple cooler[21] shown in Fig. 5. A Corning glass color filter, C.S. number 7-56, was used on the monochromator input for the infrared measurements. Because it has a relatively flat response for all three laser wavelengths, a calibrated thermopile was used to measure laser power.

To align the laser cavity initially, the following technique was used. With the discharge off, one sights through one mirror down the bore of the externally illumi-

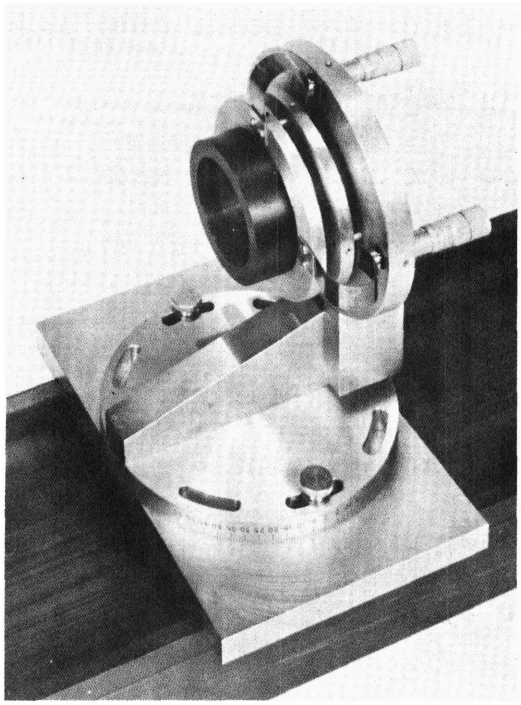


Fig. 4 - Laser mirror mount

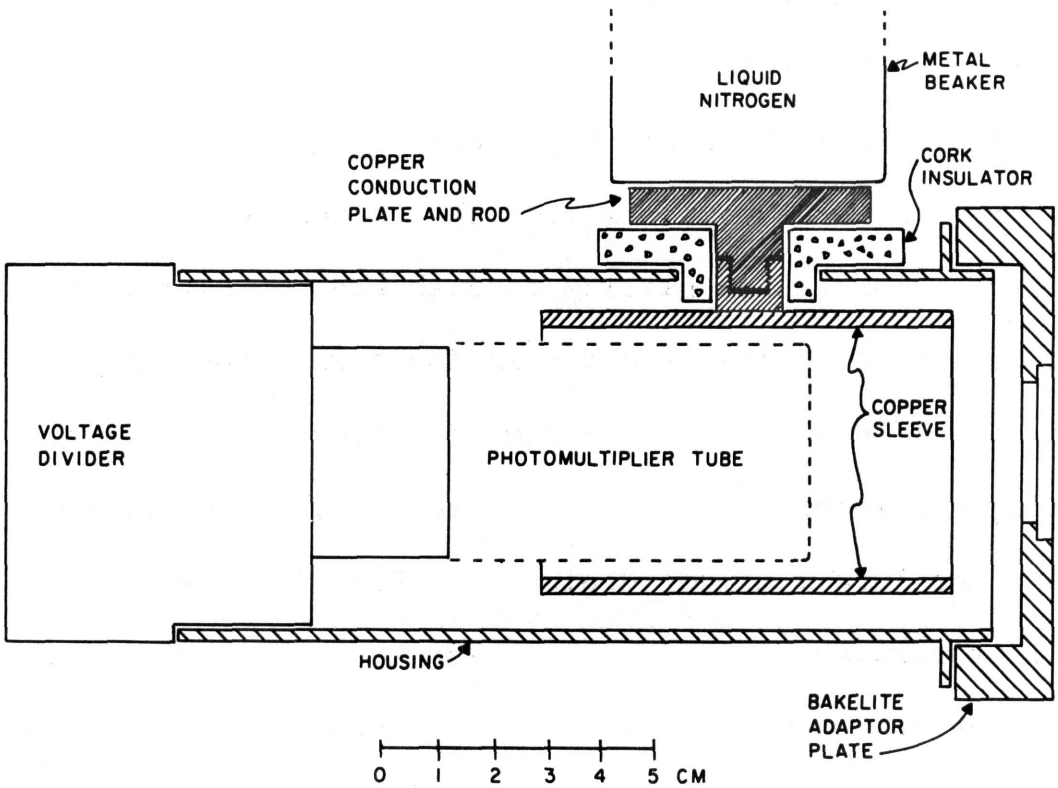


Fig. 5 - Photomultiplier cooler installed in the tube housing of a monochromator

nated laser tube such that the eye is on the laser tube axis (Fig. 6a). Then the near mirror is adjusted so that the virtual image of the eye is also on the laser tube axis (Fig. 6b). With care this method was found to align the mirror within a few minutes of arc. The same procedure was repeated with the other mirror. If this initial alignment was not good enough to sustain oscillation, gentle tapping of one mirror usually initiated laser oscillation. The mirror adjustments were varied one by one to maximize the laser output.

After this initial alignment, the laser cavity is generally in a state depicted by Fig. 7a, where the laser beam is not using the whole bore of the tube. In this configuration, which is a relative maximum, the mirror centers of curvature lie on a line passing through the two mirrors and the tube, but this line is not coincident with the laser tube axis. If one mirror at a time is adjusted from this position, the laser output will decrease. In order to obtain the absolute maximum, depicted by Fig. 7b, one mirror control is perturbed from the relative maximum, and then the controls on the opposite mirror are adjusted for a new relative maximum. If the new relative maximum is greater than the old, the perturbation is repeated in the same direction. This procedure is continued until an absolute maximum is

