

Nitrogen Laser

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August 1971

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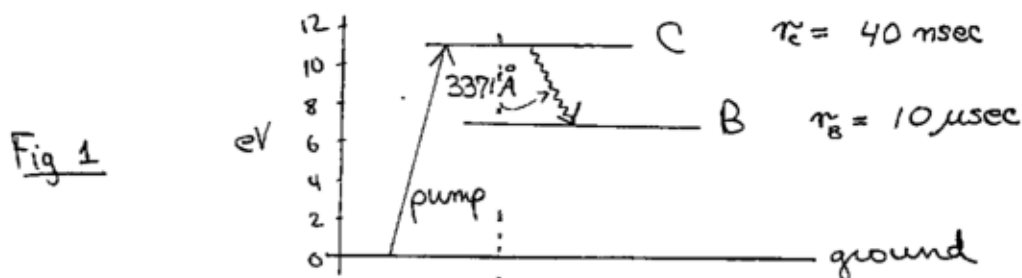
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Part II: nitrogen laser physics

Section 1: general considerations

For our purposes here, molecular nitrogen has three electronic states: ground, C and B. These levels and their lifetimes are shown in Fig 1. (A complete energy level diagram may be found in the appendix) In these states, only the bottommost vibrational



levels ($v = 0$) are of interest; higher levels are not sufficiently populated in an electric discharge, or do not have large enough matrix elements, to lase. In these lowest vibrational levels, several rotational lines have sufficient lasing gain, but all these details, as well as the details of the fine spin structure of the electronic levels, are not of direct import.

The lifetimes of the C and B states — as has been noted in every nitrogen laser article since the discovery of nitrogen's UV laser lines by Heard¹ in 1963 — are exactly wrong for CW action, so pulsed operation is a way of life. For the purpose of pumping dyes, pulsed operation is a boon since large peak powers can be developed with only modest power supply requirements. Also, thermal problems in the dye are completely avoided. Finally, laser spectroscopy does not require a CW probe and fares just as well on a pulsed basis.

Section 2: the rate equations

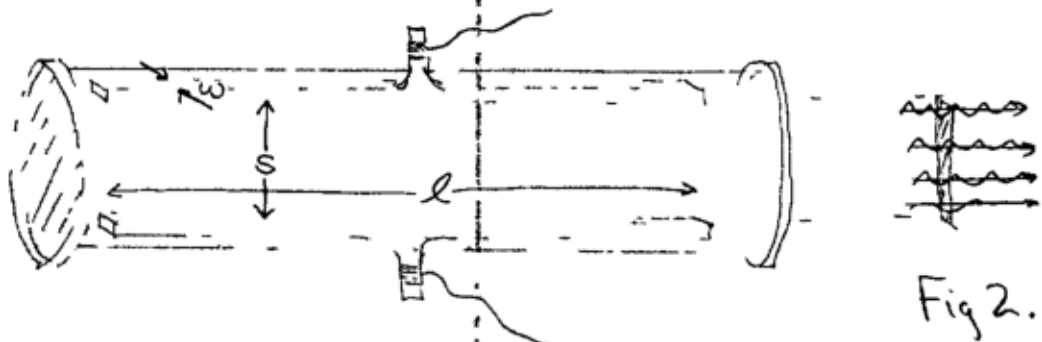
The power output of a nitrogen laser is a function of the total inversion in the laser tube. The inversion is, for practical purposes, proportional to the rate at which molecules are pumped up into the C state.

$$\text{inversion} \propto \frac{dn_c}{dt} \quad (1)$$

Of course once a molecule gets to the C state it can only stay there for a few tens of nanoseconds after which it falls back to some lower state. It is not surprising, therefore, to find that the 3371Å nitrogen laser pulses are about 10 nsec in duration.

Since it will be of interest to maximize the power output of a nitrogen laser for dye pumping purposes, it is necessary to have a rough idea of what is taking place inside the laser medium so that various geometrical and electrical factors can be optimized in actual construction.

Physically, a transverse-field N₂ laser looks something like that shown in Fig 2. The electrodes have a width w , length l , and



separation s ; they are immersed in nitrogen at pressure p . The

ends of the tube are made of quartz to pass the $3371\text{\AA}$ ultraviolet laser light which typically pours out in a superadiant fashion; that is, the gain of the nitrogen is so high that feedback in the form of mirrors is unnecessary for laser action. The UV beam has roughly the rectangular cross section one would intuitively expect from the electrode geometry. The beam divergence is $\sin^{-1}(w/l)$ and $\sin^{-1}(s/l)$ for the two beam dimensions. When a plane mirror is placed at one end of the laser, its length is effectively doubled so both beam divergences halve.

The rate at which the C level is pumped is given by

$$\frac{dn_c}{dt} = n_e n_0 R_c \quad (2)$$

We certainly expect the per-volume pumping rate to be proportional to both the electron density, since electrons do the pumping, and to the nitrogen density, since nitrogen is what gets pumped. R_c , which clearly has the dimensions cm^3/sec , is somehow a measure of the effectiveness of each electron-molecule collision in regard to that collision's ability to excite a ground state nitrogen to the C state. If there were only one electron and one N_2 molecule in each cm^3 , an excitation would occur every $(R_c)^{-1}$ seconds.

Cross section is perhaps a more graphic conceptualization of collision effectiveness for some event, and as dimensions will verify, the relation ^{between R_c and cross section σ_c} is:

