LA-UR-73-1630

Conf-731114--40

ELECTRON-BEAM-CONTROLLED GAS LASERS: DISCUSSION FROM THE ENGINEERING VIEWPOINT

PART II: PROBLEMS IN THE ELECTRICAL DESIGN OF VERY HIGH ENERGY SYSTEMS*

K. B. Riepe and R. E. Stapleton

Los Alamos Scientific Laboratory
University of California
Los Alamos, NM 87544

Abstract

Some problem areas in the design of very high energy electron-beam-controlled short pulse gas lasers are discussed. One of the prime areas of interest is the high voltage pulse generators for driving the electron gun and gas pumping. The use of pulse-forming networks for improving energy transfer efficiency is discussed. The use of thermionic cathode devices will require a large AC power installation. The properties of alternate electron sources (cold cathode and plasma cathode devices) are reviewed. The impact of laser beam energy density limitations on system geometry and electrical design are discussed last.

Introduction

Inefficiencies which can be tolerated in the design of the present (1 and 10 kJ) Los Alamos Scientific Laboratory (LASL) short pulse CO_2 laser systems[1] cannot be tolerated in a laser used in a fusion reactor, or even in a larger experimental laser. Areas which have been of particular interest have been the pumping energy store, the electron gun, the electron gun energy store, and laser beam energy density limitations, which impact system size and complexity.

Pumping Energy Store

Of particular interest is the energy store used to pump the final amplifier of the system. For example, our 10 kJ system will consist of eight beams, each with 1250 J. Each beam requires approximately 90 kJ deposited in the gas. Because a capacitive run-down circuit is used, 325 kJ will be stored in the capacitor bank with the excess energy being deposited in the crowbar circuit. The entire bank for the 10 kJ system will store 2.6 MJ in order to deliver 720 kJ to the gas. This same job could be performed by a pulse-forming network (PFN) storing less than 1 MJ. At this stage, the difference is not so important, particularly because of the cost and effort required to develop a PFN of this size. When a 10^5 J laser is built, it is expected that the laser efficiency will have been improved to 2% through the use of improved optical and geometrical efficiency, and multiline oscillators. The decision in this case will be between a 12 to 15 MJ capacitor bank and a 5 MJ PFN. The extra effort in this case is worthwhile.

The problem in the design of a PFN is to arrive at a reasonable tradeoff between waveform and circuit complexity. The ideal waveform would be a square wave with zero rise- and falltime. The waveshape is important because pumping is efficient only within a range of applied electric field. Thus, a slow risetime will cause energy to be deposited in the gas as heat rather than as population inversion. Since pumping stops when the voltage falls below a certain value, a slow fall will mean that more energy is left in the bank when peak gain is reached. In general, better waveforms are achieved at the cost of more complex networks. However, the goal is to minimize the cost per joule delivered to the load within the useful voltage range.

The constraint on voltage range means that the PFN must be reasonably well matched to the load. This is also true, however, for a capacitive run-down circuit. A capacitor may be characterized as a constant voltage source. Thus, the power delivered to the load is proportional to the current. For a given pulse length (crowbar time), shot-to-shot variations in current (due, for example, to variations in electron gun current) will affect energy delivered to the load. A PFN, on the other hand, is very close to a constant power device. If Z_0 is the PFN impedance, the load impedance may vary from $Z_0/2$ to $2Z_0$ for a ± 5% variation in energy delivered. However, the variation in load voltage over this impedance range is a more serious constraint. The highest pumping efficiency is achieved at an E/P in the range of 3.3 to 4.6 kV/cm-atm. Since

$$V_{load} = V_{match} \frac{2Z_L}{Z_L + Z_0} \qquad (1)$$

where V_{load} is the load voltage, V_{match} is the matched load voltage, Z_L is load impedance, and Z_0 is the PFN impedance, if the matched PFN output is designed to give a field of 4 kV/cm-atm, the load impedance may be in the range of 0.7 Z_0 to 1.35 Z_0, and the field will still be in the range given above. However, if the peak field is at the low end of the range, the rise- and falltime of the pulse will be more important.

There are several possible approaches to the design of a PFN. The first comparison will be: distributed vs lumped. Distributed networks will, in general, give a better waveform with better rise- and falltimes. However, for the pulse lengths required (~ 3 μsec), distributed systems do not seem appealing. For example, a mylar stripline would be 1000 feet long. Of course, it could be rolled up, but then a failure at one spot could destroy the whole line. A water line would be of reasonable size (150 feet long) but since water cannot be DC charged, it would be pulse charged from another energy store. Of course, this would be a simple capacitor bank, without induc-

*Work performed under the auspices of the U. S. Atomic Energy Commission.

MASTER

tors, etc., but it is doubtful if any cost savings would result.

One then turns to lumped element PFN's. At the beginning of our study, consideration was given to a Guillemin network.[2] This network may be cast into several equivalent forms, but each has at least one disadvantage. The network shown in Fig. 1a requires several different capacitor values, while that in Fig. 1b requires that inductors be positioned for proper mutual inductance. This may not be practical in a high voltage system. However, these forms have the advantage that capacitor inductance may be compensated. The calculated output waveform is shown in Fig. 1c.

In these studies, the major concentration has been on the uniform (flat) L-C line, shown in Fig. 2. This is the easiest line to design and fabricate. No mutual inductance is required, and all the capacitors have the same value, and only the inductors are varied to tailor the wavefall. An example of a five-section line is shown in Fig. 2. If one uses $L_0/2$ for the first inductor at the load end, the risetime will be

$$\tau_{10\% - 90\%} = 2.2 \frac{L_0/2}{R} \simeq \frac{L_0}{R} . \qquad (2)$$

Since L_0/Z_0 is the transit time of one section, L_0/R is approximately 10% of the pulse length. If one tries to reduce the risetime by using a smaller inductor, overshoot will result. However, if the resistor network shown in Fig. 3a is used, the initial load voltage is due to resistive division, and is V_0 except for any load and capacitor inductance. Very fast risetimes can result, as shown in Fig. 3b.

Capacitor inductance will affect the pulse risetime, and also the fall time. As discussed above, it is desirable to stay as close to the maximum pumping rate as possible, and thus a slowly falling pulse will be less efficient.

The amount of inductance which is tolerable in the capacitors depends on the specific conditions. As an example, a five-section line was built to drive a 5 x 8 x 100 cm amplifier at 1200 Torr. Pumping voltage was to be 35 kV at 7 kA for 4 μsec, or 10^3 J deposited in the gas. The section capacitance is 0.1 μF at 70 kV, and the section inductance is 2.5 μH. Some 0.1 μF capacitors were available which have a measured internal inductance of 0.7 μH. This is almost 1/3 the section inductance. The predicted waveform using all equal inductors had a rather slow fall, beginning rather early in the pulse. However, by tailoring the inductors as shown in Fig. 4a, the waveform shown in Fig. 4b was calculated. Because of problems getting the electron gun up to voltage, the PFN was modified for use at 600 Torr by adding another (sixth) section. In spite of the impedance mismatch (the load was 3.5 Ω), good energy transfer was achieved, as evidenced by small signal gains of over 4% per cm.