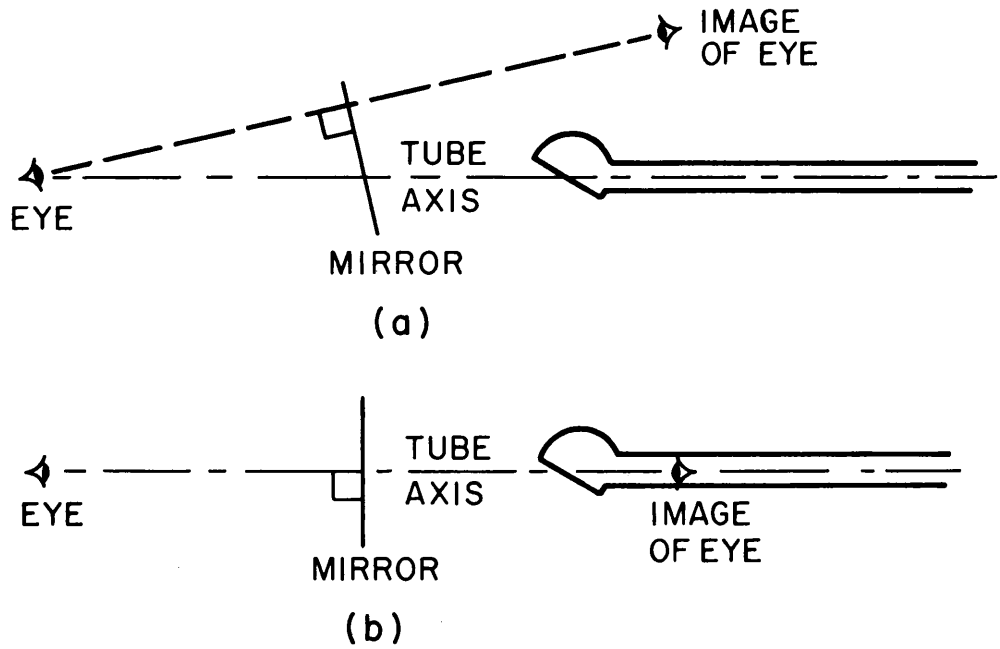


Fig. 6 - Method used for initial alignment of laser mirrors

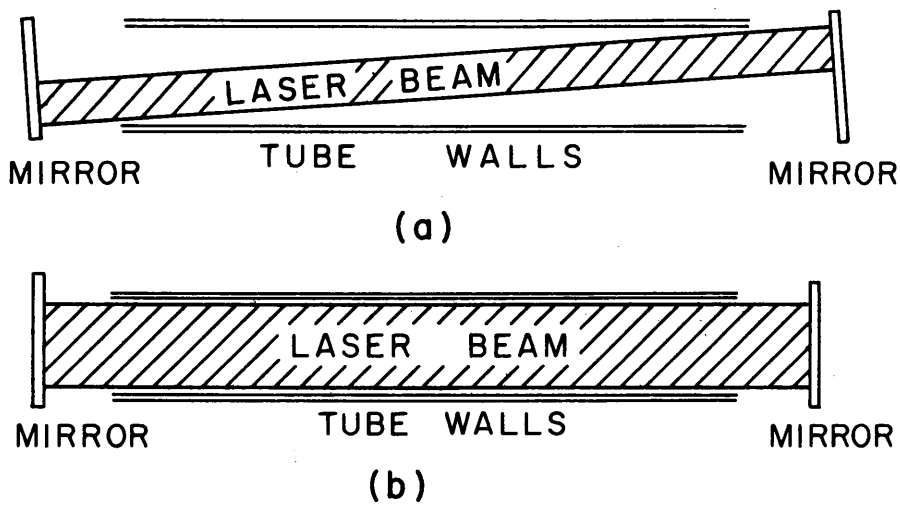


Fig. 7 - (a) Mode volume after initial alignment, (b) mode volume after final alignment

reached, where the mirror centers of curvature lie on the laser tube axis.

C. Some Experimental Difficulties

The original set of 3.39 μ fused quartz substrate mirrors also supported strong oscillation at 1.15 μ. This was due to the fact that multilayer dielectric mirrors have their primary reflection maximum where the layer thickness equals $\frac{1}{4}\lambda$ and a second reflection maximum where the layer thickness equals 3/4 λ. Thus, 1.15 μ fell in the secondary reflection band. To circumvent this difficulty, a new set of 3.39 μ mirrors was obtained with a reflectivity of only 35% at 1.15 μ. This was accomplished by shifting the primary reflection band from 3.0-3.7 μ to 3.3-4.0 μ, and by the fact that the index of refraction of the dielectric material changes with wavelength. This second set of 3.39 μ mirrors was used in all the 3.39 μ laser measurements.

A second difficulty was that the 1.15 μ mirrors supported oscillation also at 1.1614 μ ($2s_3$-$2p_5$) and 1.1985 μ ($2s_3$-$2p_2$). To overcome this, the relative 1.1523 μ laser output was measured with the Jarrell-Ash monochromator and RCA 7102 photomultiplier tube, in addition to the total laser output being measured with the thermopile.

It was found that a hysteresis effect occurs in the laser power vs tube current curves. That is, the position

of the laser power curve depends on whether the current is rising or falling. It was determined that the hysteresis effect is not due to cataphoresis because the same effect occurs when the polarity is reversed. By means of an iron-constantan thermocouple attached to the wall of the laser tube, it was found that there existed a one to one correspondence between laser power and wall temperature. This wall temperature effect has proved to be a valuable parameter for determining the saturation mechanisms.

CHAPTER V

RESULTS AND DISCUSSION

Laser power vs tube current data were taken for He-Ne mixture ratios of 5/1, 7/1, and 9/1 for neon partial pressures of 0.07, 0.16, and 0.25 Torr. Results are presented for the 5/1 mixture ratio in Figs. 8, 9, and 10 where the maximum laser outputs at normal operating temperatures are normalized to 10. The data are presented in normalized form for purposes of comparison because the reflectivities (nominally 99%) of the various wavelength mirrors are not optimized for maximum output, and because the optical properties of the surfaces undoubtedly changed slightly over the entire course of the measurements. The measurements were made in a filtered-air environment; dust shields were used on the dielectric mirrors and Brewster-angle windows so that the optical properties of these surfaces were essentially constant for short periods of time such as a day.

