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DESIGN
OF A
LASER RANGEFINDER
FOR
MARTIAN TERRAIN MEASUREMENTS

by

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LIST OF SYMBOLS

Θ = Scan angle in optical focusing (rad.).

Θ' = Angle of greatest detected intensity (rad.).

R = Range(m.).

B = Mirror laser beam seperation (m.)

τ = Encoder starting torque (in. oz.).

I = Encoder moment of inertia (in. oz. sec.^{2})

α = Encoder shaft angular acceleration (rad./sec.^{2}).

w = Encoder Angular frequency (rad./sec.).

f = Encoder frequency (cycles/sec.).

λ = Modulated wavelength (m.)

c = The speed of light (m./sec.).

γ =Modulated frequency (cycles/sec.).

Vt = Laser threshold voltage (v.)

$V_{mod.\,peak}$ = Peak modulation voltage (v.)

ϕ = Phase difference (rad.).

Vm = Multiplying voltage (v.).

Vr = Reflected laser voltage (v.).

Vfil. = Filtered signal after multiplying (v.).

w1 = Multiplying frequency (rad./sec.)

w2 = Reflected Frequency (rad./sec.).

Tr = Time resolution needed for .05 m. accuracy (sec.).

Tc = Counter frequency (sec.).

Vo = Modulating voltage

V1 = 1st mult. volt. = 1.45 Mhz.

V2 = 2nd mult. volt. = 45 Khz.

Vr1 = 1st filtered volt. = 50 Khz.

Vr2 = 2nd filtered volt. = 5Khz.

t_0 = Time delay (sec.).

t_2 = Mult. time delay (sec.)

VCO = Voltage controlled oscillator (cycles/sec.).

T = Time delay between on board and returning pulses (sec.).

T_1 = Time depth of Field (sec.)

I_1 = Expander collector current (amps).

= Transistor current gain.

o = Expander time constant (sec.).

V_{c1} = Cap. Peak volt. during T_1.

V_{c2} = Trigger voltage

dT_1 = Differential time error (sec.).

N_1 = Memory address

= Angle of filter on fouier plane (rad.).

f' = Lens focal length (cm.).

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ABSTRACT

Three methods for using a laser for rangefinding are dicussed. These are Optical Focusing, The Phase Difference Method, and Timed Pulse. For application on a Mars Rover, the Timed Pulse Method proves to be the better choice in view of the requirements set down. This is made possible by pulse expansion techniques described in detail. Initial steps taken toward building the range finder are given, followed by a conclusion which is actually a proposal for future steps.

I. INTRODUCTION

To determine the topology of the landscape ahead of the Mars Rover, it is only necessary to know the range and angular position of a number of discreet points. Four points are needed to to estimate a plane whose slope relative to the vehicle may be calculated. The position of the four neighboring points must be known accurately enough to permit a meaningful computation of the slope. It can be shown[1] that these limitations are:

1. RANGE ± .05 meters
2. ANGLE to 10 arcseconds

Also since the vehicle will be moving at the time of each measurement, the scan rate of the rangefinder will become an important factor in error introduced by vehicle pitch and yaw. Since four data points, including range,azimuthal and elevation angles are necessary for processing, a scan rate on the order of 1 msec. would allow the assumption that the vehicle was still and the four points were taken simultaneously, eliminating cumbersome calculations due to pitch and yaw error. This adds one more requirement:

3. Fast scan rate, on the order of 1 msec.

Two more requirements may be induced. The rangefinder will be travelling via rocket and powered by on board batteries. It therefore must be of:

4. Low weight
5. Low power consumption

Three methods of extracting range data from a laser will be discussed.

1. 'Optical Focusing' consists of using basic camera rangefinding techniques.

2. If the laser beam is modulated at a select frequency, the 'Phase Difference' between on board and reflected waves can be monitored to yield range.

3. The 'Timed pulse' method uses leaving and returning laser beam to start and stop (respectively) a counter. The elapsed time will yield range.

These methods will be discussed and evaluated with respect to the requirements mentioned above. A fourth method may be employed which doesn't give range, but can provide basic shape and contour of the landscape.

4. In 'Grid Coding' a pattern of light is projected onto the landscape. The reflected pattern is optically filtered and can provide contour information.

II. Optical Focusing

As mentioned earlier, this method is similar to a camera rangefinder. It's application to laser rangefinding may be explained as follows (figure 1):

1. The collimated laser beam illuminates a point in the field of scan.

2. A mirror, reflecting a small portion of the field to the detector, begins to search for the point.

3. During the scan, detector intensity and corresponding mirror angle are sampled and stored by a computer.

4. Computer methods are employed to determine at which angle, Θ', the maximum intensity occured.

5. Once Θ' is known, simple geometry yields:

$$\tan \Theta' = R/B$$

where R is the range and B is the mirror-beam seperation. This method was first investigated for use with another ranging scheme discussed in more detail by W. Pfiefer.[2] The method is called 'Stereo Angle Measurements' and Pfiefer reports a necessary resolution of $\pm$ 5 arcsec. to be accurate enough.

This may at first seem formidable, but encoders are available at this accuracy.[3] Teledyne-Gurley, of Troy New York, produces such a mechanism. It contains an encoder wheel divided by 16,384 slots per revolution. The slots are sensed by a light emitting diode-photodiode combination. Using electronic extrapolations, accuracies of 4-5 arcsec. are available. The output is in the form of an up-down counter for each 5 arcsecond increment. The encoder is cylindrical, six inches long by three inches diameter. The entire system weighs 5.5 pounds and can be bought for \$4,000 to \$5,000.

Although the encoder has been shown to deliver the required accuracy, limits do exist on its ability to scan. The maximum starting torque is given by

$$\tau = .4 \text{ in. oz.}$$

with a moment of inertia

$$I = 2.3\text{x}10^{-3} \text{ oz. in. sec}^2.$$

This yields an angular acceleration of

$$\alpha = \tau / I = .174\text{x}10^{3} \text{ rad./sec}^2.$$

The mirror will be expected to scan from 3 to 30 meters yielding

$$\Theta\text{min.} = \tan^{-1}3 = 73.3^{\circ}$$

and

$$\Theta\text{max.} = \tan^{-1}30 \doteq 90.0^{\circ}$$

assuming B = 1 meter. This results in a change in Θ of 17° or about .3 radians. Assuming an angular frequency w,

$$\Theta - 1.27 = .3\cos(w\,t)$$

$$\Theta'' = \alpha = -.3\cos w^2(wt)$$

$$\text{abs}(\alpha) = .3w^2 \quad \text{at maximum}$$

$$1740/.3 = w^2$$

$$w = 5800 \text{ rad/sec.}$$

$$f = 925 \text{ cycles/ sec.}$$

The minimum period will be about 1.1 msec , not including mirror inertia. Since some averaging must be done to insure accuracy, and four points are to be determined, about 40 scans will be necessary, if 10 averaging scans are used. This will put the period for total data acquisition at 40 msec.;way above requirements.

III. PHASE DIFFERENCE

The phase difference method is shown in figure 2. If the laser beam is modulated at a certain frequency ν, the resulting wavelength, λ, will be given by,

$$\lambda = c/\nu$$

where c is defined as the speed of light. The range finder is to have a depth of field R in meters, such that,

$$10 \leq R \leq 50 \text{ meters}$$

The maximum distance the wave will travel will be 100 meters. So λ must be equal to or greater than 100 meters to insure a unique relation between the phase difference obtained during the round trip and the range. At λ = 100 meters, the frequency of modulation is given by

$$\nu = c/100 = 3 \text{ Megaherz.}$$

Referring to figure 2, the pulse modulator will be operating at 3Mhz. , while the pulse generator at 10 Khz. The modulating amplitude should not be great enough to turn the laser on, or turn it off..If the threshold voltage of the laser is Vt, then

$$V_{mod_{peak}} \leq Vt$$

or

$$V_{mod_{peak}} \doteq Vt$$

at maximum, so that

$$V_{pulse} \doteq 2Vt.$$

This will allow maximum modulation without disturbing lasing operation.

The laser pulse will contain many cycles of modulation to allow for averaging. Sensing on board and returning waves, it will be shown how the phase difference may be expanded to give the required resolution.

A. Phase Expansion Through Heterodyning

The heterodyning principle may be proven through Euler's equations. Let

$$Vm = \cos(w_1 t)$$

be the mixing frequency, and

$$Vr = \cos(w_2 t + \phi)$$

be the returning laser beam signal with phase delay, ϕ. Then from Euler

$$Vm = \tfrac{1}{2}(\exp(iw_1 t) + \exp(-iw_1 t))$$

and

$$Vr = \tfrac{1}{2}(\exp(i(w_2 t + \phi)) + \exp(-i(w_2 t + \phi)))$$

Mixing (multiplying) yields

$$\begin{aligned} VmVr = \tfrac{1}{4}(&\exp(i(w_1 + w_2)t + i\phi) + \\ &\exp(i(w_1 - w_2)t - i\phi) + \\ &\exp(i(w_2 - w_1)t + i\phi) + \\ &\exp(-i(w_1 + w_2)t - i\phi)) \end{aligned}$$

This can be written as

$$\begin{aligned} VmVr = &\tfrac{1}{4}(\exp(i((w_1 + w_2)t + \phi)) \\ &+ \exp(-i((w_1 + w_2)t + \phi))) + \\ &\tfrac{1}{4}(\exp(i((w_2 - w_1)t + \phi)) \\ &+ \exp(-i((w_2 - w_1)t + \phi))) \end{aligned}$$

or

$$VmVr = \tfrac{1}{2}\cos((w_1 + w_2)t + \phi) + \tfrac{1}{2}\cos((w_2 - w_1)t + \phi)$$

Using band pass filtering techniques, one component may be isolated.

$$Vfil. = \tfrac{1}{2}\cos((w_2 - w_1)t + \phi)$$

To apply this result to the rangefinder, the following assumptions are made.

1. All frequency components are in phase, except for ω_4, the reflected voltage.

2. The phase will be measured by counting the time interval between zero crossings.

The first assumptions simplifies calculations, but needn't be true. The only variable phase component will be introduced by Vr. All other constant phase components introduced by the electronics may be calibrated out of the system. The second assumption directly implies that only 180° of the wavelength will give a unique phase-range relationship. This requires doubling the wave length, or halving the frequency to 1.5Mhz.

To resolve .05 meter at the speed of light, the time resolution must be,

$$Tr = 2dR/c = 2x(.05)/3x10^8 = .33nsec.$$

Typical counter frequencies are 10Mhz., or

$$Tc = 10^{-7}sec. = 100\ nsec.$$

This leads to the result that the phase angle must be magnified about 300 times. The suggested design is shown in figure 3. A frequency counter can be designed to produce four in phase signals of the required frequencies (to be discussed later). The primary signal, Vo, is used to modulate the laser beam at 1.5Mhz. Vr, the returning signal, plus phase delay is mixed with V_1 at 1.45Mhz. The result is filtered to produce Vr_1 at 50khz. This is then mixed with V_2 at 45Khz. and filtered to produce Vr_2 = 5Khz. If Vr contained a phase component, ϕ

$= pi/2$, this correspond to one-quarter period or an elapsed time of

$$t_o = \frac{1}{4} \times (1/1.5) \times 10^{-6} = .167 \text{microsec.}$$

Since phase is maintained through the heterodyning process, at 5Khz., a phase angle of pi/2 would correspond to

$$t_2 = \frac{1}{4} \times (1/5) \times 10^{-3} = 50 \text{ microsec.}$$

Notice that the elapsed time has been magnified by 300 to allow proper resolution. Also four data points will take at maximum .8msec., leaving room for 10 averaging cycles per point and still maintaining a period less than 10 msec. New state of the art counters will soon be available[4] with periods of 10 nsec. This will eliminate the last mix (V_2), simplifying and speeding up the whole process.

One immediate drawback is the length of time that the laser must be pulsed in order to set up the heterodyning process. Assuming that the fastest counters are used, $t_c = 10$ nsec. and 10 cycles are used for averaging, the laser must be pulsed for at least .2msec. per point. Semiconductor lasers have maximum pulse widths of .2 microsec. at room temperature. Other types of lasers may be used[5] and light emitting diodes (LED) have been employed[6]. LED's require a cooperative target because of their low power (50 mwatts max.) output. Gas lasers, typically Helium-Neon, have been used with great success, but do not fit the requirements of low power consumption and low weight as well as a semiconductor laser.

B. The Frequency Generator

Producing four in phase signals is accomplished by using phase locked loops and frequency dividers, all available in IC packages. Figure 4 shows the block diagram of the generator. The one input to all three branches is a 5Khz. clock. The basic operation of any one branch is to produce a voltage proportional to the phase difference between the input signal and the voltage controlled oscillator (VCO). Once the loop is locked, the frequency of the VCO will be equal the inputs and the phase difference will be zero. Putting a divide by N counter in the loop allows VCO to be locked at a frequency N times the input's. A divide by 9 counter will produce a VCO at 45Khz., a divide by 290 produces 1.45Mhz, and a divide by 300 produces 1.5Mhz. These voltages correspond to V_2, V_1, and V_o respectfully. Of course V_3 is the clock. Also shown in figure 4 is the circuit diagram for one branch of the generator. The clock inputs at pin 2 of Signetic's NE565 phase locked loop. VCO is pin 4 and N8281 is the preset divider. R_1 and C_1 controll the free running frequency of VCO. C_2 is used to stabilize VCO and should be large. Note that all outputs are square waves, except for pins 9 and 8 where VCO may be trimmed to a triangular waveform. Proper band pass filtering will produce a sine wave. If filtering is to be avoided, phase locked loops may be constructed using voltage controlled crystal oscillators which have sine wave outputs.

In conclusion then, the phase difference is an accurate rangefinding method. When using a Helium-Neon laser, accuracies[5] are reported of $\pm$ .3 microns, and using an LED[6] of $\pm$ 3cm. The Timed Pulse method can offer comparible accuracies while making use of the more desirable semiconductor laser.

IV. Timed Pulse

The timed pulse method is shown in figure 5. The operation of the system is simpler than the phase difference method, but, unfortunately, not as accurate. The system can be made to perform to specifications, as will be shown. Initial investigations showed that .25 nanosecond time resolution is needed when measuring the elapsed time of flight in order to achieve ±5 cm. accuracy.[7] The system shown in figure 5 was suggested by W. Kuriger[8], and is reported to be capable of ± 10 cm. accuracy under laboratory conditions. Some modifications can be made to improve Kuriger's design.

The range is determined by monitoring a ramp generator (most likely with an A/D converter). The amplitude that the ramp reaches is proportional to the length of time it is on. The ramp begins on a signal from the pulse generator and stops on signal from the returning laser beam. (Note that Kuriger's article contains many fine points and should be read thoroughly. We are concerned here with accuracy and will be discussing certain circuits toward this end.)

Figure 6 contains the modified circuit diagram. One important design change concerns triggering the electronics with on board and returning laser beams. Lasers have an indefinite delay time between pulse application and onset of the lasing mode. Triggering with a split laser beam will eliminate the error due to this time lag. The processing begins on signal from the storage-averaging branch. A two ma. pulse triggers the power supply to drive the laser. The time delay between on board and returning laser pulses is recorded by the detector and output as a pulse of width, T.