$$R_c = \sigma_c (\text{cm}^2) v_e (\text{cm/sec}) \quad (3)$$

where v_e is the electron velocity. At any electron temperature

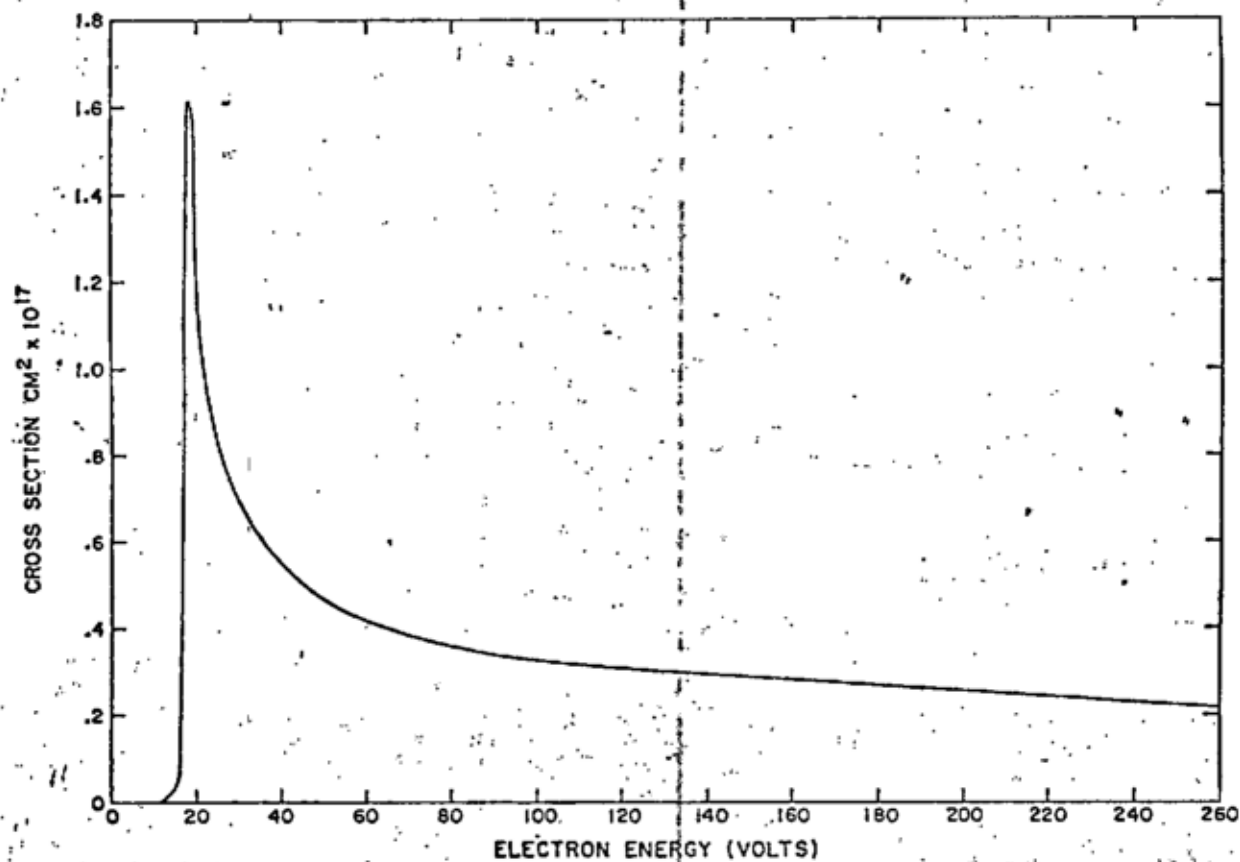
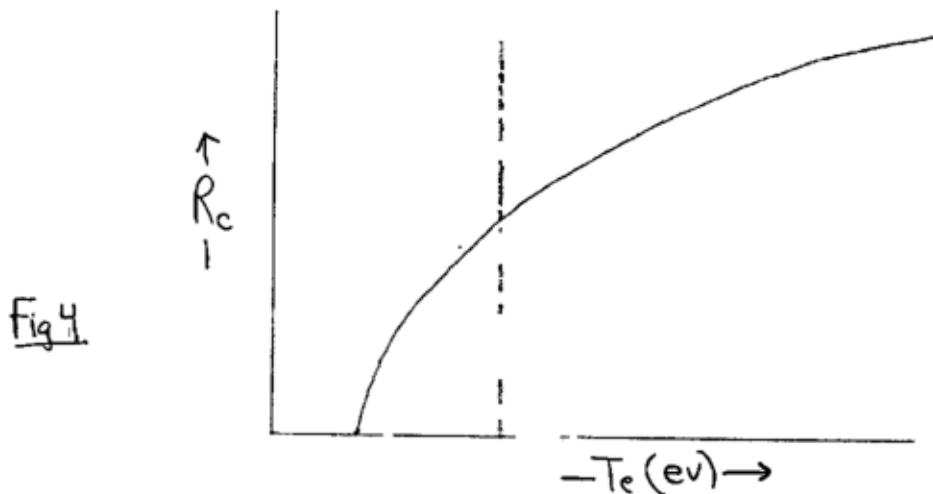


Fig. VI-13 Cross section for excitation of the $N_2C^3\pi_u (v' = 0)$ state by electron impact.

Figure 3.

there is of course a Maxwell-like distribution of electron velocities. Since σ_c is a function of temperature (see Fig 3), at a given mean electron temperature R_c is calculated by averaging $\sigma_c v_c$ over all velocities in the distribution, hence the bar over Equa 3. This averaging flattens out the sharp peak shown in the cross section plot so that a plot of R_c versus electron temperature looks something like that shown in Fig 4 .



From Equa. (2) it is apparent that the C state pumping rate is dependent on the electron temperature in two ways, (1) through R_c , and (2) through n_e :

$$\frac{dn_c}{dt} = n_e(T_e) n_0 R_c(T_e).$$

Section 3: determination of electron density n_e , and the relation between inversion and current density in the nitrogen laser.

In an electric discharge involving large currents (spark) the electron density and gas conductivity grow very rapidly as the the gas begins to break down. After a variable statistical time lag an avalanche occurs. Then, after the so-called formative time lag, streamers form, the conduction channel fills out, and the electron density is then ready to grow in a more analyzeable fashion. All this takes place in less than a nanosecond if there is a high overvoltage. When the channel is formed, n_e is still very small, perhaps only $10^6/\text{cm}^3$ and the applied voltage is still supported. N_e then grows according to the simple rate equation,

$$\frac{dn_e}{dt} = n_e n_0 R_i(T_e) \quad (4)$$

This equation is identical to the previous excitation equation except R_i is a measure of the collision effectiveness for ionization. R_i , like R_0 , is a function of electron temperature.

It is helpful to know how large n_e gets and how n_e depends on other parameters so that eventually laser power can be optimized. Equa (4), though interesting, is not very helpful in answering these questions. All that can be said from Equa (4) is that as n_e grows, at some point the voltage across the discharge starts to drop, the electron temperature falls, R_i diminishes in a way

similar to Fig (4), and n_e levels off at some peak value.

Consideration of the electron drift velocity and current limiting provide an alternative answer to the question. According to F. Llewellyn-Jones³ electron drift velocity is given by

$$W_- = \frac{2eEl}{3m_e} \left(\frac{1}{u} \right) \quad (5)$$

where E is electric field, u electronic speed, and λ the electron mean free path. λ is roughly given by

$$\lambda = \frac{1}{n_o \pi \sigma^2} \quad (6)$$

where σ is the mean radius of a gas molecule. The relation between p and n_o is of course just the equation of state,

$$n_o = \beta \frac{p}{T_{rel}} \quad (7)$$

where p is in torr, T is the gas temperature relative to room temperature in $^{\circ}K$, and β is a constant, $2 \times 10^{16}/\text{torr}/\text{cm}^3$.