Since the laser power varies with gas temperature,[4] the data for increasing current (heavy lines) were taken very slowly, allowing time for thermal equilibrium. To enhance the temperature effect, the data for decreasing current (light lines) were taken very rapidly. Thus the

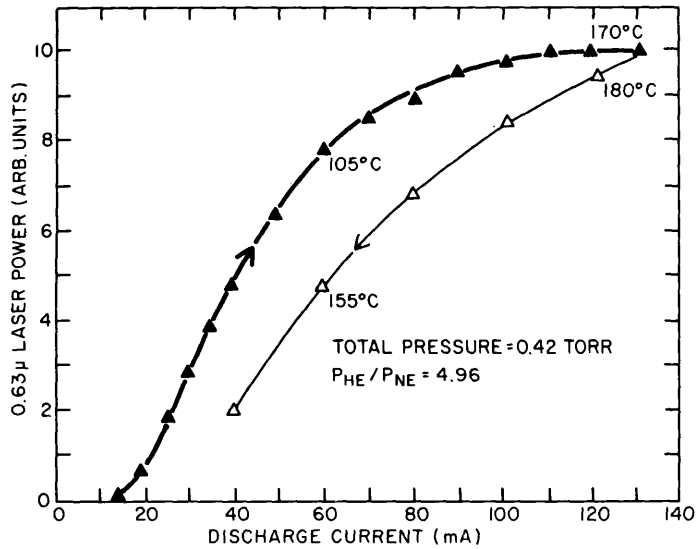


Fig. 8a - Curve of 0.63 μ laser power vs discharge current. The temperature indicated refer to the discharge tube wall temperature at that point on the curve. See text.

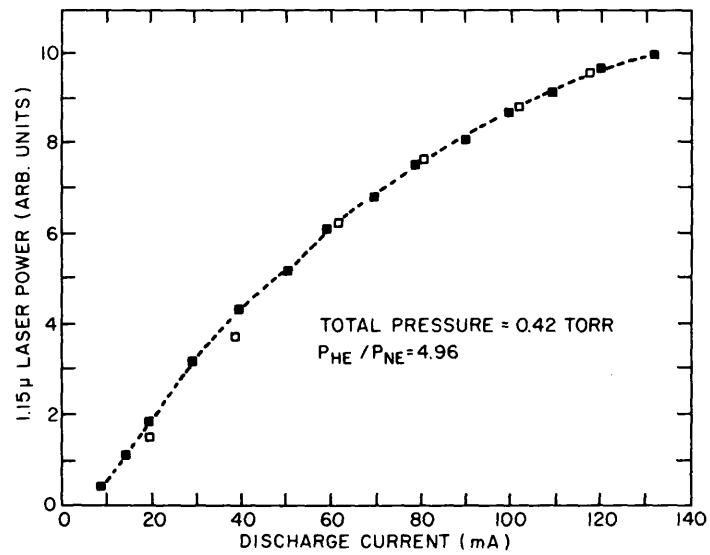


Fig. 8b - Curve of 1.15 μ laser power vs discharge current

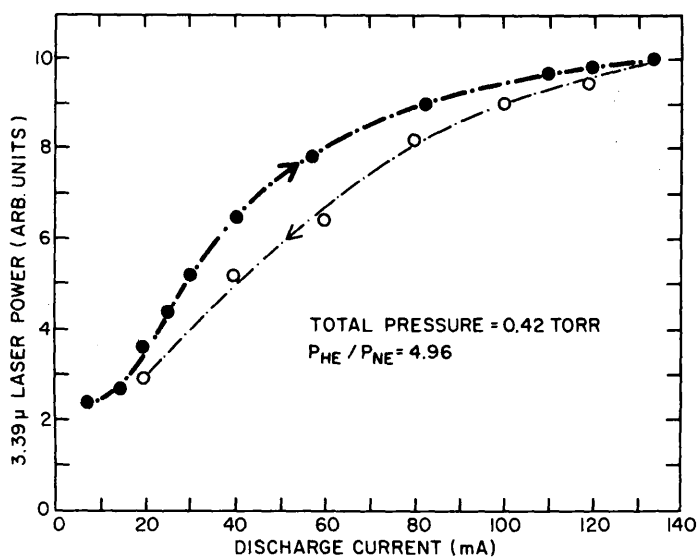


Fig. 8c - Curve of 3.39 μ laser power vs discharge current

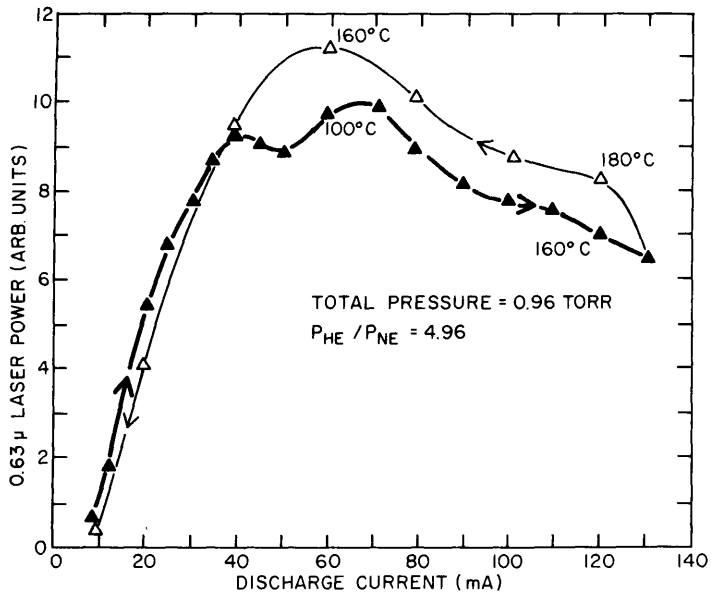
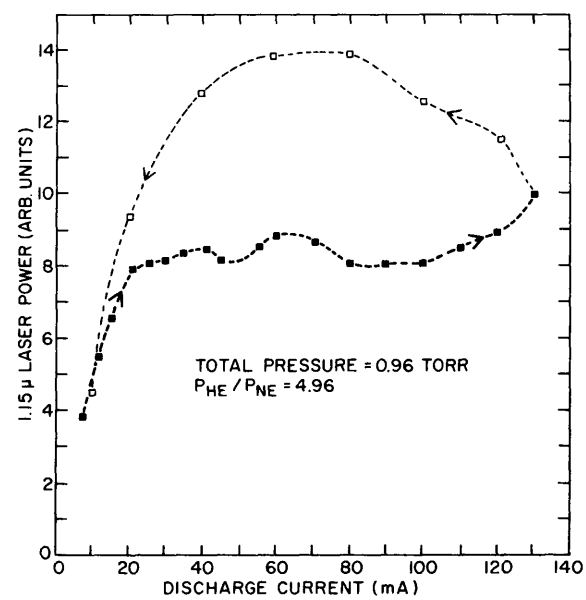