These results were encouraging enough to begin a design of a PFN for a larger amplifier. This is being designed as a Blumlein line. The circuit is shown (in the form of a distributed line) in Fig. 5. This approach has the advantage that, when the circuit has matched impedances, the output voltage is equal to the charge voltage. The normal charged line pulser must be charged to twice the output voltage. This causes no great problems, except for insulation of the high voltages. However, the lumped element Blumlein has the disadvantage that the L-C sections between the switch and the load act as a low pass filter, degrading the risetime of the output pulse. A ten-section (five on each side of the load) Blumlein is shown in Fig. 6a. The calculated waveform is shown in Fig. 6b. It is seen that the pulse shape is not very good. However, this problem may be partially solved by using a peaking switch in series with the load. This may be a simple overvolted two-electrode gap. The waveform with a peaking gap is shown in Fig. 6c. It is seen that the waveshape is improved, but the falltime is still very long.

Electron Guns

General

The electron gun design is one of the most important aspects of an electron-beam-controlled gas discharge laser. The efficiency of the gun is important and, because the electron beam controls the discharge, the reliability and reproducibility of the electron gun voltage and current must be considered. The present CO_2 lasers at LASL[1] use hot cathode diodes. These give satisfactory results, when driven from capacitive run-down circuits. However, for each shot, the 10 kJ system will use 300 kW of filament heating power for approximately 10 seconds. It would be desirable, for a very high energy single shot system, to eliminate the need for filament heating. Note, however, that for repetitively pulsed systems considered for reactor schemes, running at 10 pps, the filament heating power is a small fraction of the system electrical power requirement. Two alternates to the hot cathode diode have been sufficiently developed to be seriously considered for use in high-energy, short-pulse laser systems. These are the "cold cathode" gun and the plasma cathode gun.

Cold Cathode Electron Guns

In a cold cathode electron gun, the cathode consists of a structure with a number of protruding sharp points or edges. The emission process is not completely understood, but probably starts with field emission from "whiskers" on the highly field-enhanced regions.[3] The high current density leads to rapid heating and blowup of the whiskers, thus forming a plasma sheath which spreads over the cathode surface and provides the electrons for the high current density discharge. This process takes place in a few tens of nanoseconds. The cathode current generally increases monotonically with time, due to either further spreading of the cathode plasma over the cathode structure field-forming electrodes and back surface, or expansion of the plasma across the anode-cathode gap, or both. The plasma expansion theory probably has the most supporters. According to this theory, the current density obeys Child's Law

$$J \sim \frac{V^{3/2}}{d^2} \qquad (3)$$

where d is the distance from the plasma front to the anode, and

$$d = d_0 - V_{closure}\, t \qquad (4)$$

where $V_{closure}$ is the plasma front velocity, which is 1 to 3 cm/μsec. The current will then increase. Figure 7 shows voltage and current traces from a cold cathode gun at 180 kV and 10 cm spacing. Total cathode current and current transmitted through the foil both increase faster than t, until the total current begins to increase very rapidly, at which time the electron energy apparently drops to a value at which the foil stops most of the electrons. If the power supply is large enough, the current will increase until the circuit becomes underdamped. This event is termed "breakdown", since the anode-cathode voltage becomes very small. The time to breakdown depends on the gun geometry and power supply, and has varied from a few microseconds to over ten microseconds in LASL devices. Proper design is extremely important, since in extreme cases as little as 1% of the cathode current may pass through the anode foil into the gas chamber of the laser amplifier. Several workers have reported on experience with cold cathode devices.[4,5,6,7]

Cold cathode electron guns may have several advantages.

1. No filament heating power or high voltage isolation transfer is required.

2. The cathode structure is greatly simplified.

3. High voltage vacuum bushings for filament heating connections are not required.

4. Vacuum requirements are less stringent. Cold cathodes function best in the range 10^{-4} to 10^{-6} Torr, while hot filament devices require better than 5 x 10^{-6} Torr.

5. There does not appear to be any poisoning of the emission process.

Some of the potential disadvantages of cold cathode devices are discussed below.

1. Current pulse shape and amplitude do not show good shot-to-shot repeatability.

2. The current pulse is not flat-topped. Since the electron density in the gas is proportional to the square root of the electron beam current density, the gas current pulse will not be flat-topped.

3. The cold cathode discharge will not initiate if the anode-cathode spacing is too large. Therefore, electron beam current density will have a minimum achievable value for a given gun voltage, which is larger than the hot cathode current density usually run (~ 200 mA/cm²).

4. Long current pulses are harder to achieve.

5. Due to the change in current with time, the electron energy will vary with time, due to series limiting resistance and source inductance.

6. The pumping chamber power supply must be capable of handling higher current, with a faster rise, if the gun current is greater.

A small CO_2 laser amplifier has been run with a cold cathode controlled discharge. This confirmed that, although the cold cathode device does lead to higher gas current and faster pumping rate, the faster pumping gives higher peak gain and better overall efficiency. Figure 8 shows data comparing the small signal gain vs energy deposited in the gas for both a cold cathode and hot cathode device.[8]

Plasma Cathode Electron Guns

In a plasma cathode gun, the electron source is a plasma generated by a discharge between a hollow cathode and a grid. These have many of the advantages of the cold cathode gun: low average power consumption impulse mode, soft vacuum, rugged cathode construction which is not susceptable to poisoning. In addition, current pulses are relatively flat, and repeatable. However, results have only been reported[9] for a device with 30 cm² emitting area operating at 140 kV.

The plasma cathode gun will require an isolated power supply to drive the hollow cathode discharge. In addition, the hollow cathode discharge has a relatively high peak power requirement of 100 W/cm², compared to 6 W/cm² for a hot cathode. Since it only requires a few microseconds to stabilize the discharge, it may be useful for single shot operation, but for a repetitive system, it would be best to pulse the hollow cathode discharge rather than run it CW.

Grid-Controlled Hot Cathode Electron Guns

The diode is the simplest electron source. If the cathode provides a sufficient number of electrons, the current is space-charge-limited (Child's Law). However, if the voltage is increased until the cathode cannot supply any more electrons, the current saturates at a value given by the Richardson-Dushman equation, and becomes independent of voltage. Figure 9 illustrates graphically this general behavior. If the diode is operated in the temperature limited regime, and the temperature is carefully controlled, the current is easily controlled.

If it is desired to control the current with a grid (to pulse the current on and off with a DC source, or to control a plasma cathode device), there are some pitfalls of which one must be aware. Referring to Fig. 10, if the grid is maintained at constant (negative) potential with respect to the cathode, the current will vary as E_b (anode-cathode voltage) varies. The variation depends on the geometry and current. At high current, impedance is almost constant. If it is desired to maintain I_b (anode current), constant independent of E_b, using a feedback network, if E_b were to decrease too far, the grid could be driven positive (grid reversal). This will cause the grid current to become excessive, with catastrophic results.