This pulse width is expanded and timed. The count resulting from the timing is used as a memory address for read only memories (ROM's). The range is output from the ROM's and stored to await averaging. The pulse generator is then signaled for another range beginning the cycle over. The number of ranges to be averaged depends on how much time is allowed under the 1 msec. scan requirement..

The power supply will be covered in a following section The processing will be explained now, branch by branch.

A. Detection (Fig. 7)

The pulse width, T, proportional to the beam time of flight is produced by an exclusive or gate. The beams are detected by photodiodes, amplified and applied to the gate. The on board beam will be stonger and require less amplification, thus A_2 will be greater than A_1. The function of the gate as shown in the truth table will produce the the pulse length. Since the gate triggers at a specific voltage (5 volts), the pulse length will also depend on the slope of the leading edge of the input pulses. This won't disturb the operation of the on board circuit, but will affect the timing of the reflected circuit since the shape of this pulse will depend on distance travelled and type of terrain encountered. This has been investigated[7] and it was shown

$$dt = (T^1/2)(S/N)^{-1}$$

Where dt is the timing error, T^1 the pulse length, and S/N the signal to noise ratió. Using nominal values, the author reports maximum error of 3.75 cm. Since this is 75% of the allowable error, every effort must be made to minimize it.

Although the reflected pulse shape won't be identical to the output pulse shape, it certainly will depend on it. The laser output pulse shape must be as square and as powerful as possible. Performance of the laser and power supply will be discussed in a following section.

B. Pulse Expander

i.) Principles of Operation

The problem of extracting centimeter accuracy from the timed pulse method may be approached as follows, assuming rounded numbers for ease of calculation. The range depth of field, R, may be stated as

$$3 \leq R \leq 30 \text{ meters}$$

This is related through the speed of light, c, to the time field, $T_1 = 2R/c$.

$$20 \leq T_1 \leq 200 \text{ nsec.}$$

If a range resolution of .03 meters is required, a time resolution of .2 nsec. is necessary. As stated earlier, soon to be available counters will have resolutions of 10 nsec. (100Mhz.). A magnification of 50x is minimum (100x to be sure) for proper resolution.

ii.) Operation-Fig.8

The combination Rb, T, and C constitute a ramp generator similar to Kuriger's design. The difference here is the method of output. A large resistor was placed across the capacitor with the result shown in fig. 9. Vin is the pulse input from the detector and is width modulated depending on range. Using a capacitor of .01 microfarads and a resistor of 470K ohms, the transfer function of figure 9 was obtained. The slope, or magnification, of the system is 1300 for the first part of the curve, and 300 for the second part. Note both slopes are well over one hundred. The resistor, R', may be replaced by a high input impedance schmitt trigger shown in figure 10. The function of the circuit is to provide triggering at predetermined voltages, producing a square wave output which is more suitable for timing. Figure 10 shows the input and output wave shapes along with the cicuit's transfer function. The transfer function shows the hysterisis exhibited by the circuit, allowing precise wave shaping and timing.

iii.) Pulse Expander Theory

Assuming an input pulse of constant amplitude, V_1, and variable length, T_1, a constant current I_1 will flow into C.

$$I_1 = V_1/(Rb\beta)$$

Where β is the transistor current amplification. Let Vc be the capacitor voltage, then

$$I_1 = C\, dVc/dt$$

$$(I_1/C)T_1 = Vc_1$$

After the pulse application, voltage Vc will discharge through R'.

$$Vc_2 = Vc_1 \exp(-T_2/\tau_0)$$

Where $\tau_0 = R'C$. Assuming RC much greater than T_2,

$$Vc_2 = Vc_1(1-T_2/R'C)$$
$$Vc_2 = T_1 I_1/C(1-T_2(R'C))$$
$$Vc_2 = T_1 I_1/C - T_1 T_2 \; I_1/(R'C^2)$$

Since Vc_2 will be a constant triggering voltage

$$d/dT_1(Vc_2 = T_1 I_1/C - T_1 T_2 I_1/R'C^2)$$
$$0 = I_1/C - T_2 I_1/R'C^2 - T_1 I_1/R'C^2(dT_2/dT_1)$$
$$0 = 1 - T_2/R'C - T_1/R'C \; (dT_2/dT_1)$$

Since $R'C \gg T_2$

$$R'C/T_1 = dT_2/dT_1$$

With the values used when testing the expander and taking $T_1 = 3$ microsec.

$$dT_2/dT_1 = 1200$$

and $T_1 = 2$ microsec.

$$dT_2/dT_1 = 2350$$

The actual values of the slope taken from figure 9 is 1300 and agrees well with theory. The final result shows the slope is dependent on T_1 and therefore non-linear.

iv.) Pulse Expander Modifications

Figure 11 shows the expander with R' replaced by a transistor circuit. The two transistors are driven by pulses V_1, from the detection branch, and V_2, a pulse generator triggered by V_1. V_1 charges the capacitor as before, but now the charge is metered out at a constant current determined by the transistor. As before

$$Vc_1 = I_1 T_1/C$$

If the stored charge $I_1 T_1$ is metered out at current I_2,

$$Vc_1 = I_2T_2/C$$

Then simply

$$I_1/I_2 = T_2/T_1$$

The capacitor would supply a constant current until it's voltage dropped to the point where the transistor saturated. The discharge would then be exponential (see Vo). Little time was available to be spent on this circuit, but it shows promise.

C. Timing

Memory Address

Up till now the concern has been producing a pulse width dependent on range and long enough to allow proper resolution. It is clear from figure. 9 that the pulse expander's transfer function is not linear, and computation of range from timing the pulse width would require extensive calculation. In this section it will be shown how the pulse can be timed and hardwired to produce a memory address corresponding to the correct range.

Since T_1, the unexpanded pulse width, is related to the range by $T_1 = 2R/c$, the field of T_1 will be

$$20 \leq T_1 \leq 200 \text{ nsec}$$

and

$$T_{max.} - T_{min.} = 180 \text{ nsec.}$$

If the range is to be known within $\pm .03$ meters, a differential element of range, $dR = .06$ meters, would correspond to a differential time of

$$dT_1 = 2dR/c = .4\text{nsec.}$$

The number of unique time values needed to define the field is then

$$N = 180/dT_1 = 450$$

If a portion of the pulse expander's transfer function, say with slope = 100, was blown up, the relation would be similar to figure 12. If T_1 = 60nsec., the differential element would be from 59.8 to 60.2 nsec. as shown. This transfers to T_2 as mean time T_2 = 6 microsec. and differential element from 5.98 to 6.02 microsec. If the 10 nsec. clock is used, 4 pulses will fit into dT_2.

T_2max. will be given by 100 x T_1max or 20 microsec. With a clock period of 10 nsec., this transforms to a maximum count of 2000 at T_2max. The number of bianary digits necessary to handle this count is given by

$$2^n = 2000$$

$$n\ln 2 = \ln 2000$$

$$n = 7.6/.693 = 11^+ = 12$$

For the case being considered here, with T_2 = 6 microsec., the count will be 600. Notice that any count from 597 to 604 is representative of the same elapsed time, T_1, and the corresponding range since all are within the differential time element dT_2, see figure 12.

The memory address is produced from the count by hardwired logic gating, figure 13. A count of 600 is shown in the register. This corresponds to an elapsed time of 60 nsec. or a range of

$$60 \times 10^{-9}/2 \times 3 \times 10^8 = 9 \text{ meters}$$

This range would correspond ideally to a memory address of

$$N_1 = 9/.06 = 150$$

When the count is anywhere from 597 to 604,150 should appear in the memory address register through similar gating. If the entire transfer function is calibrated in this manner, a unique memory address will be produced for any elapsed time T_1 within the differential limits.

D. Memory

This branch is the least complicated of the system. It's purpose is to store 450 values of range for processing. Since the maximum range has been assumed to be 30 meters or 3000 centimeters, a 12 bit memory word length will be necessary, the whole memory consisting of 450 words.The range values are predetermined and programmed into the memory. These values should be calculated taking into consideration martian ambient conditions. It is known from Mariner 9 data[9], that the the change in temperature over a Martian day is about 100°C. Design technology can produce stabile circuits over a range of 150°C with many methods available to protect against thermal error. Digital circuitry has negligible temperature dependence so that most of the error will occur in the pulse expanding branch. Variation from STP will affect the speed of light, but it can be shown[10] that over 30 meters an error of only .3cm would be encountered. Assuming that the ROM's have been properly programmed, once addressed, the memory will load the proper bianary representation of the range into the memory output buffer. From here the range is transfered to a storage register to await averaging. The number of ranges available for averaging will depend on how many cycles can be run in about 1msec.

E. Averaging

Every logic gate has associated with it a delay time. This time is constant and if accounted for will not hamper operation. The typical delay time for a gate is 10 nsec. The data access time from memory is 100 nsec. Notice that the maximum output from the pulse expander will be 20 microsec., and if 100 gates (an overestimate) plus memory have to be passed, the delay from pulse expander to range will be 21.1 microsec. A safe figure for the total figure would be about 25 microsec. Since a GaAs laser is to be pulsed for 100 nsec. (maximum) at a duty factor of .1%, the minimum period allowable for laser operation is 100 micro sec. This can be lowered easily to 50 microsec. by shortening laser 'on' time, but clearly the laser is the dragging foot. At a period of 50 microsec., 4 points will be averaged 10 times in 2msec, meeting pitch and yaw assumptions.

F. Timed Pulse

Future Possibilities

The major obstacle preventing use of a timed pulse system without the pulse expander and related complications, is the limit transistor speed places on the counting frequency. The major factors determining the maximum frequency of oscillation a transistor can obtain are parasitic capacitances and carrier transit times through the device. Both these parameters are a function of device size. The smaller a transistor can be made, the faster it will be. Figure 14 shows two transistors (MOS). Transistor (a) was made by conventional diffusion doping techniques. The dimensions of the transistor are measured in microns (10^{-6}meters) since that is the closest tolerance the diffusion method can yield. Transistor (b) was produced by ion implantation of the doping atoms. The dimensions may be controlled to 100Å (10^{-8}meter). The results are that (a) can function at a maximum frequency of about 100Mhz., while the maximum frequency of oscillation for (b) is given as 14×10^9 Hz. = 14 Ghz.[11] This gives a time resolution of .07 nsec. Devices such as transistor (b) are still in the research stage and are not yet commercially available. The ion implantation method has made tremendous advances in the last few years and promises to be a major manufacturing technique soon.

V. Grid Coding[12]

Although the technique of Grid Coding does not fit into the present method of terrain modeling, it does offer an alternative approach to the problem of robot vision. A coded dodecahedron is shown in figure 15 (a). The coding consists of no more than projecting the lined pattern onto the object. A coherent optical system is then used to perform a Fourier transform on the pattern. The transform is figure 15(b). Note the intense spots of light in the first and third quadrants. These represent the different spatial frequencies created by the projection of the grid onto the dodecahedron. The transform is represented graphically in figure 15 (c). The graph shows the four energy spikes and their angular dependence. A filter of width 8° was used with the result shown in figure 16. Note that at -38°, -47°, -64°, and -68° the four frequencies were seperated and reconstructed. This illustrates how a terrain may be 'Grid Coded' and analyzed after the Fourier transform has been applied. The rover cannot climb a slope greater than 25°. If proper detection is placed in the Fourier plane, slopes greater than 25° may then be detected and avoided.

VI. Building The Rangefinder

A. Choosing a laser

Here Kuriger's article was very helpful in supplying references[13&14] on solar irradiance and Martian surface reflectivity to complete the following table.

Ar = receiver antenna area = $.49 \times 10^{-3} m^2$

Pr = signal power incident on detector

Pt = laser power output

Γt = effeciency of transmitting optics $\doteq .8$

Γr = efficiency of receiver optics $\doteq .5$

ξ = Martian surface reflectivity

Ta = Martian atmosphere transmittance $\doteq 1.0$

R = Range

Giving

$$Pr/Pt = \Gamma t \, \Gamma r \, \xi \, Ta \, Ar/2\pi R^2$$

At R = 30 meters

$$Pr/Pt = .045 \times 10^{-6}$$

Kuriger assumed the Martian surface to be a diffuse reflector of the laser beam into a solid angle of 2pi. This assumption is upheld by work done by Mason[15] who states that circulation of the Martian atmosphere will leave very fine grained deposits of sand on the surface, creating a diffuse reflector.

Kuriger suggests a 13 watt GaAs laser for the system.

$$Pr = .135 \text{ microwatts at } 30 \text{ meters}$$

The laser chosen for experimentation is RCA 40866 with maximum output of 24 watts at a current of 60 amps and wavelength of .9 microns. Ample information may be obtained from

RCA concerning this device.[16 & 17] A brief introduction will be given here.

A semiconductor laser is a diode made of GaAs typically and constructed so two edges of the chip are parallel to each other and perpendicular to the junction. The refractive index of the GaAs - air interface is such that at .9 microns it behaves as a mirror. This allows constuction of a small lasing cavity within the semiconductor material. Light is emitted when carriers cross the p-n junction of the diode. Only those modes which are reflected parallel to the junction plane between the mirror faces, can become part of the stimulated emission process essential to lasing action. Since the junction, then, becomes the lasing cavity, emission of radiation is from the junction area which typically has a width of about 2 microns. This small aperature diffuses the radiation into a 20° cone, figure 17, and makes it necessary to collimate the beam. If a 1 cm. beam width is desired the following relation holds.

$$\text{Tan } 10^{\circ} = 5\text{mm}/f'$$

where f' is the focal length of the lens. so

$$.176 = 5\text{mm}/f'$$

$$f' = 2.84 \text{ cm.}$$

Another characteristic of laser light is coherence. This is lost since the laser must be operated in the pulsed mode with pulse widths usually less than .2 microsecs. at room temperature. Normal operation of the laser at 40 amps and 8 volts introduces 340 watts into the semiconductor chip.

Short pulses are therefore necessary to avoid burn out during 'on' time and duty factors of .1% allow time for dissapation of heat to avoid eventual burn out.

B. Laser diode power supply

The major features of a power supply for laser operation are the high current needed for onset of lasing (10 amps) and The narrow pulse width necessary to avoid burn out. At first a supply was designed for use with the phase difference method. In order for modulation of the laser, the current pulse must have a flat top, Figures 2 and 18. Transistor 2N5262 was chosen for it's speed and current capabilities, with the expected output shown in figure 18. The final design is figure 19 with 15 transistors in parallel to supply 45 amps to the laser. The circuit was never constructed because 2N5262 could not be obtained. The circuit would have been ideal for experimentation allowing low current (non-lasing) pulses of long length for heterodyning experimentation and short, high current pulses for timed pulse experiments. When it became obvious that 2N5262 would not arrive, an alternate design was chosen.

