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RESEARCH ON STORAGE DIODE LASERS

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ACKNOWLEDGMENTS

The research described herein covers the period from 1 April 1963 through 15 May 1964. Some preliminary concepts regarding storage diode lasers were developed prior to that time particularly as a part of research sponsored by Contract No. AF19(604)-7271 from the Air Force Cambridge Research Laboratories to Northeastern University. Research on storage diode lasers continues subsequent to the reporting intervals and some of this work is also described.

In addition to the listed authors, the following graduate students have contributed to this research effort Peter Hansen, Charles Hawkins and Syed Rizvi. In addition, Neal A. Sullivan and Edward L. Withey have contributed valuable part-time consulting effort especially as regards to instrumentation.

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SUMMARY

Research on Storage Diode Lasers

Research on a proposed storage diode laser is described in detail. The project objectives are (1) completion of design theory (2) basic parameter measurements (3) experimental proof (4) fabrication of effective devices. The proposed storage diode laser was originally and independently conceived by the authors. The desirability of such a device in many potential applications is discussed. The design theory is presented in detail. Representative estimated numbers are presented. Four possible storage diode laser configurations are described, of which the most promising involves a low current storage pulse and high current trigger pulse in a long lifetime material. The possibility of obtaining long lifetime by the shift from direct to indirect transition is discussed. Negative experimental results with extreme high current pulses in germanium and silicon are presented. Additional experiments required for proof are described. Related experimental results on the observation of reverse emission of gallium arsenide, and on the shift of the absorption edge in germanium are presented. The design of diode laser pulsers is reviewed in general. Three specific circuit configurations are presented. An electrical double pulser is described. And finally the technology of image converters and coolers used is described.

OBJECTIVES

The general objective of this program has been to perform research on development on a proposed storage diode laser.

More specifically, the objectives have been:

(1) completion of conceptual and design theory of storage diode lasers,

(2) perform basic measurement on various materials for possible use in storage diode lasers,

(3) experimental proof of storage diode laser principle,

(4) fabrication of effective storage diode lasers.

DESIGN CONCEPTS

Definition

A storage laser may be defined as any laser which stores energy prior to lasing. A storage diode laser is then obviously defined as a diode laser which stores energy prior to lasing. Stated in more detail, a storage diode laser may be defined as an active p-n junction device in which some carriers are electrically excited (injected minority carriers) for a period of time which is longer than the period of time during which laser action from these excited states takes place. Thus, a storage diode laser, exhibits power gain, that is during some portion of the operating time more optical power is emitted than electrical power input during that same portion of operating time. A storage diode laser is just a mechanism for converting a low power (low current) long time input into a high power short time output. Essentially a long time electrical energy pulse is converted into a short time optical energy pulse. Under optimum conditions 1 joule 100 microsecond pulses might be converted to 10 nanosecond pulses in areas of 2 to 10 millimeters square.

A storage laser is just another, somewhat more general, term for a class of lasers which includes switched or giant pulse lasers. The authors prefer the more general term, especially as it applies to diode lasers not appropriately described otherwise.

Requirements

Qualitatively speaking, a storage diode laser has requirements almost opposite to those of a good diode laser. Namely, one desires a high threshold inversion density and a long spontaneous optical time constant from the upper to lower laser level. But, the device must still be capable of laser action.

Potential Applications

There are numerous potential applications in which a short high intensity, peak power, coherent laser pulse is desired. These include optical ranging, some clases of optical communication (where absorption and not background noise is a problem), certain drilling and cutting and shock wave application. In all these applications a high efficiency, direct conversion, high peak power storage diode laser would be of extreme value. Indeed, in the opinion of the authors, a number of these applications will never become truly practical until such a storage diode laser, operating at room temperature is developed.

DESIGN THEORY - BASIC LASER EQUATION

The basic laser equation first derived by Schawlow and Townes, can be derived from several different approaches, all equivalent, and each of which emphasizes certain physical aspects, parameters or measurements.

Oscillation occurs in a cavity for which the gain exceeds the losses at some specific frequency

$$G > L \quad \text{at some frequency in a cavity.}$$

Coherent laser radiation occurs from a stimulated emission oscillation. The simplest expression for the basic laser equation is just

$$G_{stim} \geq L = L_{stim} \quad \text{at some frequency within a cavity.}$$

For a linear cavity (the simplest case) we may write

stimulated gain per unit length ≥ loss per unit length.

But the gain per unit length is just the absorption constant α

$$\frac{\text{(gain)}}{\text{(unit length)}} = \frac{\frac{dI}{I}}{dx} = -\alpha \qquad (\text{from } dI = -\alpha I dx). \tag{2}$$

So the basic laser equation may be written from the absorption viewpoint

$$\alpha_{stim} \geq \alpha_{loss} \qquad \text{at some specific frequency } \nu \tag{3}$$

where α_{loss} includes all loss mechanisms at the frequency ν.

All the losses can, in general, be described in terms of an effective uniformly distributed absorption constant. The simulated emission is always correctly described in terms of a negative absorption.

It should be emphasized that these two statements are the laser starting conditions (threshold conditions). The sustaining condition is considerably more complicated.

DESIGN THEORY - THE TIME CONSTANT APPROACH

The basic laser equation stated from the time constant viewpoint is just

$$n > p'_{\Delta\nu} \frac{t_{32\ \mathrm{spon}}}{t_{\mathrm{all\ loss\ in\ cavity}}},$$

where

$n = n_3 - n_2$ is the net inversion density between the upper and lower laser levels in excited states per cubic meter;

$p'_{\Delta\nu}$ = is the mode density within the optical line width in modes per cubic meter;

$t_{32\ \mathrm{spon}}$ = is the spontaneous optical time constant connecting the upper and lower level of the line in seconds;

$t_{\mathrm{all\ loss}}$ = is a characteristic combined exponential time constant describing all energy loss mechanism for the optical energy in seconds.

This expression may be obtained from the previously stated general statement of the basic laser equation by appropriate substitution [see for example A. Yariv and J. P. Gordon, PIEEE, vol. 51, pp. 4-29, January 1963].

DESIGN THEORY - THE DIODE CURRENT APPROACH

The basic laser equation stated from the absorption viewpoint may be elaborated to obtain an expression including the diode current density J_{TH} at threshold, the diode optical recombination width W, and the optical recombination efficieny η.

To do this we note the connection between the absorption constant and the Einstein B coefficient for stimulated emission. To obtain the stimulated emission rate we use the ratio between the spontaneous and stimulated emission coefficients. And we make the key assumption that the spontaneous rate is known from the current flow. (This result was first obtained by Lasher. The derivation here is slightly different.)

We assume the case of a four level laser scheme. The stimulated emission coefficient is given by

$$\alpha_{stim} = n\sigma = (n_3 - n_2)\sigma \qquad (4)$$

in units of $\frac{1}{cm}$ (σ in cm^2).

Both α and σ are dependent on frequency. The absorption cross section in cm^2 is related to the Einstein B coefficient for stimulated emission by

$$\sigma = B \frac{h\nu}{c} \frac{1}{\Delta\nu} . \qquad (5)$$

Sometimes knwon as the Fuchtbaver-Ladenburg relation. Note that the dimensions and units balance as B is

$$\frac{\text{transitions}}{\text{state}} \; \frac{1}{\text{second}} \; \frac{1}{\frac{\text{joule}}{cm^3}} \; \frac{1}{\frac{1}{\frac{\text{cycles}}{\text{second}}}} = \frac{cm^3}{\text{joule-sec}^2} = \frac{cm^3}{\text{joule-sec}^3} .$$

And further the ratio of the spontaneous to stimulated coefficients is

$$\frac{A}{B} = p(\nu)\ h\nu \qquad \text{or} \qquad B = \frac{A}{p(\nu)\ h\nu}\ , \tag{6}$$

where $p(\nu)$ is the mode density. Substituting B, from (6) into (5), and then into (4), we obtain

$$\alpha_{stim} = (n_3 - n_2)\ \frac{A}{p(\nu)\ h\nu}\ \frac{h\nu}{c}\ \frac{1}{\Delta\nu} \tag{7}$$

$$= \frac{A}{p(\nu)c}\ \frac{1}{\Delta\nu}\ . \tag{8}$$

Now A is just the spontaneous transition rate

$$\left(\frac{dn_3}{dt}\right)_{\substack{spon \\ 3-2}} = n_3 A_{32} = n_3 A \tag{9}$$

in transitions per second per centimeter cubed (for the whole emission line or frequency spread). For the case n_2 small compared to n_3, we can substitute (9) in (8)

$$\alpha_{stim} = \left(\frac{dn_3}{dt}\right)_{spon}\ \frac{1}{p(\nu)}\ \frac{1}{c}\ \frac{1}{\Delta\nu}\ . \tag{10}$$

Now we assume that the spontaneous emission all comes from the injected current carriers and this the rate depends upon J, the current density. Specifically we assume the injected carriers are converted to photons with an constant efficiency η uniformly in a volume of width w. The rate is just

$$\left(\frac{dn_3}{dt}\right)_{spon} = \left(\frac{J\eta}{ew}\right) \tag{11}$$

where we have divided by the charge per carrier to get transition per unit area and divide by w to get transition per unit volume.