The situation with a tetrode is illustrated in Fig. 11, and is seen to be much better. The current for fixed E_{grid} is almost independent of E_b, and if the desired current is small enough, there is little possibility of grid reversal.

Electron Gun Power Supplies

General

In general, the electron beam power supplies store much less energy than the pumping chamber power supplies. However, in a high energy laser system, this will still be a large supply. Because it is important that the electron range be sufficient to cross the cathode-anode gap in the pumping chamber, little voltage droop is allowed in the electron beam power supply. In our present system, 10% droop is allowed; this means that, in a capacitive run-down circuit, the bank must store five times the energy put into the electron beam. Thus, the use of a PFN can make the power supply considerably smaller. This may become more important if one goes to considerably shorter pumping times. Since our discharge is recombination limited, the gas current scales as the square root of the electron beam current. Thus, the energy in the electron beam is inversely proportional to the pumping time.

Since the electron range, hence energy, is very important, impedance matching is extremely important if a PFN is used. Matching a PFN to a cold cathode gun will present some difficulties for two reasons. First, cold cathode devices at present have poor shot-to-shot current reproducibility. Second, the impedance varies during the current pulse. The second problem could be solved by tailoring the PFN impedance to match the varying impedance of the load, if the impedance varied in a reproducible way.

It thus appears that, if a PFN is used as the electron gun power supply, a well-controlled electron source is desirable. The other devices which are now considered to be possible candidates are the plasma cathode and the hot cathode. The plasma cathode current is controlled by the grid voltage, and thus may be passively or actively controlled. This device is suitable for single shot operation in a high energy laser system. The hot cathode is not considered to be desirable for use in a single shot, high energy laser system because of the high filament heating energy used per shot. However, in a repetitively pulsed system, the hot cathode may be a suitable candidate. Experience shows that the emission in a hot cathode diode can be regulated using a saturable core reactor to control the filament current,[1] so that the impedance may be set to match the source within the required limits. It is not known if this is true of plasma cathode devices, since these have been operated using a grid to control the current. The characteristics of grid-controlled electron guns (triodes and tetrodes) will be discussed in the next section.

Grid-controlled guns are also of interest because, with a repetitively pulsed laser system, an attractive mode of operation would be to apply DC (with a power supply with sufficient capacitance) to the cathode, and pulse the current on and off with the grid control. In fact, since the gas current is controlled by the electron beam current, DC voltage may be applied to the pumping chamber, with the current pulsed on and off with the electron beam, if the pumping chamber capacitor bank is of sufficiently low inductance so that the "inductive kick" does not cause gas breakdown at shut-off.

Beam Energy Limitations

Although uniformity and symmetry of target illumination will probably require some minimum number of output beams (probably no more than eight), it is desirable to minimize the number of output beams within this constraint. The limitations on beam energy density will be discussed, followed by a discussion of the implications in terms of electrical design.

The beam energy density is limited by three factors: optical frequency electrical breakdown of the laser gas; optical frequency electrical breakdown of laser window material; and surface damage to windows, mirrors, and other optical components. These effects are related to the peak instantaneous electric field.

For nanosecond pulses, the optical breakdown threshold of 3:1/4 :1 ::He:N_2:CO_2 laser mix, at the electron densities used in our amplifiers, is somewhat greater than (5/P) J/cm^2, where P is expressed in atmospheres. Optical breakdown is defined here as the condition when the optical loss rate due to inverse bremsstrahlung is equal to the gain due to stimulated emission. Notice that, while DC or impulse breakdown strength is generally proportional to pressure, optical breakdown strength goes inversely as pressure due to the increase in collision frequency. The dielectric strength of NaCl, the presently used window material, is approximately 10^6 V/cm; therefore, for nanosecond pulses, the damage threshold is about 3 J/cm^2. The damage threshold for reasonably prepared gold surface mirrors is determined by I^2R losses (the reflectivity is approximately 0.99), and is about 3 J/cm^2 for pulses shorter than one nanosecond. For longer pulses, thermal conduction reduces the surface temperature and the damage threshold is greater.

As an example, consider a 10^5 J, 1 nsec, CO_2 laser system. If this is operated at a flux of 2 J/cm^2 at beam center, the mean flux will be about 1.5 J/cm^2 (the exact beam profile is determined by saturation effects in the amplifiers). It is desirable to keep the pumping voltage below 300 kV (200 kV would simplify matters considerably). If the pressure is 2.5 atm, and the field is near the optimum of 4 kV/cm-atm, the beam diameter will be 30 cm. This turns out to be close to the maximum window size one would want to use. The window area is then about 700 cm^2, the beam energy is about 1 kJ, and 100 such beams are required for 10^5 J.

This is not a very attractive solution to the design of a laser system. At present, no way is seen to synchronize multiple oscillators. Therefore, it would be necessary to split the beam from a single oscillator 100 ways. This would entail tremendous losses. It is apparent that another approach is required. A much better geometrical arrangement is to use annular laser amplifiers. The gain medium of a 10 kJ annular laser amplifier for short pulses must be approximately 200 cm long with a major diameter of 100 cm and a minor diameter of 25 cm for the annular optical aperture. The oscillator pulse will then be split to form ten annular beams for amplification.

Consider now the pumping supplies for the power amplifiers. Depending on developments for improving the efficiency of the short pulse CO_2 lasers, such as multiline and multiband operation, the power amplifiers will need an energy input of 25 to 50 times the laser energy output, or 250 to 500 kJ per 10 kJ beam. High voltage PFN inductance effects limit the energy delivered to about 100 to 200 kJ for efficient transfer on the required time scale. A power amplifier of such a size as to require more than this can be driven by parallel PFN "modules". Such a module might have the characteristics:

output voltage	-	300 kV
load impedance	-	2 Ω
pulse length	-	3 μsec
stored energy	-	150 kJ .

It is necessary to transfer the energy from the store to the load through a low inductance transmission line. The solution to this problem today is coaxial cables, which are at best bulky, expensive, and difficult to handle. The development of better high voltage transmission lines is a necessity.

References

1. R. E. Stapleton, et. al., "Electron-Beam-Controlled Gas Lasers: Discussion from the Engineering Viewpoint. Part I. Design of the LASL 1 kJ and 10 kJ CO_2 Lasers.

2. G. N. Glascoe and J. V. Lebacqz, Pulse Generators (Radiation Laboratory Series, V. 5), McGraw-Hill, 1948, pp. 175-207.