Figure 20 shows a power supply and the current waveform it produces. The operation is to charge the storage capacitor through the transistors until the capacitor voltage reaches Vcc. SCR GA201 is triggered to allow discharge through the laser diode. This pulser was built with the waveform resulting shown in figure 21. Note, this is not the current waveform, but the signal waveform received at the photodiode. The rise time of the pulse (100 nsec.) is far from the current rise time given for the circuit (20 nsec)[18,19]

VII. Conclusion:

A Proposal

Recalling the requirements placed on the rangefinder, they are:

1. Range ± .05 meters
2. Angle ± 10 arcsec.
3. Fast scan rate
4. low weight
5. low power consumption

The Timed Pulse method meets all requirenents and is recommened for further developement in two main areas of study, the laser power supply with related detector electronics, and the modified pulse expander including counters and registers.

Supplying 40 amps to the laser becomes a problem, but can be solved by eliminating all unnecessary components and wire lengths in the laser's circuit. Figure 22 shows a suggested power supply scheme to eliminate the 3 1N914's as an example of power supply improvement. The detection may be improved by adding a differentiating op-amp[20] to eliminate received pulse rise time and the error introduced by this rise time.

The modified pulse expander is not a unique design. Hewlett-Packard counters model numbers 5360 and 5379 boast .1 nsec. resolution and use pulse expanding techniques. They cost around $6,000.00. Therefore further research into the modified expander is recommended towards a possible linear transfer function to simplify processing. If the pulse expanding technique can be debugged and made practicle, the timed pulse method, as described, is a laser rangefinder for Martian terrain modeling.

