1964

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Recommended Citation

Faga, Martin Clark, "The pin diode as a microwave modulator" (1964). *Theses and Dissertations*. 3247.
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THE PIN DIODE AS A MICROWAVE MODULATOR

by
Martin Clark Faga

A THESIS

Presented to the Graduate Faculty

of Lehigh University

in Candidacy for the Degree of

Master of Science

Lehigh University

1964

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

August 19, 1964
(date)

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Acknowledgements

The opportunity to perform this work was provided by the United States Air Force whose assistance is gratefully acknowledged.

The writer is deeply indebted to Dr. Daniel Leenov for his assistance and direction in the theoretical development, experimental application, and actual writing of this paper. Without his assistance this project could not have been completed.

Credit is due to Dr. T. B. Ramachandran for the loan of much equipment used in the experimental work.

I wish to thank the Bell Telephone Laboratories for the PIN diodes and diode packages supplied.

I am grateful to James W. Caskey, Lieutenant Colonel, USAF, for his aid and encouragement which helped make my entire graduate endeavour possible.

My fiance, Miss Susan Kresge, deserves credit for her moral encouragement and assistance in the preparation of the final manuscript.

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THE PIN DIODE AS A MICROWAVE MODULATOR

Martin Clark Faga

Abstract

Increased use of radio communication has brought use of higher and higher frequencies in the electromagnetic spectrum. While transmission frequencies have risen, intelligible and useful information is still contained in audio and other low frequency signals. Hence modulation, the electronic process of mixing these two signals, is a fundamental part of this development.

Unfortunately, modulation methods used with low frequency carrier circuits do not work well, if at all, at microwave carrier frequencies.

The PIN diode is a simple semiconductor device whose properties lend it to effective use as a modulator at microwave frequencies.

This paper is concerned with a brief theoretical presentation of actual modulating circuits and discussion of their operation and results obtained.

I. Introduction

A consequence of man's ever increasing use of radio communication is the necessity of using a greater portion of the electromagnetic spectrum for this communication. Before World War II, use of the electromagnetic spectrum above 30 megacycles was unusual. The press for communication channels has brought use of this spectrum into the thousands of megacycles. The use of these higher frequencies presents many engineering problems, hence has brought new equipment, new technique, and greater knowledge into the field.

One important technique in all of radio communication is modulation, the process of electronically mixing an information signal with a radio signal or carrier which will conveniently propagate through space. Techniques used at low frequencies are not applicable to high frequency purposes. The development of effective modulation methods is basic to the effective utilization of higher frequencies (100 megacycles and higher).

A new semiconductor device recently developed by the Bell Telephone Laboratories is the PIN diode (p-type-Intrinsic- n-type). This device responds differently at high and low frequencies. Its properties make it useful as a high frequency or microwave modulating device.

It is the purpose of this paper to develop a technique for the use of the PIN diode as a modulator. This will be done in two frequency ranges: near 600 megacycles where carrier power is carried by copper conductors in a coaxial configuration, and near 8000 megacycles where transmission is through hollow waveguide sections. These two important transmission media present differing physical configurations for a PIN modulator with which experiments will be performed.

This paper will consist, basically, of four sections. First basic modulation theory and an electrical description of the PIN diode will be presented. Second, the expected modulation performance will be analyzed theoretically. Third will be a discussion of experimental techniques followed, fourth, by a discussion and presentation of results obtained.

II. Theory of the PIN Diode Modulator

1. Basic Modulation Theory.

Modulation is a technique almost as old as radio communication itself. While many types of modulation exist, amplitude modulation is most widely used largely because of the relative simplicity involved in producing and detecting such modulation. The PIN diode is useful in producing amplitude modulation which will be our entire interest in this work.

According to Schwartz,[1] amplitude modulation implies the availability of sinusoidal energy with an output voltage or current waveform of the type

$$V(t) = A \cos(\omega_c t + \theta) \tag{1}$$

where ω_c is carrier frequency, θ is phase and A is amplitude. In amplitude modulated (AM) systems only A varies with time. It is assumed that the modulating signal varies slowly compared with the carrier. Thus, an envelope variation of the carrier is produced. The AM carrier may be described in the form

$$f_c(t) = K\left[1 + mf(t)\right] \cos \omega_c t. \tag{2}$$

So long as $|mf(t)| < 1$ the envelope will be an accurate representation of the modulating wave.

It is our desire to modulate our high frequency sinusoidal signal with low frequency signals which are also sinusoidal.

Thus $f(t) = \cos \omega_m t \quad (\omega_m \ll \omega_c)$

where ω_m is modulation frequency.