Substituting (11) in (10)

$$\alpha_{stim} = \left(\frac{J\eta}{ew}\right)\left(\frac{1}{p(\nu)} c\Delta\nu\right) \tag{12}$$

and substituting (12) in (3) and rewriting for the current we obtain

$$J_{TH} \geq p(\nu)\, \Delta\nu\, c\, ew(1/\eta)\alpha_{loss}. \tag{13}$$

This expression may be rewritten three different ways to emphasize different points. Since

$$p(\nu) = \frac{8\pi\nu^2}{c^3} = \frac{8\pi\nu^2}{\frac{c^3}{n^3_{index}}} = \frac{8\pi n^2_{index}}{\lambda_{vac}} \frac{1}{c}\ , \tag{14}$$

then

$$J_{TH} \geq \frac{8\pi\nu^2}{c^2} \Delta\nu \frac{ew}{\eta} \alpha_{loss}\ , \tag{15}$$

$$J_{TH} \geq \frac{8\pi}{\lambda^2} n^2_{index} \Delta\nu \frac{ew}{\eta} \alpha_{loss}(\nu)\ , \tag{16}$$

$$J_{TH} \geq 6.3.10^4\, n^2_{index} \frac{w}{\eta} E^2\Delta E\, \alpha_{loss}(\nu)\ , \tag{17}$$

where $E = h\nu$ in electron volts

$\Delta E = h\Delta\nu$ in electron volts.

The Loss Terms

In general α_{loss} is made up of several terms which describe all radiation loss mechanisms, some or all of which might be frequency dependent. For example

$$\alpha_{loss}(\nu) = \alpha_{\substack{free\\carrier}} + \alpha_{scatt} + \alpha_{mir} + \alpha_{diff} + \alpha_{unknown}.$$

For a linear cavity wherein the beam undergoes multiple reflection at the ends or mirrors, one effective distributed loss term is

$$\alpha_{mir} = \frac{T}{L}$$

where L is the length of the cavity and T is the fractional transmission of the end mirror. Written more properly from the integral viewpoint

$$\alpha_{mir} = \frac{\gamma}{L} = (\frac{1}{2} \ln R_1 R_2)/L.$$

For a narrow radiating width w, diffraction losses from the slit will be important and

$$\alpha_{diff} = .42 \frac{\lambda}{n_{index} w^2} .$$

Another important loss mechanism is the so called "free carrier absorption", that is, the "intraband absorption" of the injected carrier themselves. This loss mechanism is the absorption of photons by the carriers which raises the carriers to higher energy state within the band, but not across the band. These excited carriers quickly return to the lower energy state by a thermal process (multiple phonon emission). An expression for the free carrier absorption is

$$\alpha_{\substack{free \\ carrier}} = n_3 \sigma_{free} = n_3 \frac{e^3}{4\pi^2 c^3 n_{index} \epsilon_o} \cdot \lambda^2 \frac{1}{n_{eff}^2 \mu} .$$

Note the dependence on the number of carriers on the square of the wavelength.

The other loss mechanism cannot be easily described or evaluated.

LASER START CONDITION AND LASER SUSTAINING CONDITION

The previous expressions for the basic laser equation are all laser start conditions. Once the threshold condition is reached, the radiation field builds up exponentially in space and time. After a few (5 to 10) internal reflections, the field distribution is probably quite stablized (but not necessarily constant in space and time). Because of the radiation field build up, the laser sustaining condition for current (or inversion density) can be much less stringent than the laser start condition. [This condition has not been observed in diode lasers.]

The sustaining condition in its simplest form is identical with the elementary statement of the laser equation, namely

$$\alpha_{stim} = \alpha_{loss}.$$

The new equality results because either the losses increase or the inversion density goes down. Losses may increase because of field dependent loss mechanisms, or because of new loss mechanism observable only at high field, etc. The inversion density may decline due to limitation on pump capacity. The exact solution of the rate equations which determine the inversion density and field condition is very difficult. However, adding a field dependent, variable, unknown loss mechanism compounds the difficulty. It is doubtful that any solution obtained would have practical meaning.

SOME NUMBER ESTIMATES

Atomic Density

The number of atoms per cubic centimeter is given by

$$N = L/(MW/d)$$

where I is avogader's number, MW the modlecule weight and d the density

For germanium and silicon

$$N_{Ge} = 4.4 \cdot 10^{22} \text{ atoms/cc}$$

$$N_{Si} = 3.7 \cdot 10^{22} \text{ atoms/cc.}$$

Most semiconductors do not differ greatly from these values. We shall assume $N_{general} = 4 \cdot 10^{22}$.

Maximum Energy Storage

If we assume a relatively large band gap of 2.0eV ana since no more than one excited state per atom is possible, the maximum energy storage is

$$E_{max} = N_{gen} \cdot 2\text{eV}.$$

Since $\quad 1\text{ev} = 16 \cdot 10^{-19}$ joules,

then $\quad E_{max} = (N_{gen} \cdot 2\text{eV})\ 1.6 \cdot 10^{-19}\ \text{J} = 12.8 \cdot 10^{3}$ J/cc.

This number is not greatly different from chemical binding energies.

In any laser, diode or otherwise, it would be extremely difficult to get over 5% excited states or

$$E_{max,5\%} = 6.4 \cdot 10^{2} \text{ J/cc.}$$

The maximum inversion density in a diode laser is given by the maximum number of doping carriers on one side of the junction. Degenerate doping levels as high as $4 \cdot 10^{20}$ have been achieved which corresponds to roughly 1% impurity atoms. Such a case might give a maximum stored energy of

$$E_{max,1\%} = 1.3 \cdot 10^{2} \text{ J/cc}$$

which is still a large number.

Since convenient doping levels of $5 \cdot 10^{19}$/cc are obtained and since complete elimination of the junction by injection is impossible, then a more convenient and practicable injection inversion number is $1 \cdot 10^{19}$/cc or

$$E_{store,10^{19}} = 13 \text{ J/cc}.$$

This number corresponds to the maximum energy storage for optimum ruby and neodymiun glass. In fact, a few joules per cc have been stored and lased out, somewhat below the anticipated limits.

Practical Size Limitations

Based on experience with silicon power diodes, one can estimate a maximum practical diameter of the storage diode of a few inches. A basic square unit of 5cm on a side has a storage volume of

$$V_{store} = L^2W = 36 \cdot .5 = 10\text{cc}$$

or stored energy of

$$E_{max,1\%,6cm} = 2300 \text{ joules per diode.}$$

A more modest and practical diode of leV energy gap, with an area of 1cm^2 and a diffusion length of 1mm and a storage inversion density of $1 \cdot 10^{19}$/cc would store

$$V_{ac} \approx .1\text{cc}$$

$$E_{store,10^{19},1eV} \approx .16 \text{ joules per diode.}$$

Current Requirements

The pulse current requirements are large but practical. The low injection, linear theory is

$$J_e = e \frac{P}{L} \eta_{AT\ JCT} \cdot$$

where J_e is the current density and $n_{AT\ JCT}$ is now the excess non-equilibrium charge density at junction which can be taken as the inversion. This relation gives approximate numbers.

However, the large signal case may be approximated from just a knowledge of the number of carriers to be injected, the percentage recombination, and the number of diffusion lengths being injected into.

Thus for the 10^{19} case,

$$J \approx 16{,}000 \text{ amps/cm}^2,\ 10^{-4} \text{ secs.}$$

For the extreme case of $4 \cdot 10^{-4}$ carriers, currents approximate 200,000 amps/cm^2 for 10^{-4} secs and smaller if the time constants are longer.

Efficiency

Above threshold, the output of a diode laser is generally linear with the input pump current. This implies a constant efficiency. A constant efficiency is somewhat surprising.

There are at least three possible interpretations of constant efficiency:

(1) constant, 100%, internal quantum efficiency in either the spontaneous or stimulated condition,

(2) a dominate energy loss mechanism which is linearly dependent on inversion density or current,

(3) a precise, constant (fractional) current or optical division within the diode.

The first effect, a constant 100% conversion efficiency, would not permit variation in external efficiency.

The second effect has more implications.

A dominate loss mechanism may actually be a combination of two or more mechanisms each dependent on inversion density. Since diffraction losses, α_{diff}, and end mirror losses $\alpha_M = \frac{T}{L}$, or $\alpha_M = \frac{\gamma}{L}$, are independent of inversion density they cannot be the dominate loss mechanism. Similar comments apply to junction irregularities and material imperfections (except in current division). All the these factors can only effect the threshold level.