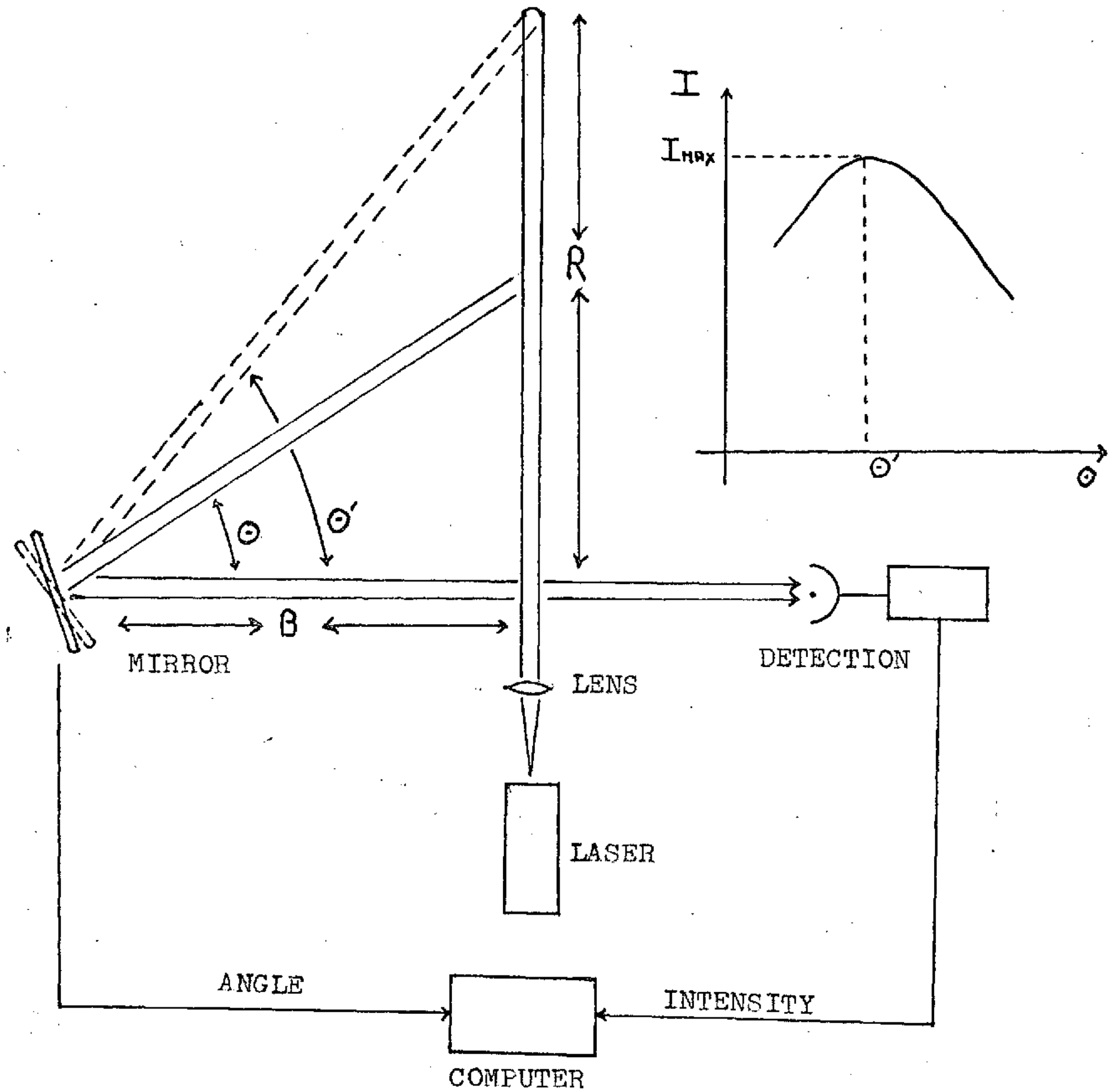


FIGURE 1
OPTICAL FOCUSING

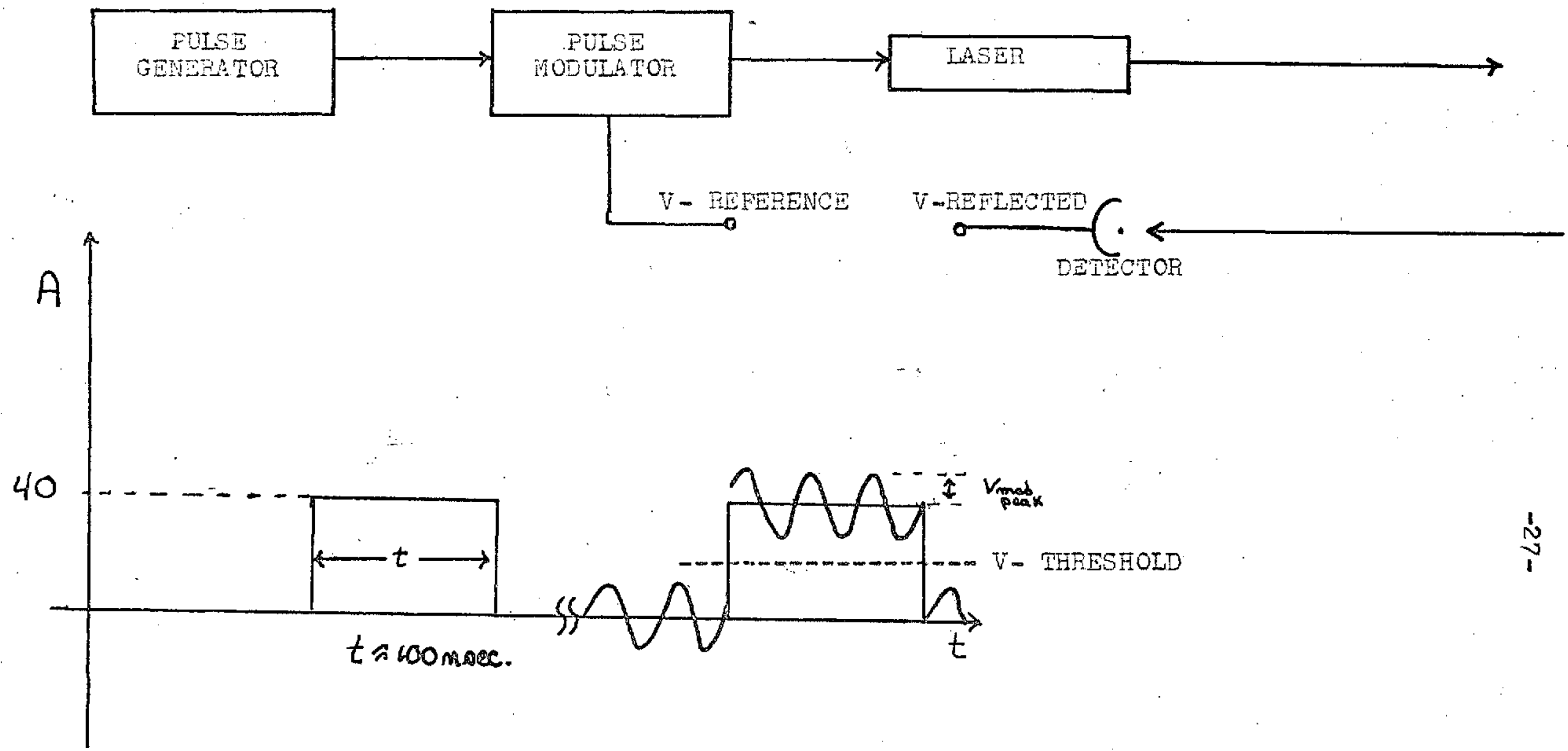


FIGURE #2 SHOWING PHASE DIFFERENCE BASICS

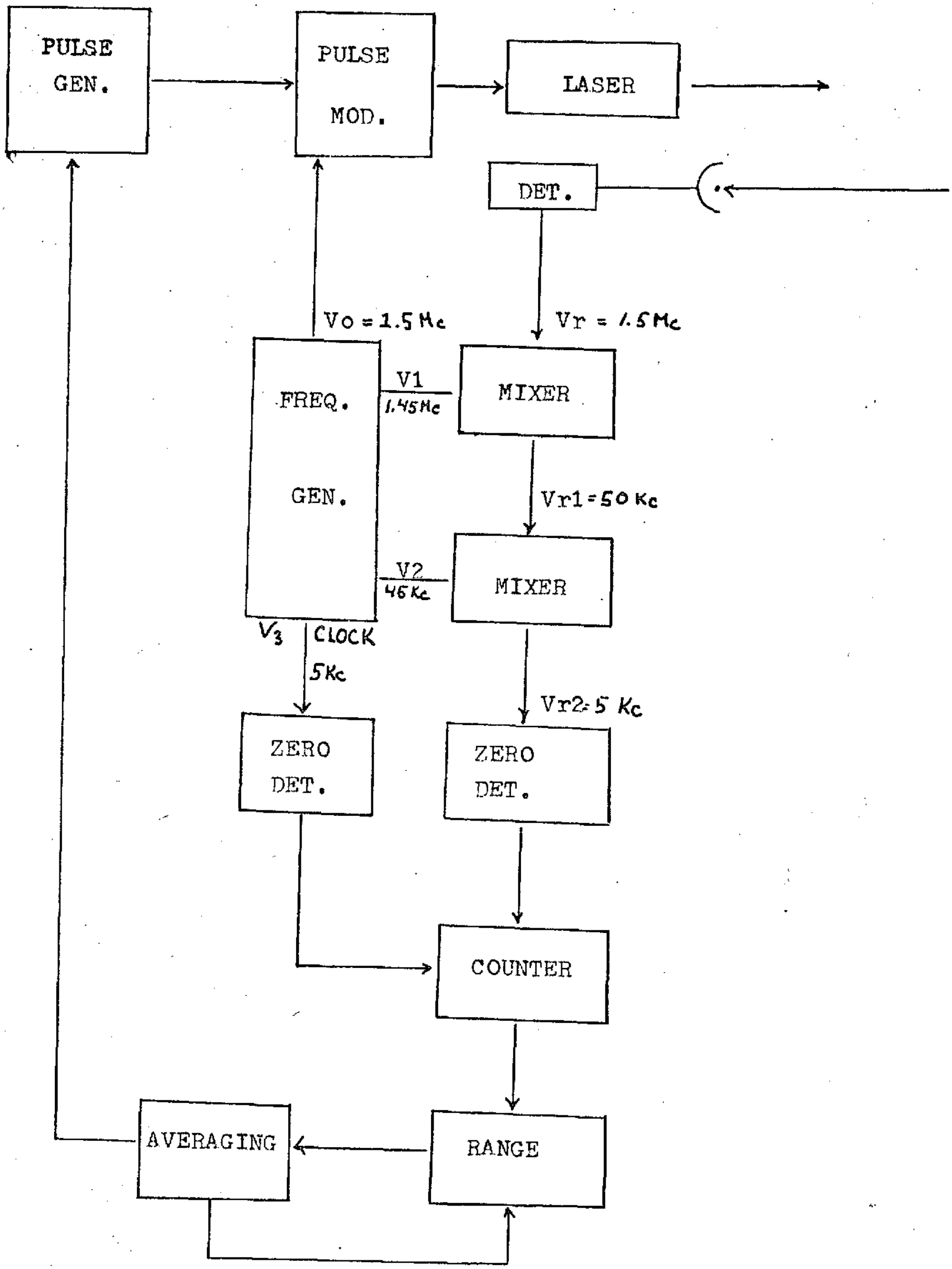


FIGURE 3
HETERODYNING CIRCUIT

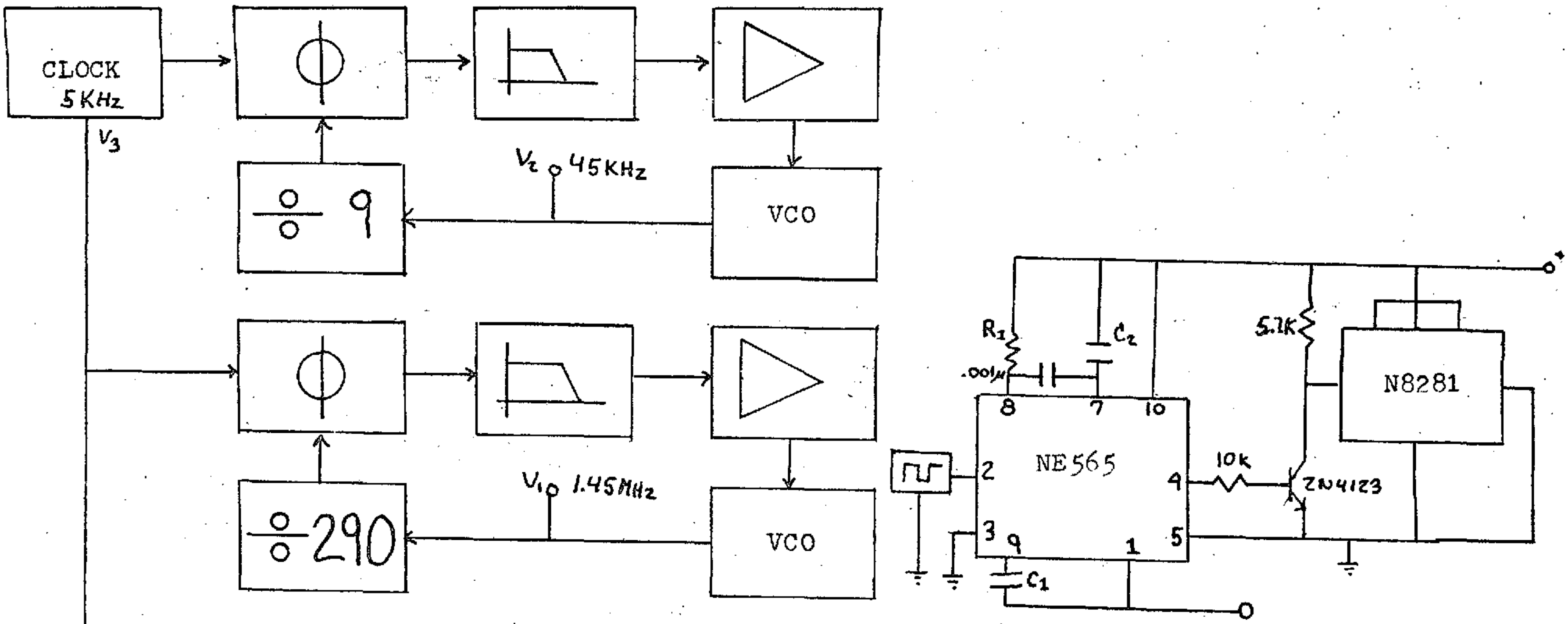


FIGURE 4

THE FREQUENCY GENERATOR

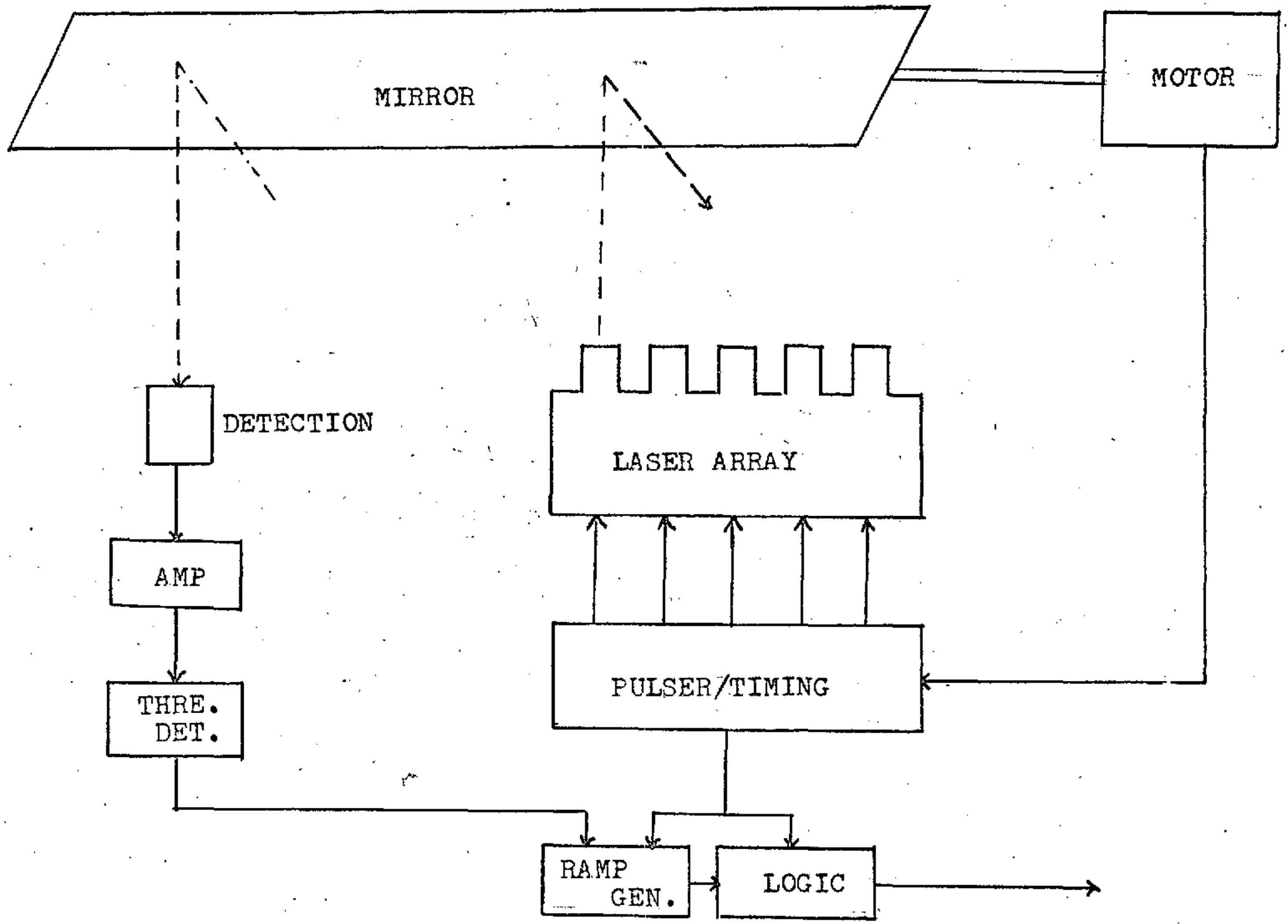


FIGURE 5

TIMED PULSE

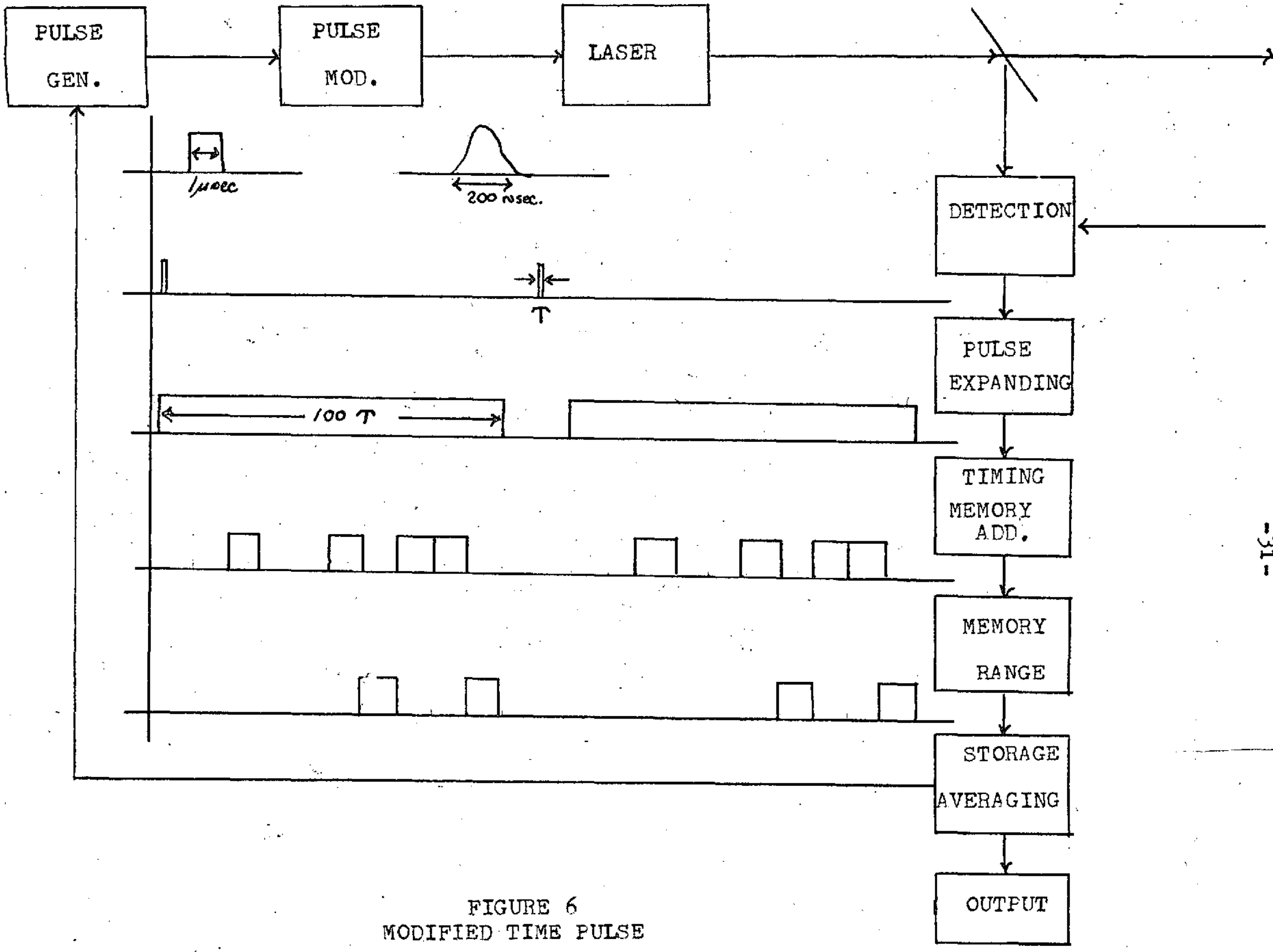


FIGURE 6
MODIFIED TIME PULSE

EXCLUSIVE OR		
A	B	C
0	1	1
0	0	0
1	0	1
1	1	0

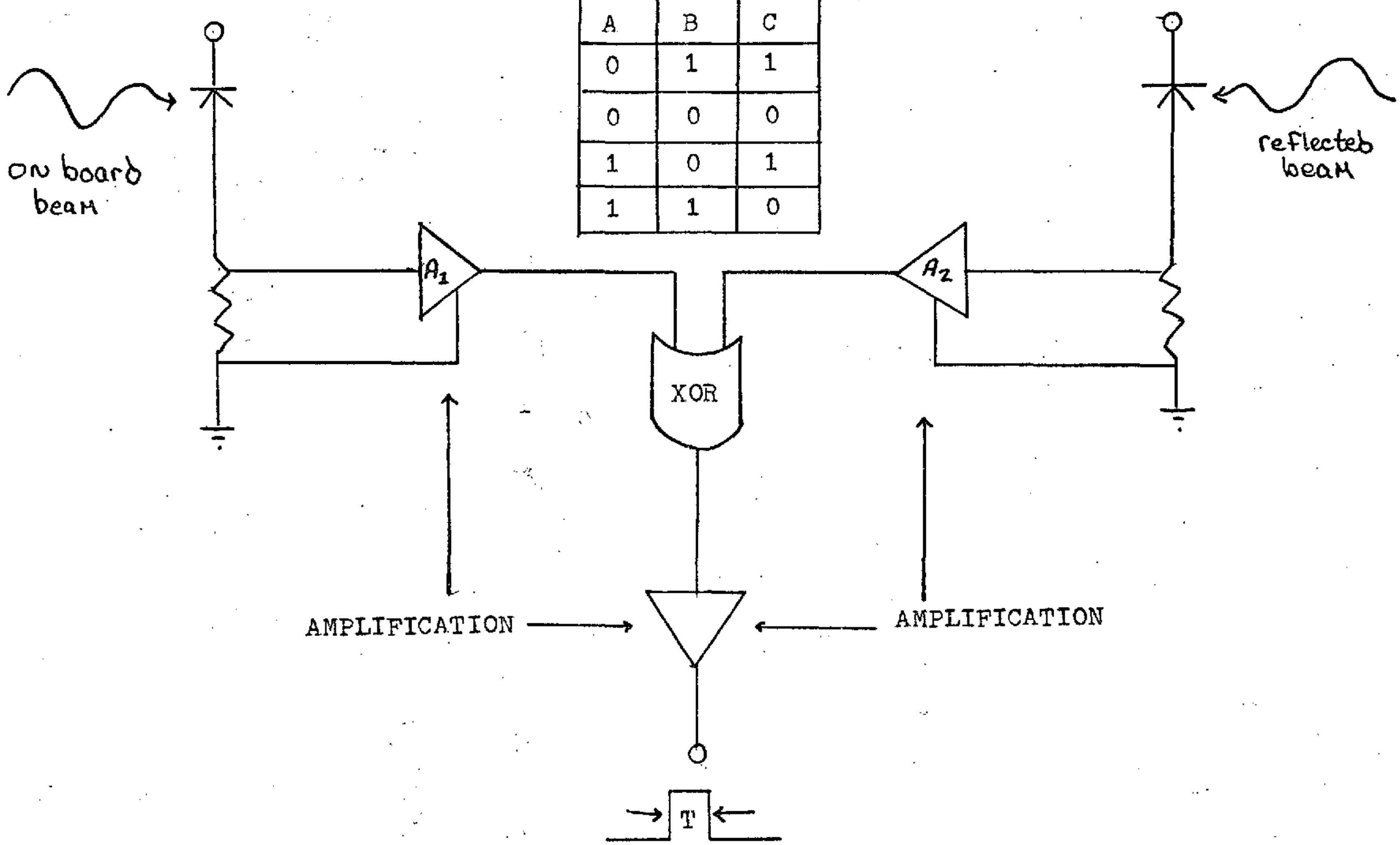
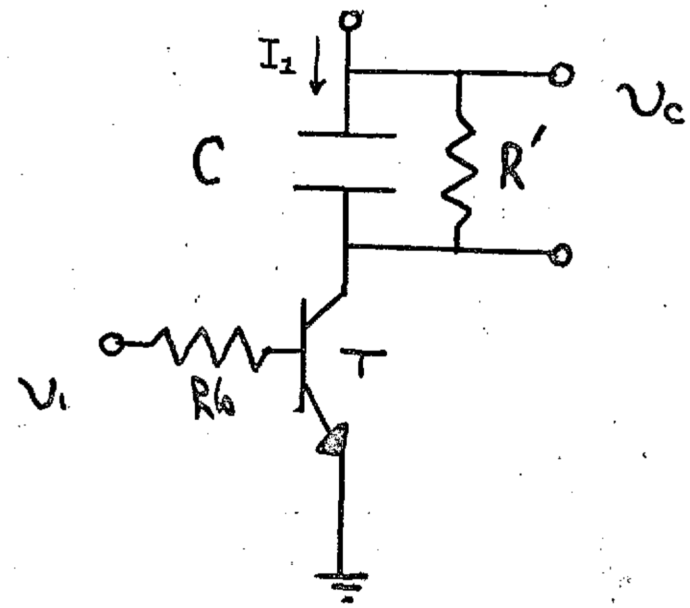