3. G. K. Kartsev, et.al., Soviet Physics-Doklady 15, 475 (1970).

4. H. G. Ahlstron, et. al., Appl. Phys. Lett. 21, 492 (1972).

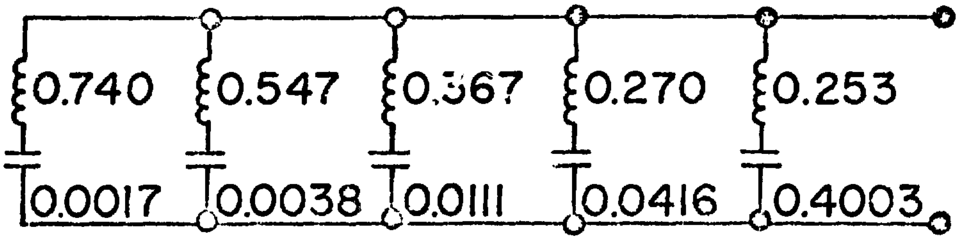
5. G. Dezenberg, C. Cason, and R. Huff, to be published.

6. R. O. Hunter, et. al., 1973 IEEE/OSA Conference on Laser Engineering and Applications, Washington, D. C., May 1973.

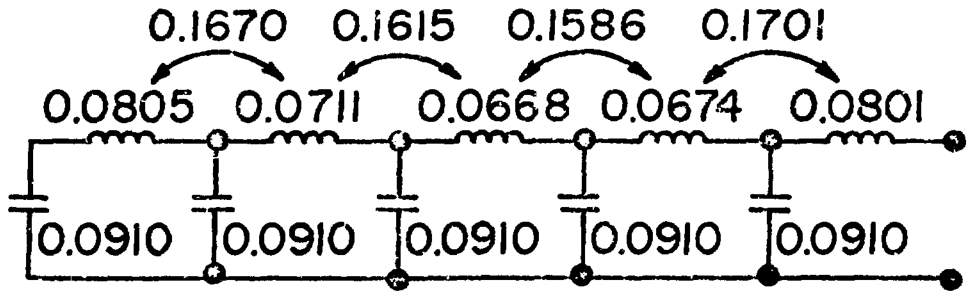
7. V. A. Danilychev, 1973 IEEE/OSA Conference on Laser Engineering and Applications, Washington, D. C., May 1973.

8. W. Leland, et. al., Twenty-fifth Annual Gaseous Electronics Conference, London, Ontario, October 1972.

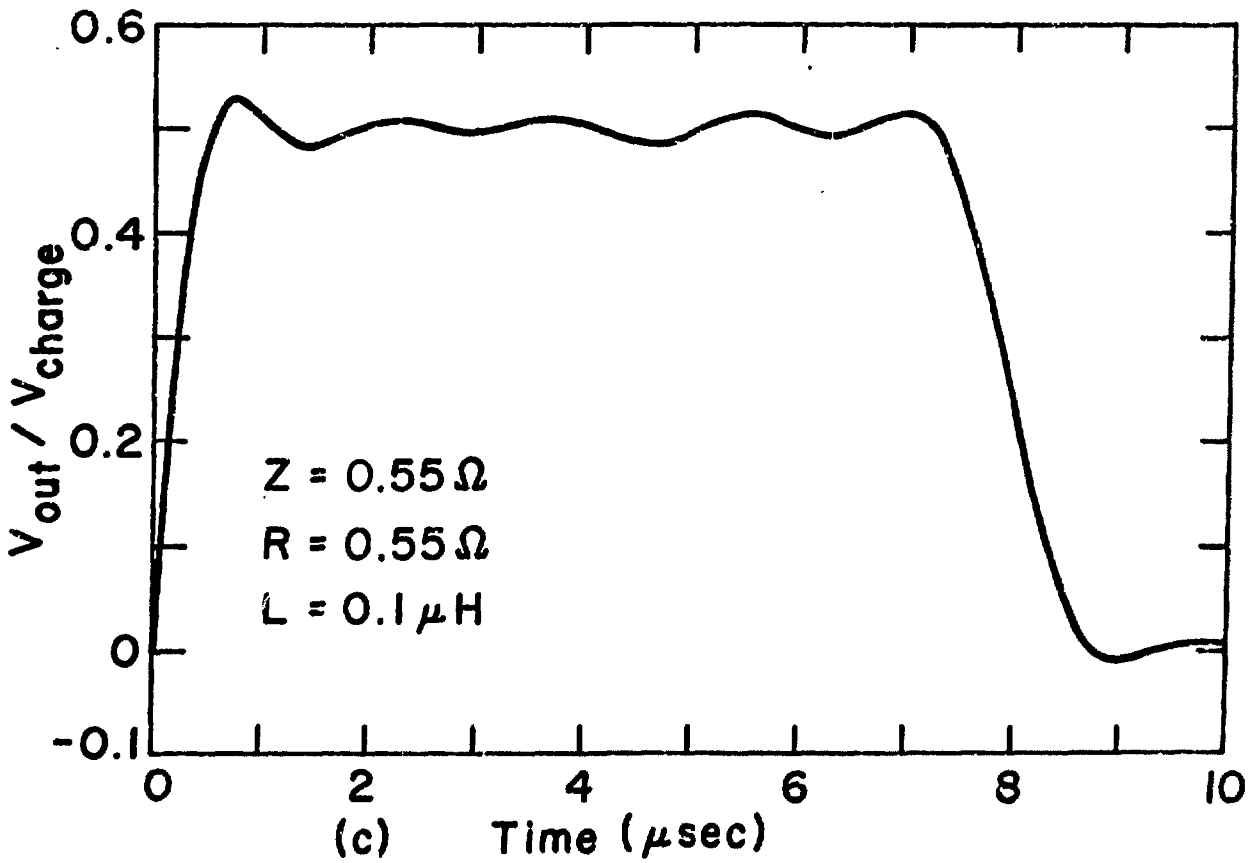
9. R. C. Knechtli and G. N. Mercer, 1973 IEEE/OSA Conference on Laser Engineering and Applications, Washington, D. C., May 1973.


0.740
0.547
0.367
0.270
0.253
0.0017
0.0038
0.0111
0.0416
0.4003

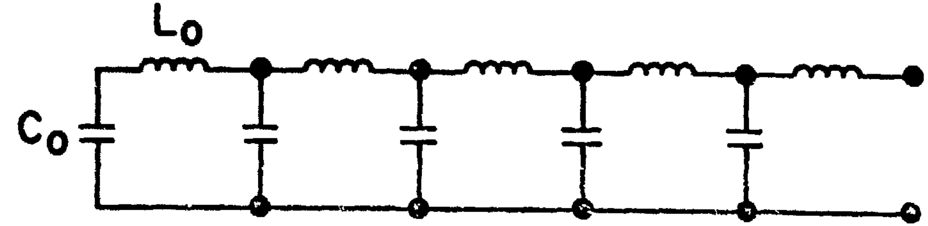
(a)


0.1670
0.1615
0.1586
0.1701
0.0805
0.0711
0.0668
0.0674
0.0801
0.0910
0.0910
0.0910
0.0910
0.0910