Thus we can write,

$$\lambda = \frac{T_{rel}}{\pi \sigma^2 \beta p} \quad (8)$$

and Equa (5) becomes,

$$W_- = \frac{2eT_{rel}}{3\pi\sigma^2\beta m_e} \times \frac{E}{p} \times \left(\frac{1}{u} \right). \quad (9)$$

The electronic mean kinetic energy, or electron temperature, is found to be,

$$\bar{\epsilon} = \frac{1}{2} m_e \overline{u^2} = \frac{3}{2} k T_e = \frac{e E \ell}{\sqrt{3} \Delta} \quad (10)$$

where Δ is a constant indicative of how much an electron is stopped by a collision,

$$\Delta = \frac{2 m_e m_o}{(m_e + m_o)^2} \approx 2 \frac{m_e}{m_o} \quad (11)$$

If Δ is small, the electron accumulates energy picked up from the electric field over many mean free paths. Replacing ℓ in Equ. (10) with Equ. (8) we get,

$$\bar{\epsilon} = \frac{e T_{rel}}{\pi \alpha^2 \beta \sqrt{3} \Delta} \times \left(\frac{E}{P} \right) = \frac{3}{2} k T_e \quad (12)$$

Note that the gas and electron temperatures are not the same. The thermalization time is much longer than the time it takes for a nitrogen laser to lase. For our purposes, then, T_{rel} is just unity, room temperature, a constant.

From Equ. (12), then, it is apparent that electron temperature and the fractions E/p or E/n_o are all proportional to one another; they are all measures of the same property of the electron gas, namely the mean kinetic energy.

With a certain degree of mathematical looseness, π can be eliminated from Equas. (9) and (12) to give,

$$W_- = \left(\frac{2eT_{el} \sqrt{3\Delta}}{9\pi\sigma^2 \beta m_e} \right)^{1/2} \times \sqrt{\frac{E}{P}} \quad (13)$$

The drift velocity is also seen to be a function of E/p and hence of electron temperature.

Nitrogen is not an ideal gas, and many loose assumptions have been made. Nevertheless, the results for electron temperature and drift velocity as functions of E/p (or E/N) at least show the correct monotonic relationships. An experimentally derived plot of these two quantities versus E/N for nitrogen at 77°K is shown in Fig. (5).

To get a feel for the magnitude of some of the quantities that are being thrown around here, some numbers are appropriate. The calculations which follow were all made from the preceding equations using values for E and p that might be found during the laser pulse in a nitrogen laser.

$$E = 1000 \text{ volts/cm}$$

$$p = 20 \text{ torr}$$

$$T_{el} = 1$$

$$\Delta = 8 \times 10^{-5}$$

$$\sigma = 1.8 \text{ \AA} \text{ (CRC)}$$

$$n_0 = 4 \times 10^{17} / \text{cm}^3$$

$$l = 25 \mu$$

$$\bar{E} = 150 \text{ eV}$$

$$T_e = 10^6 \text{ }^\circ\text{K}$$

$$\bar{u} = 700 \text{ cm}/\mu\text{sec}$$

$$W_- = 4 \text{ cm}/\mu\text{sec}$$

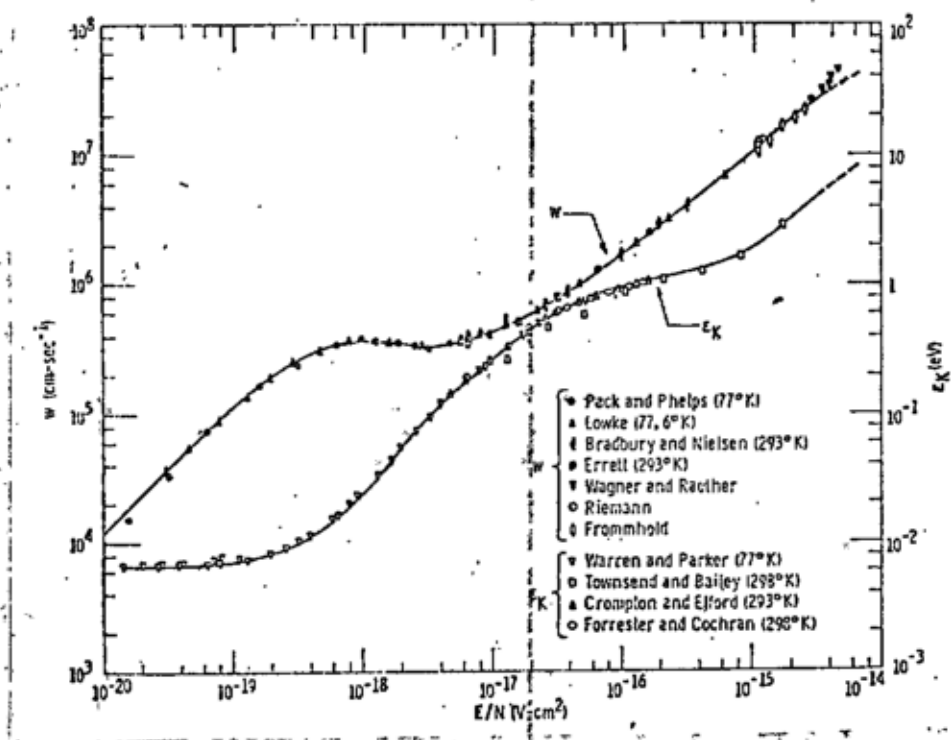


Figure 5.

We are in the process of seeking the electron density n_e . Since the electrons are light, they account for most of the current in the discharge, so

$$J = n_e e W_- \quad (14)$$

J , it turns out, is limited by factors external to the nitrogen discharge itself (otherwise it would become infinite*). At the time of the laser pulse, the current density J — as will be shown later — is limited by the impedances of the discharge circuit as well as by the slight inductance of the discharge itself. It will also be shown that the electron temperature, E/p , and hence W_- are essentially controlled by the electrode geometry and external discharge circuitry.

If n_e is eliminated between Equas. (14) and (2), the result is,

$$\text{inversion} \sim \frac{dn_e}{dt} = p J \frac{R_c (E/p)}{W_- (E/p)} \quad (15)$$

The important conclusion to be drawn here is this: for a given laser geometry and drive current, E/p is already determined (as will be shown). Once an optimum value of pressure is found, the amount of inversion per cm^3 and hence the amount of available power is directly proportional to the current density supplied.

*At 20 torr and with the drift velocity calculated earlier, if every molecule was singly ionized, the current would be 256,000 amperes, a large though finite current density.

Section 4: overvolting and E/p

The spark process resulting in the formation of a conduction channel, as discussed above, occurs very quickly when the gas is overvolted by more than a few per cent (Typically in N_2 lasers the gas is overvolted by 500%). Very near the spark potential it may take several seconds for a channel to form because in the case of low overvolting the statistical time lag amounts to waiting for a cosmic ray or photoionization to start an avalanche.