Fig. 9a - Curve of 0.63 μ laser power vs discharge current. The temperature indicated refer to the discharge tube wall temperature at that point on the curve. See text:

Fig. 9b - Curve of 1.15 μ laser power vs discharge current



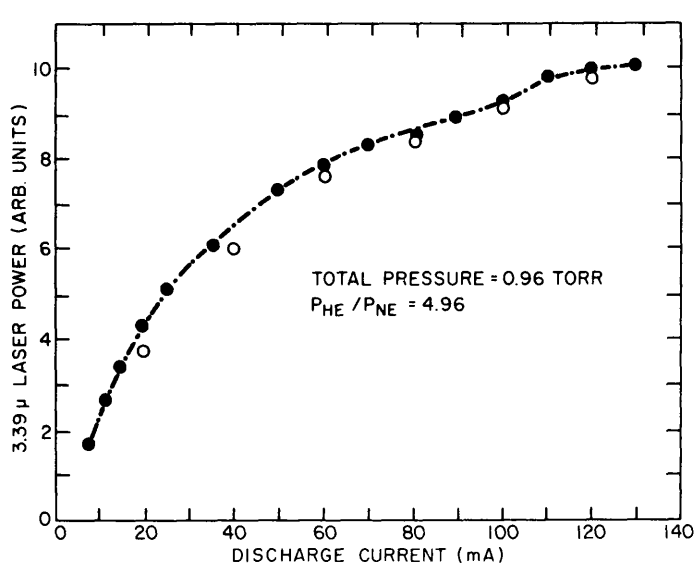


Fig. 9c - Curve of 3.39 μ laser power vs discharge current

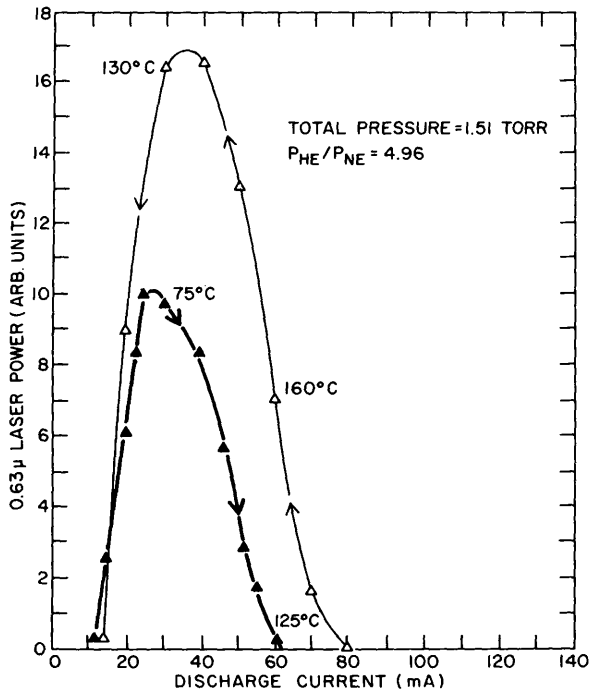


Fig. 10a - Curve of 0.63 μ laser power vs discharge current. The temperatures indicated refer to the discharge tube wall temperature at that point on the curve. See text.

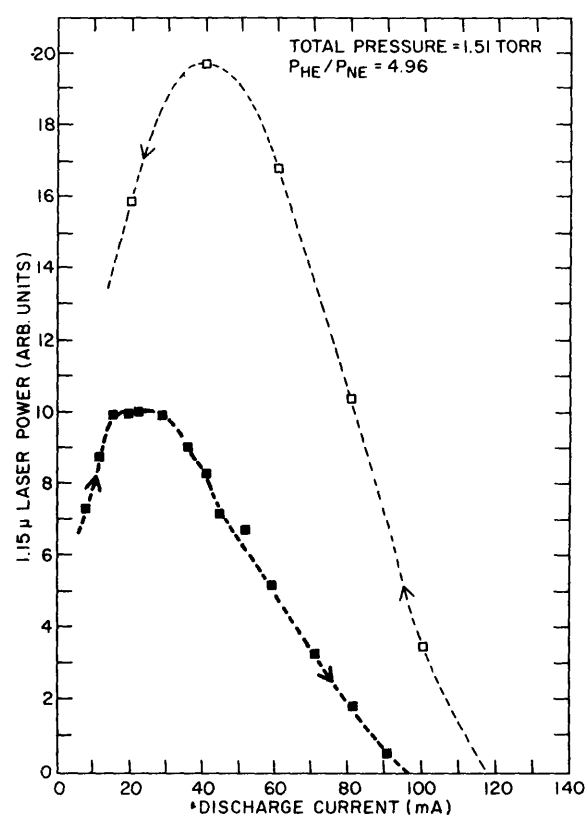


Fig. 10b - Curve of 1.15 μ laser power vs discharge current

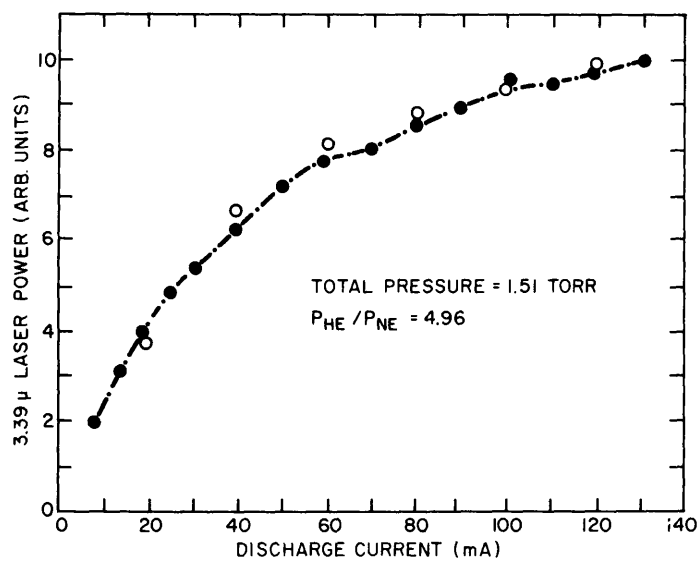


Fig. 10c - Curve of 3.39 μ laser power vs discharge current

light line curves represent higher tube wall temperatures than the heavy line curves.

