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INVESTIGATION OF RF EXCITED CW CO2 WAVEGUIDE LASERS "LOCAL OSCILLATOR - RF EXCITATION"

Final Report
for
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Submitted by
U.Hochuli
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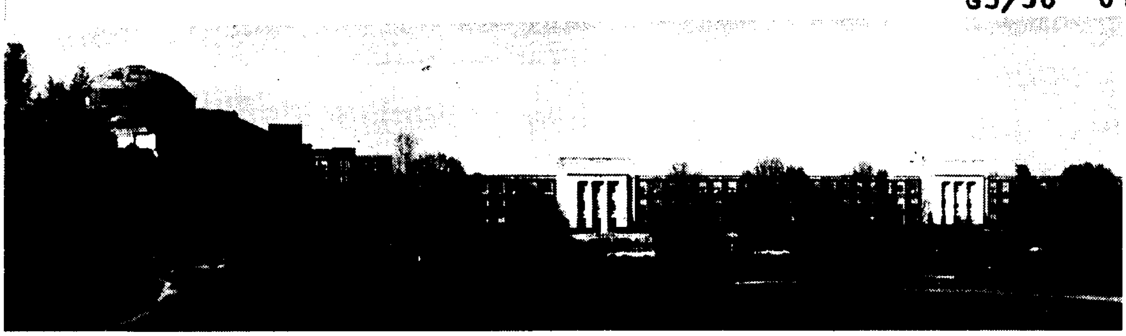


COLLEGE OF ENGINEERING: GLENN L. MARTIN INSTITUTE OF TECHNOLOGY

Introduction

We have successfully shown that RF excited CO_2 waveguide lasers can have a life in excess of 20,000 hours. Despite these results, the CO_2 laser used as local oscillator in the laboratory model of a computer controlled IR radiometer had an unusually short life of only a few days. Evacuation and refilling with a new gas mixture always brought the local oscillator output power back to the initial power level. Repeated H_e leak testing and pressure monitoring did not reveal any measurable air leaks. This leaves outgassing products as the main trouble source. Lack of access to a good mass spectrometer prevented gas analysis to pinpoint the outgassing sources. Suspected outgassing and contaminating sources were the mirror "O" ring and the repaired indium "O" ring seal lip of the main housing. The original cover hole in the main housing was too large to effectively squeeze the indium "O" ring. The rim area was corrected by milling a groove and soft-soldering a small frame with the correct dimensions in place. We were afraid to heli-arc the delicate area because of heat warp danger. Ultrasonic cleaning may not have been sufficient to clean out all the acid flux in the tiny seams. Instead of analyzing and repairing the original laser housing, we decided to do it right and start with a new laser housing.

Efficiency of the old RF coupling-starting network used between the RF transmitter and the laser was a deplorable 55% as mentioned in our April 1987 report. The RF resistivity of the stainless steel housing and a less than carefully designed network seemed to be responsible for the poor result. The shortcomings have now been corrected as shown in the following report.

Laser Housing.

The new housing was again fabricated from type 416SS because of a better thermal match to the B_eO waveguide parts and Z_nS optics. The mirror elastomer "O" ring was replaced with an indium "O" ring, and the internal water cooling of the waveguide was replaced by improved thermal conduction cooling. (The housing can still be modified for internal water cooling if later desired.) Conduction cooling eliminates a fair number of seals between the cooling water circuit and the gas chamber. The disadvantage of thermal cooling is a further gas volume reduction caused by additional cooling fingers and an increase of internal areas that are not easy to outgas. A sketch of the internal laser-cooling configuration is shown in Figure 1. It should also be mentioned that even if the cooling fingers do well in the laboratory, they may not survive future vibrational test requirements.

The housing was finally plated with a 0.025 mm thick silver layer to reduce RF feed-in losses. The several skin depth thick silver layer was covered with a gold flash for additional corrosion protection.

Coupling Network

Silver-gold plating of the laser housing, a larger plated Kovar feedthrough pin, and better electrical contact with the new coupling network box increased the loss resistance across the laser capacitance from $15K\Omega$ to about $30K\Omega$. The helical autotransformer was replaced with a single series coil L_1 as shown in Figure 2. This series coil transforms the load conductance $G + G_\ell$ to a conductance G_1 as seen across C_1. G_1 should be around 0.02 mho. The function of the "Π" section formed by C_1, L_2, and C_2 is twofold: it has to exactly match G_1 to the 50 ohm line when the gas discharge is on, and it also has to provide the proper phase angle of the starting input admittance when the gas discharge is off. All of these conditions have to be achieved with as much overall efficiency as possible. Both of the coils have Q factors of about 280, which could be slightly raised by using silver instead of tin-plated coil wire.

Adjusting the network was more difficult than anticipated. Computer modeling gave a fair representation of the effects of changes in the different network components. Accurate adjustment of the components had to be done in the final position with the help of a grid dip meter. L_1 was adjusted by varying the coil length till it resonated with the laser capacitance C_ℓ at $f_r = 135MHz$. Resonance was observed with the grid dip meter with C_1 shorted out with a copper strap. It can be shown that to a first order approximation

$$\left[\left(\frac{f}{f_r}\right)^2 - 1\right]^2 = \left[\left(\frac{144}{135}\right)^2 - 1\right] = 0.019 \simeq \frac{G + G_\ell}{G_1}.$$

This brings G_1 near 0.02 mho.

The three compoents C_1, L_2, and C_2 of the "Π" network have now to be adjusted to represent an admittance of exactly 0.02 mho with the discharge on and the constraint that the phase angle of the input admittance is around 180° for the discharge off. Computer modeling indicates that this can be achieved with C_1 around 60 pF. L_2 can then be calculated and adjusted in place for the correct phase shift. Figure 3 shows that this could indeed be done for an RF power input of 10, 20, and 30 W into the laser by simply tuning C_1 and C_2. The starting admittance was measured with an old GR 1602B admittance meter. Figure 3 shows that the resulting SWR range is between 15 and 40. These values were reproducible but certainly too high by a factor of about 2. Computer calculations using the Q values for the coils and capacitors as well as the known feedthrough losses yield SWR values between 8 and 20. The discrepancy stems partly from admittance values that are too close to zero to be read accurately and partly from the fact that accuracy suffers if the measured admittance values are too far away from the reference admittance $Y_o = 0.02mho$.