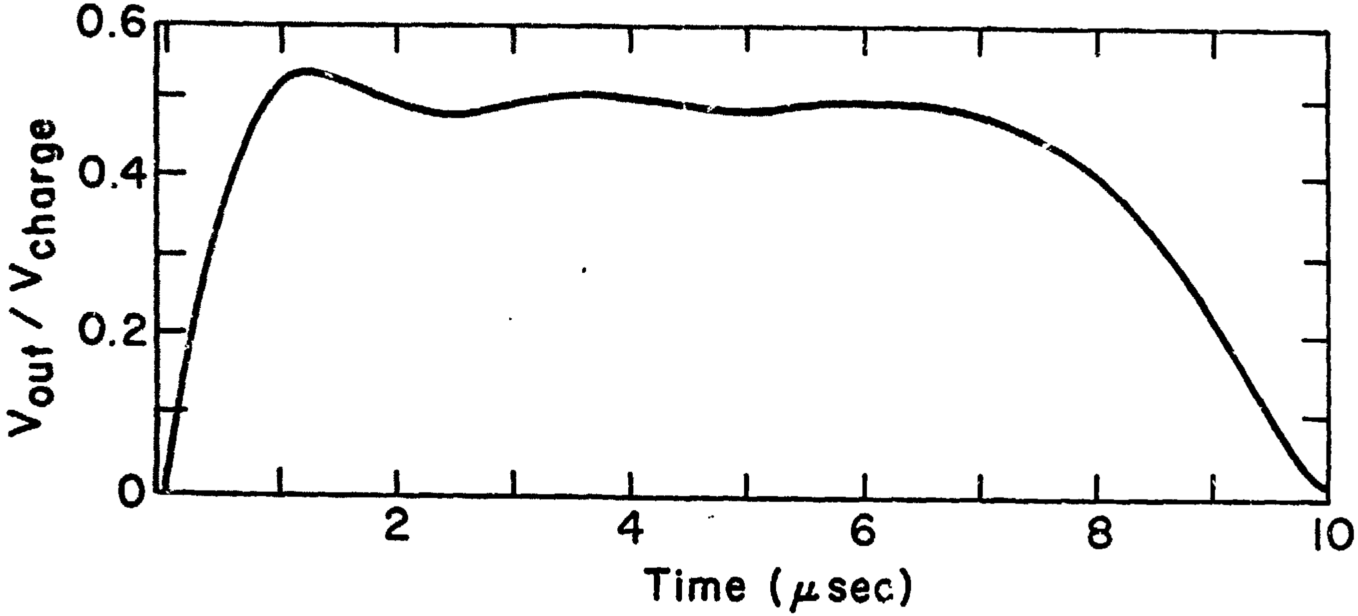
(b)


V_{out} / V_{charge}
0.6
0.4
0.2
0
-0.1
Z = 0.55 Ω
R = 0.55 Ω
L = 0.1 μH
0
2
4
6
8
10
Time (μsec)

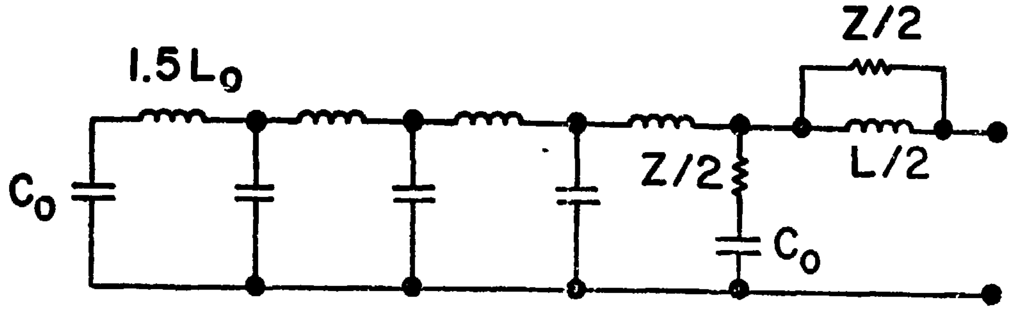
(c)



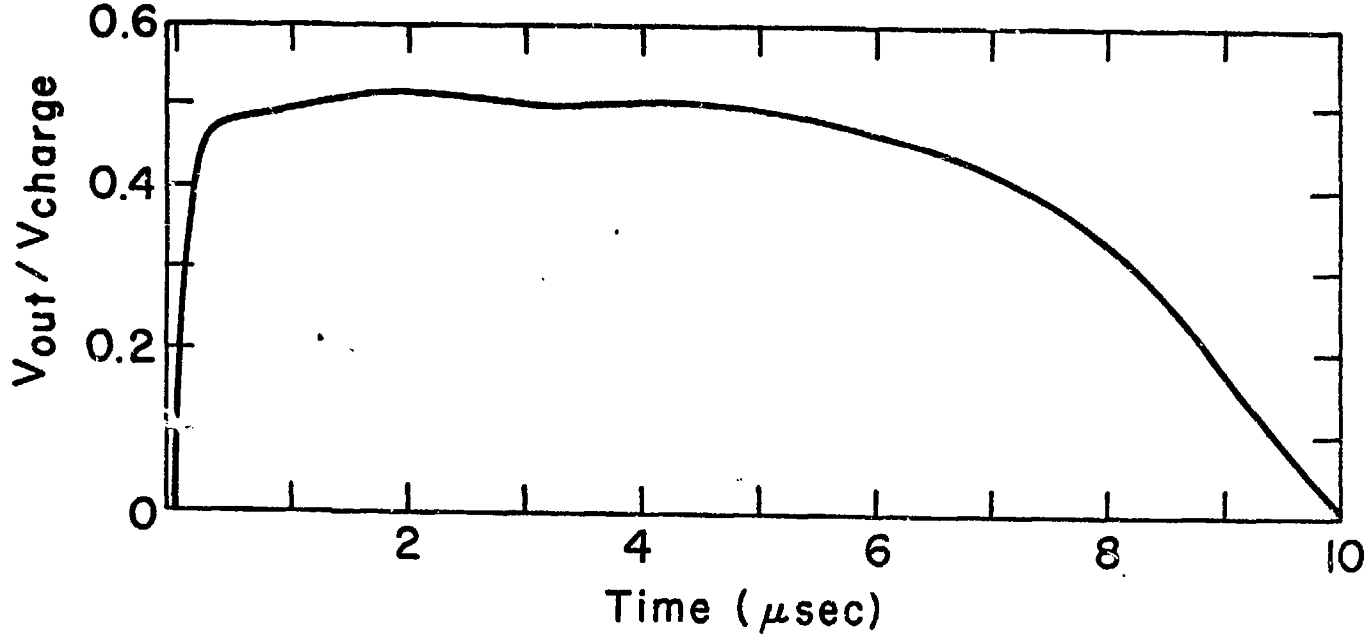
(a)