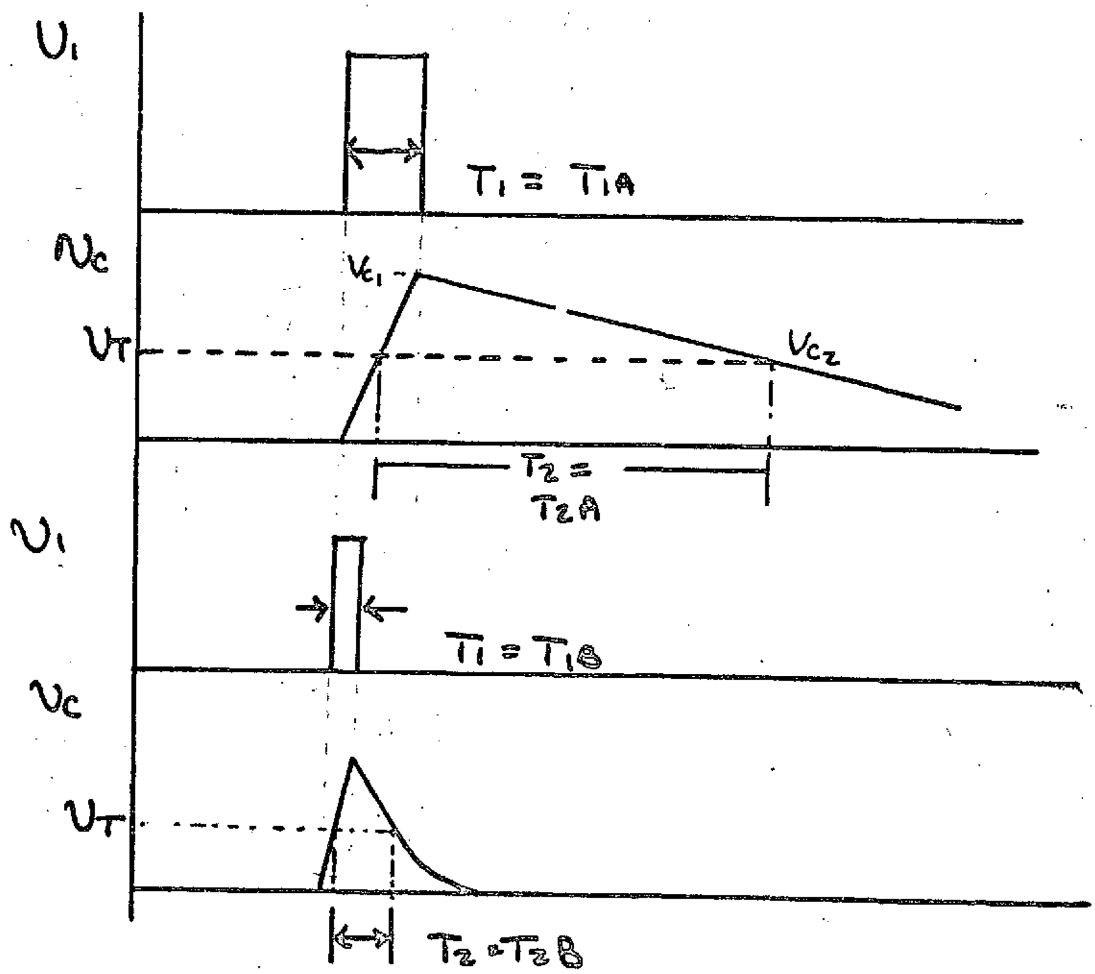
FIGURE 7

DETECTION CIRCUIT

Figure 8

PULSE EXPANDER - FREE RUNNING





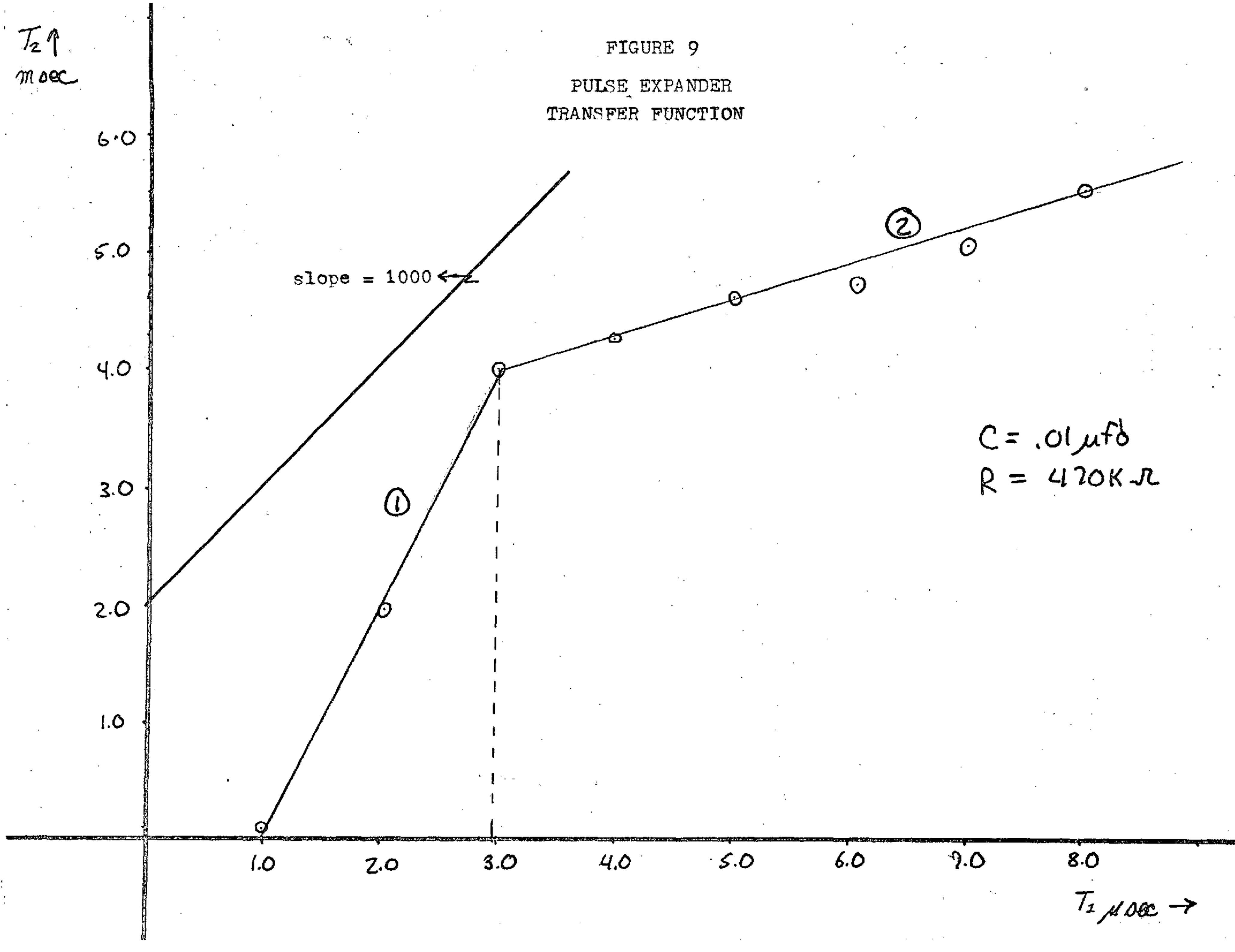


FIGURE 9
PULSE EXPANDER
TRANSFER FUNCTION

FIGURE 10

SCHMITT TRIGGER

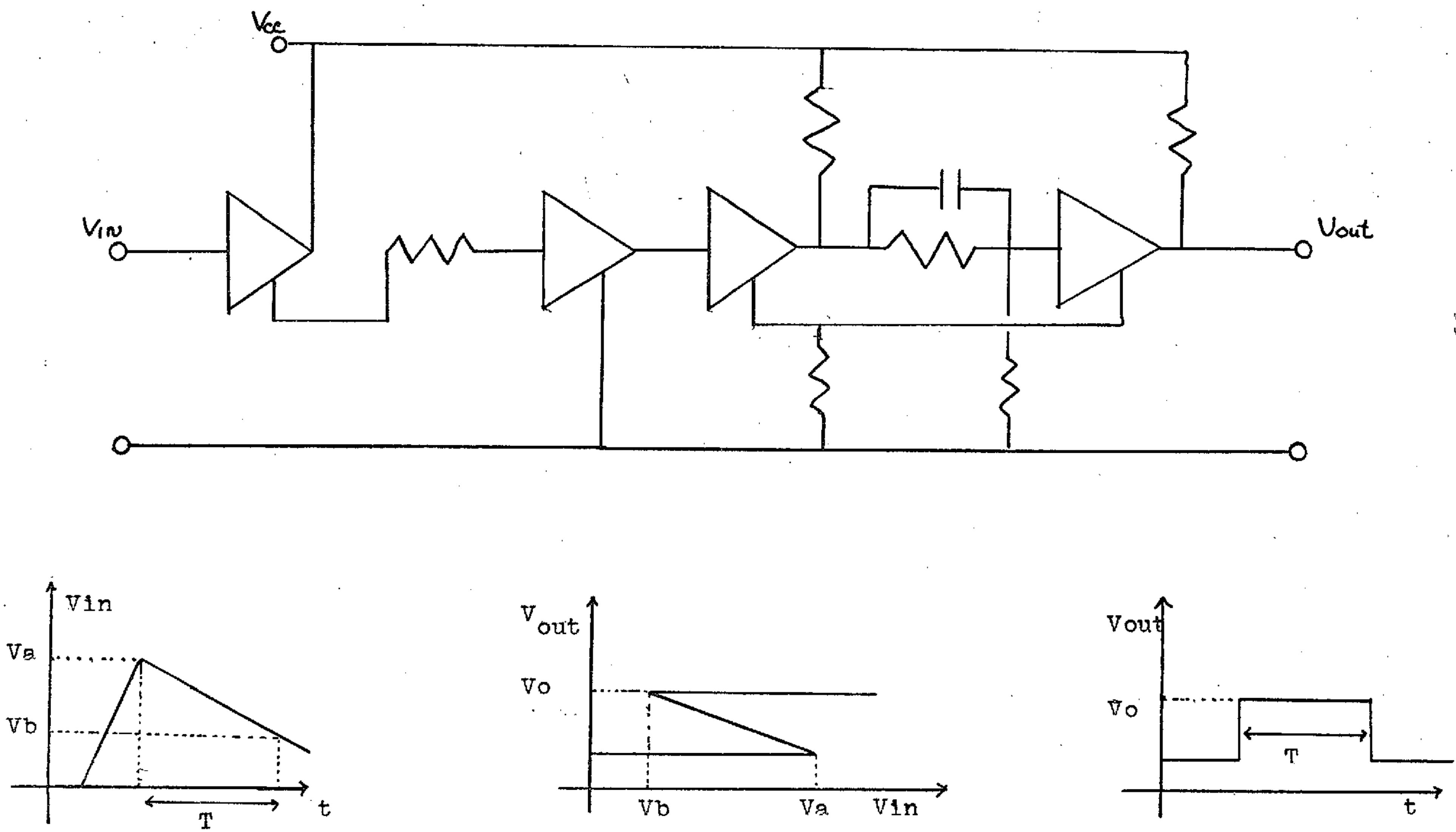
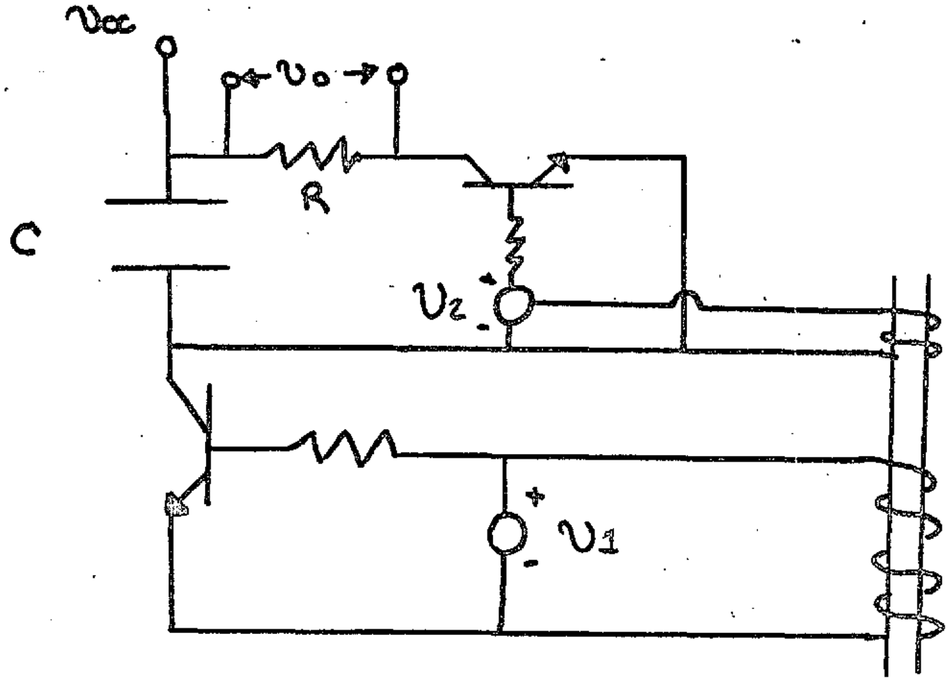
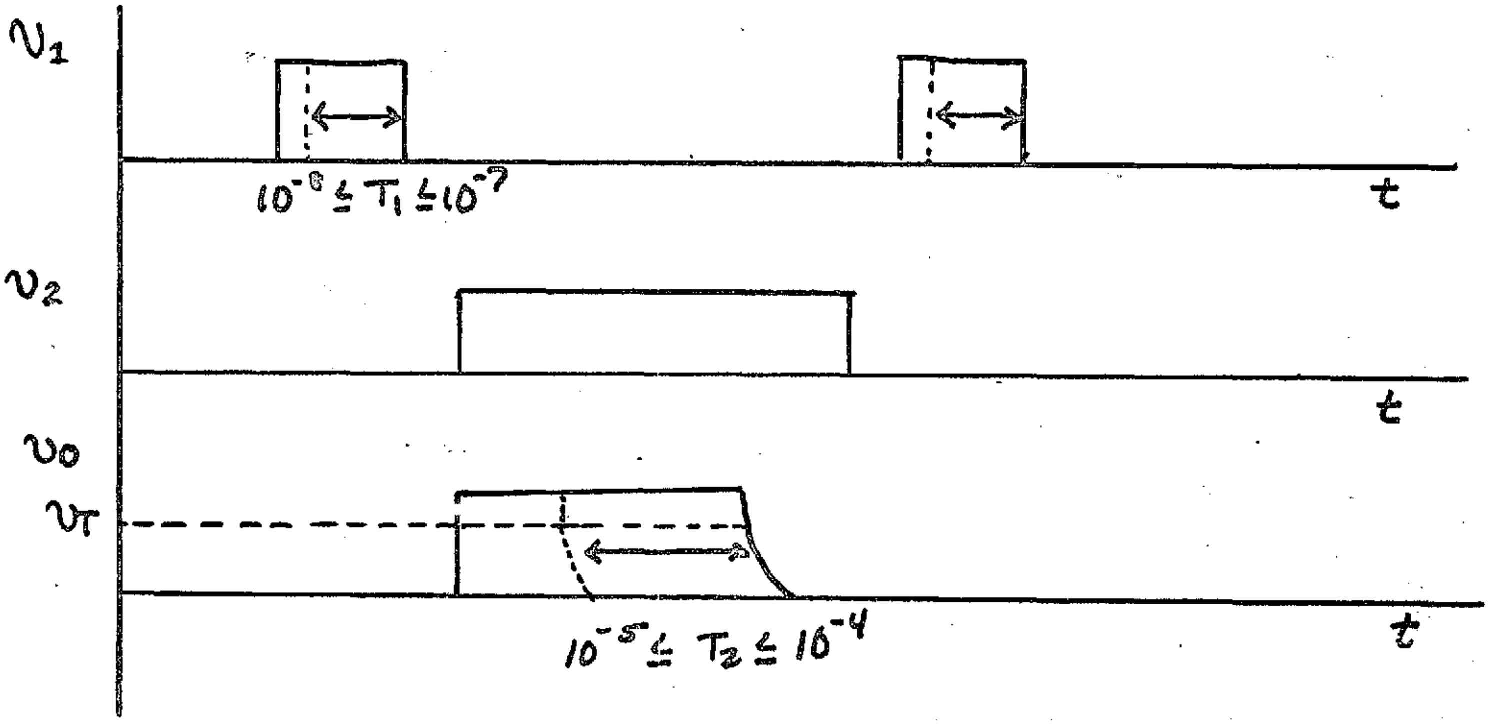