Adjustment of the coaxial cable length between matching network and transmitter was done as described in the appendix paper: a parallel cluster of 17 69 ohm 2 W composition resistors was used to construct a 4 Ω load corresponding to Z_o/SWR for SWR = 12.5. This load was then connected to the transmitter by using a $\lambda/2$ long line made from GR airline sections and a line stretcher. Assume that adjusting the line length till the transmitter DC current reaches a maximum results in a line length ℓ_{max}. The nearest reference plane location ℓ_r is now given by $\ell_r = \ell_{max} - \lambda/2$. This distance is about 5 cm away from the transmitter output. The transmitter current maximum was about 4 A, which is close to three times the normal working current. A 35 cm long semi-rigid section of transmission line was then selected for the final connection joining the coupling network to the transmitter.

Network efficiency calculates to about 90%. This value could be experimentally measured by using two similar, tuned networks back to back so that input and output impedance levels of the combined network are both 50 ohms. This would facilitate power transfer measurements. The disadvantage of the method is the fact that feedthrough losses and the laser capacitance C_ℓ have to be simulated and added to each network.

Conclusion.

A new local oscillator housing was built which seems to have improved laser life. Laser cooling was changed from internal water cooling to the more convenient thermal contact cooling. At the present time, we are not able to conclude if a 20% reduction in power output is the result of poorer cooling or poorer grating alignment.

The new coupling-starting network efficiency was improved from 55% to about 90%. It can be adjusted by varying trimmers C_1 and C_2 to match RF power levels between 10 and 30 W. If the laser admittance changes greatly with laser life rematching will have to be achieved by remote control for space applications. The same holds true if the RF power level has to be changed with a maximum efficiency constraint.

Appendix

A copy of the paper titled "Efficient 30 W 140 MHz Amplifier for CW CO_2 Waveguide Laser Excitation" forms the appendix. The article describes the transmitter and coupling-starting network theory and was accepted for publication in the *Review of Scientific Instruments.*

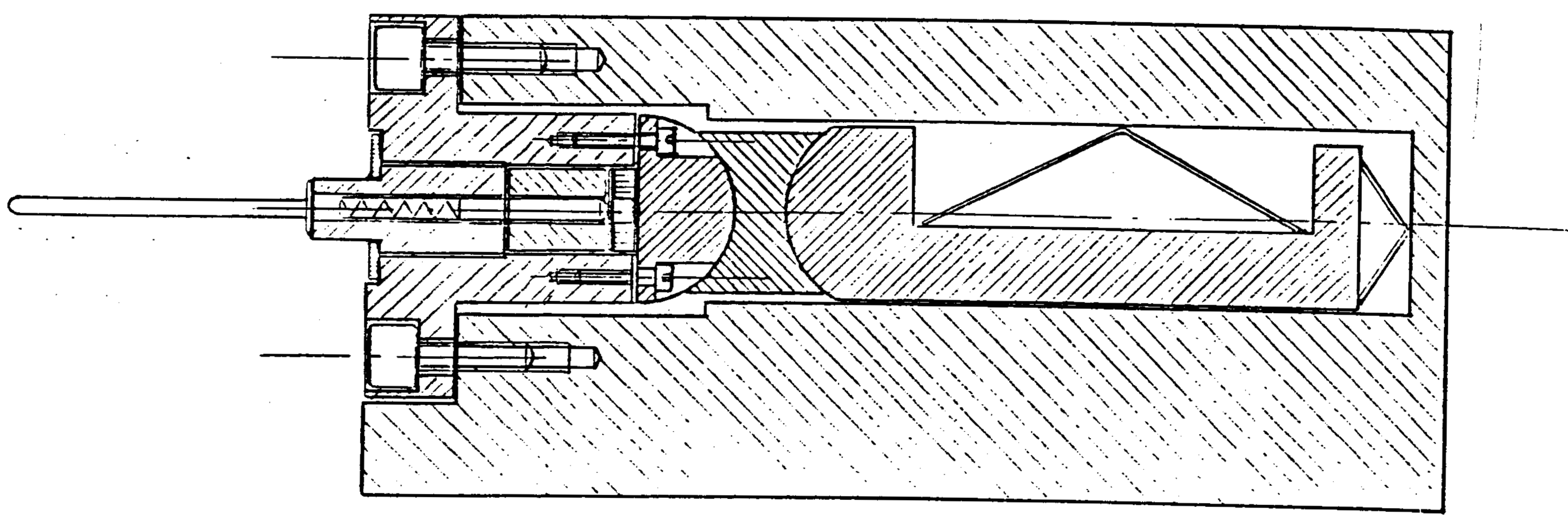
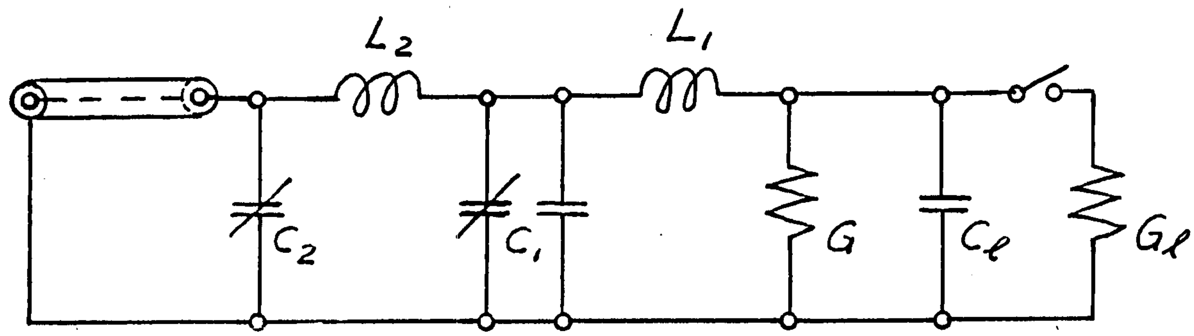