Thus the dominate loss mechanism is probably the so called "free carrier absorption   the injected carriers; i.e., intraband absorption of injected carriers. However, this leads to serious difficulties because the injected carrier density is quite low (10^{14} - 10^{16}/cc) and the known free carrier absorption cross section is too low to give a combined large absorption.

The third effect current or optical division is self-explanatory. Two separate diode regions operating independently would give a constant efficiency.

STORAGE DIODE LASER CONFIGURATIONS

These are at least four conceivable storage diode laser configurations, namely

( ) simple storage diode laser utilizing long time constant material and an electrical double pulser,

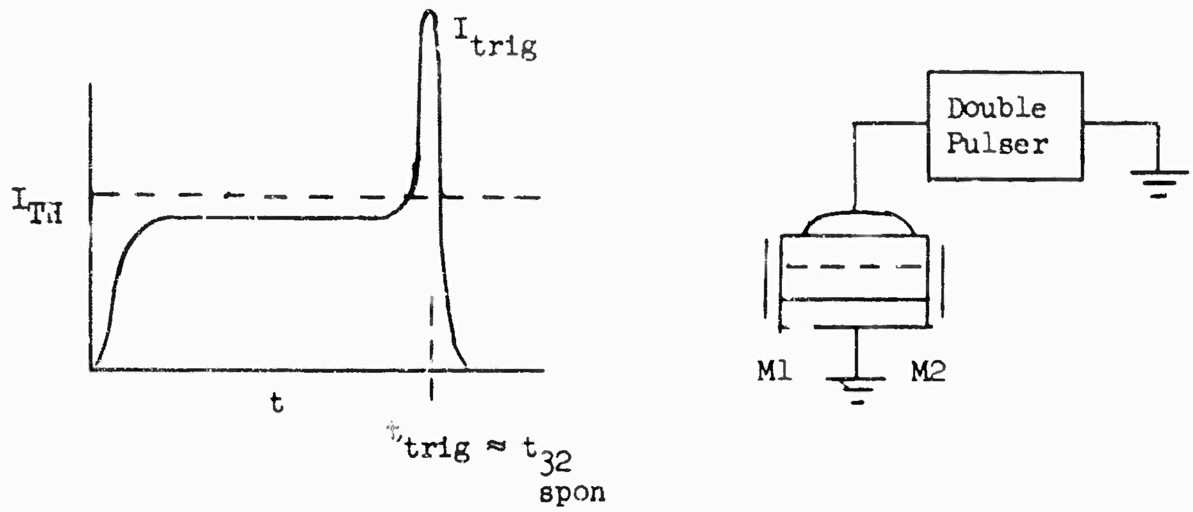
(2) a two region diode including separate storage and trigger regions,

(3) a Q-switched storage diode laser, i.e., an anti-reflection coated diode and an external shutter,

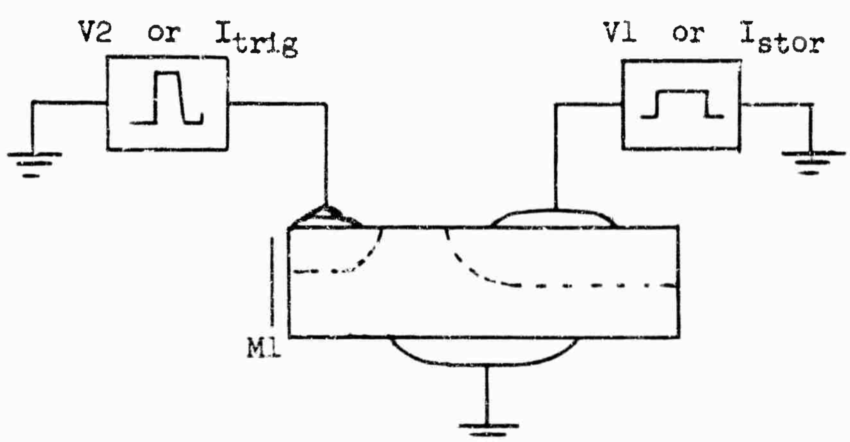
(4) an optically triggered simple storage diode (not an oscillator - amplifier).

These are schematically illustrated in the accompanying figures.

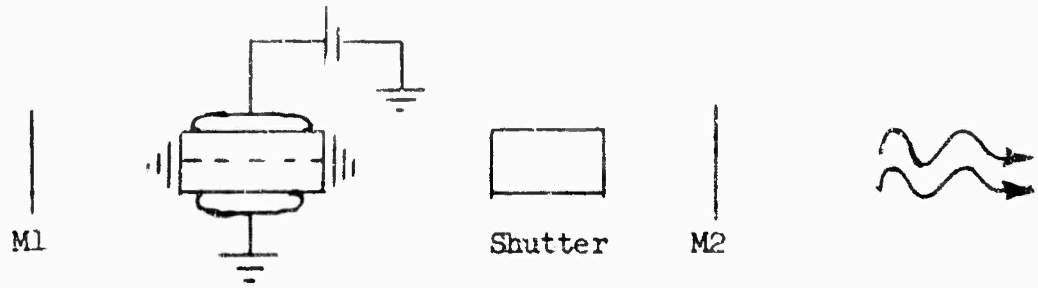
Each configuration is designed to store injected charge prior to lasing.



Storage Diode Laser Utilizing Long Time Constant Material
and an Electrical Double Pulse

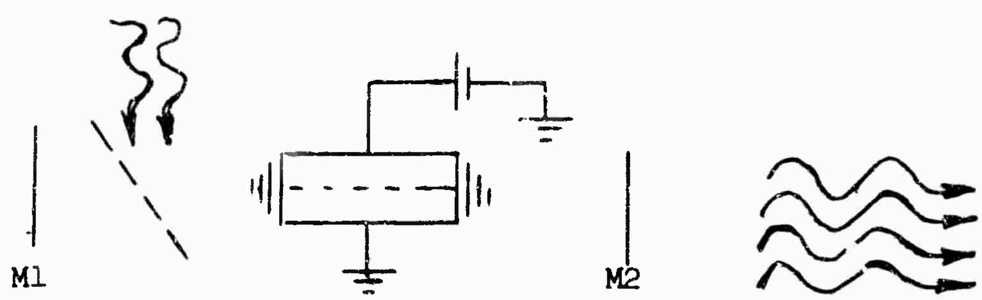


Two Region Diode Comprising Separate Storage and Trigger Regions



Q-Switched Storage Diode Laser

C1, C2	Anti-Reflection Coatings on Diode Laser
M1, M2	External Mirrors
Shutter	Electro-Optical Kerr Cell or Rotating Prism, or Passive Q-Switch, etc



Optically Triggered Storage Diode Laser Undergoing Internal Oscillation, Not Necessarily Amplification

LASING DIFFICULTIES IN INDIRECT MATERIALS - THE QUICK DECAY OF THE PHONON FIELD

According to present, simple, laser theory as described in the previous sections the laser condition is dependent only on the optical time constant (or equivalently, the cross section) for the optical reaction. Indirect materials have been pumped at levels close to those which should produce laser action according to the simple theory.

Thus one is led to suspect that there may be some consideration which maintains the basic symmetry of the physical process but which reduces substantially the probability of occurrence. Stated another way; if there is spontaneous emission there must be stimulated emission, but the probability of stimulated emission must be extremely low.

Such a consideration is available in the quick decay of the phonon field.

The indirect optical recombination process involves the emission of photon and at least one phonon. The symmetric process, indirect stimulated emission, involves the simultaneous emission of both photon and phonon, induced by simultaneous coherent photon and phonon fields. However, at normal temperatures a vibrational radiation field degrades much quicker (10^3 to 10^6 times) than an optical field.

The basic laser equation for a direct process, from the mode viewpoint, states that

$$n > p'_{\Delta\nu} \frac{t_{32_{\text{spon}}}}{t_{32_{\text{spon}}}}$$

where the symbols are as previously defined.

Since the photon and phonon fields are completely uncoupled, the laser equation must be satisfied simultaneously and independently for both photons and phonons. Thus

$$n > p'_{\Delta\phi} \frac{t_{\phi_{32}}}{t_{\phi_{\text{all loss}}}}$$

where the subscript ϕ represents the phonon, and ϕ the phonon frequency in cycles per second.

The phonon equation is much harder to satisfy for two reasons. The phonon mode density within the emission line width $p'_{\Delta\phi}$ is much larger because the velocity of propagation is much smaller. And the phonon loss time constant $t_{\phi_{\text{loss}}}$ is determined by phonon-phonon and phonon-electron collisions. At temperatures above 30°k this is essentially the time between collisions which is very short, typically 10^{-9} to 10^{-12} seconds.

However, at very low temperatures near 0°k, there is a well-known anomaly in the thermal conductivity of most solids which implies the phonon mean free path becomes comparable to sample dimensions, or $t_{\phi_{\text{loss}}}$ goes to 10^{-5} seconds. Under such conditions the phonon laser equation could be satisfied and indirect stimulated transitions possible.