Figure 11

PULSE EXPANDER - METERED



TRANSFORMER GIVES DC ISOLATION, WHILE ALLOWING EXTERNAL TRIGGERING



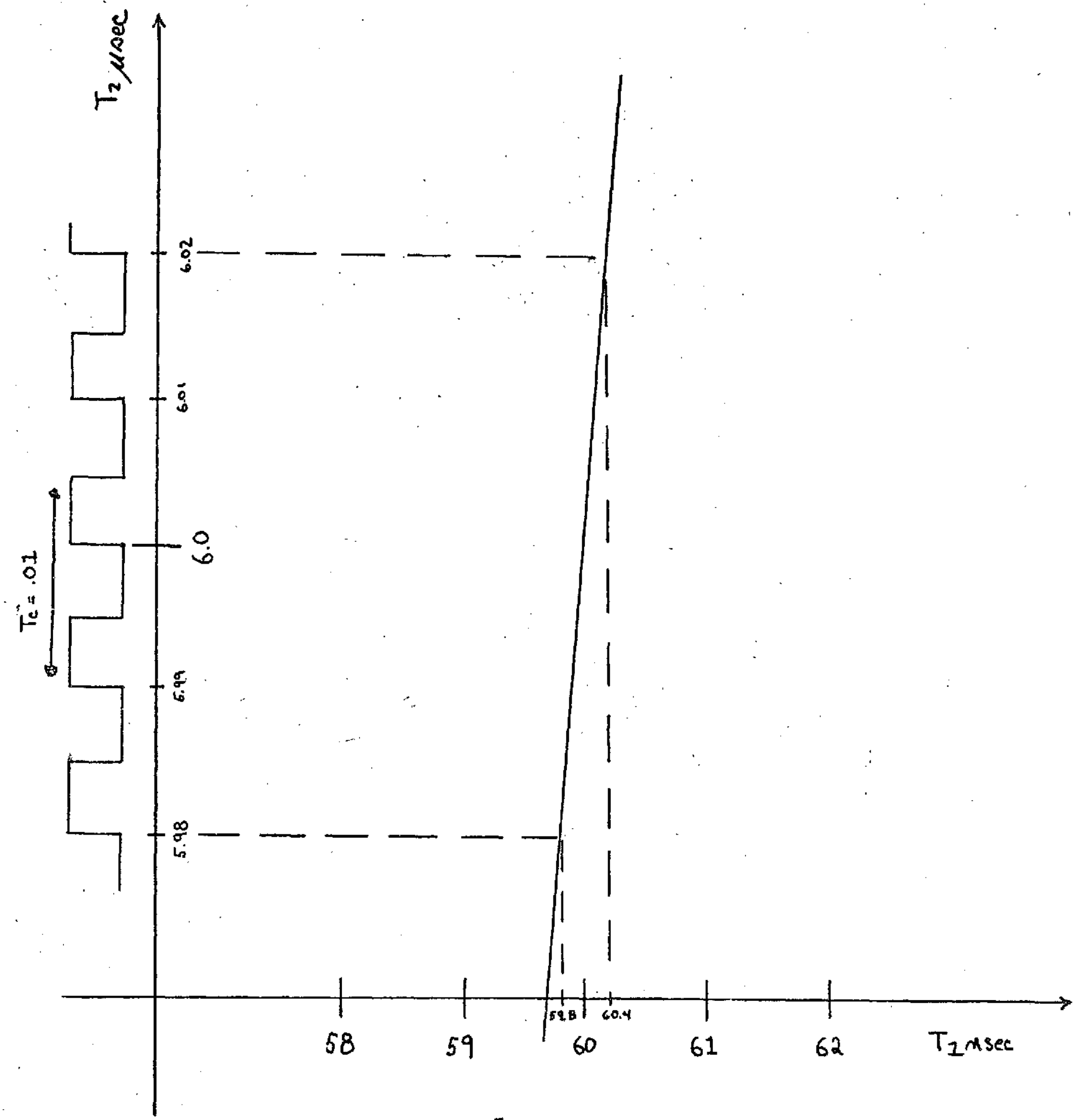


Figure 12
Blown-up Portion of
Transfer Function

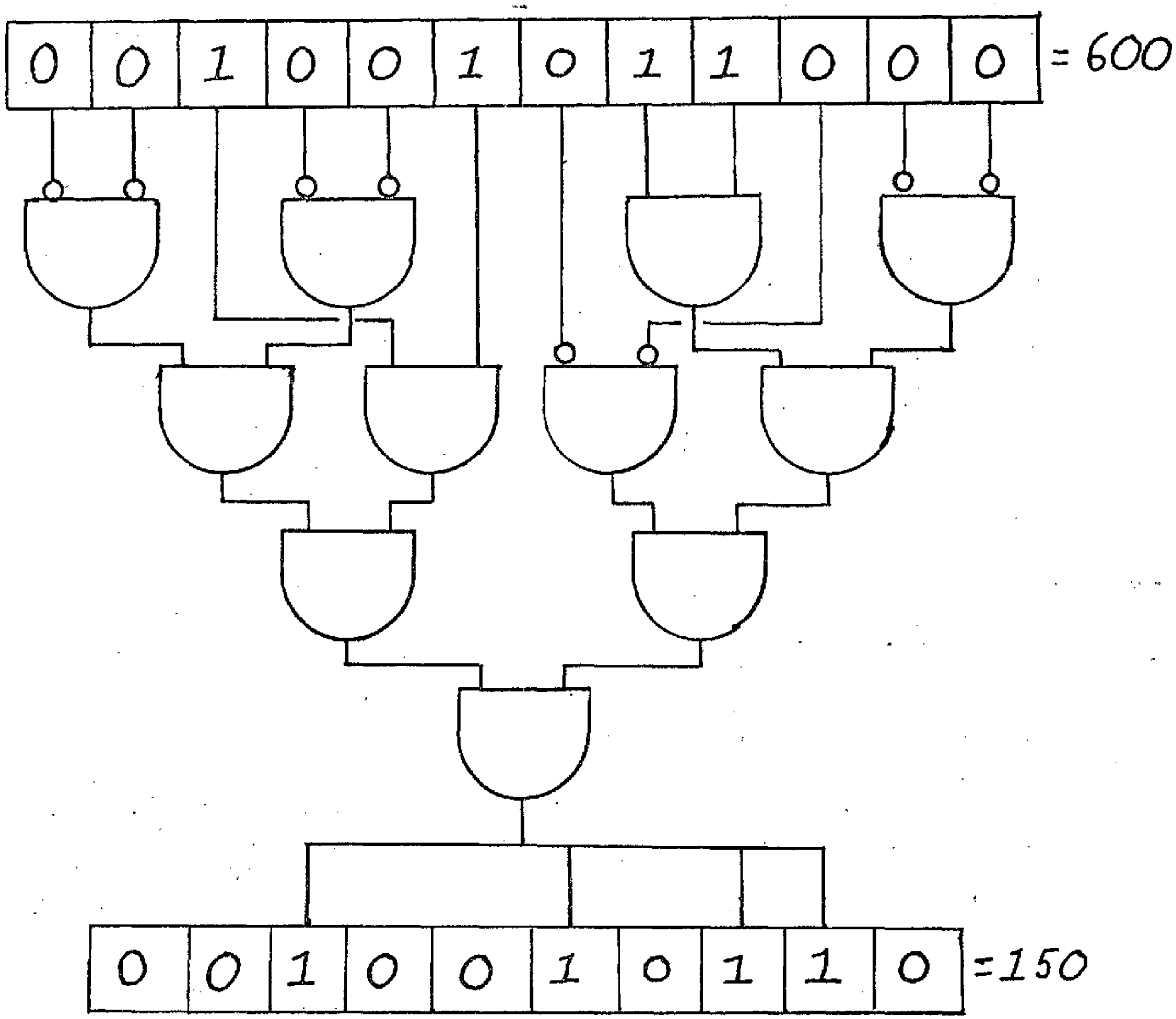
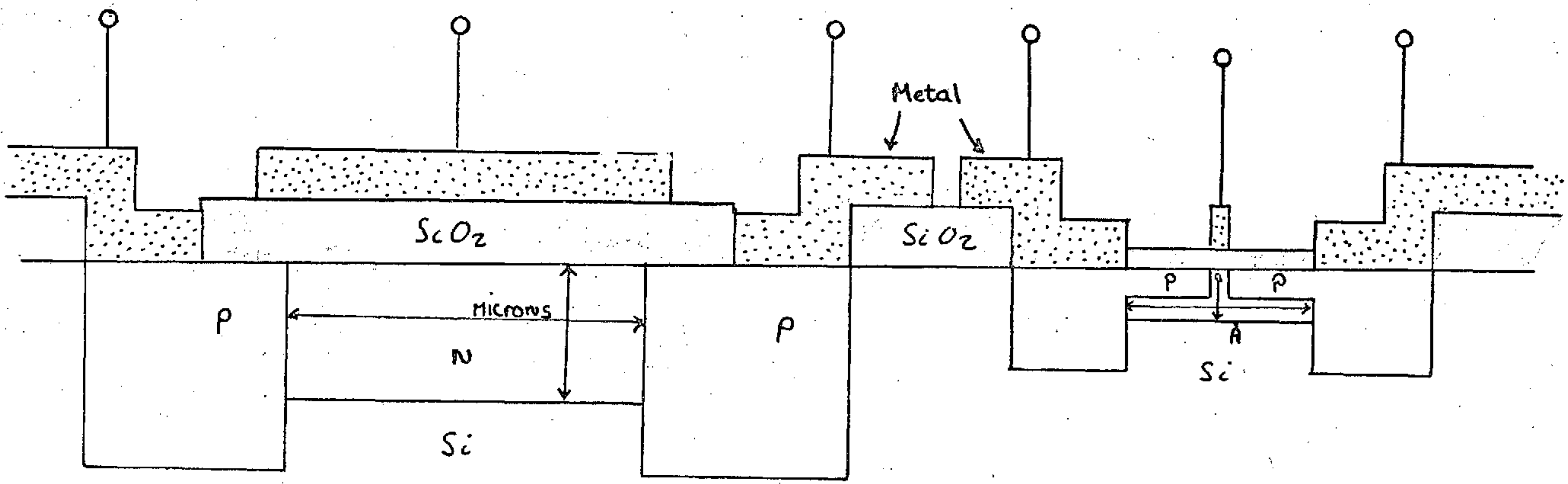