From Fig. 8 it is seen that the 0.63 μ curve is more similar to the 3.39 μ curve. Both the 0.63 μ and 3.39 μ lasers decrease in power with increasing gas temperature. This suggests that their common upper level ($3s_2$) is controlling the laser output at this low pressure. In Figs. 9 and 10 the 0.63 μ curve is more similar to the 1.15 μ curve. At these pressures, both the 0.63 μ and the 1.15 μ lasers increase in power with increasing gas temperature. This indicates that their common lower level ($2p_4$) controls the laser output at these higher pressures.

Laser power as a function of discharge tube wall temperature is shown in Fig. 11. The data were taken at constant current while the discharge section of the tube was heated with heater tape. The discharge tube wall temperature was monitored with an iron-constantan thermocouple. It was necessary to bake the tube at 600°C for several hours under vacuum to obtain repeatable data. It is seen that the 0.63 μ and 1.15 μ laser powers increase with wall temperature but the 3.39 μ laser power does not. This indicates that the increase in the 0.63 μ and 1.15 μ laser powers is due primarily to a decrease in the shared $2p_4$ population. Since the $2p_4$ population is coupled to the metastable 1s

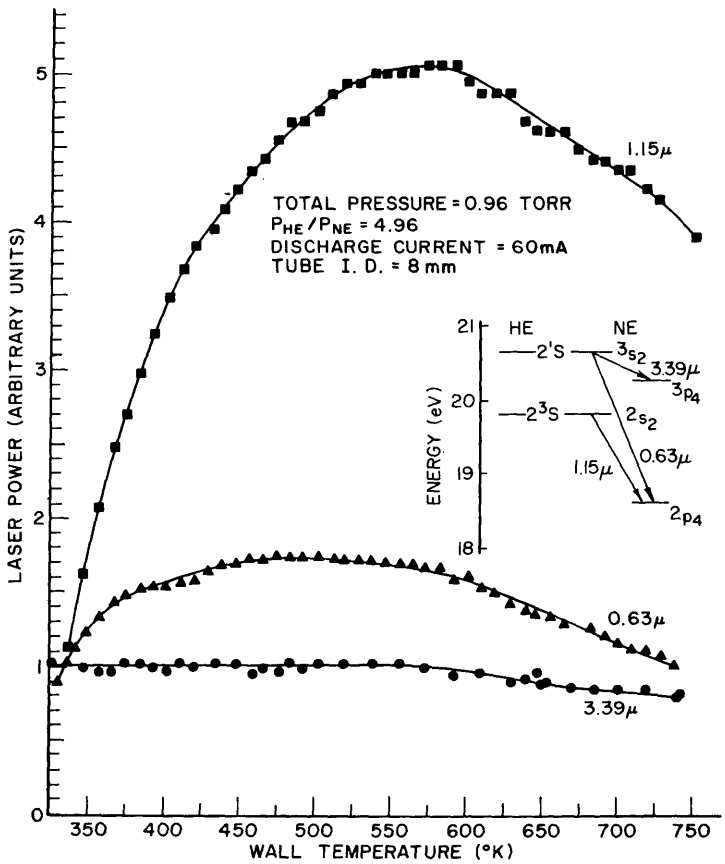


Fig. 11 - Laser power vs discharge tube wall temperature at constant current

population by electron collision and radiation trapping, increased diffusion of the neon metastables to the wall is responsible for the decrease in the $2p_4$ population.

The fact that the 3.39 μ laser power does not increase with wall temperature implies that the increase in the 0.63 μ laser power is not due to an increase in the shared $3s_2$ population rate. Since the helium singlet metastables pump the neon $3s_2$ level, this means that the increase in excitation transfer rate between the helium singlet metastables and the neon ground state atoms is not significant.

The fall-off of all laser powers at higher wall temperatures is probably due to increased destruction rate of helium metastables by diffusion to the walls.

Figures 12, 13, and 14 show laser power vs discharge current curves at constant neon partial pressure with the helium partial pressure as a parameter. The presence of the helium has at least two important and conflicting effects. The helium metastables pump the upper laser levels by resonant energy transfer on collision; however, the helium also acts as a buffer gas which inhibits diffusion of the neon metastables to the walls. In Fig. 12 it is seen that the latter effect is more important for the 0.63 μ laser because saturation and quenching is reached at lower current for higher helium pressures. In Fig. 13 it appears

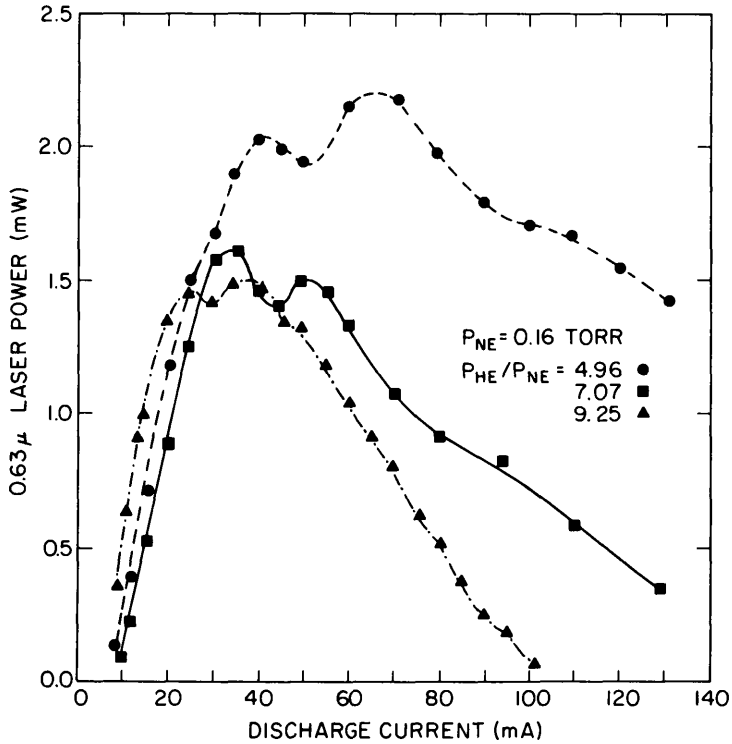


Fig. 12 - 0.63 μ laser power vs discharge current at constant neon partial pressure with the helium partial pressure as parameter