SHIFT FROM DIRECT TO INDIRECT TRANSITIONS

It has occurred to the authors that the shift from indirect to direct transition or vice versa might be a mechanism for controlling the optical time constant of the transition, and in particular, a mechanism for getting acceptably long lifetime for storage effects.

The lasing difficulties in indirect materials should be kept in mind. Such concepts were not well developed when the shift idea was first conceived.

It was thought that carriers could be stored in an indirect gap and laser action commenced in a slightly higher energy, direct gap, with short high current injection pulse (band filling). The laser action would then empty the lower indirect gap by virture of the high intensity stimulating radiation field. But it would now appear that without the simultaneous phonon field, at very low temperature, such stimulated emission would be impossible.

There are two physical processes for controlling the direct-indirect transition

(1) single crystal alloy mixtures of direct and indirect materials (such as investigated at length by N. Holonyak and co-workers),

(2) heavy doping of selected single crystal materials for which the direct and indirect band edge are not greatly separated (e.g., Ge or GaSb).

An attempt was made to partially fill the indirect gap in germanium by heavy impurity doping. [See the section on absorption shift in germanium.] With heavy doping the direct gap does become smaller due to other effects. The density of states in the indirect gap is, however, so great that band filling appears to be impossible. In the case of other materials, with extreme parabolic bands, some filling might be possible.

Gallium atimonide appears to have an indirect gap slightly above the direct. Diodes might be constructed with thresholds too high for the direct gap. Heavy current pumping could store carriers lased out of the lower level by an optical pulse or a Q switch.

Mixed crystals might product direct and indirect gaps at exactly the same energy and partial storage in the indirect gap might be possible.

EXPERIMENTAL PRELIMINARIES AND TRAINING

For experience and training purposes, a variety of gallium arsenide diode lasers were fabricated. Operation has been obtained from 20°K to 300°K. Threshold current densities obtained in the best cases from 500 a/cm^2 to 300,000 a/cm^2 depending on the temperature. Sizes from .1 by .1mm to .5 by 1.5mm were operated successfully.

Diode fabrication techniques were either independently developed or copied, with the end results very similar to those used elsewhere and by now common. Principal steps were

(1) carefully flat polished slices,

(2) evacuated, sealed, quartz ampoule diffusion,

(3) overpressure of diffusants and sublimation products in ampoule [for GaAs, $ZnAs_2$],

(4) evaporated, micralloy ohmic contacts [usually Au],

(5) cleaved faces for cavity.

The most important quality elements seem to be

(1) selected or proper crystalline material,

(2) junction planarity including uniformity of diffused impurities,

(3) excellent cleaved cavity including perpendicularity,

(4) proper thermal mounting.

Diode lasers were fabricated in gallium arsenide. Diode radiation sources were fabricated in germanium and silicon. Preliminary diode attempts were made with indium arsenide and indium antimonide.

EXPERIMENTAL RESULTS - NEGATIVE

In the search for long time constant materials, germanium and silicon diode radiation sources were investigated in detail.

Silicon diodes doped with the acceptors of zinc and boron and donors of phosphorous were fabricated. Pulsed currents up to 100,000 amperes per centimeter squared at temperature down to 77°K were tried. Pulse lengths were about 40ns. No laser action was observed.

Germanium diode radiation sources were pulsed up to 500,000 amp/cm^2 at liquid nitrogen temperature (77°K).

Further Experiments Required - 4°K

A clear, negative result in indirect gap, long time constant, semiconductive materials cannot be stated until similar currents are passed through these diodes at temperatures below 20°K, preferably below 5°K. Such results may be forthcoming.

(Note added in manuscript preparation)

The Probability of Storage Action in InSb

Recent results by the Lincoln Laboratory group on indium antimonide suggest the high likelihood of experimentally observing storage diode laser action. In particular, Melngailis et al [Appl. Phys. Lett. Vol. 5 No. 5, p. 99, 1964] have demonstrated large volume laser action and optical time constants in the microsecond time region.

Significant storage effects are almost assured.

MISCELLANEOUS EXPERIMENTAL RESULTS

In the process of performing research on storage diode lasers experimental results were obtained in three areas: (1) reverse bias light emission in gallium arsenide, (2) direct absorption edge shift in N type germanium and (3) complex emission mode structure in gallium arsenide diode lasers. Except for the second subject, this information, although interesting and related to storage does not directly contribute to storage diode laser technology. These results are described in the following three sections briefly. The first two sections are in short article form.

REVERSE BIAS LIGHT EMISSION FROM GaAS DIODES

Broadband visible light has been observed from reverse bias GaAS diodes at room and at liquid nitrogen temperatures. The light from most of the diodes can easily be seen by the naked eye in a dimly lit room. Diodes do not all produce the same intensity of light; the output varies considerably from unit to unit. Similar emission has been studied in reverse-biased Si, Ge, GaP and SiC[1-5], but not previously observed or reported for GaAs[6,7].

A spectral measurement on a typical "soft" diode at room temperature is shown in Fig. 1. The radiation was still quite strong at the low frequency cutoff of the S-1 response phototube. By using an S-4 response phototube, radiation was detected at 4500 A on the high energy end of the spectrum.

Fabrication

The GaAs diodes are Te doped on the n-side (5×10^{17} cm^{-3}) and Zn doped by diffusion on the p-side. The Zn was diffused into a polished face of the slice at 850°C for 5-1/2 hours. A junction was thus formed approximately 50μ beneath the surface. The diodes were lapped to 150μ thickness, sliced to 450μ width, and then broken into pieces 630μ long. Indium contacts were alloyed to both the n and p sides, and the diode was then mounted on a molybdenum tab.

Visual Observations

The light appears to fall into two classes. One class is associated with diodes having a soft reverse characteristic. These diodes begin to emit light before avalanche breakdown occurs. The light emitted by the soft diodes is relatively bright and can be observed in a dark room at a distance of 150 cm (5 feet). Under a low power microscope, (10X), the light can be observed to emanate from the junction region in a line of white spots (microplasmas). The line of spots can be seen in some diodes to extend completely around the diode, while in most of the soft diodes the spots show a preference for one particular area of the exposed junction. The light spots in the soft diodes threshold at a current about 15 mA. At threshold, one or two spots can be recognized, and then as the reverse current is increased more spots appear. Fig. 2(b) is a photograph of light from the diode in Fig. 2(a).

The second class of light is observed from diodes which exhibit a sharp reverse characteristic. Relatively little leakage current is found in these diodes. There are three observed differences in these sharp diodes compared to the soft diodes. First, light is observed only after the avalanche breakdown voltage has been reached. Second, the microplasmas are smaller and the total light output for any given current is considerably smaller than for the soft diodes. Third, the threshold current for visual observation of the light spots is about 100 mA, a substantial increase over soft diode threshold of 15 mA. The light spots from the sharp diodes can be seen through a low power microscope to arise from the junction region. The locations of the spots of a given diode are always reproducible with current cycling.

Interpretation

Those units which have a soft inverse breakdown and emit more visible light probably conduct mainly through surface leakage, while the units which have a sharp inverse characteristic breakdown uniformly throughout the junction. One is tempted to interpret these as surface field or tunnel breakdown in the first case and bulk avalanche or collision breakdown in the second case. The emitted light due to carriers injected through surface leakage is much more likely to escape from the crystal without being absorbed than light emitted deep within the crystal when the junction breaks down uniformly. This effect of the absorption constant can be seen in the abrupt increase of measured intensity just below the approximate band edge of 8800 A. The magnitude of this absorption change is approximately consistent with the size of the diodes and the known absorption constants. On the other hand, the data is not inconsistent with an abrupt change of emission of a factor of 5 to 10 at the absorption edge frequency.