Then

$$f_c(t) = K(1 + m\cos \omega_m t)\cos \omega_c t = \tag{3}$$

$$K\cos \omega_c t + \tfrac{1}{2}Km \cos (\omega_c + \omega_m)t + \tfrac{1}{2}Km \cos(\omega_c - \omega_m)t$$

by the trigonometric sum and difference formulas. The original modulation frequency f_m has been shifted up in frequency and split into two frequencies, one on each side of the carrier frequency f_c. This is the desired result as the sidebands contain our information but at a high frequency suitable for radio transmission.

In seeking a method for producing modulation, we note that the mathematical expression for AM appears as a product function (Eq. 2),

$$f_c(t) = K\left[1 + mf(t)\right] \cos \omega_c t$$

We need, then, a device in which the output appears as the product of the input quantities. One such device is a nonlinear resistance. The nonlinear output may be expanded in a power series of the form

$$e_o + a_1 e_i + a_2 e_i^2 + a_3 e_i^3 + \ldots\ldots\ldots + \tag{4}$$

where e_o is output and e_i is input.

For the circuit in figure 1

$$e_i = \cos \omega_c t + f(t) \tag{5}$$

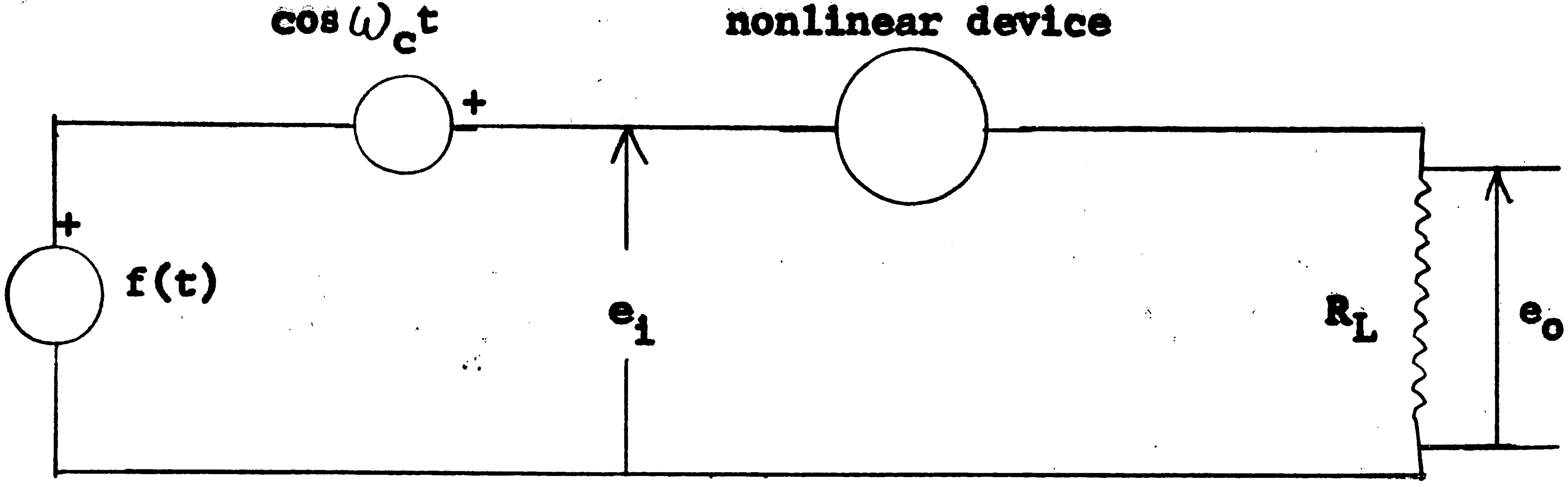


Figure 1. Simple Modulator

Retaining only the first two terms of our power series, we get

$$e_o = a_1\cos\omega_c t + a_1 f(t) + a_2\left[\cos^2\omega_c t + 2f(t)\cos\omega_c t + f^2(t)\right] = a_1 f(t) + a_2\cos^2\omega_c t + a_2 f^2(t) + \underbrace{a_1\cos\omega_c t\left[1 + \frac{2a_2}{a_1}f(t)\right]}_{\text{AM Modulation}} \tag{6}$$

The second term, by comparison with eq. (2) is the desired AM signal ($m = 2a_2/a_1$, $K = a_1$). The unwanted terms are all different frequencies from our modulated term and may be filtered out easily.