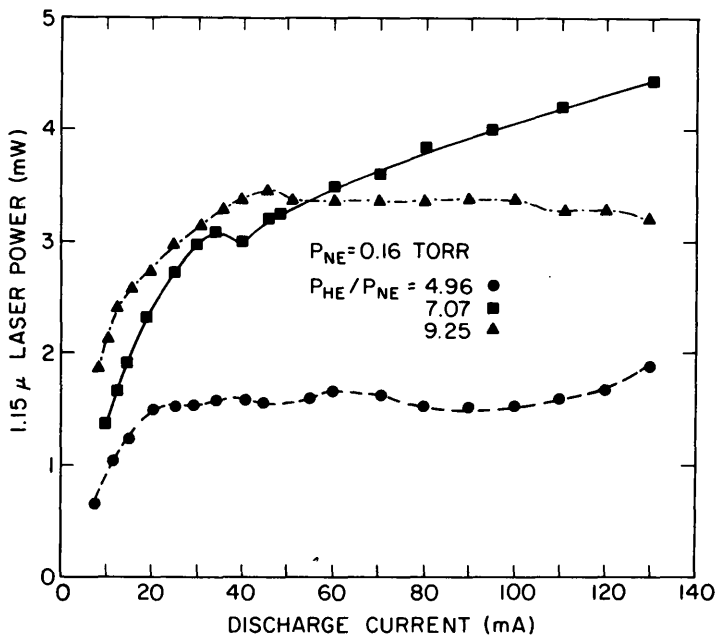


Fig. 13 - 1.15 μ laser power vs discharge current at constant neon partial pressure with the helium partial pressure as parameter

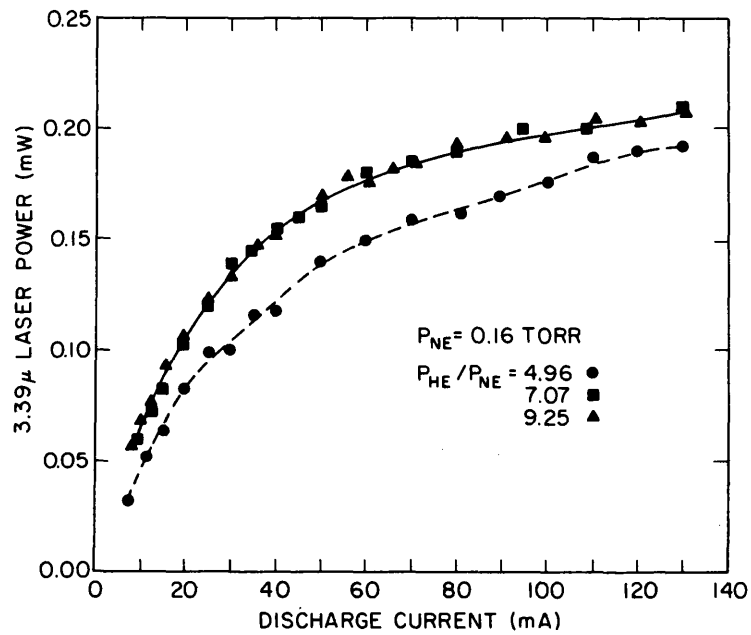


Fig. 14 - 3.39 μ laser power vs discharge current at constant neon partial pressure with the helium partial pressure as parameter

that both effects are important for the 1.15 μ laser with the pumping effect dominant.

The lower level ($3p_4$) of the 3.39 u laser is not as well coupled to the neon metastables as is the $2p_4$ level. Thus from Fig. 14, it is seen that the pumping effect of helium is more important for the 3.39 μ laser.

The wavelengths monitored in spontaneous emission were 3593 Å ($3p_4$-$1s_2$), 5433 Å ($3s_2$-$2p_{10}$), 6096 Å ($2p_4$-$1s_4$), and 11,523 Å ($2s_2$-$2p_4$). The curves are similar to those in Fig. 1 of Ref. 6. In general the spontaneous light intensity did not increase with current as rapidly as the laser power. The only exception was the 1.15 μ spontaneous light at very low pressures (well below optimum for lasing). In this case, with proper normalization, the spontaneous light curve was collinear with the laser power curve. This indicates that at lower pressures the upper laser level controls the output power.

The change in spontaneous light intensity with gas temperature was only a few per cent, much less than the change in laser power. All of the monitored lines showed only a few per cent change in intensity when laser oscillation affecting the particular energy levels was stopped, except for the 3593 Å line which decreased by a factor of 2 when 3.39 μ oscillation was stopped.

CHAPTER VI

CONCLUSION

The results indicate that at low pressures the upper level population rate controls the output power for all three laser lines, and at high pressures (greater than one Torr) the lower level depopulation rate is more important for the 0.63 μ and 1.15 μ lasers. For the 0.63 μ laser, both effects are important at intermediate pressures, which are near optimum for maximum power output. The wall temperature of the laser tube is an important parameter affecting laser power, which can be either increased or decreased depending on the gas pressure.

APPENDIX A

PREPARATION OF GAS MIXTURE

During the course of the study, precise mixtures of helium and neon were prepared and stored in the reservoir flask. To avoid backstreaming across a valve, gas was never admitted to the manifold unless it was first thoroughly evacuated. In preparing a mixture, it was desirable to avoid errors in the mixture ratio due to the manometer cold trap being at a much lower temperature than the rest of the system, and errors due to the volume displaced by movements of oil in the manometer. The procedure was as follows: The tube, manifold, and reservoir flask were evacuated, and then V1 (Fig. 2, p. 6) the valve to the tube, was closed. The reservoir flask and the manifold were filled with a certain measured pressure of helium, and then V4, the valve to the flask, was closed. The manifold was evacuated again and then filled with a certain measured pressure of neon. The valve to the cold trap, V5, was closed, and V4 was opened to allow the gases to mix. The mixture ratio was calculated from the measured pressures and the volume ratio of the manifold to the flask. Then V4 was closed and the gas to be used was stored in the flask.