Fig. 1. Laser Housing Cross Section



L_1 = 4 turns No 18AWG, 0.36" O.D., 0.070" pitch

L_2 = 3 turns No 18AWG, 0.36" O.D., 0.065" pitch

C_1 = 33 pF, ATC type 175, in parallel with 2 Johanson 5601, 1-30 pF trimmers

C_2 = 2 Johanson 5601, 1-30 pF trimmers in parallel

C_ℓ = Laser and feedthrough capacitance

G_ℓ = Laser gas conductance

G = Loss conductance approximating all of the network and feedthrough losses

Fig. 2. Starting-Coupling Network

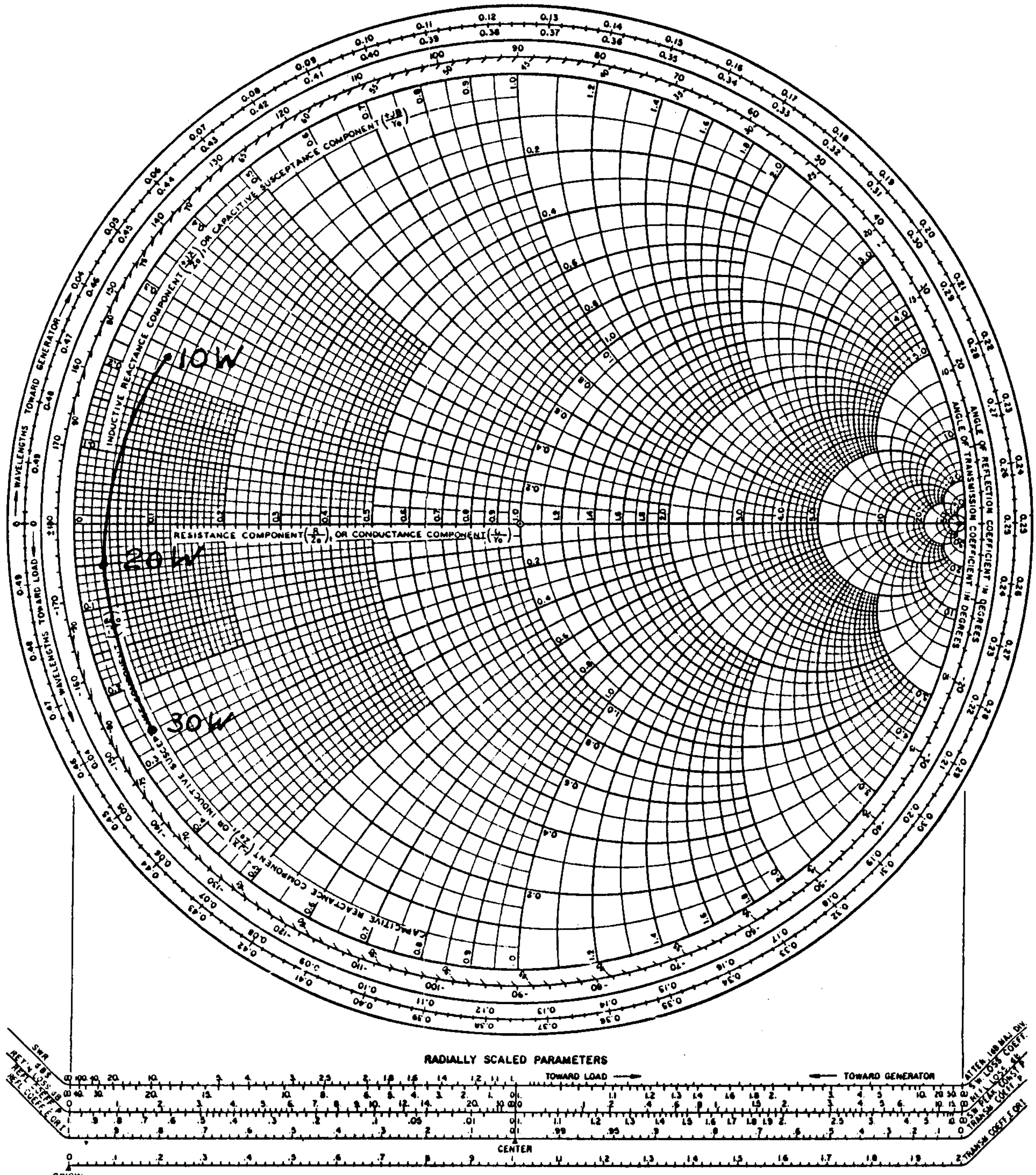


Fig. 3. Normalized Starting Input Admittance for different laser RF power levels.

APPENDIX

EFFICIENT 30 W 140 MHz RF AMPLIFIER FOR CW CO_2 WAVEGUIDE LASER EXCITATION

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Details of a 30 W 140 MHz RF amplifier for CW CO_2 waveguide laser excitation are presented. The amplifier delivers 30 W into a 50 Ω load while requiring only 40 W of DC power from a 28 V supply and 100 mW of RF drive power for an overall efficiency of 75 percent.

Coupling-starting network design theory is given that provides the initiation over voltage for the discharge plasma from a RF power source of limited output voltage capability. The network then matches the drive circuit to the new input impedance of the operating discharge without any adjustments. This design theory applies to the whole class of networks whose losses can be approximated by a loss conductance in parallel with the gas discharge.

INTRODUCTION

RF excitation of the gas discharge in small CO_2 waveguide lasers is becoming more common.[1,2] Efficiency of the RF circuits is usually not of great concern for laboratory applications where sufficient RF power is available to start even reluctant gas discharges.