A very simple analysis of ionization buildup in a discharge — first done by such gas greats as J.S. Townsend⁴ and J.J. "Electron" Thomson⁵ in the early part of the century — shows that the number of electrons reaching the anode of a discharge is

$$n_d = n_0 \left[\frac{e^{\alpha d}}{1 - \frac{w}{\alpha} (e^{\alpha d} - 1)} \right] \quad (16)$$

where n_0 is the number that leave the cathode, d is the length of the discharge, α is the number of ionizations per cm caused by each electron, and w is the number of electrons "created" at the cathode per cm of travel of each electron in the discharge as a result of so-called "secondary processes." w is thus seen to be a sort of feedback. When d is large, n_d is some small number indicative of the gas leakage current. However, when d is reduced to a value which makes the denominator approach zero, it is like

a loop transmission going to unity, and n_d blows up. This, Thomson tells us, is what sparks are all about. The spark condition, or "Townsend criterion," is thus,

$$\frac{\omega}{\alpha} (e^{\alpha d_s} - 1) = 1. \quad (17)$$

It can be shown that α/p and ω/p are both functions of the familiar variable $E/p = V/pd$, so Equa. (17) can ~~thus~~ be rewritten,

$$\frac{\omega(V_s/pd_s)}{\alpha(V_s/pd_s)} [e^{\alpha(V_s/pd_s)pd_s} - 1] = 1. \quad (18)$$

Solving this equation for $V(\text{spark})$ one gets,

$$V_s = V_s(pd_s), \quad (19)$$

which goes under the name of Paschen's Law⁶. For example, Wolff (check this footnote for evidence of recent research) found that, for nitrogen, Paschen's Law is approximately (for reasonable pressures),

$$V_s = 300 [12.08(pd_s) + 5.0] \quad (20)$$

where V is volts, p atmospheres, and d mm.

For practical purposes, Paschen's Law can be approximated as

$$V_{dc} = Aps \quad (21)$$

where A is some constant, and s is the electrode separation of

a nitrogen laser. The discharge circuit with its inherent $\frac{dV}{dt}$ will cause the discharge to overvolt by some factor B, so

$$V_{ac} = B V_{dc} = AB p s \quad (22)$$

Thus is obtained the result promised earlier that

$$E/p = \frac{V_{ac}}{ps} = AB. \quad (23)$$

That is, as long as the voltage supplied to the laser is greater than V_{ac} by a sufficient factor (λ), the ratio E/p is determined entirely by external circuitry through B, the overvoltage factor. E/p at breakdown is independent of both pressure and electrode separation. (This of course is only true in our simplified zeroth order analysis. In fact, E/p does vary slightly with these parameters, but not much.)

Part III: nitrogen laser engineering

Section 1: discharge circuit analysis

A simple discharge circuit is shown in Fig. 1. G is a triggered spark gap having a very fast rise time of perhaps 10 nsec. D is the discharge tube. The sum of all circuit inductances is L. Capacitor C is initially charged up to some high voltage V_0 , the switch is triggered by an external circuit, and a pulse of current

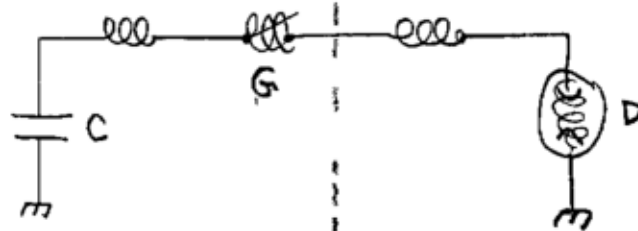


Figure 1.

is delivered to the gas.

After the spark gap has switched on and when the discharge has broken down enough so that its resistance is small compared to reactances, the circuit can be roughly approximated by a simple LC circuit. The peak current of such an LC circuit is easily shown to be

$$I_{\max} = \sqrt{\frac{C}{L}} V_0. \quad (1)$$

The current density J in the discharge is proportional to I , so to increase J and hence the amount of inversion we can (1) increase C , (2) increase V_0 , or (3) decrease L . Once a power supply is selected, V_0 is fixed. The marginal benefit of adding an extra capacitor to bank C drops off fast when there are already 10 or so capacitors, and more capacitors also increases circuit

inductance. The best thing to do is to design the discharge circuit geometry so that the various inductances are minimized. The total inductance, however, can never be less than that of the spark gap. Typical numbers are

$$\begin{aligned} L &= 80 \text{ nH} \\ C &= 20 \text{ nF} \\ V_0 &= 30 \text{ kV} \\ I_{\text{MAX}} &= 15 \text{ kA.} \end{aligned}$$

In order that the power be delivered mostly to the discharge rather than to the gap itself, the gap must switch on speedily. This necessitates its operation at high pressure (several atmospheres). High pressure sparks are long and narrow, so they have high inductance. The self inductance of a round conductor is, by the way,^[1]

$$L(\text{nH}) = 2\ell \left[\ln \frac{2\ell}{r} - \frac{3}{4} \right]. \quad (2)$$

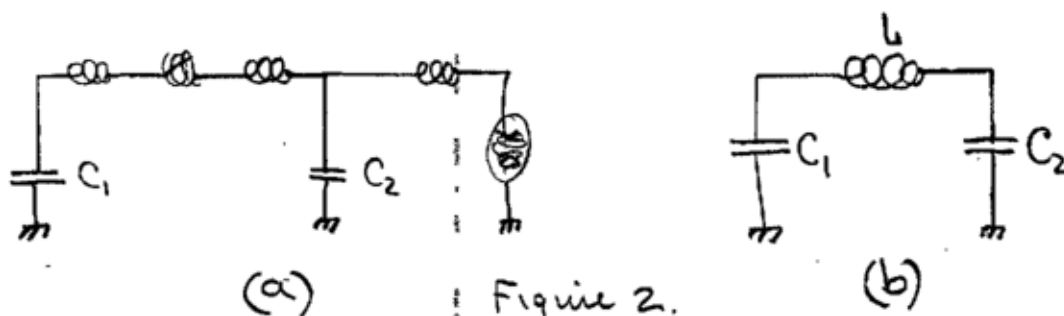
so that the inductance of a 2 cm spark, 1 mm in diameter, is about 15 nH.

Using the circuit of Figure 1, the only way to reduce inductance below that of the gap is to use many gaps in parallel so that $L_{\text{total}} = L_{\text{gap}}/n$. Typically $n=20$ and $L_{\text{total}} = 1 \text{ nH}$. The multiple gap approach is effective but expensive, and an alternative is to use the circuit shown in Figure 2.

Before leaving circuit 1, however, one other observation should

be made which applies to all drive circuits. As can be seen from the plot of the excitation rate R_0 in Figure 4 (Part II) and from equation 15 (Part II), the inversion increases with increased electron temperature, which is to say, with increased E/p . Back on p. 12 of Part II it was shown that $E/p = AB$ where A was a Paschen constant and B was the overvoltage factor. The faster the voltage rises on the discharge, the more it will tend to overvolt though there is no strict linear connection. In Figure 1, since the discharge has very small capacitance, dV/dt is very large; this is an advantage of circuit 1. Factor B is thus large, electron temperature is high, and pumping of the C state is efficient.