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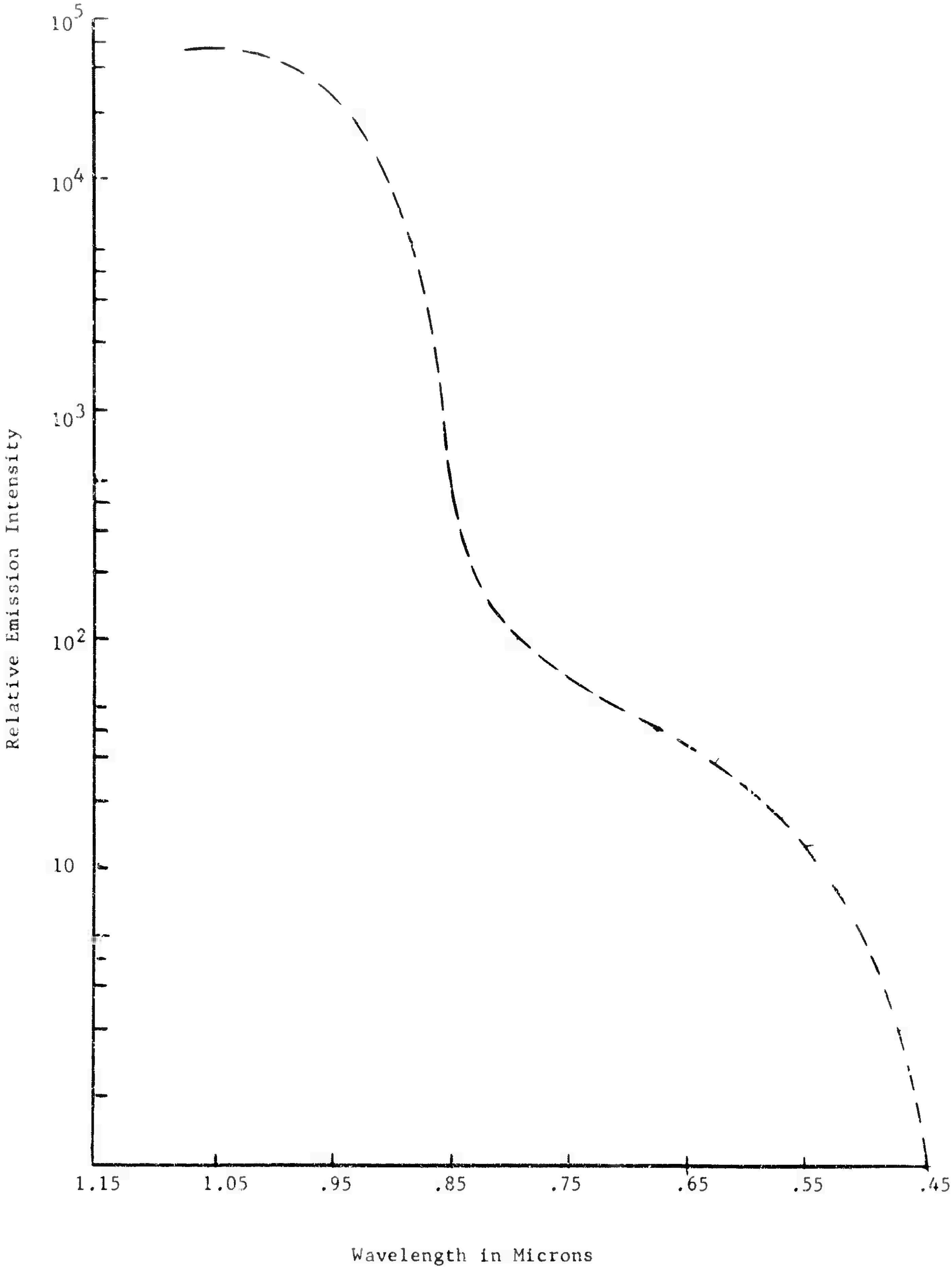

10^5
10^4
10^3
10^2
10
Relative Emission Intensity
1.15
1.05
.95
.85
.75
.65
.55
.45
Wavelength in Microns

DIRECT ABSORPTION EDGE SHIFT IN N-TYPE GERMANIUM

Infrared absorption studies of single crystal N-type germanium have shown that an increase in donor concentration allows direct transitions to begin for lower photon energies. Germanium has not been reported to exhibit a Burstein shift[1], and in fact, our experiments indicate an opposite effect. The following is a brief description of our experimental efforts and results.

We obtained absorption spectra using a Beckman DK-2 spectrophotometer outfitted with a lead sulphide detector. In order to measure absorption coefficients over a range from $1 cm^{-1}$ to $10^3 cm^{-1}$, it was necessary to piece together data taken from samples of varying thickness. Our thinnest samples were lapped to 75 microns in the (111) direction. In all cases, direct transitions began to take place for $\alpha < 10^2 cm^{-1}$, thus obviating the construction of ultra-thin samples.[2]

We have included graphs (Fig. 1) of absorption coefficients <u>versus</u> photon energies for N-type samples with donor concentrations of $10^{14} cm^{-3}$, $5 \times 10^{18} cm^{-3}$ and $2 \times 10^{19} cm^{-3}$. Free carrier absorption was estimated at less than $30 cm^{-1}$ in the $2 \times 10^{19} cm^{-3}$ material $10 cm^{-1}$ in $5 \times 10^{18} cm^{-3}$ material and $1 cm^{-1}$ in $10^{14} cm^{-3}$ material. We normalized all our data to a free carrier absorption coefficient of zero. Direct transitions begin at .748 ev for $10^{14} cm^{-3}$ doping, .726 ev for $5 \times 10^{18} cm^{-3}$ doping and at .712 ev for $2 \times 10^{19} cm^{-3}$ doping. From the apparent convergence of the three curves in the region of low absorption, we conclude that the indirect transition threshold is insensitive to donor concentration.

We have alloyed P-N junctions from $5 \times 10^{18} cm^{-3}$ and $2 \times 10^{19} cm^{-3}$ arsenic doped germanium. In the first case, we note a reverse break of

.4v while the second material produced backward diodes and showed some tunneling. We are in the process of measuring light emission from these diodes.

We are indebted to the Photochemistry Department at Northeastern University for the use of their spectral equipment.

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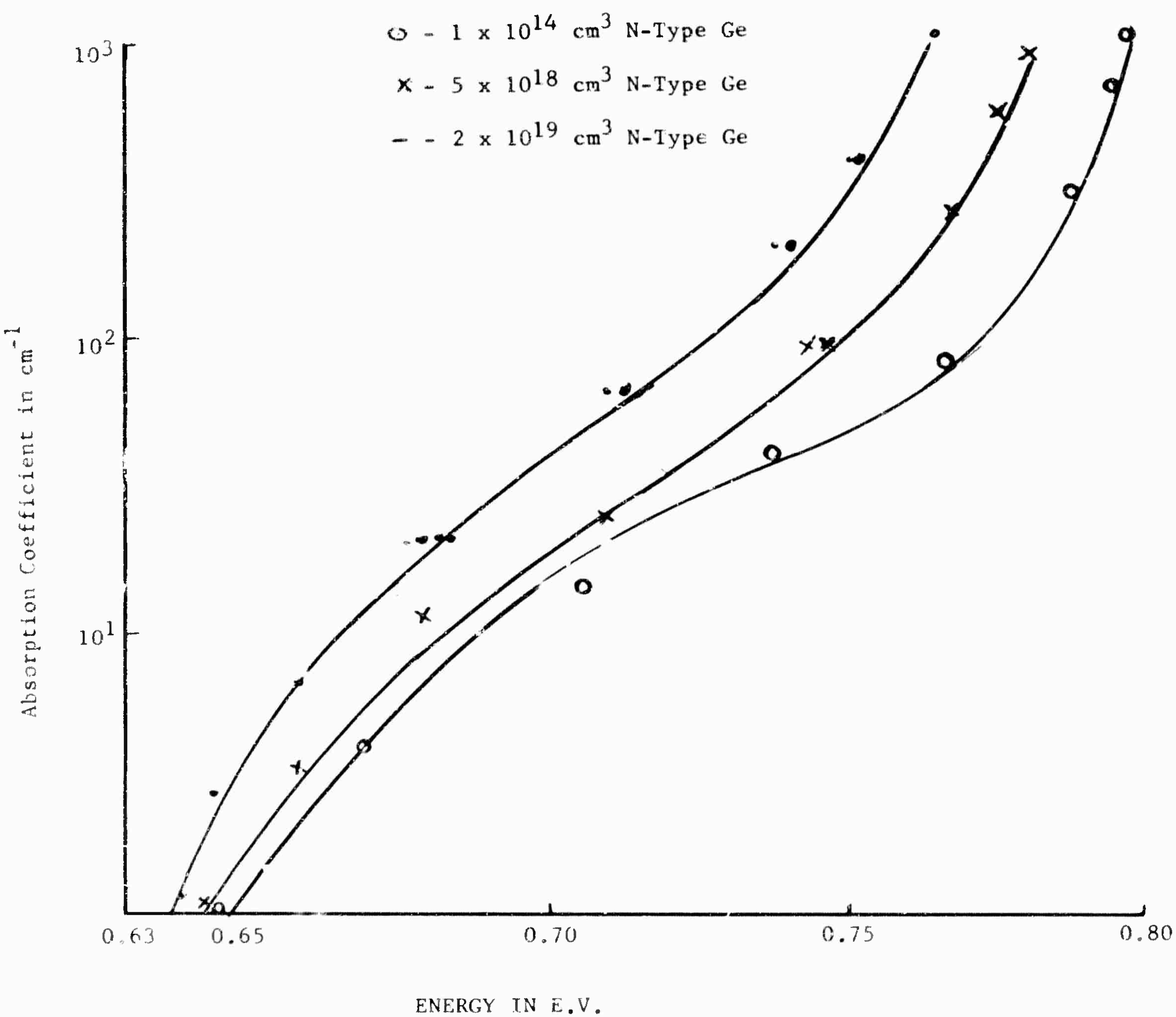


○ - 1 x 10^14 cm^3 N-Type Ge
× - 5 x 10^18 cm^3 N-Type Ge
– - 2 x 10^19 cm^3 N-Type Ge
Absorption Coefficient in cm^-1
10^3
10^2
10^1
0.63
0.65
0.70
0.75
0.80
ENERGY IN E.V.