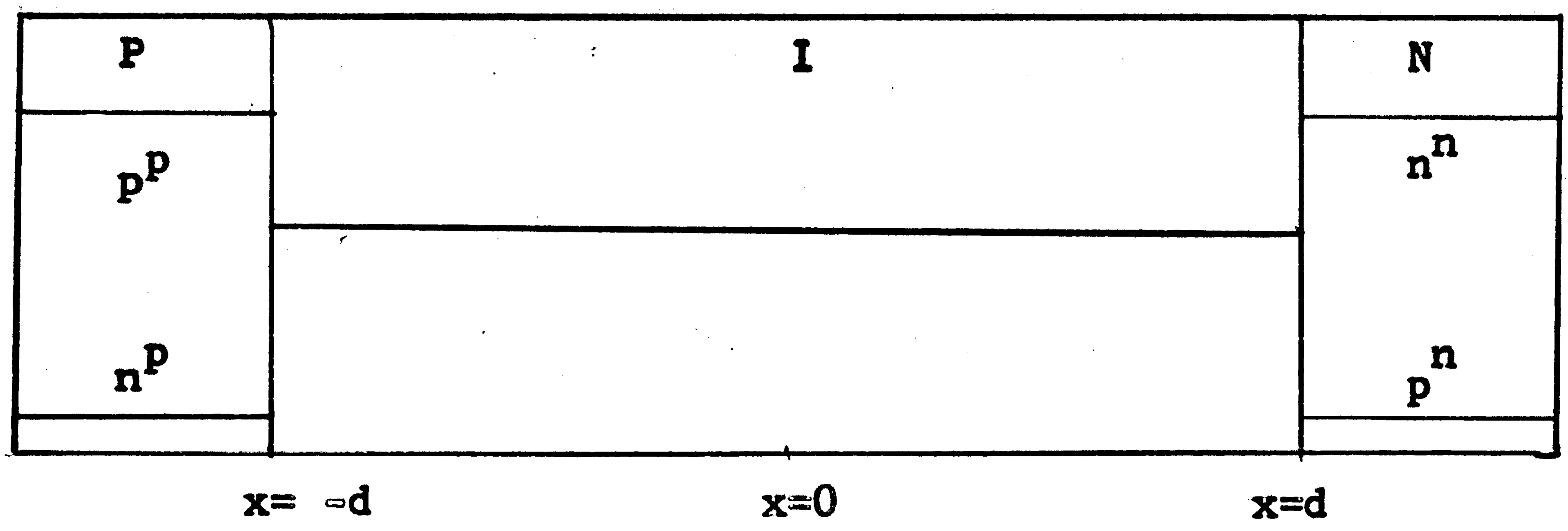
2. The PIN Diode

The PIN diode is a three layer semiconductor device consisting of a layer of p-type semiconductor material, a center layer of intrinsic material, and another outer layer of n-type material. The P and N layers are wide relative to the I layer which is less than one diffusion length in total width. The diode is a nonlinear, one-port device hence is potentially useful as a modulator as our earlier discussion would indicate.

The nonlinear action of the diode is due to the variation of I layer resistance with applied signal. At zero bias, the I layer shows a high resistance, thus acts as a high Q capacitance at microwave frequencies. In the forward biased state, the I layer resistance is considerably lower due to conductivity modulation, and the diode becomes a low resistance element. The forward biased state may be caused by d.c. bias or rectified high level microwave power.

Before any quantitative analysis of the diode is begun, a few qualitative remarks are in order about diode processes by which currents are conducted.