Figure 13

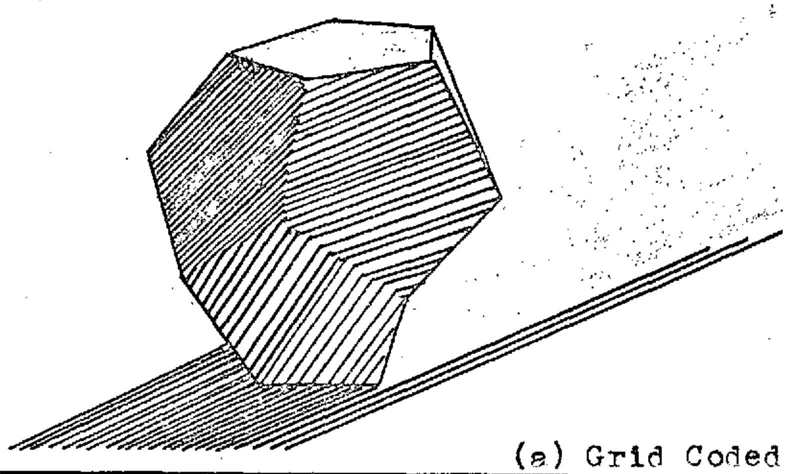
Memory Address Fabrication



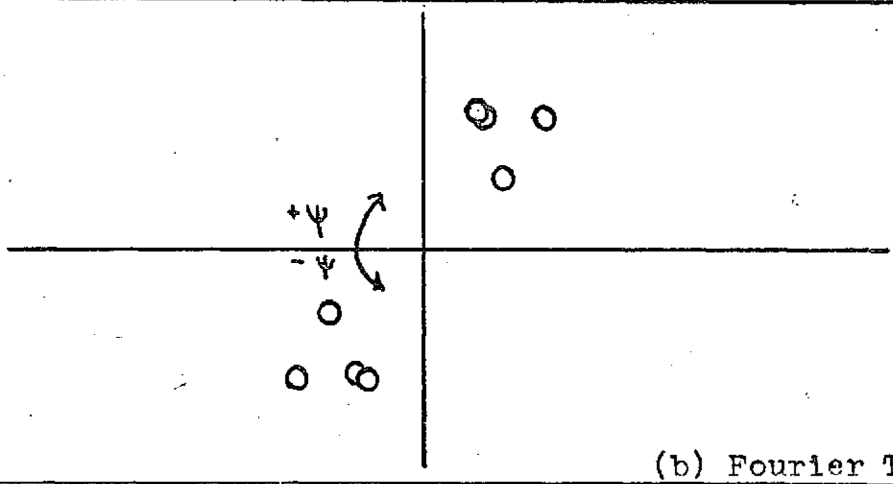
Transisto(a)-diffused

Transistor(b)
Ion Implant

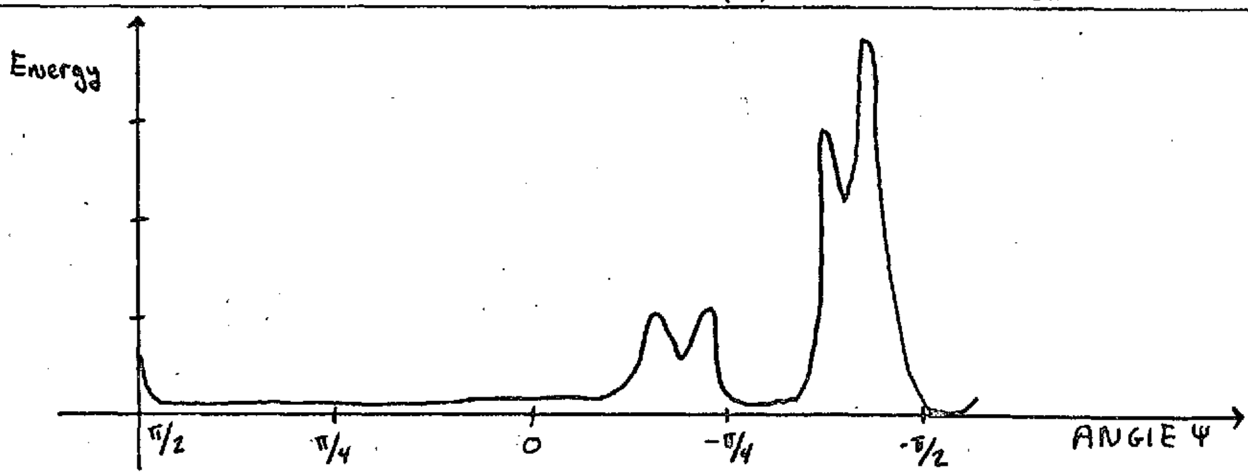
Figure 14
Future possibilities



(a) Grid Coded Pattern

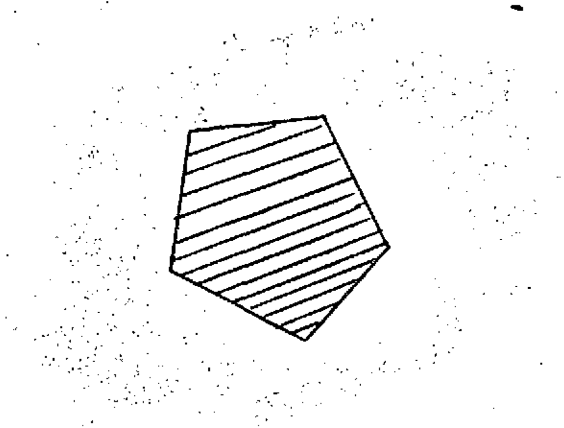


(b) Fourier Transform

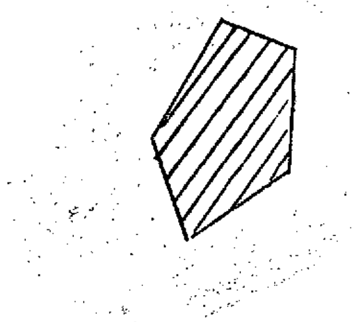


(c) Energy Distribution

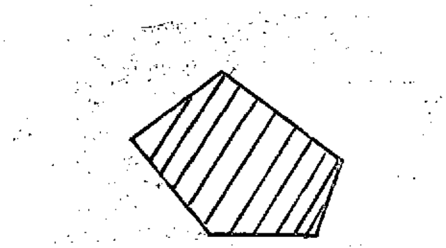
Figure 15



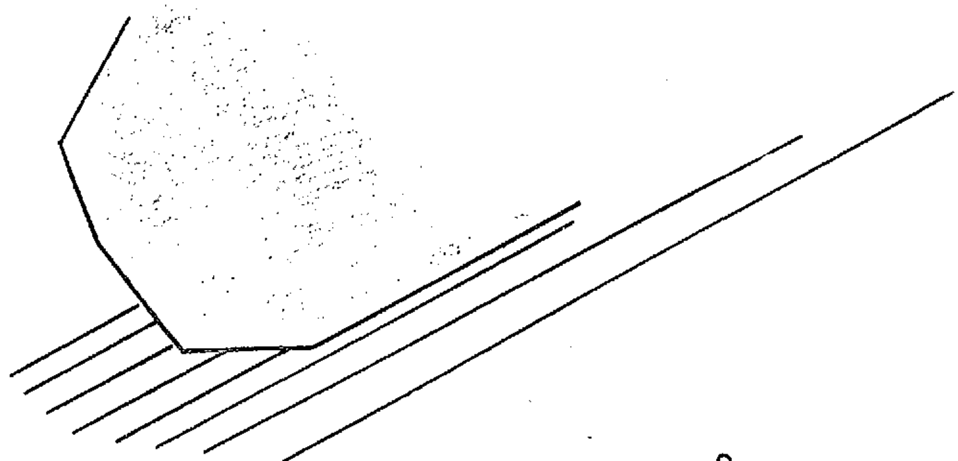
Filter at -38°



Filter at -47°

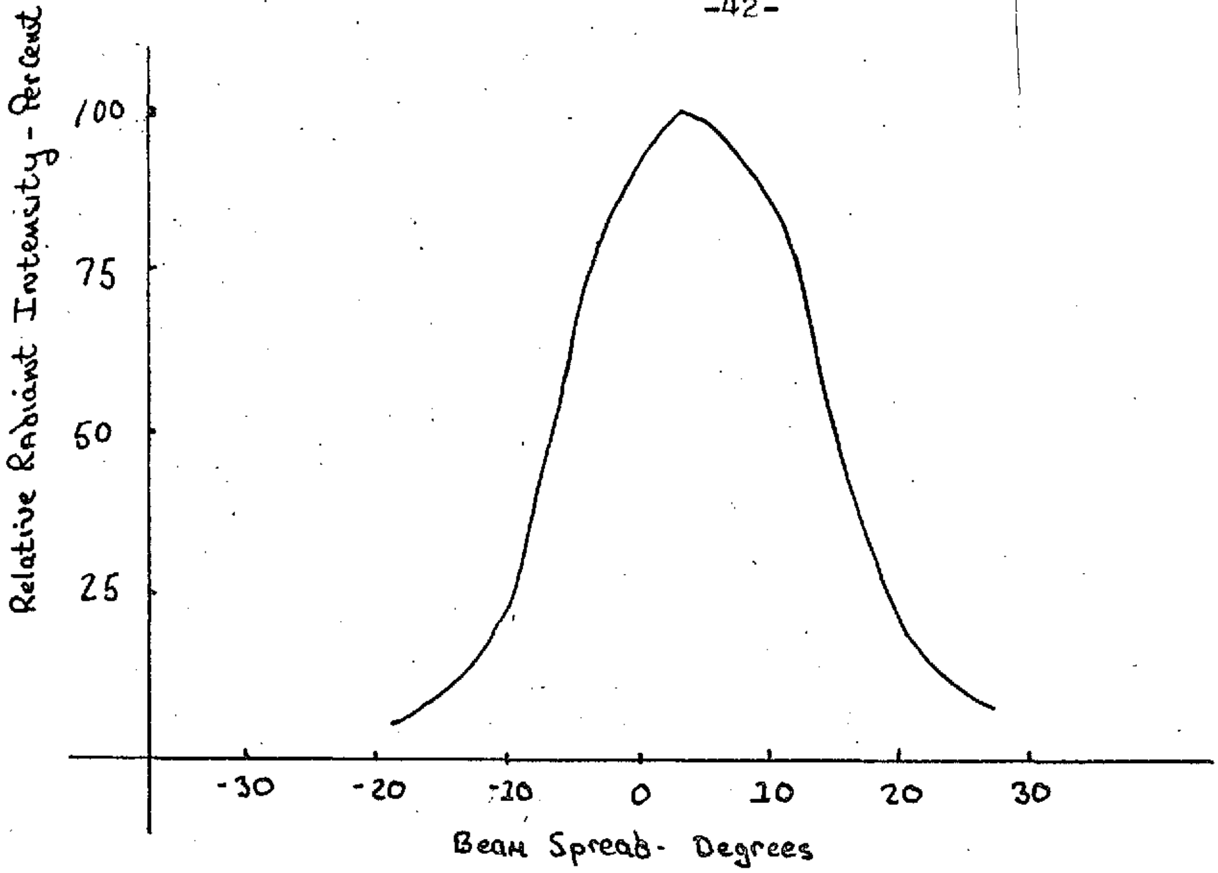


Filter at -64°



Filter at -68°

Figure 16



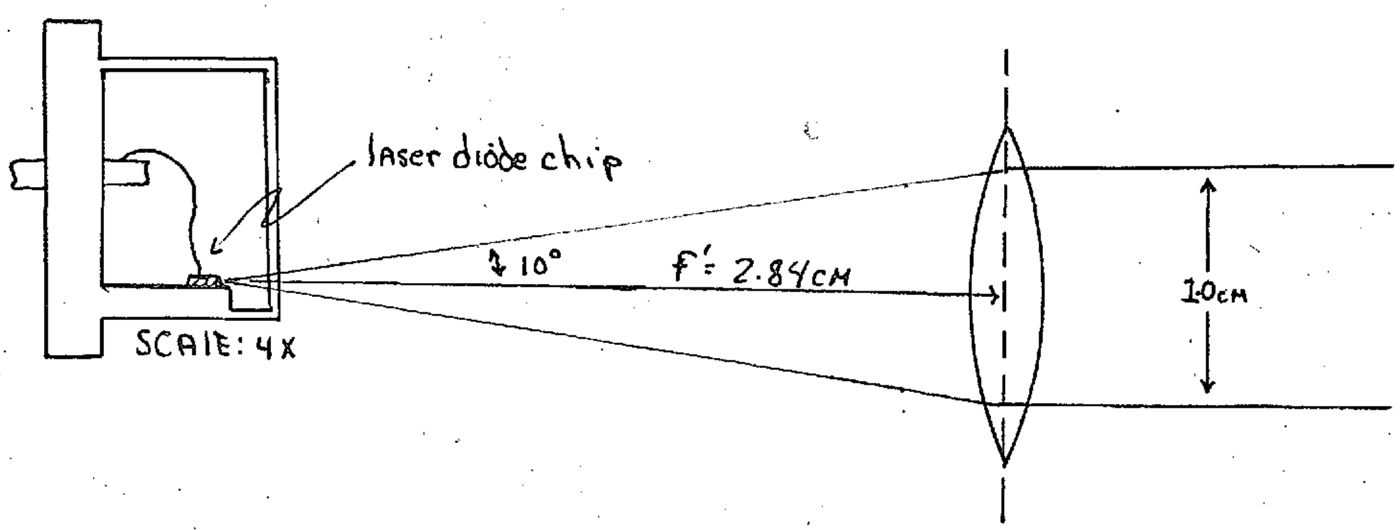


FIGURE 17

Collimating the

Laser Beam

PULSE CURRENT AMPLIFIER
FOR GaAs LASER

1. OUTPUT CURRENT MAXIMUM, Imax = 40 AMPS
2. MINIMUM OBTAINABLE PULSE WIDTH = 100 NANOSECONDS
3. MUST GIVE FLAT TOPPED SQUARE WAVE OUTPUT

RCA 2N5262

MAXIMUM RATINGS:

Vceo = 50 VOLTS

Ic = 3 AMPS

CHARACTERISTICS

TURN ON TIME = 20 NSECS.

TURN OFF TIME = 35 NSECS.

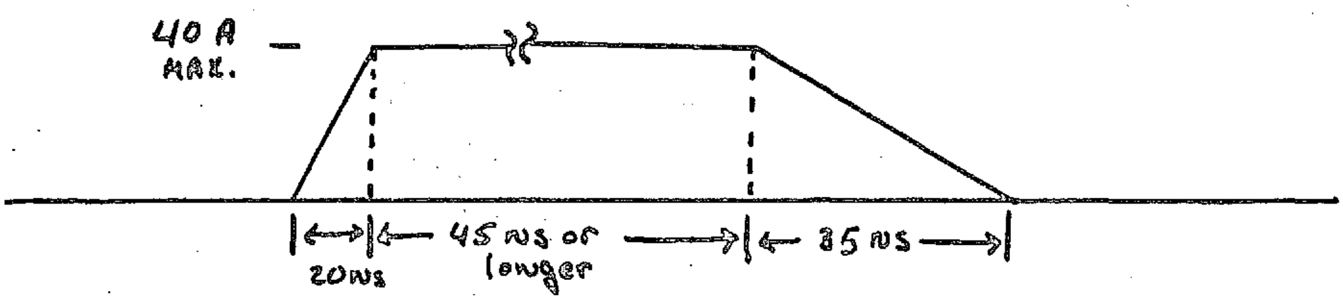
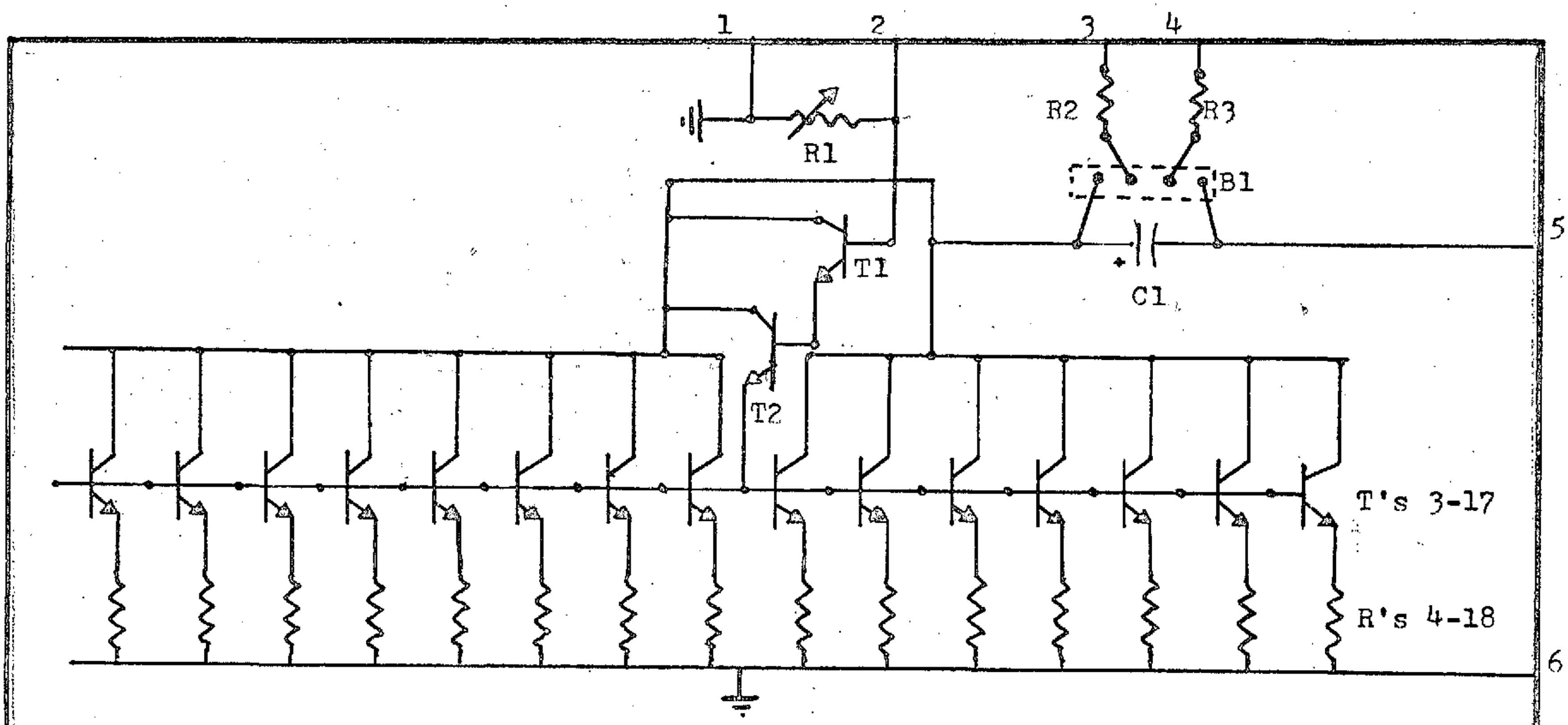