OUTPUT MODE PATTERNS

The radiation output of diodes and diode lasers has been routinely measured with photomultiplier tubes, vacuum photodiodes, and silicon solar cells.

Some early measurements on gallium arsenide showed an apparent delay in the peak emission compared to the driving current pulse; a delay from between 100 to 500 nanoseconds. Detailed measurements were carried out to evaluate this peculiarity. Measurements of output versus angle, driving pulse height, and driving current duration were made. A small area was sampled with a light pipe and a fast (50 Mcps) photomultiplier. The radiation output pattern was found to very irregular and complex. Much variation with position and time was noted. The results were consistent and reproducible, however.

The apparent delay in emission was observed to occur only at particular angles. The [illegible]al radiation is consistent with the current pulse. Radiation output at certain angles, peaks at different times. At different selected narrow angles almost any variety of behavior could be obtained. The delayed emission was thus attributed to emission from off angles or less favored modes which required more pumping; or which became active only when the most favored modes were saturated, or heated, or limited in some other way. This might even occur after the peak of the current pulse. The effect is apparently not due to any storage.

As the quality of the cavity improves with improving cleaving techniques, the output patterns becomes considerably simpler. On occasion the output pattern approaches that of the diffraction from a long rectangle (crossed slits) with crossed principal maximum, etc.

The radiation pattern is always confused by superimposed interference lines from light reflection from the mounting tabs.

Optical Frequency Output

It is not generally appreciated that near threshold the individual modes at the diode laser are readily observable even on a long pulse basis (up to 5μs). The mode frequency spread is not resolvable on the best spectrometers (less than .1A).

As the current increases, the modes increase from 1 to 4 near threshold to 5 to 15 at several times threshold.

At the latter currents the mode wavelength spread increases and the modes begin to overlap due to internal instantaneous heating. As the pulse length is shortened, the condition of mode smearing is postponed to higher currents.

Presumably at any small instant (less than 10^{-9} seconds) the output wavelength pattern comprises the isolated narrow frequency spread modes. The apparent shift is due to the time dependent heating shift of the whole pattern.

DIODE LASER PULSERS - GENERAL

The diode laser is, in many senses, a natural pulse type device. For many applications optimum performance is obtained in pulse operation. Room temperature operation invariably requires strenuous pulsing. The present principal requirements are: high current (5 - 5000 amps), short pulse length (5000 - 5ns), high repetition rate (10^2 - 10^5pps), low output impedance (1 to .01 ohm). Occasionally requirements for high impedance arise as in series operation or for poor diode devices such as new experimental materials, etc.

For pulser design there is only one practical approach; namely, an energy storage element and fast switch. Alternative designs such as pulse squaring and amplification; a single stroke trigger circuit of positive feedback; and others, are substantially less desirable because of limitations on speed or power (impedance).

The energy storage element can be a transmission line, either distributed or lumped constant (pulse forming network). The switching element may be a mercury relay, a silicon controlled rectifier, a fast thyratron, or a vacuum switching tube. At the shortest pulse lengths the diode package, transmission line, and pulser, must be made integral. Integral coaxial lines, and foil or strip line transmission lines are used.

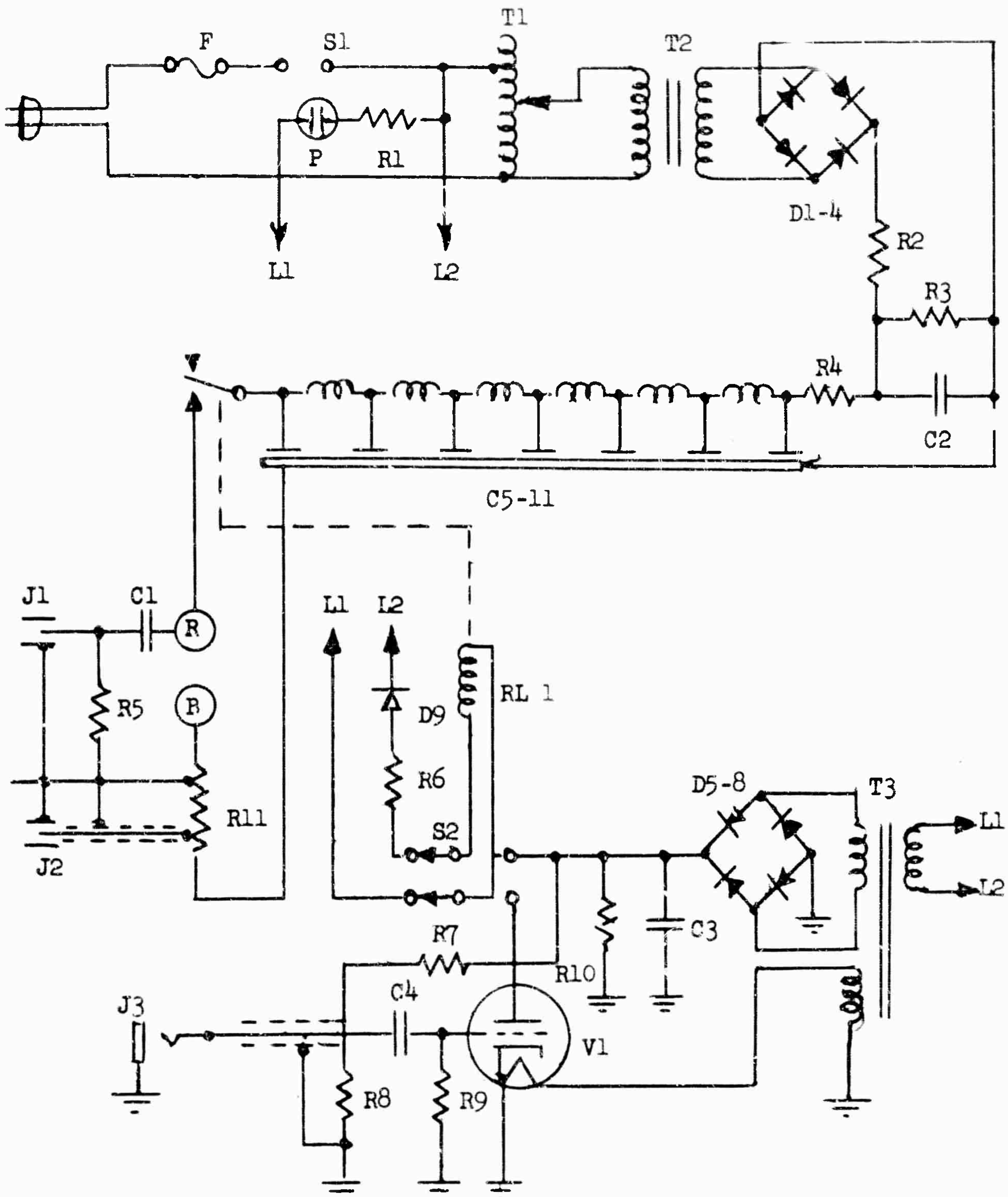
The circuit design for two diode laser pulsers are given in the attached figures. The range of performance specifications is given for each.

In general, diode laser pulsers are limited by the lack of a fast, low impedance, high current, high voltage switching device.

A good pulse shape is dependent on an exact impedance matching of pulser and diode laser. The nonlinearity of diode lasers makes this generally impossible. Impedance matching may be obtained in some cases by the use of specially designed pulse transformers or a tapered line (either distributed or lumped constant). Such transforming sometimes has the advantage of simplifying pulser design.

The principle failure mechanism of pulsers is the gradual deterioration of the switching element which is particularly serious in the case of fast thyratrons.

Finally, it may be noted that the diode lasers themselves sometimes fail due to excessive reverse voltage from pulser overshoot. The mechanism of failure is not clearly understood, but may be eliminated by the use of a fast series diode of very low impedance and high breakdown and/or a parallel shunt diode, both of which limit the reverse voltage applied to the diode laser.