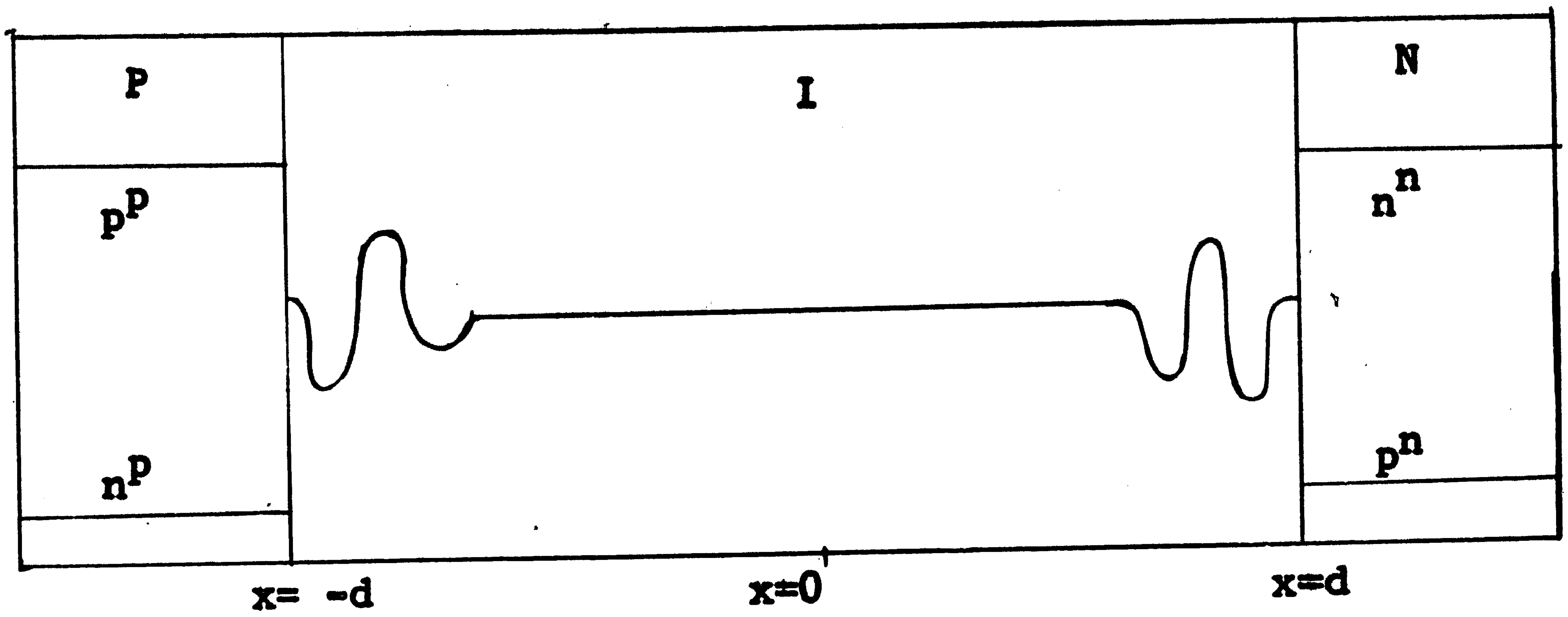
When the PIN diode is carrying direct current only, the I layer is filled with injected holes and electrons whose concentrations are about equal and are many times the equilibrium concentrations normally contained in the I layer. At low power levels, minority carrier injection into the P and N regions is negligible; recombination of holes and electrons takes place almost entirely in the I layer. Carrier concentrations are greatest at the I layer boundaries and decrease to a minimum at a plane inside the I layer. However, this effect is small and the concentration may be represented as constant for most purposes (see Figure 2).



(Not to scale)

Figure 2. Carrier density distribution in the forward biased PIN diode

When the PIN diode is driven by microwave power the mechanisms of current conduction differ somewhat from the above. Near the boundaries carrier concentration waves are set up. A substantial part of the microwave current is carried by diffusion in these two regions. However, these waves are damped out very close to the edges of the I layer; through the rest of the layer the carrier concentrations are constant with time and the high frequency current is conveyed by oscillations of the carriers about their mean postitions. Thus carrier concentration at the center of the I layer has the same shape as for d.c. or low frequencies. However, the response of the diode is different to microwave frequencies than to d.c. or low frequencies. This fact is an important reason for the usefulness of the diode as a microwave modulator. As we shall see shortly, the diode I layer resistance varies strongly with d.c. bias and low frequency current but is not varied by microwave current to any appreciable extent.



(Not to scale)

Figure 3. Carrier density in the PIN diode at high a.c. drive

3. PIN Diode I Layer Resistance.

The most important quantity in the PIN diode is the I layer resistance. The basic equation for calculating I layer resistance is

$$R = \rho W/A \tag{7}$$

where $\rho = 1/(nqu_n + pqu_p)$

and ρ = resistivity of I layer, assumed uniform

w = uniform I layer thickness

A = uniform I layer cross-sectional area

n = number of electrons in I layer per cc

p = number of holes in I layer per cc

u_n =electron mobility

u_p =hole mobility

In calculating the I layer resistance, R, it is assumed that of the variables in eq. (7) only the carrier densities p and n are strong functions of bias current, I_o. An expression for the carrier densities is obtained assuming that all recombination takes place in the I layer at a rate determined by the carrier lifetime τ. In the steady state I_o is just the current required to replace carriers lost by recombination:

$$I_o = Q/\tau = qnAw/\tau = qpAw/\tau \qquad (8)$$

assuming charge neutrality in the I layer ($n = p$).