The situation is quite different for the case of a prototype heterodyne IR radiometer, developed by NASA. The instrument requires 30 W of RF power at 140 MHz for the excitation of its computer controlled CO_2 waveguide laser local oscillator. Future space applications of this system demand an efficient 140 MHz amplifier that can be driven with 100 mW from a crystal-controlled 140 MHz oscillator. The amplifier also has to have the capability of starting the gas discharge of the CO_2 laser with a minimum of circuit complexity. These requirements are satisfied with the circuits described below.

Coupling-starting network theory is given later that provides the initiation over voltage for the discharge plasma from a power source of limited output voltage capability. The network then matches the drive circuit to the new input impedance of the operating discharge without any adjustments. This design theory applies to the whole class of matching networks whose losses can be approximated by a loss conductance in parallel with the gas discharge.

POWER AMPLIFIER

The power amplifier circuit shown in Figure 1 uses a DU 2880 RF power MOSFET transistor, made by M/A COM-PHI, to produce the desired 30 W of RF power at 140 MHz with 0.75 W of drive power. The use of an 80 W device to produce only 30 W will be justified later. The tunable input network matches the transistor input to its 50 Ω driving source. Output matching that transforms the 50 Ω load into the optimum transistor load is achieved with another, tunable, network. Matching can be checked with the built-in directional coupler. The measured drain efficiency, for 30 W delivered into a 50 Ω load, is 79 percent. This figure already includes the losses of the output coupling network and is considerably higher than the usual 50 to 60% minimum efficiencies specified by RF transistor manufacturers.

DRIVER

Figure 2 shows the driver circuit which uses a MOTOROLA MRF 134 RF power MOSFET transistor to provide an additional power gain of 10 dB. The tuning networks again provide matching to a 50 Ω input source and to the 50 Ω load presented by the power amplifier input. The 50 Ω 2 W resistor was necessary for stability reasons, specifically, to provide a 50 Ω drive source for the power amplifier. Replacement of the MRF 134 by the larger MRF 136 transistor provides a sufficiently large transistor output conductance to make it appear as a 50 Ω source without this resistor.

EFFICIENCY AND SIZE

40 W of input power from the 28 V DC power supply and less than 100 mW of 140 MHz RF input power produce 30 W of 140 MHz output power into a 50 Ω load for an overall efficiency of 75 percent.

The circuits shown in Figures 1 and 2 are located in an aluminum housing with external dimensions of $10 \times 7.5 \times 3 \text{cm}^3$. Heat dissipation occurs through the bottom plate of the housing to the water cooled main chassis.

STABILITY

Stern[3,4] has analyzed the stability of tuned transistor amplifiers. His analysis uses a stability factor K which includes the transistors Y parameters as well as input and output loading. This stability factor is

$$K = \frac{2(g_{11} + G_s)(g_{22} + G_\ell)}{|Y_{12}Y_{21}| + Re(Y_{12}Y_{21})}. \tag{1}$$

The circuit is potentially unstable if $K < 1$. Leighton[5] has simplied Eq. (1) to give

$$K \simeq \frac{2(g_{11} + G_s)G_\ell}{\sqrt{(\omega C_{rss})^4 + (\omega C_{rss} g_m)^2} - (\omega C_{rss})^2}. \tag{2}$$

At 140 MHz this expression can be simplified, for all practical purposes to

$$K \simeq \frac{2(g_{11} + G_s)G_\ell}{g_m \omega C_{rss}}. \tag{3}$$

Here,

$g_{11} \simeq 0.05A/V$ given by the 10 Ω gate loading resistor and its leads;

$G_s \simeq 0.2A/V$ the transformed source conductance seen by the gate;

$G_m \simeq 0.5A/V$ from the DU 2880 characteristics;

$C_{rss} = 32pF$ gate-drain capacitance.

These values yield a $K \simeq 2.7$. If the driver behaves like a current source, $G_s \simeq 0$ and consequently $K \simeq 0.54$. This happens if the 50 Ω 2 W resistor in the MRF 134 output circuit is omitted in which case the power amplifier becomes unstable. For space applications very careful attention has to be paid to these stability considerations.

COUPLING AND STARTING NETWORK

This network has to match the laser admittance, given by the gas conductance in parallel with the laser capacitance, to the 50 Ω transmitter output. It also has to provide the necessary starting over voltage to give gas breakdown. Typical values for the gas conductance and starting voltages for our CO_2 waveguide laser are shown in Figures 3 and 4.

A representative circuit for such a coupling-starting network could be the one shown in Figure 5. The auto transformer tap brings the laser admittance close to the 50 Ω impedance level of the transmitter output, and the tunable "$\prod$" network in front of the tap permits exact matching. A piece of 50 Ω coaxial cable is here considered as part of the network, which is usually close to the laser, and links it to the transmitter.

The largest losses in such a network occur in the coil with the largest voltage across it, in this case the auto transformer. Concentration of all the network losses in a loss conductance G in parallel with the laser conductance G_ℓ, in conjunction with lossless network components, represent a reasonable approximation to the actual network. This situation is shown in Figure 5.

ANALYSIS OF THE NETWORK

It can be shown that the input admittance of a linear network must change when a power consuming resistor, in this case the gas discharge conductance G_ℓ is removed. From transmission line theory, it is known that if the starting input admittance Y_{in_s} is required to be real, then it must have the following values:

(i) $Y_{in_s} = Y_0$ SWR, low impedance starting (LIS)

(ii) $Y_{in_s} = Y_0/\text{SWR}$, high impedance starting (HIS) where SWR is the standing wave ratio on the input coaxial cable under starting conditions. If, in general,

(iii) Y_{in_s} = complex, it has to be consistent with the SWR on the lossless coaxial line.