Schematic
0-200 Ampere Dioder Laser Pulser

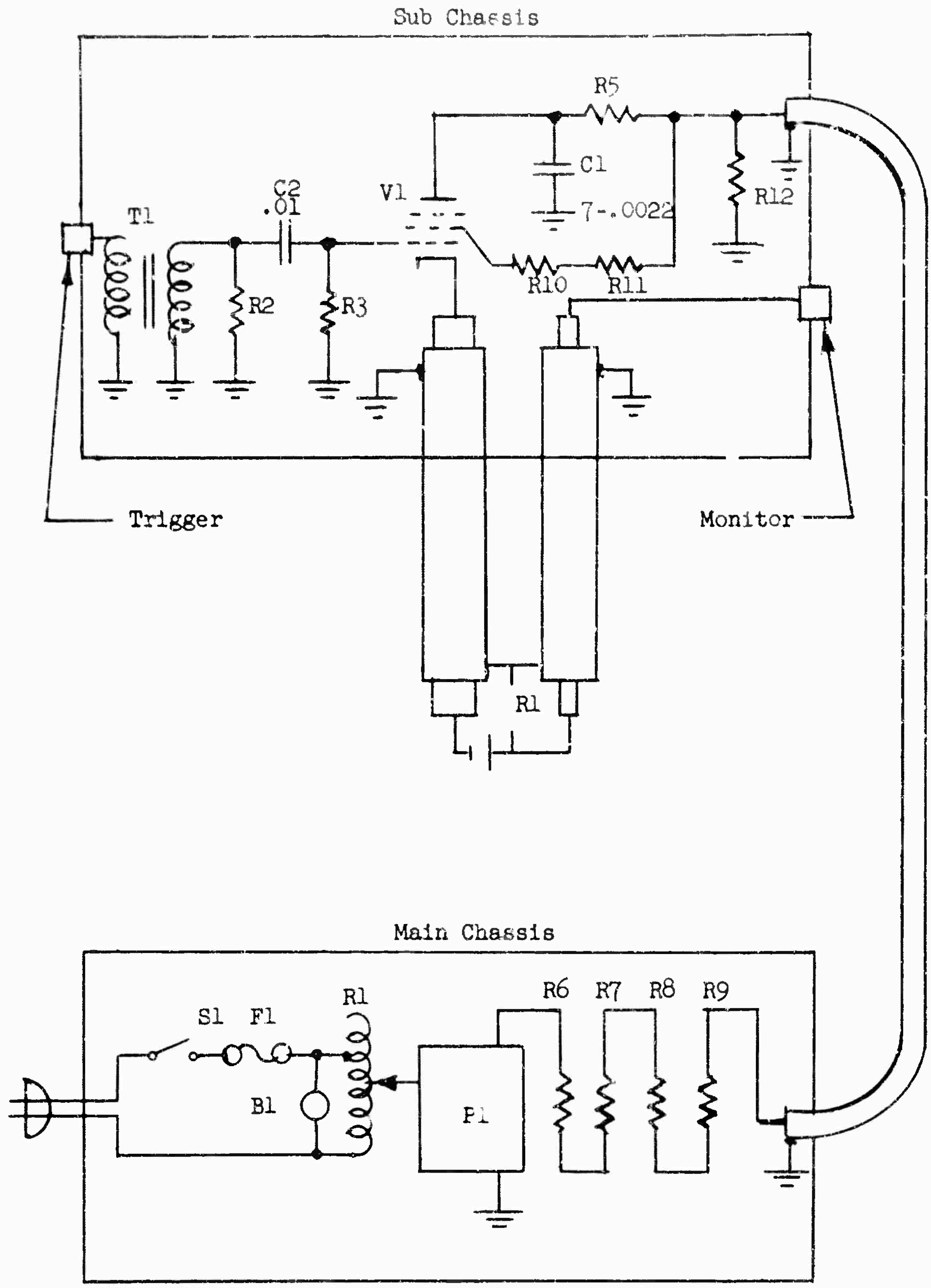
0-200 AMPERE DIODE LASER PULSER

Parts

C1	-	100 μμfd, 600 Volt Capacitor
C2	-	100 μfd, 450 Volt Capacitor
C3	-	20 μfd, 150 Volt Capacitor
C4	-	0.1 μfd, 100 Volt Capacitor
C5-C11	-	Cornell Dubilier NFF-315D Capacitors
D1-4	-	1N2615 Silicon Rectifier
D5-8	-	1N2612 Silicon Rectifier
D9	-	1N2612 Silicon Rectifier
F	-	Fuse, 1 Ampere, 3AG
J1	-	"+ Trigger" BNC Connector
J2	-	"Diode Current" BNC Connector
J3	-	"External Drive" Jack
P	-	Line Pilot, NE-2
R1	-	68K Ohm, 1/4 Watt, ± 10% Resistor
R2	-	10 Ohm, 1 Watt, ± 10% Resistor
R3	-	270K Ohm, 1 Watt, ± 10% Resistor
R4	-	2K Ohm, 20 Watt, ± 10% Resistor
R5	-	20K Ohm, 1/2 Watt, ± 10% Resistor
R6	-	3.5K Ohm, 5 Watt, ± 10% Resistor
R7	-	10M Ohm, 1/2 Watt, ± 10% Resistor
R8	-	1M Ohm, 1/2 Watt, ± 10% Resistor
R9	-	68K Ohm, 1/2 Watt, ± 10% Resistor
R10	-	100K Ohm, 1/2 Watt, ± 10% Resistor
R11	-	Viewing Resistor, Special
RL1	-	Hg Relay, C.P. Clare HG-1002
S1	-	Line Switch, SPST
S2	-	PRF Selector Switch, DPDT
V1	-	1/2 12AT7 Vacuum Tube

PERFORMANCE

t	Pulse length	1.7μs
prf	Pulse repetition frequency	0-100pps
I	Pulse current	0-200amps
Z_o	Design impedance	1 ohm
t_r	Rise time	.2μs
t_f	Fall time	.5μs



Schematic
2000 Ampere Diode Laser Pulser

PARTS LIST AND PERFORMANCE 2000 AMPERE - DIODE LASER PULSER

Part No.	Value	Description
V1		Trigger Tube
P1	5KV-10MA	Power Supply
T1		Pulse XfMV
C1	.022/6000V	Discharge Capacitor
C2	.01/500V	Blocking Capacitor
R1		Rheostat
R2	1 ohm 1/2W	Sample Resistor
R3	10K ohm 1/2W	Grid Resistor
R4	2.2K 1/2W	Load Resistor
R5	100K/2W	Isol Resistor
R6	100K/2W	Isol Resistor
R7	100K/2W	Isol Resistor
R8	100K/2W	Isol Resistor
R9	100K/2W	Isol Resistor
R10	22 meg 2W	Hold off Bias
R11	22 meg 2W	Hold off Bias
R12	22 meg 2W	Bleeder Resistor
S1		Line Switch
B1		Pilot Light
F1	1.75A	Fuse Holder

PERFORMANCE

t	Pulse length	40as
prf	Pulse repetition frequency	0-1000pps
I_{px}	Peak pulse current dependent on prf	100-2000a

Aside from the general pulsers previously described, the investigation of the storage effect requires an electrical double pulser. The double pulser comprises a long time low current storage pulse followed immediately by a short time high current trigger pulse.

Electrical Double Pulser

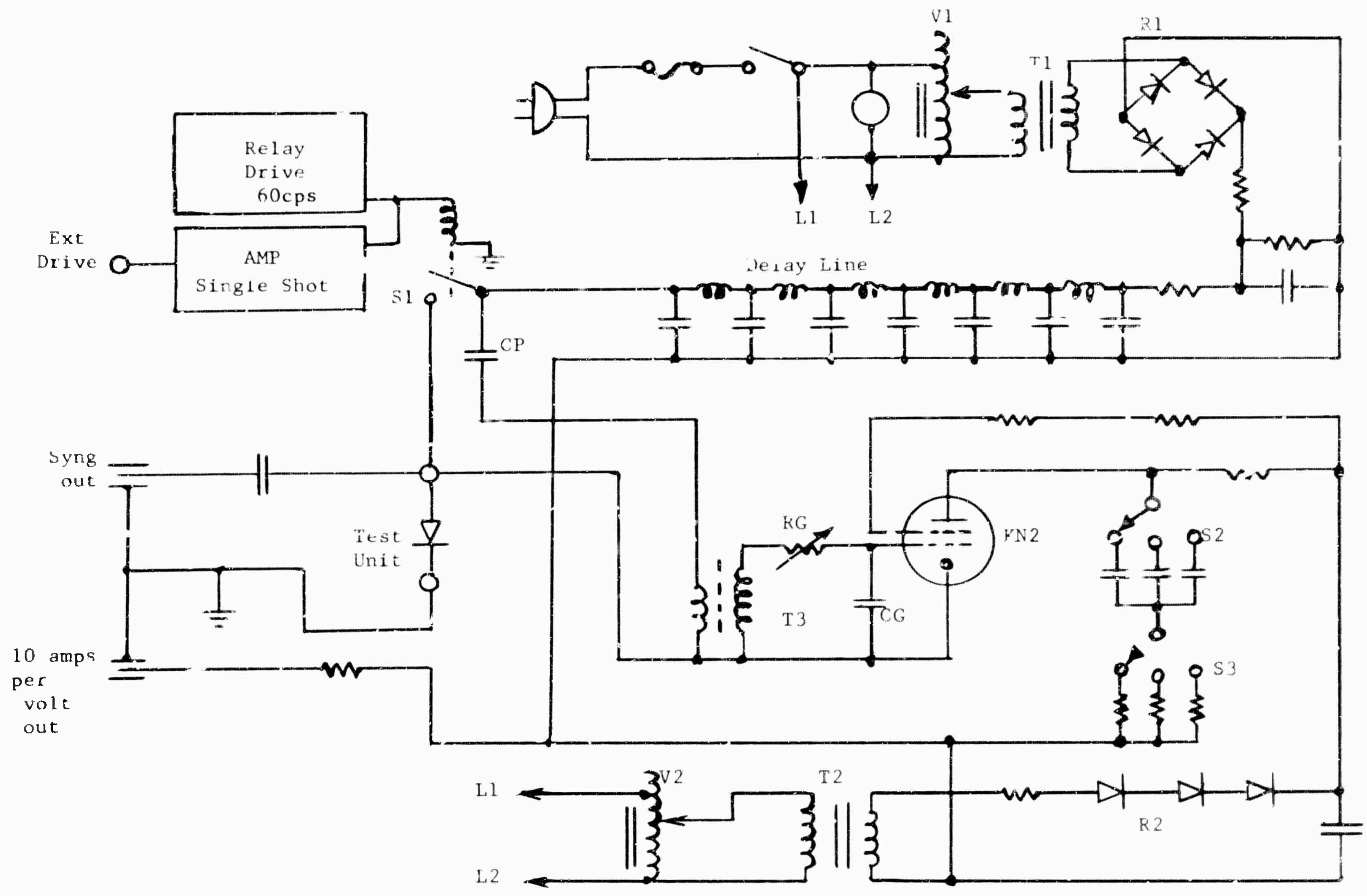
The base (or long) pulse for the double pulser is generated by a nominal 1 ohm, 1.75 μs delay line, as shown. The line is charged to any desirable voltage by means of Variac VI, transformer T1 and bridge rectifier R1, and will deliver approximately 175 amps into a 1 ohm load.