The total density of carriers in the I layer of both p and n types is then

$$2n = 2I_o\tau/qAw \text{ carriers/cc} \qquad (9)$$

and from eq. (7) the resistance of the I layer for d.c. injection is given by

$$R = w^2/2uI_o\tau \qquad (10)$$

assuming the mobility of both carrier types to be ambipolar mobility, u. Eq. (9) has been derived under the assumption of uniform carrier distribution throughout the I layer as well as uniform mobility and lifetime. It is important to note that R is a function of current which is the basis for its application to modulating circuits.

A more rigorous analysis has been made by Leenov[2] but uses small signal assumptions. Fletcher[3] uses large signals but for d.c. only which is different than the a.c. case. In the case of large signal (relative to d.c. bias) a.c. problems a more rigorous approach becomes extremely difficult if not impossible. Furthermore, our approximate approach is found to be quite accurate for diodes of the physical dimensions such as are used in this work.

4. The Series Modulator Circuit.

With the establishment of the basis for resistance variation, we are ready to examine actual modulation circuits. Our first interest is the series circuit which is represented in the following manner:

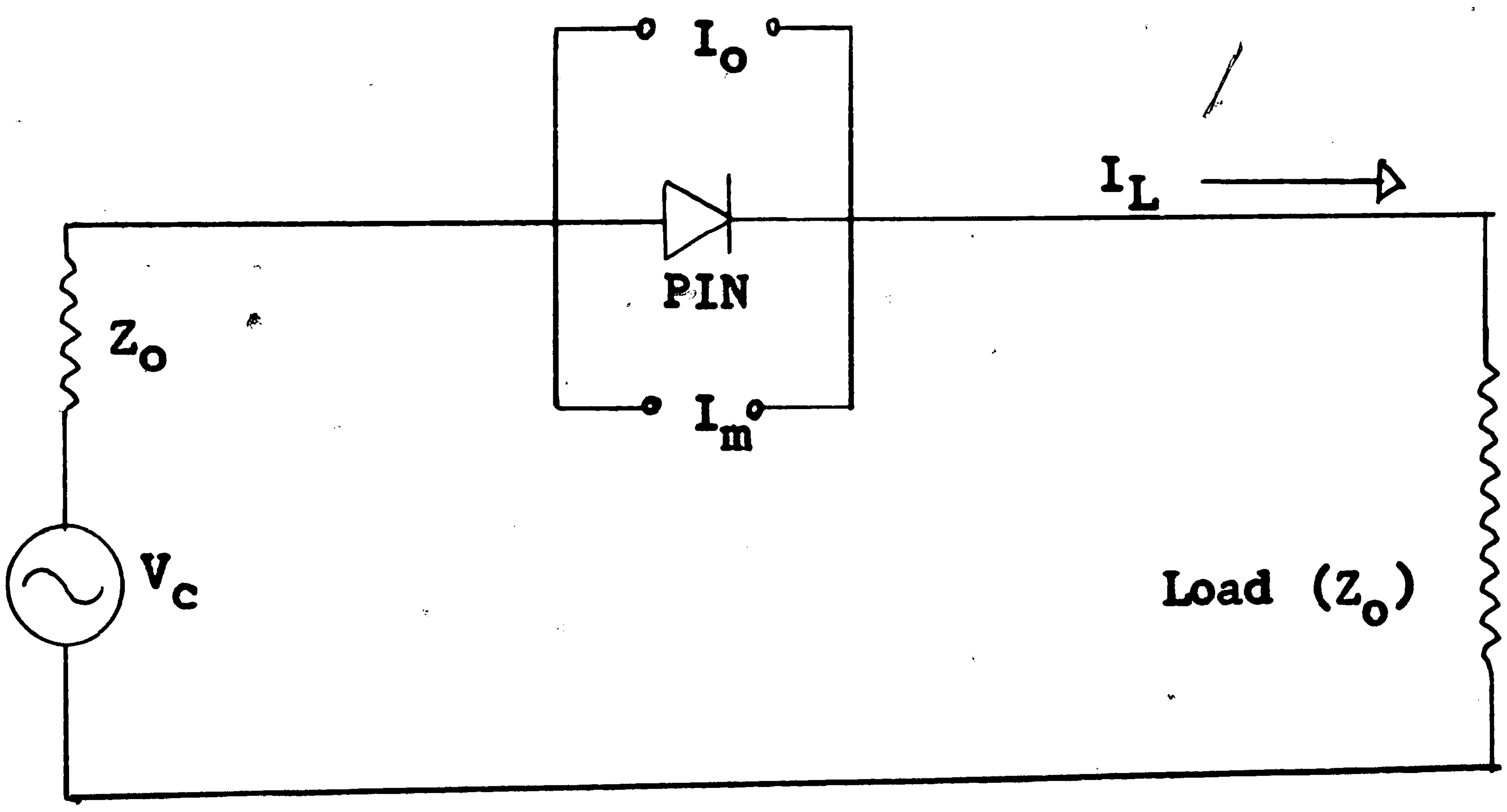


Figure 4. Series Modulator Circuit

where V_c = carrier frequency voltage generator

I_o = d.c. bias current

I_m = modulation frequency current

I_L = load current

Z_o = characteristic impedance of transmission line

Load is matched to line impedance.