If the lossless network is described by it "$\prod$" equivalent, as shown in Figure 6, the following operating conditions have to hold for matching to the 50 ohm coaxial cable and transmitter output:

$$Y_{in} = Y_{11} - \frac{Y_{12}^2}{Y_{22} + G + G_\ell} = 0.02 + j0. \tag{4}$$

Separating the real and imaginary parts of equation (4), remembering that if all of the networks losses are represented by G, then all the Y_{ij}'s are pure susceptances, results in:

$$-\frac{Y_{12}^2(G + G_\ell)}{|Y_{22}|^2 + (G + G_\ell)^2} = 0.02 \text{ and} \tag{5}$$

$$Y_{11} + \frac{Y_{12}^2 Y_{22}}{|Y_{22}|^2 + (G + G_\ell)^2} = 0. \tag{6}$$

Using the LIS starting condition of (i) and removing the gas discharge conductance (switch open or $G_\ell = 0$) yields the starting input admittance

$$Y_{in_s} = Y_{11} - \frac{Y_{12}^2}{Y_{22} + G} = 0.02SWR + j0. \tag{7}$$

Separating the real and imaginary parts of equation (7) yields:

$$-\frac{Y_{12}^2 G}{|Y_{22}|^2 + G^2} = 0.02SWR \text{ and} \tag{8}$$

(9) $$Y_{11} + \frac{Y_{12}^2 Y_{22}}{|Y_{22}|^2 + G^2} = 0.$$

To satisfy equations (6) and (9) simultaneously requires that $Y_{11} = Y_{22} = 0$. Equations (5) and (8) now yield:

(10) $$-Y_{12}^2 = 0.02(G + G_\ell),$$

(11) $$SWR = 1 + \frac{G_\ell}{G}.$$

Equating the input and output powers of the lossless network leads to:

(12) $$\frac{|V_2|^2}{|V_1|_r} = \frac{0,02}{G + G_\ell} \text{ under running conditions,}$$

and to

(13) $$\frac{|V_2|^2}{|V_1|_s} = \frac{0.02SWR}{G} \text{ for starting conditions.}$$

V_1 and V_2 stand for input and output voltages of the network as shown in Figure 6. The subscript r refers to running condition (switch closed in Figure 6) and s refers to starting conditions (switch open). Combining (12) and (13) shows that

(14) $$\frac{|V_2|}{|V_1|_s} = \frac{|V_2|}{|V_1|_r} \text{ SWR for LIS.}$$

Adding or subtracting a quarter wave long section of the coaxial cable leads to the HIS condition of equation (ii), where

$$Y_{in_s} = \frac{0.02}{SWR}.$$

Repeating all the steps from equation (7) on, leads to:

(15) $$\frac{|V_2|}{|V_1|_s} = \frac{|V_2|}{|V_1|_r}.$$

The network, under these conditions, acts as an ideal 1:1 transformer. Any voltage increase for starting must be provided by the transmitter itself. An efficiently loaded transmitter cannot provide the necessary starting voltage for HIS unless the DC power supply voltage is increased.

The starting condition, equation (iii), calls for a complex Y_{in_s}, commensurate with the SWR on the line. If, for example, $Y_{in_s} = 0.02 + jB$, by using the relations between reflection coefficient magnitude $|\Gamma|, Y_{in_s}$, and SWR, we obtain

$$|\Gamma| = \frac{|Y_{in_s} - Y_0|}{|Y_{in_s} + Y_0|} = \frac{SWR - 1}{SWR + 1} : \tag{16}$$

$$|B| = 0.02 \frac{SWR - 1}{\sqrt{SWR}}. \tag{17}$$

Using equations (12) and (13) again yields for this case:

$$\frac{|V_2|}{|V_1|_s} = \frac{|V_2|}{|V_1|_r}\sqrt{SWR}. \tag{18}$$

An input susceptance $B_s = -B$ can be switched in to make $Y_{in_s} = 0.02$ for startup. In this case, the full transmitter power is used to cover the losses of the network. As soon as the gas discharge is started, the transmitter load changes to $Y_{in} = 0.02 + jB_s$ because B_s cannot be switched out fast enough. The discharge can only stay on if the transmitter can provide sufficient voltage under this load.

For all three cases, (i), (ii), and (iii), the efficiency η of the network is given by

$$\eta = \frac{G_\ell}{G + G_\ell} = 1 - \frac{1}{SWR}. \tag{19}$$

The starting problem is now reduced to the large signal behavior of the transmitter. The analysis given applies to any type of linear RF coupling network whose losses can, to a good approximation, be represented as a resistance in parallel with the laser load.

For the three starting conditions mentioned, only the first one, LIS, will be pursued further. It is simple and does not require a single additional circuit element.

If it is assumed that the transmitter output coupling network is lossless, it can be shown that the transistor "sees" the same SWR that is present on the 50 Ω coaxial line. The network merely transforms the reference impedance from the 50 Ω characteristic impedance of the coaxial cable to the optimal parallel load resistance of the transistor.

The 50 Ω cable input voltage can be kept constant, namely,

$$|V_1|_r = |V_1|_s, \text{ if the starting transistor current is}$$

$$|I|_s = |I|_r \text{ SWR},$$

where

$$|I|_r = \text{ running transistor current.}$$

The starting transistor current $|I_s|$ is limited by

$$|I|_s \leq I_{\max}, \text{ the maximum permissible transistor current.}$$

Under constant input voltage conditions

$$|V_2|_s = |V_2|_r \text{SWR}.$$

If $|I|_s = I_{\max} < |I|_r$ SWR, then the cable input voltage is $|V_1|_s < |V_1|_r$ and the starting-to-running voltage ratio becomes:

$$\frac{|V_2|_s}{|V_2|_r} = \frac{I_{\max}}{|I|_r}. \tag{20}$$

This latter condition will always hold for an efficient coupling network where SWR ≥ 10. The 80 W transistor capability was chosen specifically for LIS conditions. For starting, it can be driven hard enough that $I_{\max} = 2|I|_r$ or $3|I|_r$, resulting in sufficient voltage for starting purposes. Transistor dissipation is high but within reasonable limits during LIS. Monitoring of the directional coupler for reflected power can be used to confirm that the gas discharge is on. The selection of a relatively large transistor that works most of the time in underrated load conditions offers the advantage of a long transistor life. The