In circuit 2,^(a) because of the presence of capacitor C_2 , dV/dt is somewhat sacrificed as a cost of obtaining increased discharge current. Experimental evidence seems to show that increasing dV/dt beyond 1500 volts/nsec does not in fact improve the overvolt



factor B, so with small C_2 there is no sacrifice. The reason for this is probably an effect of the finite switching time of the spark gap. That the circuit of Figure 2 can deliver a higher peak current can be demonstrated as follows. After the gap has

switched, but before the discharge begins to break down, the circuit is that shown in Figure 2(b). If C_1 is initially charged to V_0 , the current in the circuit is

$$I(t) = \left(V_0 \sqrt{\frac{C_{11}}{L}} \right) \sin \left(\frac{1}{\sqrt{LC_{11}}} t \right) \quad (3)$$

and the voltage rise on C_2 is;

$$V_{C_2}(t) = 2 \frac{C_{11}}{C_2} V_0 \sin^2 \left(\frac{1}{2\sqrt{LC_{11}}} t \right). \quad (4)$$

If C_2 is small compared to C_{11} (perhaps 1:4 or less), $C_{11} \approx C_2$ and then

$$I \approx V_0 \sqrt{\frac{C_2}{L}} \sin \left(\frac{t}{\sqrt{LC_2}} \right) \quad (5)$$

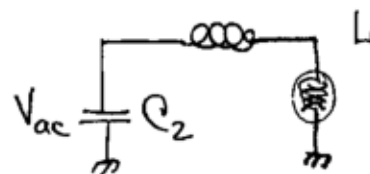
$$V_{C_2} \approx 2 V_0 \sin^2 \left(\frac{t}{2\sqrt{LC_2}} \right). \quad (6)$$

Whereas the voltage rietime for circuit ~~xxx~~ 1 was nearly zero, here it is seen to be $2\sqrt{LC_2}$. As compensation, though, C_2 is charging toward twice the supply voltage and this tends to improve dV/dt .

When V_{C_2} reaches the overvoltage $V_{ac} = B V_{dc}$, the discharge very quickly begins to break down, the circuit is that shown in Fig 3.

~~if C_1 is initially charged to V_0~~

Figure 3.



The crux of the matter is this: now the peak current in the discharge is no longer limited by the gap and external inductances. L , the inductance of the metal plates connecting C_2 to the electrodes, can be made much smaller than L_{gap} . Typical numbers might be:

$$L = 1 \text{ nH}$$

$$C = 4 \text{ nF}$$

$$V_{\text{ac}} = 20 \text{ kV}$$

$$I_{\text{max}} = \sqrt{\frac{C}{L}} V_{\text{ac}} = 40 \text{ kA.}$$

Thus, the discharge current and inversion are more than doubled.

These peak currents demonstrate a point, but are probably not actually realized since the various losses, including the excitations of the various molecular states, have been neglected. They appear, of course, as time varying resistances.

Section 2: optimizing pressure

In equation I-15 it was shown that

$$\text{INVERSION} \propto \frac{p J R_c (E/p)}{W_-(E/p)}$$

Given a particular laser geometry and a discharge circuit, J and E/p are predetermined, as has been shown, as long as $V_{\text{supply}} \geq V_{\text{ac}}$. When p is low, the inversion is low. As p increases, E increases so as to keep E/p constant, R_c and W_- remain fixed, and the inversion grows linearly with p . When p reaches a certain value, $E = V_{\text{ac}}/d$ can no longer increase due to the voltage limitation, E/p drops and R_c falls off fairly steeply (see Figure II-4) as electron temperature falls. The product of p with R_c , a function which increases as p increases, is what produces a maximum inversion and an optimum pressure. With V_{supply} around 30 kV and $s = 3$ cm, the optimum pressure is found to be 20 torr.

Section 3: optimizing nitrogen laser design

The more power supply voltage available, the more power output that can be obtained from the laser because (1) electrode separation can be made large for large volume, and (2) overvoltage will be high.

Practically, a power supply of some reasonable voltage is chosen, perhaps with consideration to the breakdown voltage of available high voltage, low inductance capacitors, and then the optimization begins. From economic considerations, the maximum size of $C_1 + C_2$ is also determined. The questions are: (1) How should the electrodes be connected to C_2 ? (2) How should the capacitance be distributed between C_1 and C_2 ? (3) What should be the electrode dimensions, shape, and separation?

- (1) To keep inductance low, the C_2 capacitors should be as close to the discharge tube as is possible; they should be arranged along the length of the tube and should be connected continuously to the electrodes via copper sheets. An inductance calculation will be done later.
- (2) Choosing the ratio of C_1/C_2 is a payoff between peak current and overvoltage and is best determined experimentally, as is the optimum pressure. In our laser, a ratio of $C_1/C_2 = 4$ was found to optimize power.
- (3) The current density in the discharge at any point is (see

Figure II-2) given by

$$J = \frac{I}{w \times l} \quad (7)$$

and the total inversion per cm of electrode separation is controlled by I which, as has been shown, is determined by external parameters. Thus, changing the width and length of the electrodes does not change the amount of inverted population. The separation should be as large as can be overvolted effectively by the power supply, since the total inverted volume is proportional to separation s . Practically, however, the separation is chosen so that the laser beam can be collimated by available lenses to the desired beam shape. Even though the total inversion is unaffected by the length of the electrodes, their length is important because of saturation effects. The electrodes should be made long enough so that for most of their length the nitrogen population is saturated. Increasing length further will not increase power output (for a fixed drive current). However, if the C_2 coupling circuit is extended along with the laser tube, the total drive inductance is halved each time the tube length is doubled, so there is some benefit in peak current. Most researchers, however, seem to agree that with a single plane-mirror system, an electrode length of 1 m is about as long as is useful. In the single spark gap scheme of Figure 2, all the current must ultimately pass through the spark gap and increasing tube length beyond 1 m merely raises ^{the} primary circuit inductance with a resultant deterioration in dV/dt . In a multiple gap scheme where

everything is extensive along the tube, power output for long tubes is linearly proportional to length. The operational cost is an increased demand on ^{the} power supply current to charge all the capacitors.

Section 4: the question of discharge uniformity

That a uniform discharge is, first of all, desirable can be easily demonstrated. For simplicity, assume that the discharge "sparks" in N equally spaced channels along the electrodes as shown in Figure 4. The total gain of all the channels is

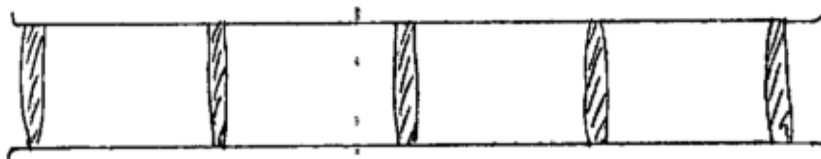


Figure 4.

determined by the total current I which, as has been remarked about 5 times, is fixed. If the total gain is G_0 , then the gain of each channel is $1 + G_0/n$. As $n \rightarrow \infty$ the beam passes through each differentially thin channel with unity amplification.