PIN diode has resistance R_d.

I_o and I_m are fed through the PIN diode by the use of appropriate isolating components which will be seen in the actual circuit descriptions to follow.

By simple circuit analysis we see that

$$I_L = V_c/(2Z_o + R_d) \tag{11}$$

where $R_d = C/(I_o + I_m \cos \omega_m t)$ by eq. (10)

Thus a sketch of I_L versus $I_o + I_m$ looks like the following:

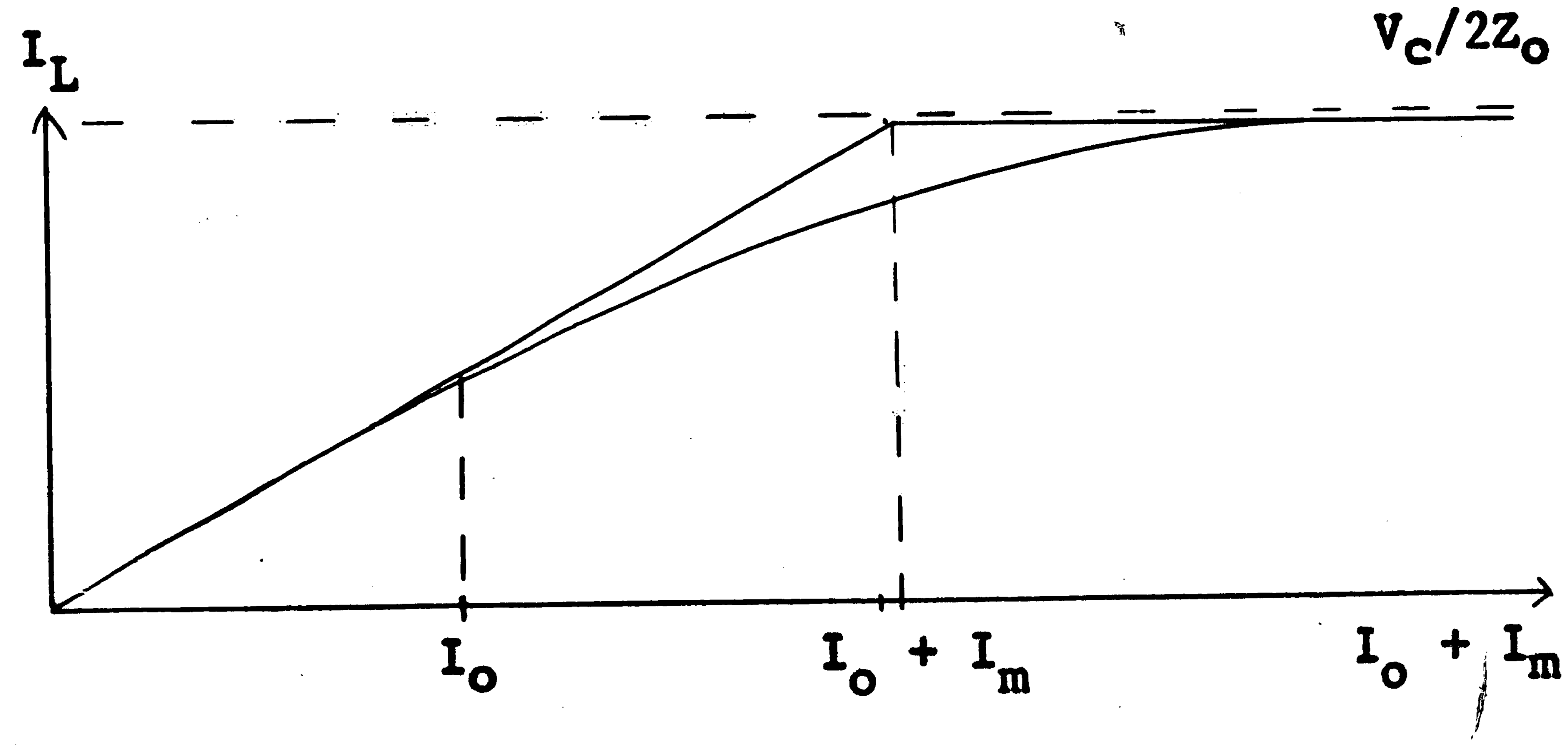


Figure 5. Sketch of I_L versus $I_o + I_m$. Series case

The heavy straight lines in Figure 5 represent a linear approximation to the curve.