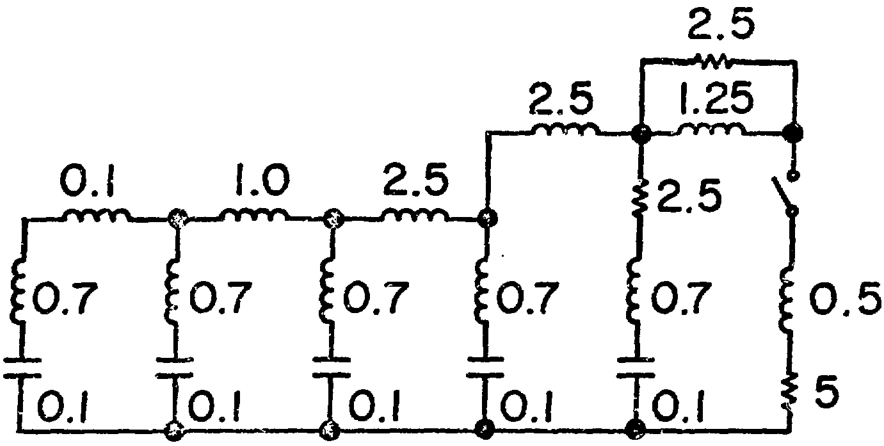
(b)



(a)

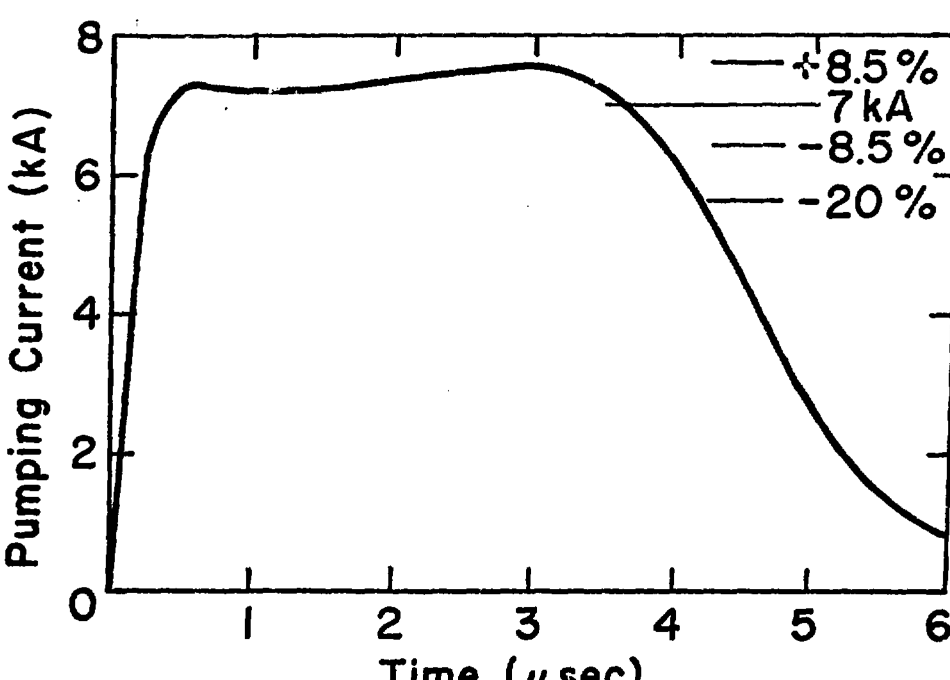


(b)



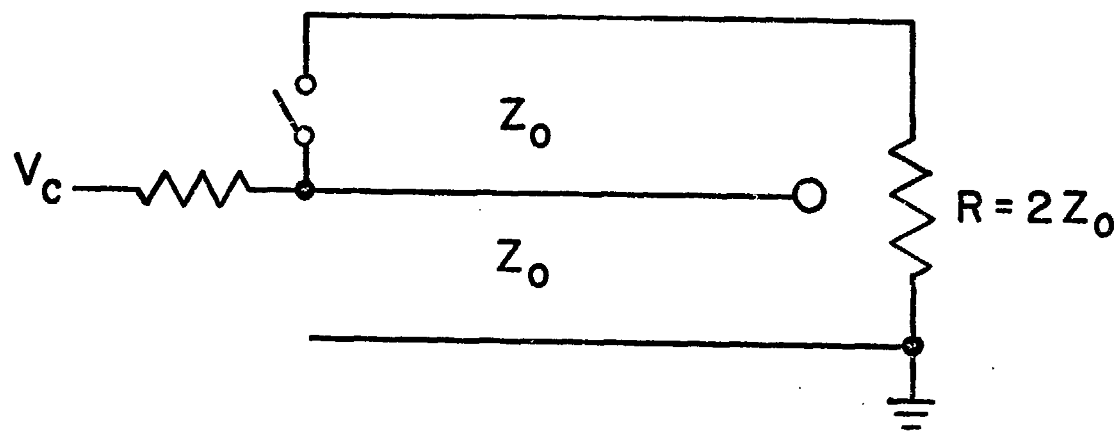
2.5
2.5
1.25
0.1
1.0
2.5
2.5
0.7
0.7
0.7
0.7
0.7
0.5
0.1
0.1
0.1
0.1
0.1
5

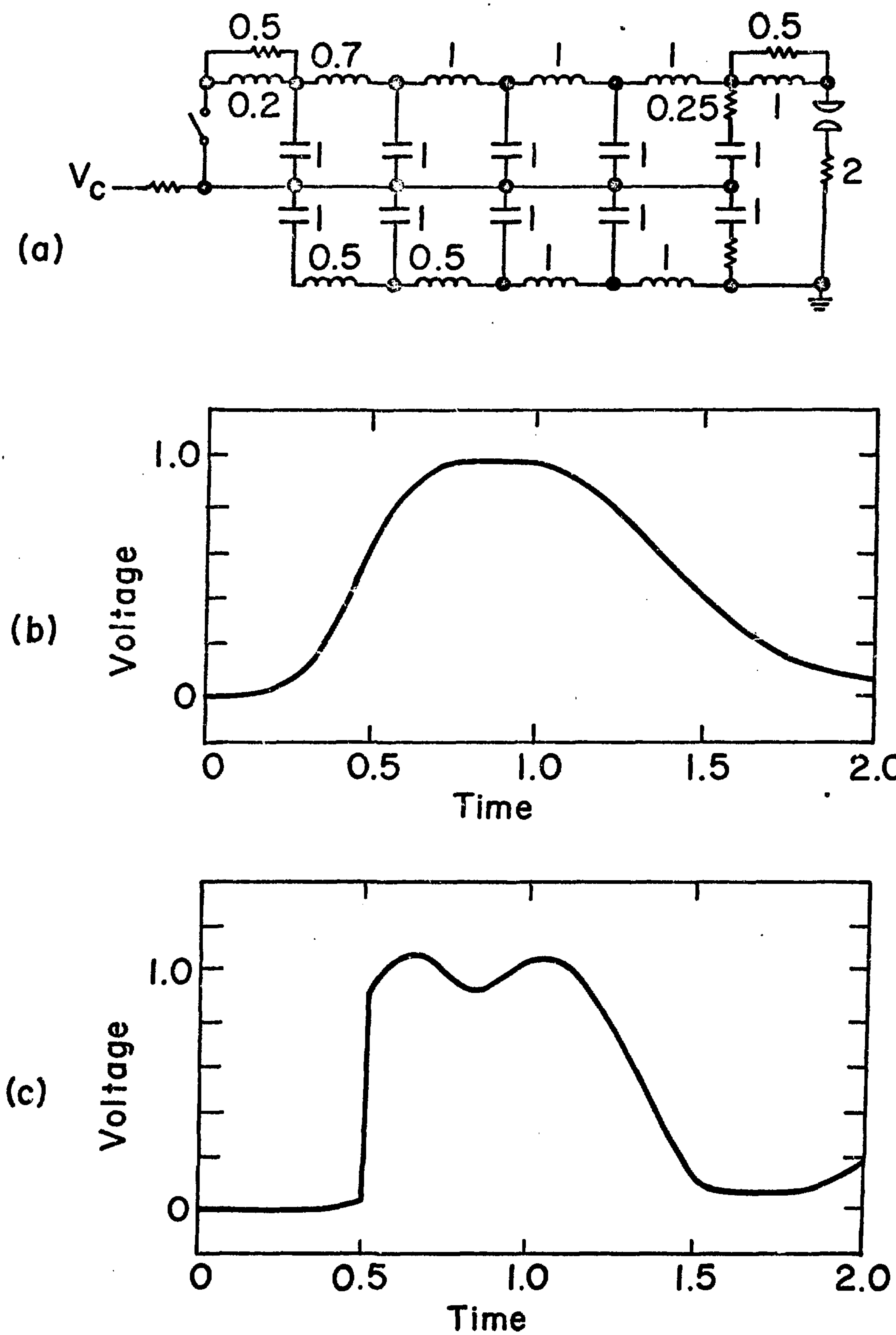
(a)