The volume ratio of the manifold to the flask was measured by the following procedure. Let V_m, V_f, and V_c refer to the volume of the manifold, flask, and cold trap respectively. The valve to the tube was closed and V_m, V_f, and V_c were evacuated. V_f was filled to a measured pressure P_f, then V4 was closed and V_m and V_c were evacuated. V6 was closed and V4 was opened to expand the gas from V_f into V_m and V_c. The resulting pressure P_{fcm} was measured. We have then

$$\frac{P_f V_f}{T} = \frac{P_{fcm}(V_m + V_f)}{T} + \frac{P_{fcm} V_c}{T_c} \qquad \text{(I)}$$

or

$$\frac{P_f V_f}{P_{fcm} T} = \frac{V_m + V_f}{T} + \frac{V_c}{T_c}, \qquad \text{(Ia)}$$

where T refers to room temperature, and T_c refers to the temperature of the cold trap. Again V_m, V_f, and V_c were evacuated. This time V4 was closed and V_m was filled to a measured pressure P_m. Then V5 was closed and V_c was evacuated. V6 was closed and V4 and V5 were opened to expand gas from V_m into V_f and V_c. The pressure P_{mcf} was measured and we have then

$$\frac{P_m V_m}{T} = \frac{P_{mcf}(V_m + V_f)}{T} + \frac{P_{mcf} V_c}{T_c} \qquad \text{(II)}$$

or

$$\frac{P_m V_m}{P_{mcf} T} = \frac{V_m + V_f}{T} + \frac{V_c}{T_c}. \qquad \text{(IIa)}$$

Equating the left hand side of Eq. (IIa) to the left hand side of Eq. (Ia) we have

$$\frac{P_m V_m}{P_{mcf} T} = \frac{P_f V_f}{P_{fcm} T} \tag{III}$$

or finally

$$\frac{V_m}{V_f} = \frac{P_f P_{mcf}}{P_m P_{fcm}}, \tag{IIIa}$$

APPENDIX B

OPTIMIZATION OF OUTPUT POWER

In order to find the optimum pressure and mixture ratio for maximum output power, maximum laser power was measured as a function of total pressure with the helium-neon mixture ratio as a parameter.[7] The results are shown in Figs. 15, 16, and 17.

Only the vacuum system gas supply was changed for these measurements. Three gas bottles containing He/Ne mixture ratios of 9/1, 7/1, and 5/1 respectively were used in place of separate helium and neon bottles. Again the vacuum system and tube were thoroughly evacuated and baked before the measurements were made.

For each of the laser wavelengths, the mirrors were carefully aligned for maximum laser output. Dust shields were used on the laser windows and mirrors to keep cavity losses constant. At each pressure step, the tube current was adjusted for maximum laser output. This optimum current varied from 5 mA at high pressures to 220 mA at low pressures. Ample time was allowed for thermal equilibrium to become established at each pressure step before readings were taken. The discharge tube was cooled

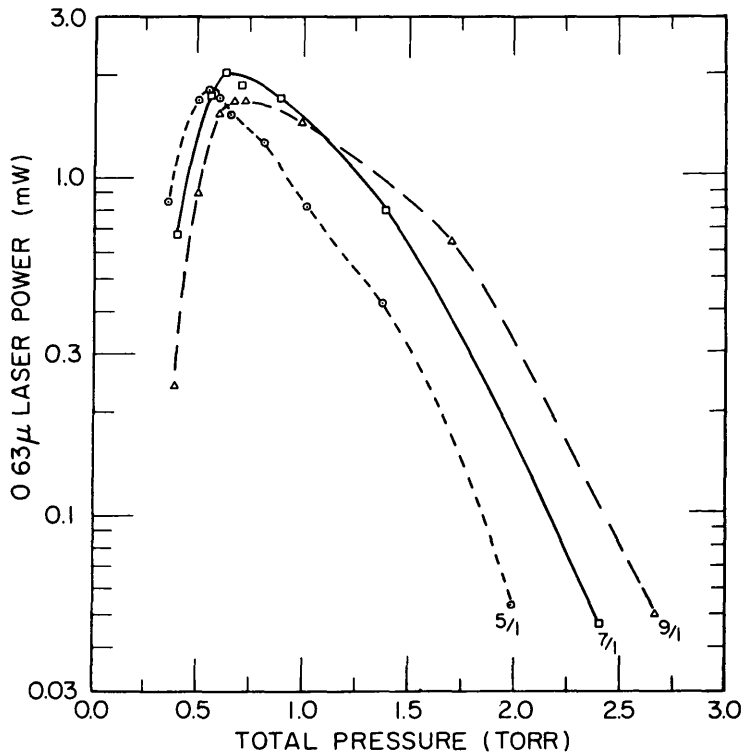


Fig. 15 - 0.63 μ maximum laser power vs total pressure with the He/Ne mixture ratio as parameter

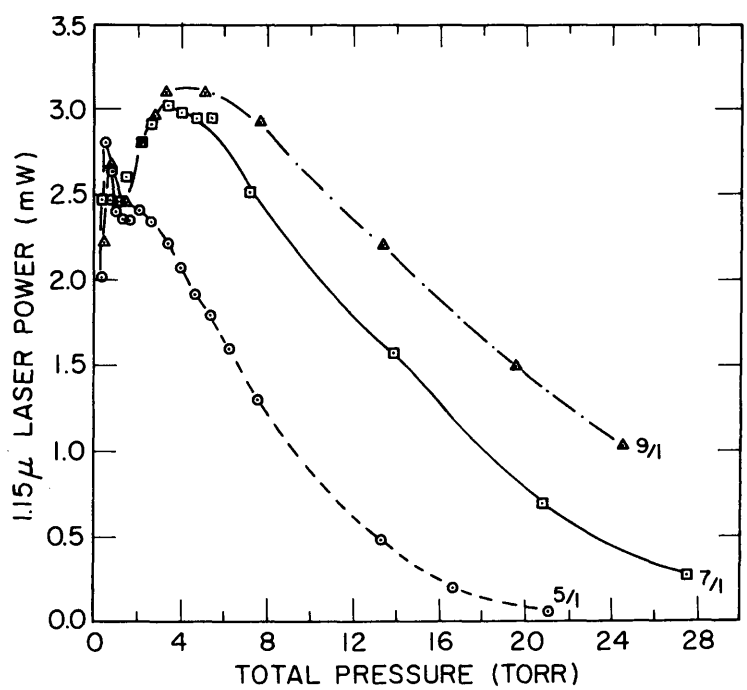


Fig. 16 - 1.15 μ maximum laser power vs total pressure with the He/Ne mixture ratio as parameter