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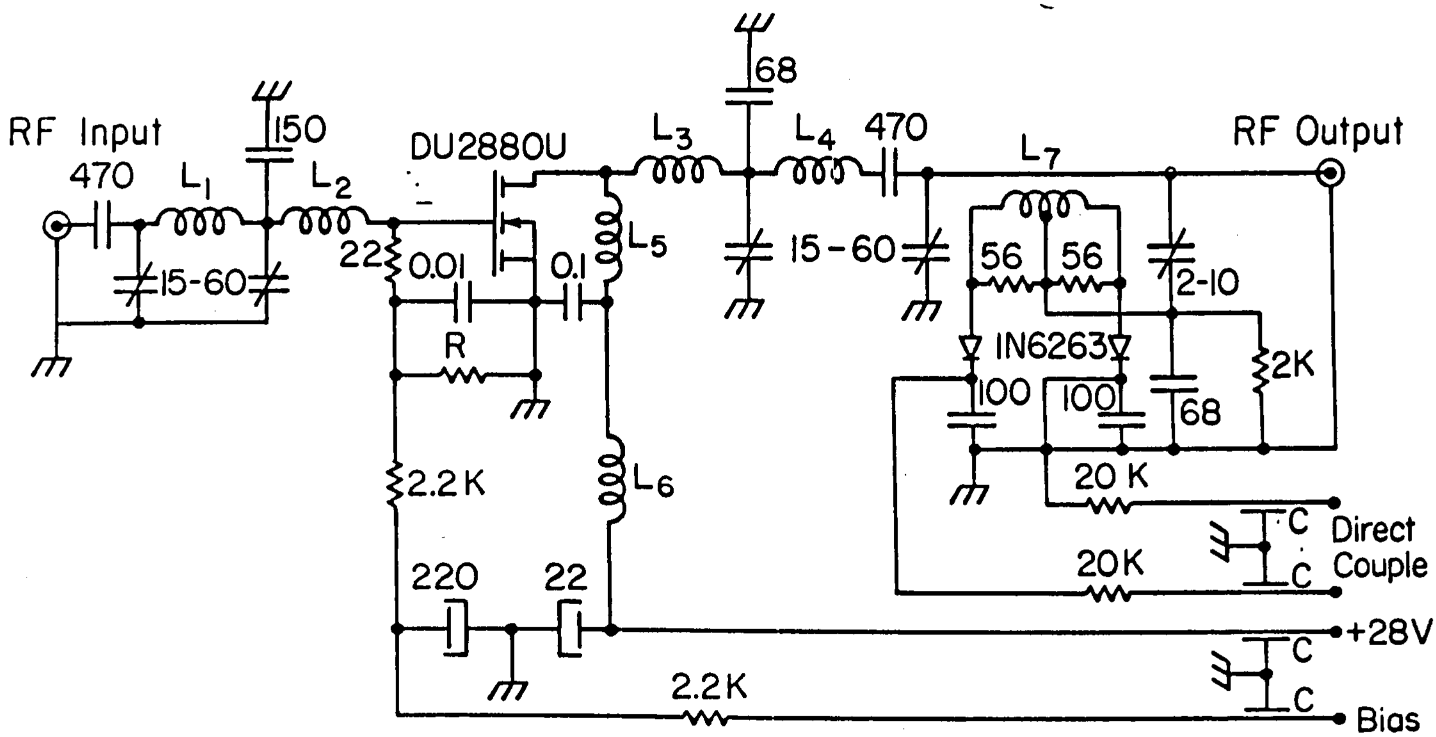


L_1 2 Turns, No. 20 AWG, .14″ I.D.

L_2 Hairpin, No. 20 AWG, .2″ W, .312″ H

L_3 1 Turn, No. 18 AWG, .28″ I.D.

L_4 Hairpin, No. 18 AWG, .28″ W, .35″ H

L_5 11 Turns, No. 20 AWG, on Micrometal T-37-0 Core

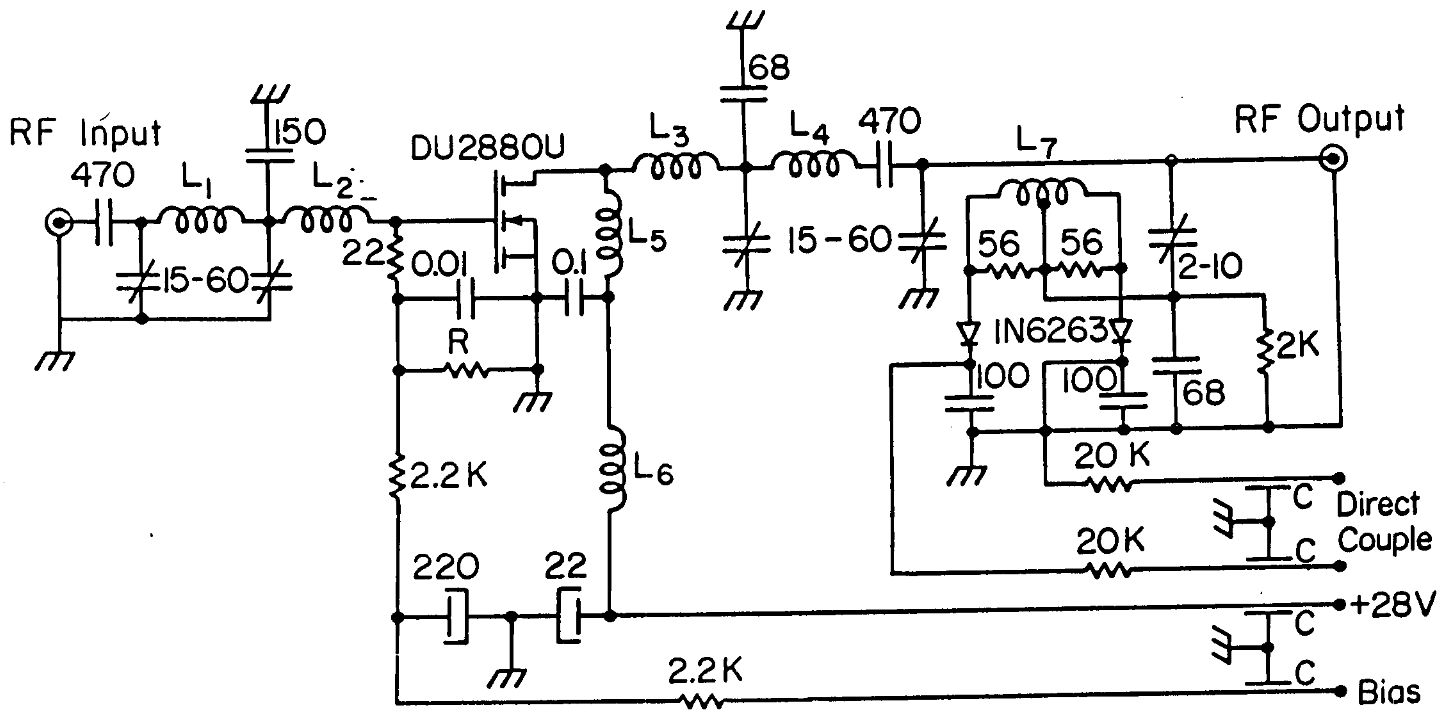
L_6 15 Turns, No. 24 AWG, on 3.3 Ohm 1W Resistor