If one of the end channels generates spontaneous noise P_0 , the power output of the tube is

$$P_{out} = P_0 \left(1 + \frac{G_0}{n}\right)^n$$

P_{out} is thus a monotonically increasing function of n and has

a limiting value of

$$P_{out}(n=\infty) = P_0 e^{G_0}$$

This limiting value is effectively reached when

$$n = 10 G_0$$

For a uniformly discharging laser tube that saturates at 10 kW from 10 mW of noise, G_0 is

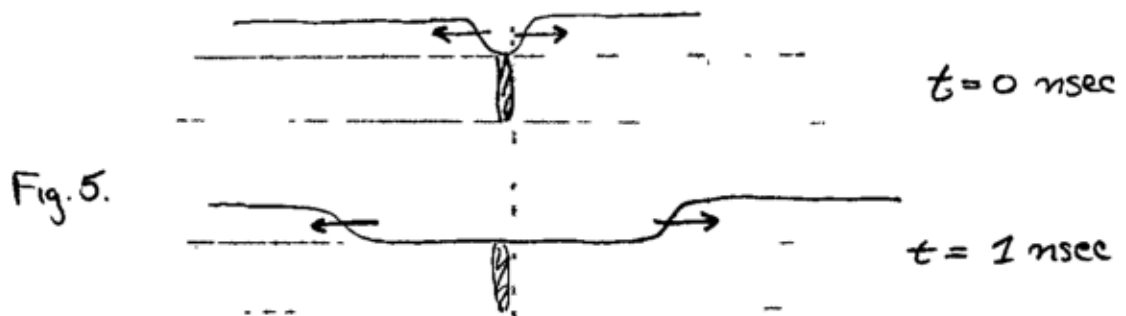
$$\ln \frac{P_{out}}{P_0} = 2.3 \log \left(\frac{10^4}{10^{-2}} \right) = 15$$

And for effective utilization of this gain, there should be at least 150 channels. If the discharge only sparks at 5 of 6 places, the gain, instead of being 10^6 , is only

$$\frac{P_{out}}{P_0} = \left(1 + \frac{15}{5} \right)^5 \approx 10^3$$

This loss in gain is another reason why overvolting the discharge is important (besides the fact that overvolting provides a high electron temperature). When the electrodes are highly overvolted, B of $V_{ac} = B \cdot V_{dc}$ is large, the channel-initiating avalanches form very quickly. The faster the channels are formed, the closer together they can be for the following reason. When one channel is formed, it tends to short the electrodes and the local potential

falls. This potential drop propagates as a pulse down the electrodes at something resembling the speed of light, so no new channels can be formed where this pulse has passed by (see Figure 5). Thus, if the channels all start forming in some



time τ , they can occur as close together as

$$x = c \tau$$

Overvoltage has the effect of drastically reducing τ . When the electrodes are overvolted by 500%, τ , the time for a channel to begin forming after the first channel has formed, is down to a few picoseconds, so x is on the order of mm, and the gain of the laser is very high since n , the number of channels into which the total current is divided, is very large.

Section 5: laser tube description

A nitrogen laser which was constructed for the purpose of pumping organic dyes, had the following characteristics:

The electrodes were 45 cm long, of polished semicylindrical brass tubing, diameter 2.5 cm, smoothed ends, separation 3 cm.

The discharge circuit supplied 30 kVDC at 5 ma. The spark gap used was an EG&G GP-14 capable of handling 100 kA. Capacitor banks were made from Sprague 2500 pF 30 kV units. All wiring consisted of copper sheet, 30 cm wide (see Figure 6). The discharge circuit

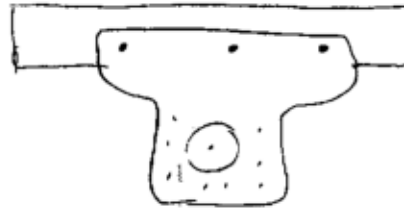
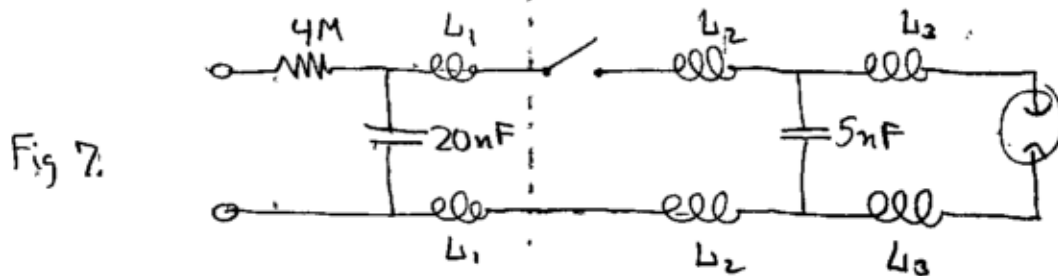


Figure 6.

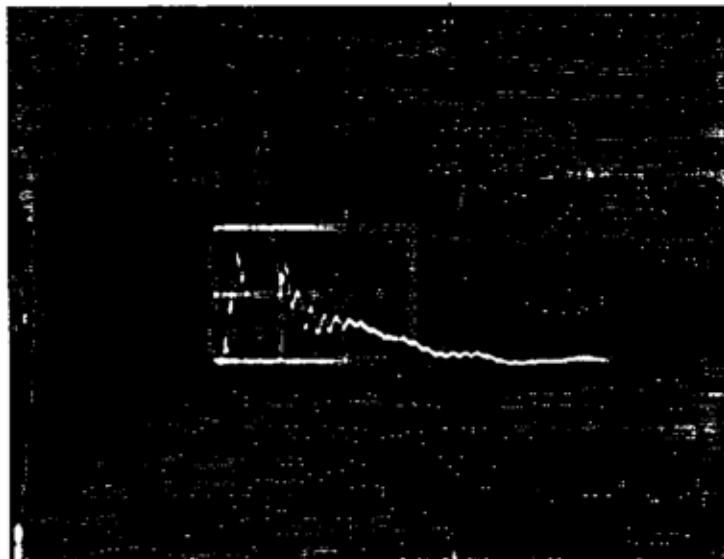
is shown in Figure 7.



Nitrogen gas was flowed at a very slow rate through the tube; optimum pressure was 22 torr.