It is seen that maximum I_L is obtained when R_d is nearly zero as is the case with relatively high bias. Under zero bias (total bias = d.c. plus modulating current), R_d is extremely high (relative to $2Z_o$) and I_L is nearly zero. The exact curve is determined by the specific diode constant, C, which controls R_d (eq. 11) as well as V_c of the carrier frequency generator and the Z_o of the line used for transmission of power. For any such curve it is seen that I_o should be a current chosen so as to fall midway between zero load current and maximum load current as shown on the sketch. As $I_o + I_m$ gives maximum I_L and $I_o - I_m$ must give zero bias, hence minimum I_L, it follows that

$$I_o \approx I_m \tag{12}$$

Actually I_m must be slightly greater than I_o because of the tendency for the PIN diode to store charge which necessitates a small negative signal to "clear" the diode of the stored charge.[4]

5. Parallel Modulator Circuit.

The parallel case is similar in many ways to the series case just discussed. It may be represented schematically by the following figure:

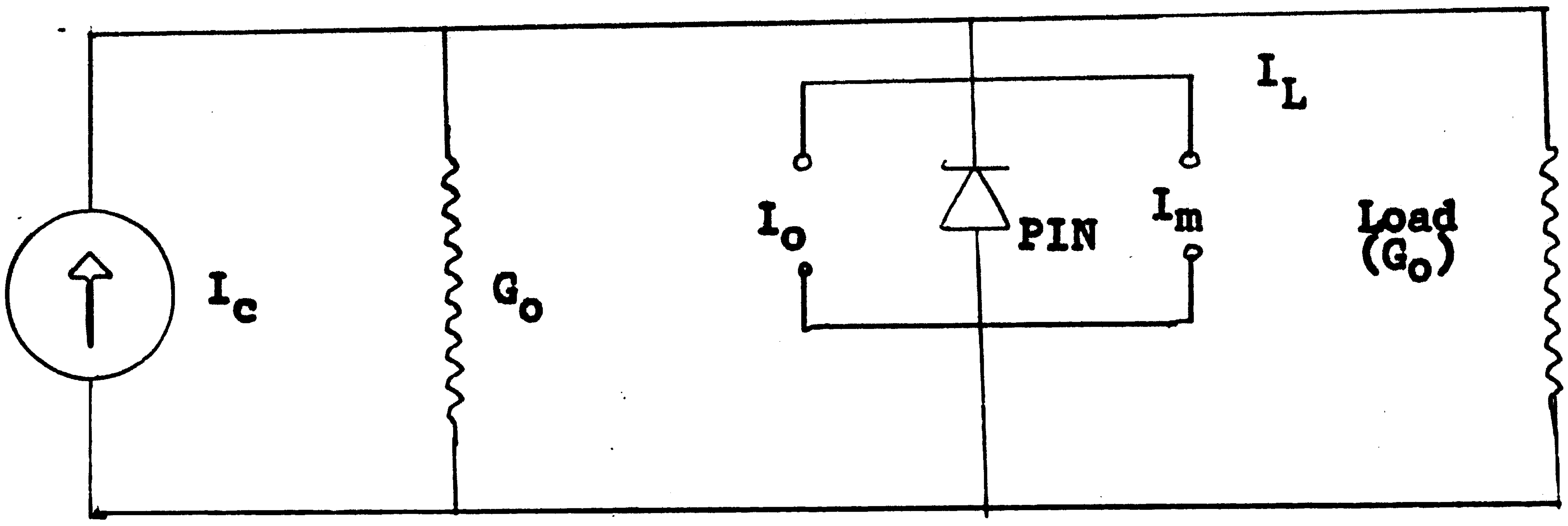


Figure 6. Parallel Modulator Circuit

I_c = carrier frequency current generator

I_o = d.c. bias

I_m = modulating current

I_L = load current

G_o = characteristic admittance of transmission line

Load is matched to the line admittance.

PIN diode admittance is represented as G_d.

I_o and I_m are fed to the diode with the use of appropriate isolating elements as will be seen in the actual circuit descriptions to follow.

Again, by circuit theory we see that

$$I_L = G_o I_c/(2G_o + G_d) \tag{13}$$

where G_d is given by eq. (10) as

$$G_d = K(I_o + I_m \cos \omega_m t)$$

where K is a constant dependent on diode characteristics.