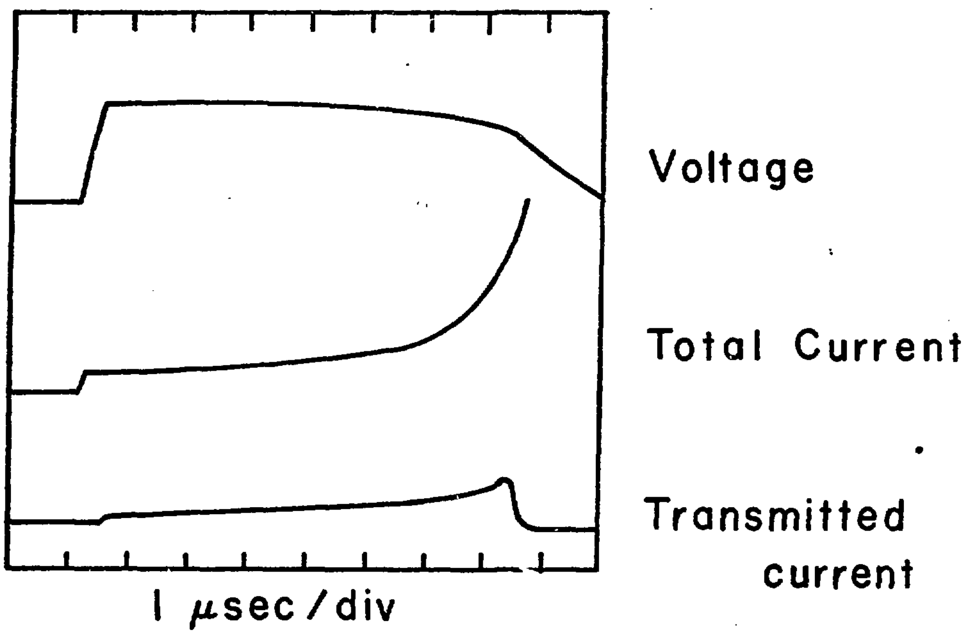


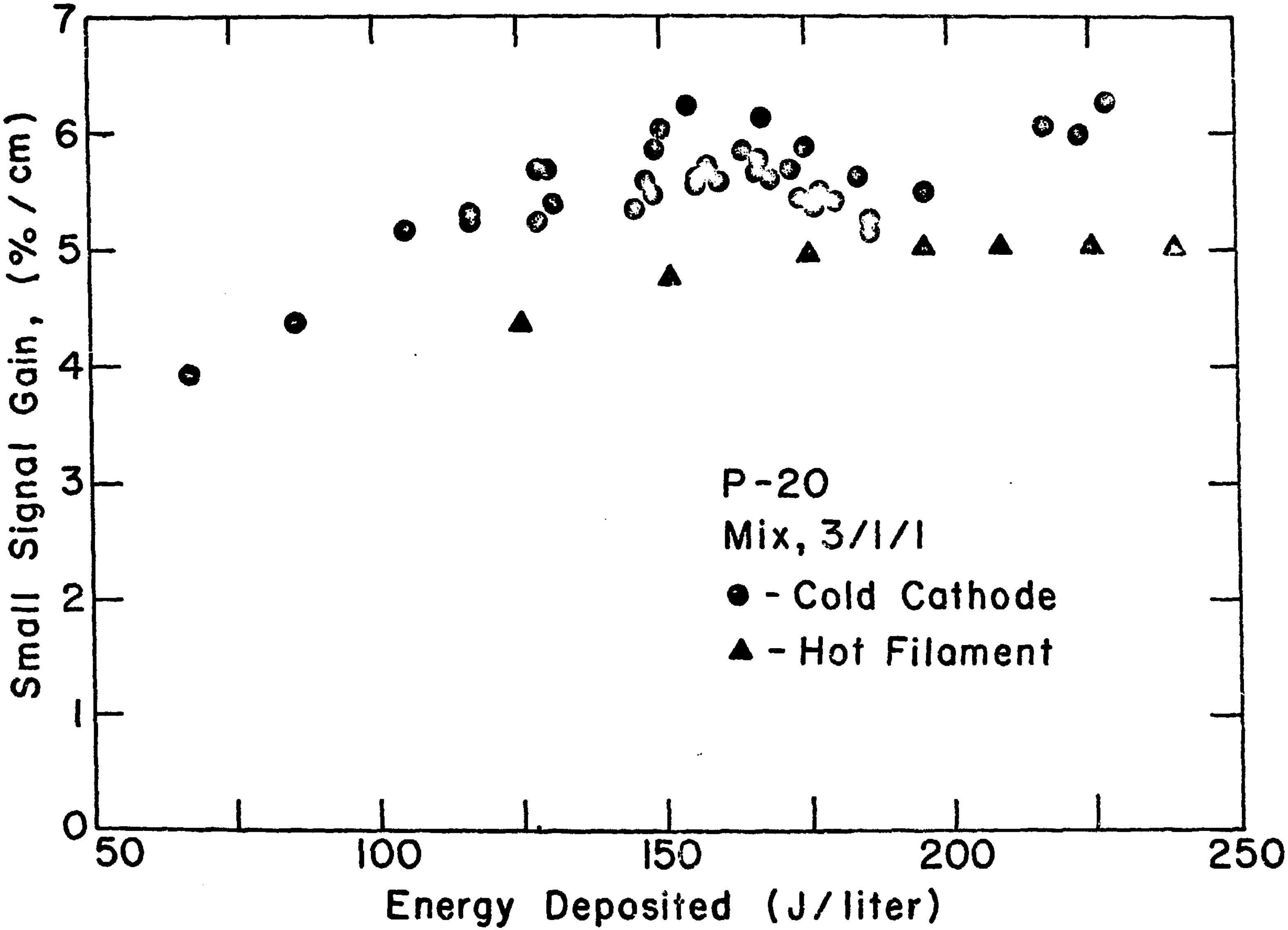
+8.5%
7 kA
-8.5%
-20%
Pumping Current (kA)
Time (μsec)
0
2
4
6
8
1
3
5