The voltage and laser pulse are shown in Figure 8. The laser pulse is some 10 nsec long and occurs some 50 nsec after the discharge

(a) voltage across discharge
tube. Vert: 10 kV/cm
Base: 50 nsec/cm



(b) laser pulse. Vert: un-
calibrated. Base:
50 nsec/cm

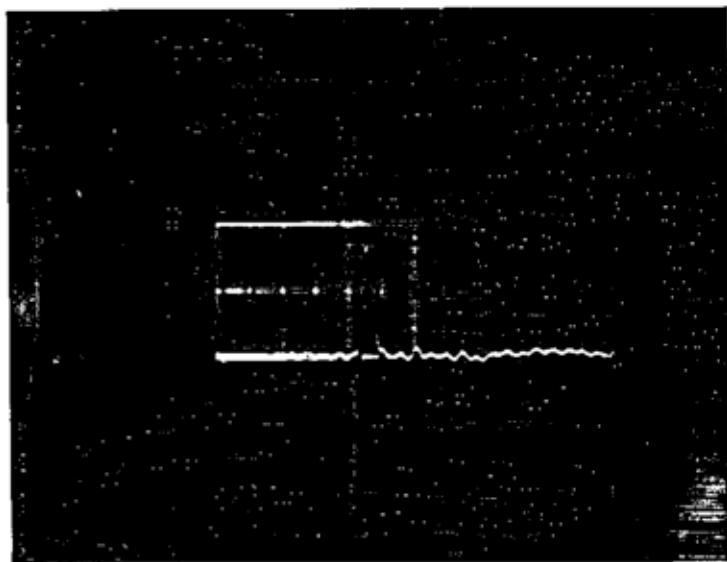


Figure 8.

voltage begins to fall, which is consistent with inductance calculations for L (to come).

Energetics: the power supply is capable of supplying 150 watts of power. The energy required to charge the primary capacitors C_1 is

$$W_{ch} = CV^2 = 18 \text{ joules.}$$

Thus, the maximum pulse rate is about 8 pps. The energy stored in C_1 is, of course, only 9 J; the energy per laser pulse, as measured by a calorimeter, was $.50 \pm 5 \text{ mJ}$, for a wall-to-laser-pulse efficiency of 3×10^{-5} . The average power during the laser pulse is

$$P_{av} = \frac{W}{\tau} = \frac{.5 \times 10^{-3}}{10^{-9}} = 50 \text{ kW.}$$

At 8 pps, the average laser power output is about 4 mW.

Misc: The electrodes were each mounted on three bolts inside a 3" O.D. plastic tube. The end windows were $\frac{1}{2}$ " Corning No. 7740 pyrex glass plates with a loss of .3 db per window at 3371 A. The spark gap was triggered by an EG&G TR-153 pulse transformer driven by a transistorized pulser (schematic in appendix).

Section 6: inductance calculations

The inductances shown in Figure 7 are not entirely trivial to calculate; an attempt will be made here to calculate L_3 . Since the electrodes were connected to the current carrying sheets by three bolts, the sheets were not as effective as they might have been in reducing inductance. The inductance from C_2 into the discharge can be modelled as three rings connected in parallel as shown in Figure 9. Using another of Grover's formulas²

$$L(\text{nH}) = 4\pi a \left[\ln \frac{8a}{b} - \frac{1}{2} \right] \quad (11)$$

and using $a = 5 \text{ cm}$, $b = 1 \text{ cm}$, we find that the inductance of each

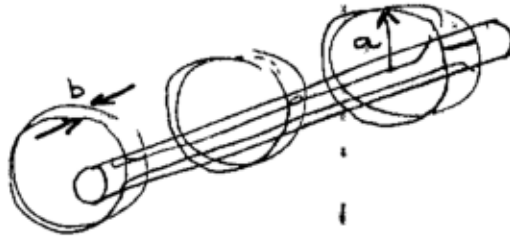


Fig 9

ring is 192 nH, so that the three rings in parallel give 64 nH, suggesting that the L_3 's in Fig. 7 are about 30 nH each. The other inductances shown in Fig. 7 are probably also of the same order of magnitude.

A new laser tube is presently being constructed with the intention of reducing the critical current-limiting inductance L_3 . The electrodes for the new tube are 1 m long, and the current sheets and electrodes are all formed from the same piece of metal as

shown in Fig. 10. The secondary capacitors C_2 are mounted so close that they actually touch the plastic gas tube. The L_3 inductance can be

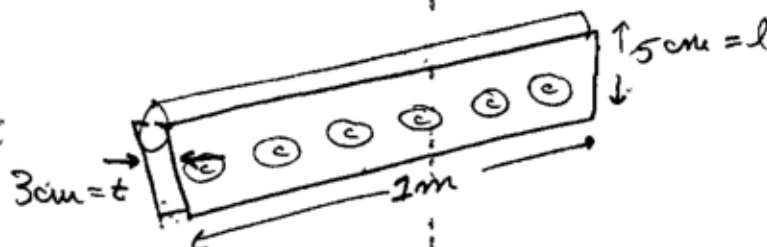


Figure 10.

modelled as a short-circuited transmission line. According to Bleaney & Bleaney³, the inductive reactance of a short, short-circuited transmission line is

$$X_L = Z_0 \tan \left(\frac{2\pi l}{\lambda} \right)$$

Since we are on a time scale of tens of nsec, typical λ is several meters and l is a few cm so we can say $\tan(x) \approx x$ to get