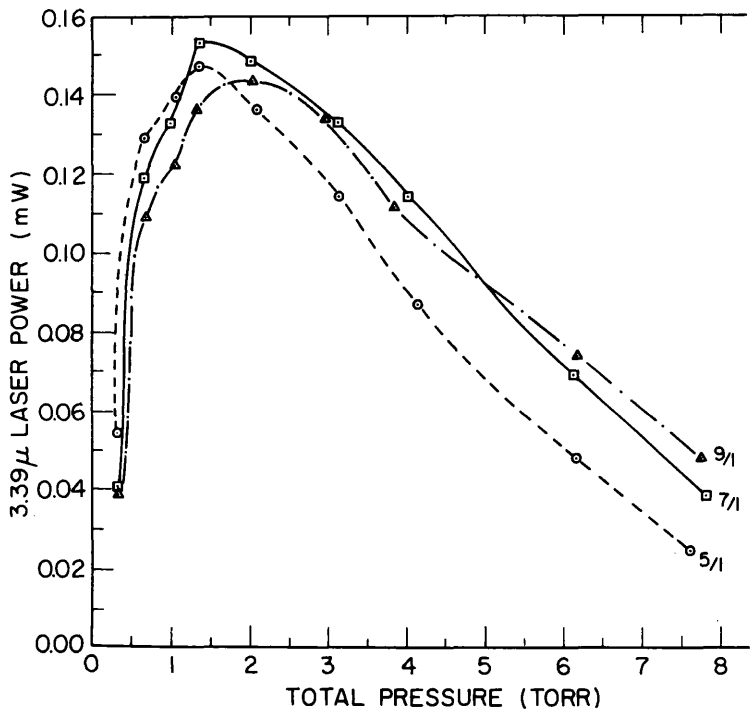


Fig. 17 - 3.39 μ maximum laser power vs total pressure with the He/Ne mixture ratio as parameter

only by natural convection of the room air so that the tube wall temperature was higher at the higher currents. All measurements were completed for one laser wavelength before going on the next, in order to avoid changing the mirror alignment.

It is seen from Fig. 15 that the 0.63 μ laser power is quite sensitive to pressure changes. Note that the power ordinate is a log scale in Fig. 15, whereas the scales are linear in Figs. 16 and 17. There are similarities between Figs. 15 and 17 in that the highest output occurs for a 7/1 mix, the next highest for a 5/1 mix, and the lowest maximum occurs for the 9/1 mix. Since the 0.63 μ and the 3.39 μ lasers share a common upper level, these similarities suggest that under optimum pressure and excitation conditions, the upper level population rate is more important than the lower level depopulation rate in determining the power output.

It is seen in Fig. 16 that the maximum output for the 1.15 μ laser occurs for the 9/1 mix at a pressure of 4 Torr. This pressure is about four times higher than that previously reported as the optimum.[22] The peaks in the output near 0.7 Torr may be due to the increased temperature of the gas due to the higher optimum current.

The most surprising thing in the data of Fig. 16 is the fact that cw 1.15 μ oscillation at a considerable power level occurs at such high pressures. Since the laser output was monitored with a monochromator, there is no doubt that it is 1.15 μ oscillation. Also since the pressure was measured with an oil manometer, and since the optimum currents were low (about 10 mA) so that discharge pumping effects[19] were negligible, there can be little doubt about the actual pressure in the tube. These results indicate that oscillation should be obtainable in a large diameter tube. In a separate experiment oscillation has been in fact observed at 1.15 μ in a 37 mm i.d. Brewster-angle tube with a discharge length of one meter. The maximum output power was 6.7 mW for a 9/1 mixture at the optimum pressure of 0.4 Torr.

These results also throw some doubt on the importance of the de-excitation of the neon metastables by the tube walls for the 1.15 μ laser. The de-excitation of the helium triplet metastables by the walls may be a counter-balancing effect. At higher pressures the effect of the walls on both the neon metastables and the helium triplet metastables is less. Thus the effective lifetimes of both these metastables are longer, so that the net result is that the laser power is not affected very much by small pressure changes. Of course, higher pressure causes a decrease in the electron

temperature, so that the net production rate of helium metastables will be less.

However, the preceding discussion does not apply to the 0.63 μ laser because the helium singlet metastable lifetime is very short. (It is shorter than the electron thermalization time.)[5] Thus the population of the helium singlet metastable is not much affected by the tube walls, so that increasing the pressure does not increase its effective lifetime, but only increases the effective lifetime of the neon metastables with the resulting deleterious effect.

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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)* Naval Research Laboratory Washington, D.C.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

HELIUM-NEON LASER DISCHARGE PARAMETER STUDY

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

An interim report on a continuing problem.

5. AUTHOR(S) *(First name, middle initial, last name)*

Wayne T. Whitney

6. REPORT DATE June 21, 1967	7a. TOTAL NO. OF PAGES 48	7b. NO. OF REFS 22

8a. CONTRACT OR GRANT NO. NRL Problem R08-45 b. PROJECT NO. RR 008-03-46-5674 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 6536 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

An experimental study is made to determine which energy level is dominant in limiting the output power of the helium-neon laser. This is done by comparing laser power versus discharge current data for the three main laser transitions, with the temperature and pressure as parameters. Such a comparison is informative because two of the laser transitions (0.6328 and 3.39 microns) share a common upper level ($3s_2$); and two (0.6328 and 1.15 microns) share a common lower level ($2p_4$). Relative saturation behavior indicates that at low pressures the upper level population rate controls the output power of all three laser lines; and at high pressures (above 1 torr) the lower level depopulation rate is more important for the 0.63 and 1.15 μ lasers. The optimum pressure for maximum output of the 0.6328 μ laser occurs at an intermediate pressure (0.7 torr) where both effects are important. All of the data were taken on the same tube, (8 mm. i.d.), utilizing ultra high vacuum techniques to maintain gas purity. It has been found that an increase in the laser tube wall temperature will produce an increase in laser power at high pressures (as much as 500% for 1.15 μ); but will decrease the power at low pressures. Also of interest in the data is the fact that the 1.15 μ line can be made to oscillate at total pressures at least as high as 20 torr.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Lasers						
Helium						
Neon						
Temperature						
Pressure						
Output power						
Energy levels						
Discharge current						
Experimental data						

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