Figure 18

PULSE CURRENT AMPLIFIER FOR

GaAs LASER



T's 1-17: 2N5262; C1:300microf.; B1(full wave bridge): SK3105

R1: 100K potentiometer; R2-3: 15 ohm; R4-18: 5 ohm

CONNECTOR: (1) GROUND; (2) PULSE GENERATOR-MODULATOR;
(3-4) 25.2v TRANSFORMER; (5) p-side GaAs LASER;
(6) n-side GaAs LASER

Figure 19

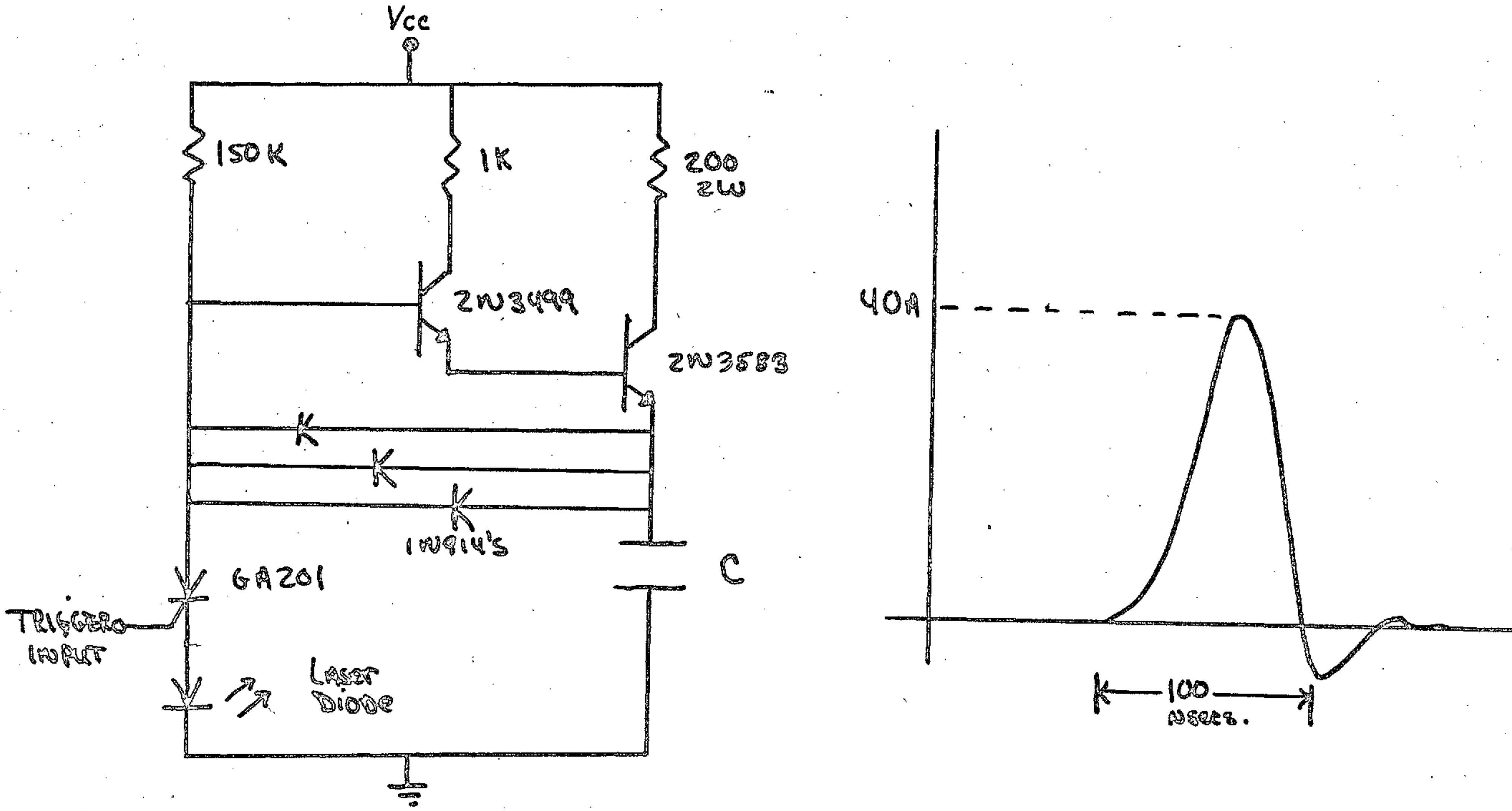


Figure 20

Conventional power supply

and output waveform

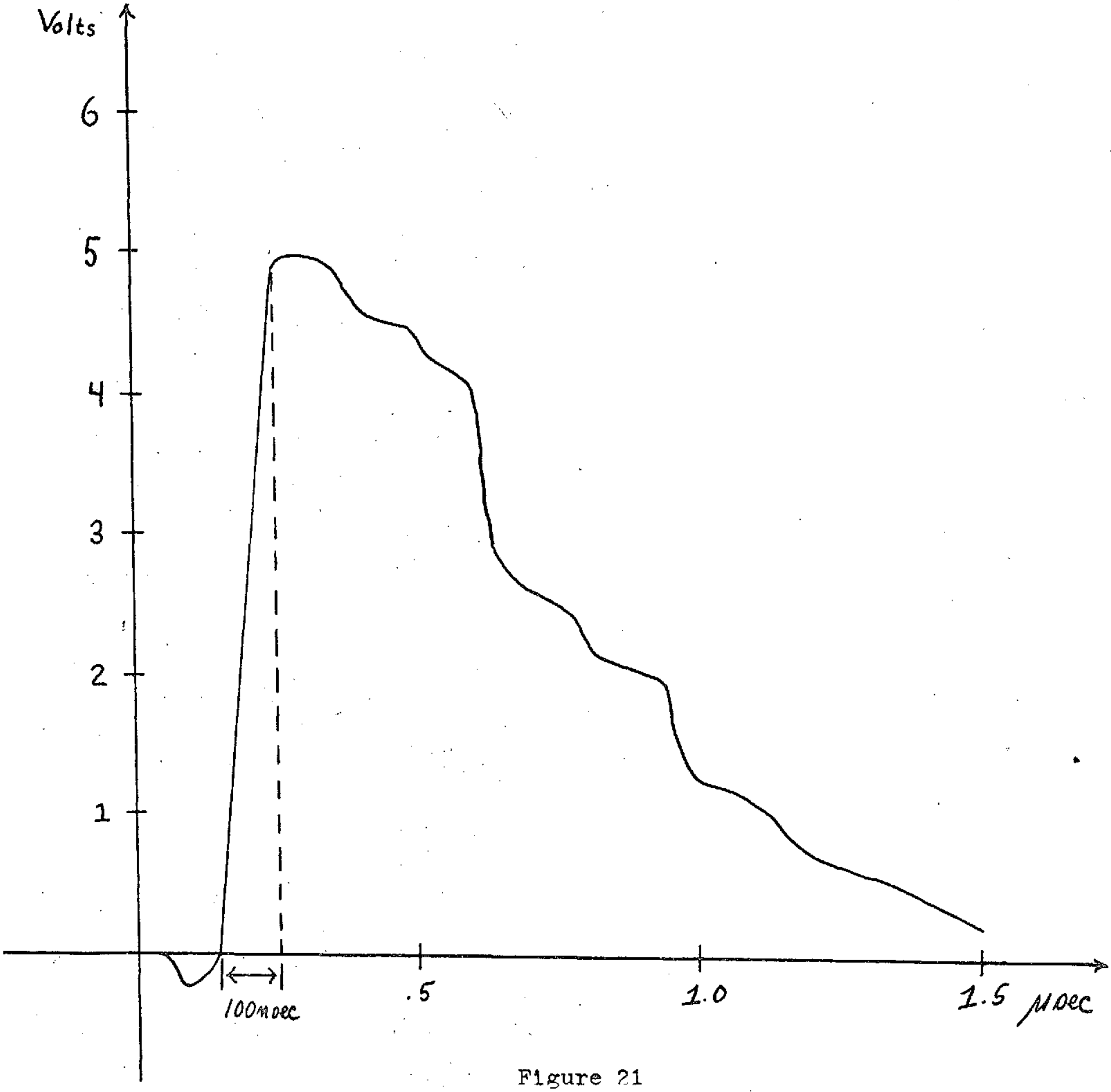


Figure 21

Received signal waveform

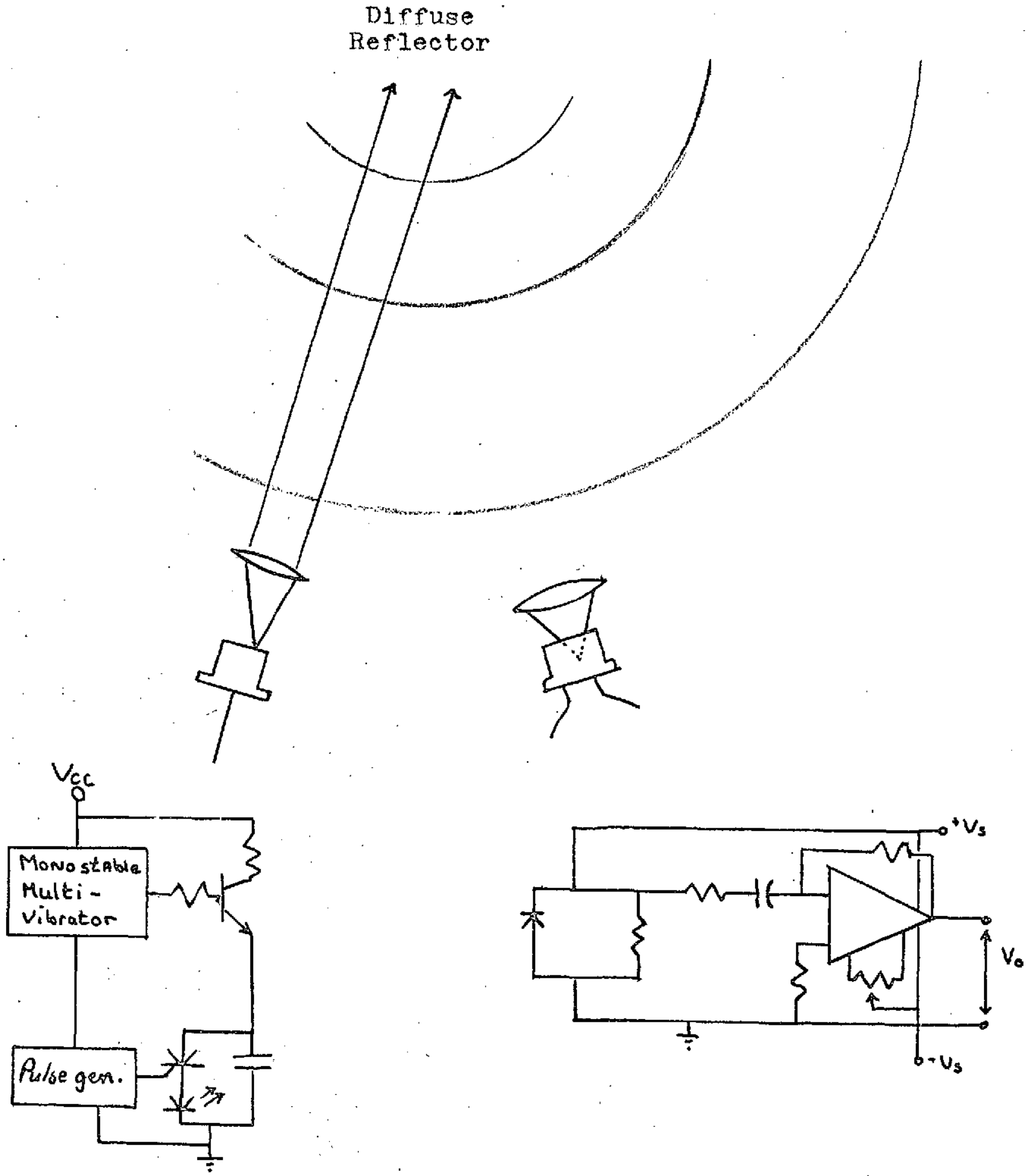


FIGURE 22

Proposed Power Supply and

Detection Circuitry

REFERENCES

1. Burger, P., "Stochastic Estimate of Gradient from Laser Measurements for an Autonomous Martian Roving Vehicle", 3rd IFAC Symposium on Identification and System Parameter Estimation, The Hague, Netherlands, June 1973.

2. Pfiefer, W.,"Gradient Estimate from Stereo Measurements for Martian Terrain Modeling", to be published.

3. Teledyne Gurley,"Incremental Rotary Encoder", Dta Sheet #8605, December 1970.

4. Personal communication with Fairchild Semiconductor Co.

5. Dukes, J. N., and Gordon, G. B.,"A 200 foot Yardstick with Graduations Every Microinch", Hewlett-Packard Journal, 21 , p.2. August 1970.

6. Nakazawa, N.,"Electro-optical Rangefinding Unit has 1,000 meter accuracy of ± 1 cm", Japan Electronic Engineering, p.30, July 1971.

7. Zuraski, J."Laser Range Measurement for a Satellite Navigation Scheme and Mid-Range Path Selection and Obsacle Avoidance", Rensselaer Polytechnic Institute, Troy, New York,June 1972.

8. Kuriger, W., K.,"A Proposed Obstacle Sensor for a Mars Rover", Journal Spacecraft, 10, p.1043. October 1971.

9. Jet Propulsion Laboratory, NASA Headquarters Press Conference of Mariner 9 Science Results, p.G.N.-4, February 2, 1972.

10. Ditchburn, R. W.,"Light", Interscience Publishers Inc., New York, p. 59, 1953.

11. Morehead, F.F., and Crowder B.L., "Ion Implantation", Scientific American,228, p.65,April 1973.

12. Will, P.M., and Pennington, K.S.,:Grid Coding: A Preprocessing Technique for Robot and Machine Vision", Artificial Intelligence, 2,p.319. 1971.

13. Allen, C.W.,"Astrophysical Quantities",University of London Athlone Press, p.140, 1955.

14. Meisenholder, G.W.,"Planet Illuminance," TR 32-361, Jet Propulsion Laboratory, Nov. 1962.

15 Mason, C.C.,"Nature of the Martian Surface as Inferred from the Particle-Size Distribution of Lunar-Surface Material", Geology Society Bulletin.

16. RCA, "15-W Gallium Arsenide Single-Diode Laser", File Number 521 September 1971.

17. RCA, "Solid State Injection Lasers", #OPT-100B, June 1972.

18. DeVilbiss, W.F., and Klunk, S.L., "A High Speed Pulser for Injection-Laser Diodes", RCA Application Note #AN-4741, Sept. 1971.

19. RCA, Application Notes #AN-4469, June 1972.

20. Sprague Engineering Bulletin, #27111, 1970.