L_7 8 Turns, Bifilar, No. 30 AWG, on Coretronics CT-10-4142 Core

C 1500pF, Erie 1250-003

R Adjusted for I_{DQ} = 100-150 mA

Fig. 1, 30W 140 MHz Power Amplifier



L_1 4 Turns, No. 32 AWG 24 ohm/m Resistance Wire, .063″ I.D.

L_2 5 Turns, No. 20 AWG, .25″ I.D.

L_3 2 Turns, No. 20 AWG, .25″ I.D.

L_4 34 Turns, No. 24 AWG, on Micrometal T-50-0 Core

L_5 15 Turns, No. 24 AWG, on 10 Ohm 1W Resistor

C 1500pF, Erie 1250-003

R Adjusted for I_{DQ} = 20 - 30 mA

Fig. 2, 1W 140 MHz Driver

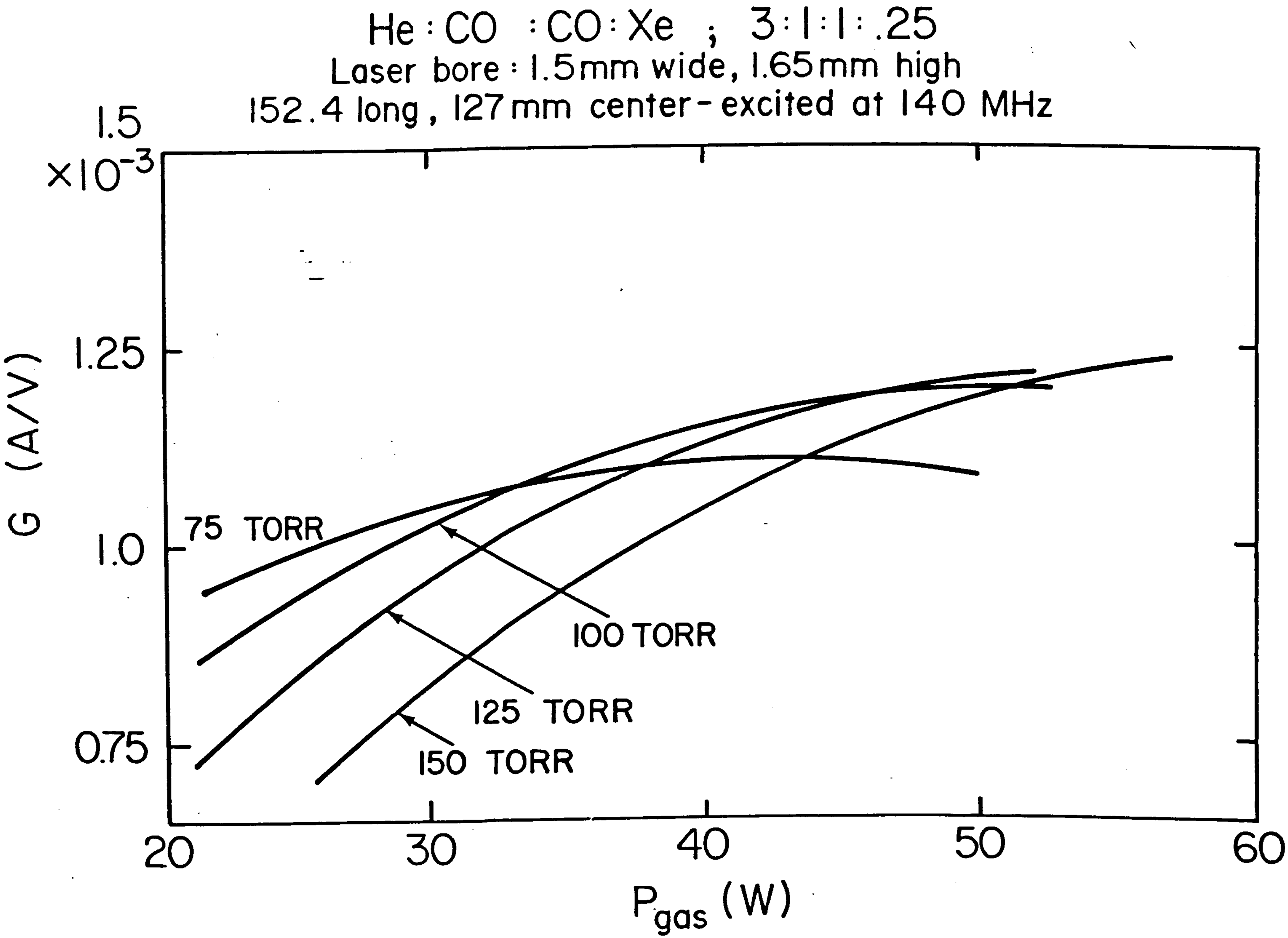


Fig. 3, Center RF-Conductance G vs. RF Power

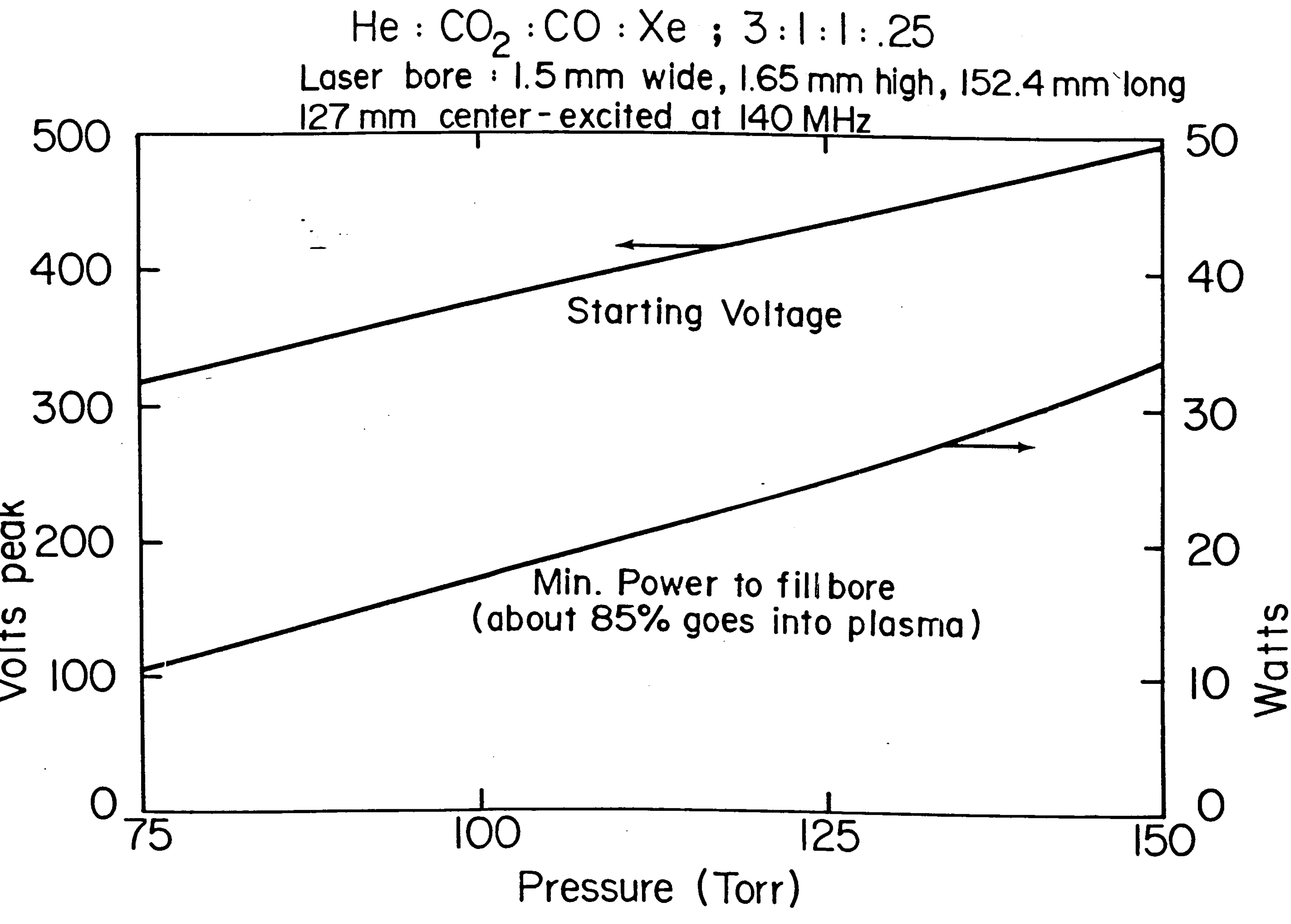


Fig. 4, Starting Voltage and P_{min} vs. Pressure

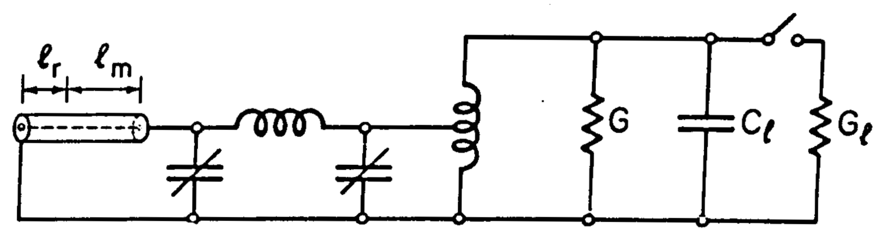


Fig. 5, Typical Coupling-Starting Network

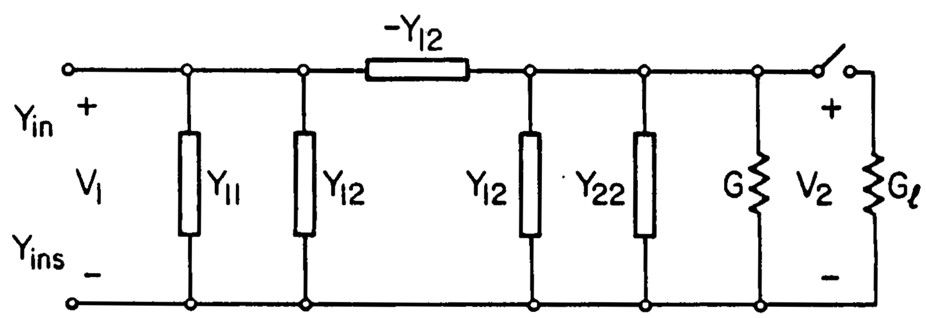


Fig. 6, Equivalent "∏" Network