(b)

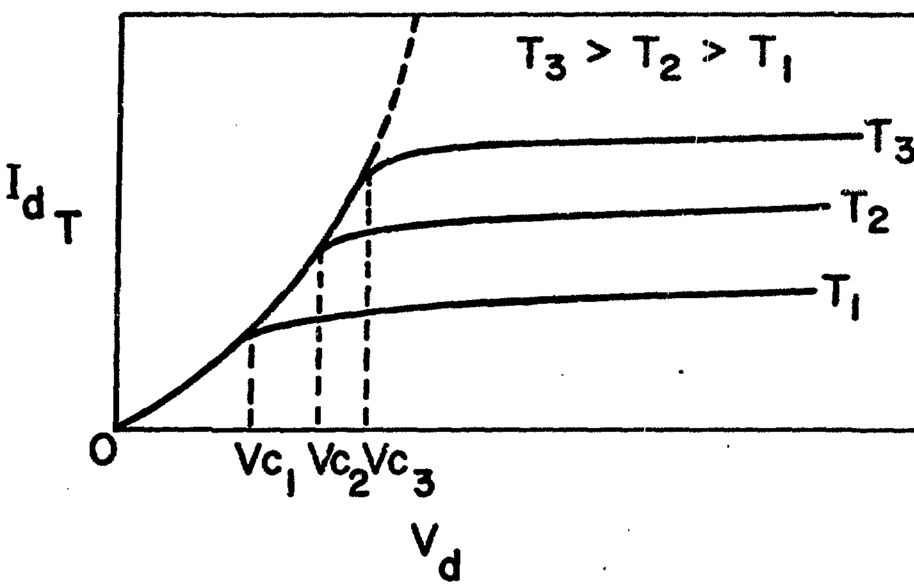

Vc
Zo
Zo
R = 2 Zo

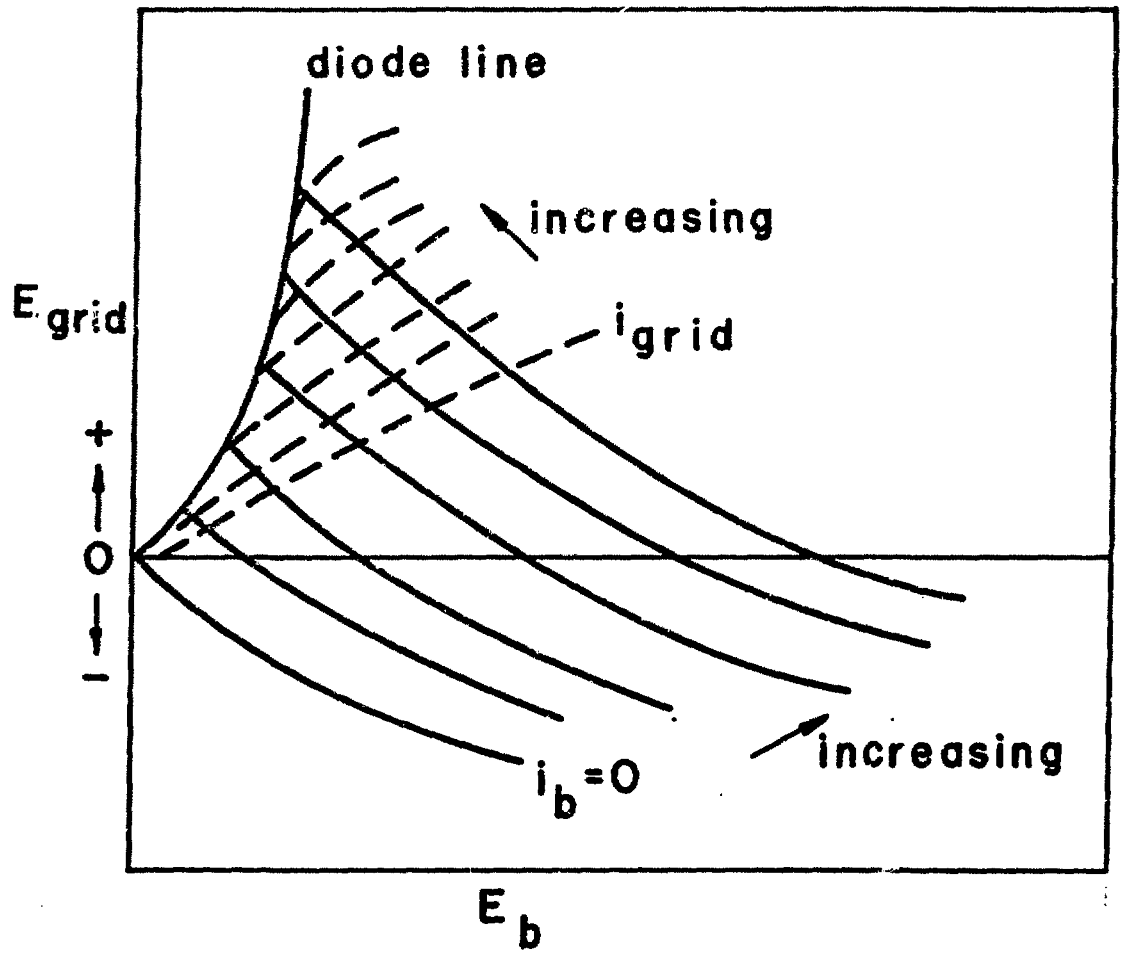

(a)
0.5
0.7
0.2
0.25
0.5
1
2
Vc
(b)
Voltage
Time
1.0
0
0.5
1.0
1.5
2.0
(c)
Voltage
Time
1.0
0
0.5
1.0
1.5
2.0


Voltage
Total Current
Transmitted current
1 μsec/div



7
6
5
4
3
2
1
0
Small Signal Gain, (% / cm)
50
100
150
200
250
Energy Deposited (J/liter)
P-20
Mix, 3/1/1
● - Cold Cathode
▲ - Hot Filament


T3 > T2 > T1
T3
T2
T1
Id T
O
Vc1 Vc2 Vc3
Vd


diode line
increasing
E grid
i grid
+
0
−
increasing
i b = 0
E b