The switch for discharging the line into the load ("test unit") is a mercury relay, S1, which can be driven at a 60 pps rate, or operated "single shot". By means of an external audio oscillator, an integral amplifier also permits operation from about 5 pps to about 200 pps.

The spike is generated at the end of the base pulse by an E. G. and G. Kryotron, type KN2. Variac V2, transformer T2 and Rectifier R2 provide an adjustable 1500 volt power supply for charging the plate capacitors of the KN2. V2 controls the pulse amplitude, and the pulse width may be controlled from approximately .01 to .1 μs by means of S2 and S3. These switches control the size of the capacitor and resistor, giving various RC time combinations.

The trigger for firing the KN2 is derived from the switch S1. When the S1 contacts are open, CP charges from the delay line power supply: when S1 closes, the charge on CP is discharged through the primary of the pulse transformer T3. The pulse on the secondary of T3 is adjusted by the integrator RG-CG to trigger the KN2 just as the base pulse is ending, as observed on the oscilloscope.

This system, then, allows independent control of the amplitudes of the storage pulse and the trigger pulse, as well as some adjustment of the tail pulse width and position.



Electrical Double Pulser for Storage Diode Lasers

IMAGE CONVERTER

In order to examine the output of a variety of diode lasers an near infrared image converter is very desirable. Image converter tubes are available with spectral response from the visible to 1.2μ. An adjacent sheet gives the schematic diagram of a general purpose laboratory image converter designed and built for examination of diode laser output. The image tube is mounted in a tubular metal head with removable rod for adaptable use on an optical bench or ring stand. The viewing head may be arranged to look thru the optics of a laboratory microscope.

The separate image tube power supply of 10KV comprises a radio frequency oscillator, step-up transformer and rectifier-filter.

COOLER

Design theory establishes that most diode lasers thresholds are reduced at low temperature. The efficiency substantially above the threshold may not be temperature dependent especially if the lower laser level is emptied at a rapid rate.

Thus, for experimental purposes, very low temperature operation in the range 0 to 30°K is desired. Liquid nitrogen temperature (77°K) is readily and economically obtainable. Below 30°K there are three alternatives: liquid helium dewars, closed cycle hydrogen coolers and expansion value hydrogen coolers.

We have found liquid hydrogen from a two stage Joule-Thompson expansion value very convenient. The commercial "cryotip" unit gives 2 watts of cooling at 20°K for about 8 hours per tank of high pressure hydrogen and nitrogen.

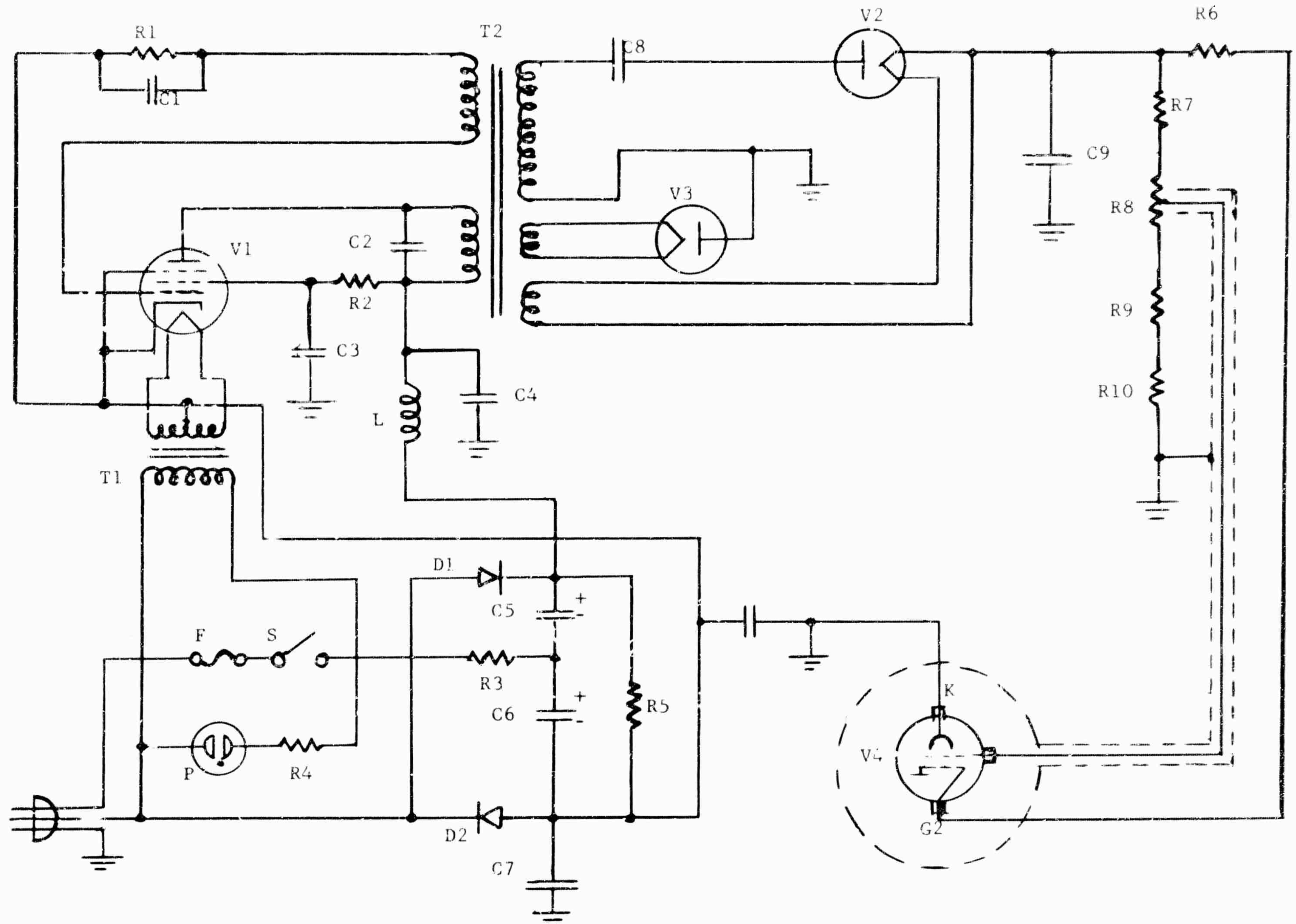


Image Converter for Diode Lasers

REPORTS, PUBLICATIONS, AND ORAL PRESENTATIONS

Reports

Research on Storage Diode Lasers

First Quarterly Report

Second Quarterly Report

Third Quarterly Report

Final Summary Report

Publications

None

Submissions on "Reverse Bias Light Emission in Gallium Arsenide" and "Storage Diode Lasers"

Oral Presentations

"Storage Diode Lasers", R. G. Seed, ONR Laser Review Meeting, Washington, D. C., March 19, 1964.

"Comments on Power and Storage Diode Lasers", R. G. Seed, Third Boston Laser Conference, August 6-7, 1964.

"Diode Laser Pulsers", N. A. Sullivan and R. G. Seed, Third Boston Laser Conference, August 6-7, 1964, also abstracted in "International Symposium on Laser Physics and Applications", Bern, Switzerland, October 12-14, 1964.

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