$$X_L = \frac{2\pi l Z_0}{\lambda}$$

or

$$L = \frac{l Z_0}{c}$$

or

$$L(\text{nH}) = \frac{l(\text{cm}) Z_0(\Omega)}{30} \quad (12)$$

For a parallel plate transmission line, Z_0 is

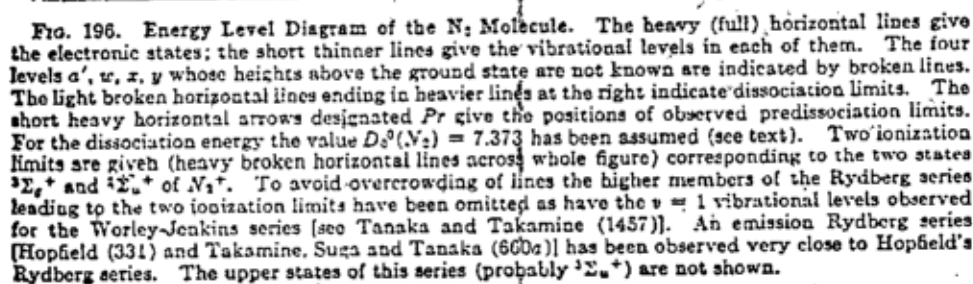
$$Z_0 = 377 \frac{t}{s} \quad (13)$$

Thus, the total inductance of the secondary discharge circuit is,

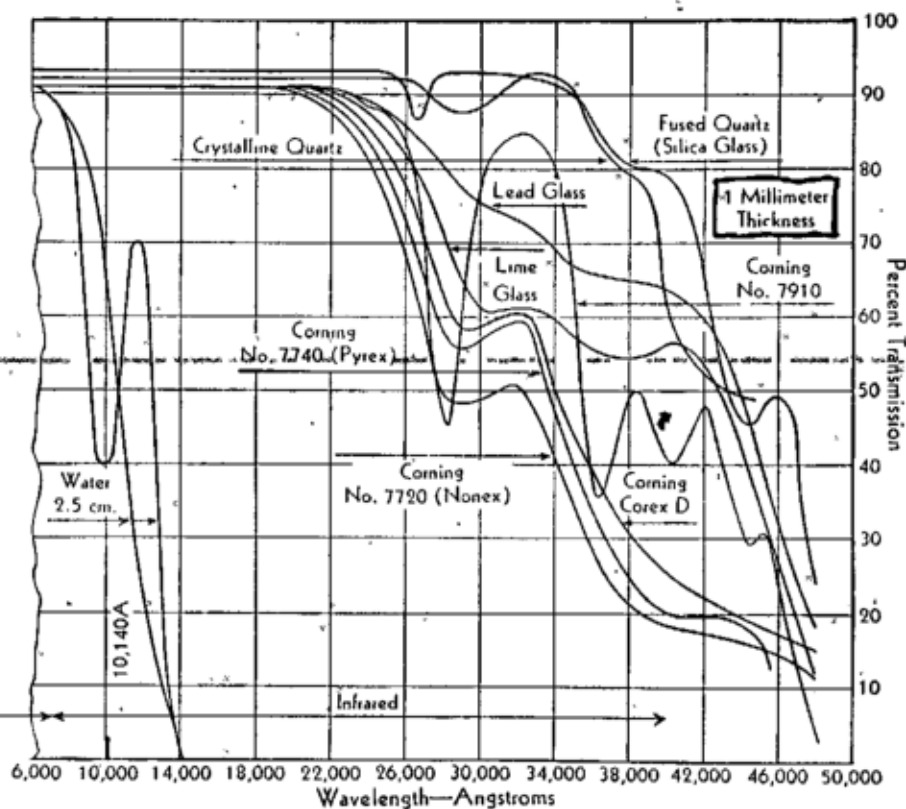
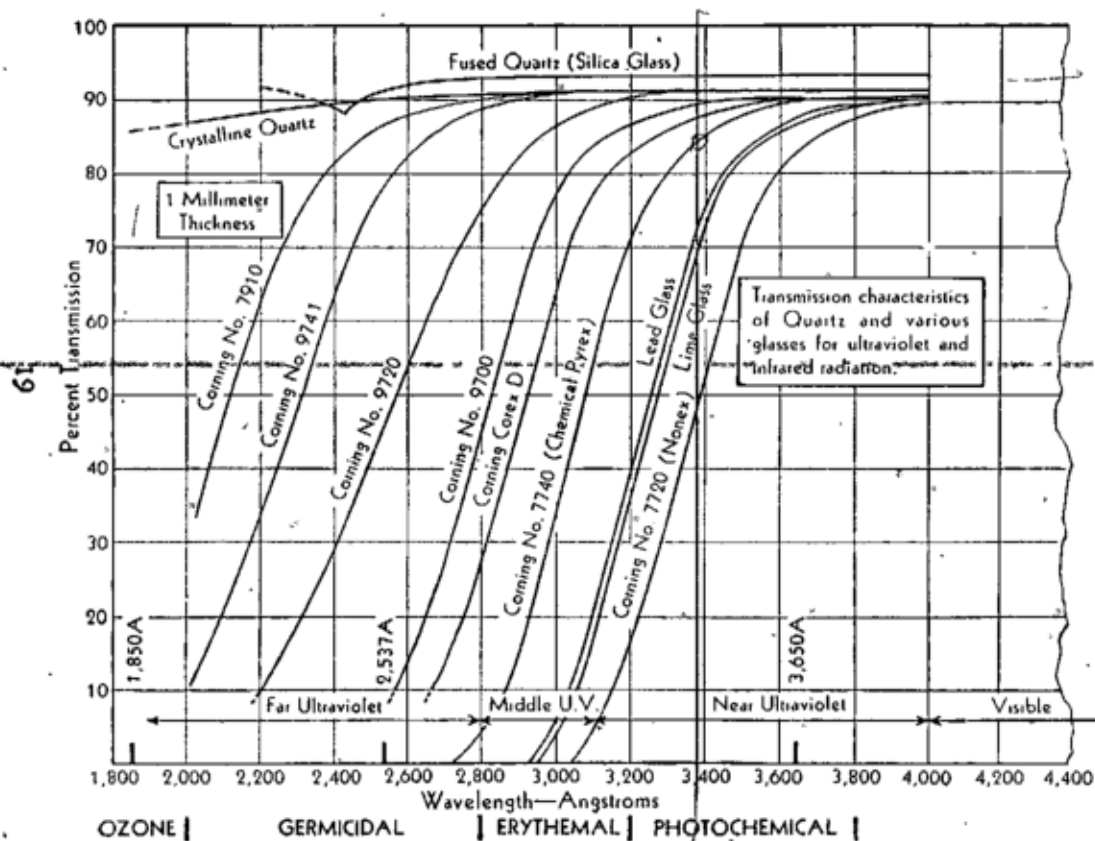
$$L(\text{nH}) \approx 12 \frac{lt}{s}, \quad (14)$$

where lengths are in cm. Putting in numbers as shown in Fig. 10, we get $L = 1.8 \text{ nH}$, a vast improvement over the former design, since now each L_3 is only $.9 \text{ nH}$ as opposed to 30 nH . This 30-fold reduction of inductance could, according to equation (5), increase current and laser output by a factor of 5 or 6 to 300 kW .

The characteristic impedance of the transmission line used here is about 12Ω . For an example of a nitrogen laser driven by a much lower impedance line ($Z_0 = .1 \Omega$) see Geller et al.⁴



TRANSMISSION CHARACTERISTICS OF QUARTZ AND VARIOUS GLASSES



The data for these curves were furnished through the courtesy of the Research Laboratory of the Corning Glass Works, the National Bureau of Standards and the Lamp Development Laboratory of General Electric Company.

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- ⁶Friedrich Louis Carl Heinrich Paschen is also responsible for the Paschen-Bach effect.
- ⁷W. Wolff, Wied. Ann. XXXVIII, 1889, p222. (Wied. Ann. was the Annalen der Physik und Chemie; now just Annalen der Physik)

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¹F.W. Grover, "Inductance Calculations: Working Formulas and Tables" (Dover, New York, 1962), p. 35.

²Grover, loc cit, p. 143.

³B.I. Bleaney and B. Bleaney, "Electricity and Magnetism", 2nd ed, (Oxford, Clarendon Press, 1965), p. 309.

⁴M. Geller, D.E. Altman, and T.A. DeTemple, Appl. Optics, vol. 7, pp 2232f (1968).