In this case a sketch of I_L versus $I_o + I_m$ yields the following curve:

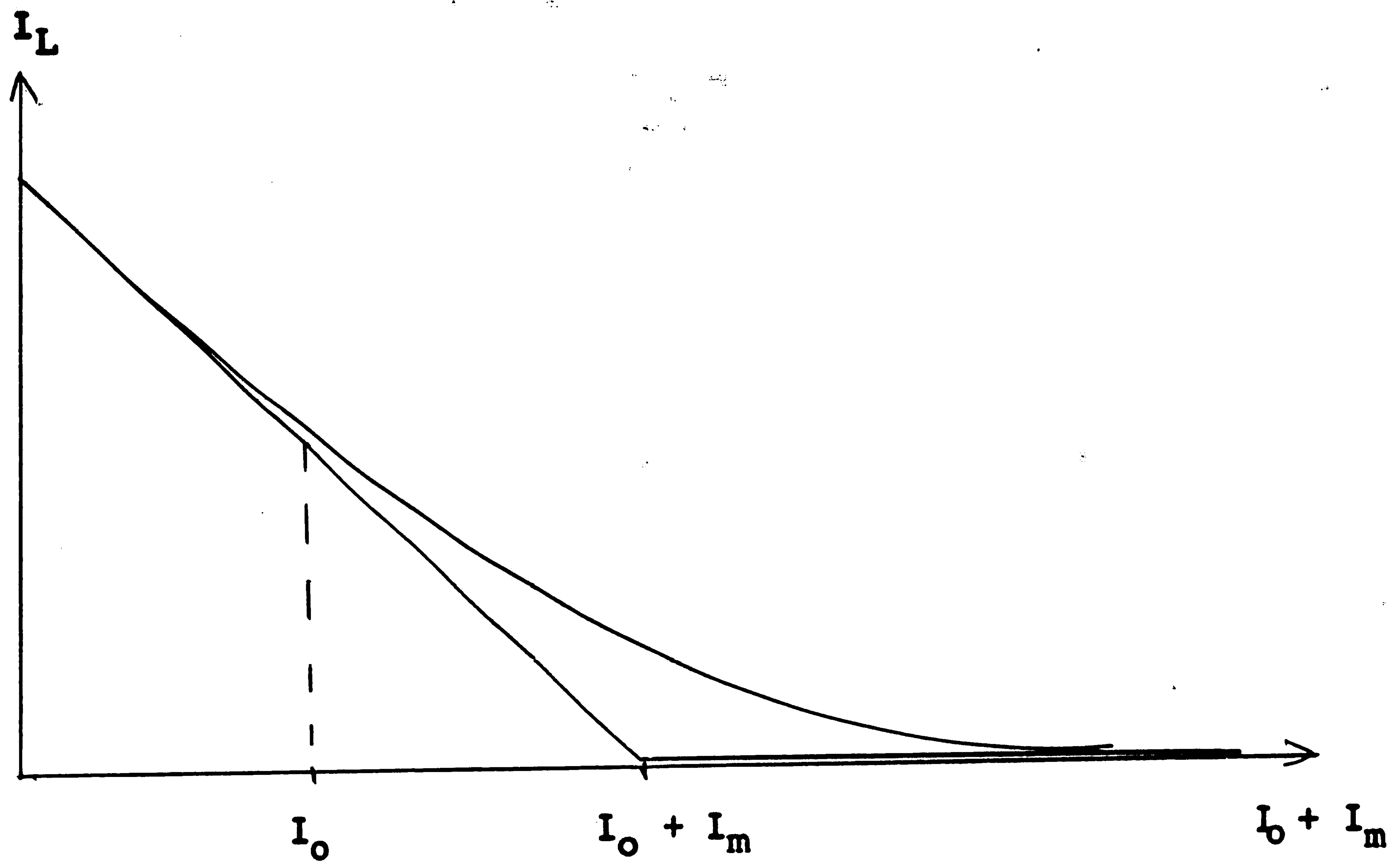


Figure 7. Sketch of I_L versus $I_o + I_m$. Parallel case

Again the straight lines represent a linear approximation to the actual curve.

In this case I_L is minimum when G_d is high which occurs when $I_o + I_m$ is high. I_L is maximum when G_d is minimum which occurs when $I_o + I_m$ is algebraically zero. Thus I_o and I_m are approximately equal for proper circuit operation in order that $I_o - I_m$ may yield zero bias. This is the same as with the series modulator case.

The shape of the actual curve depends on the properties of the particular diode in use, the carrier generator output, and the transmission line properties.

6. Frequency Dependence.

It is expected that modulated output with constant input current will show a frequency dependence in transport mechanisms discussed earlier in this section.

At low modulation frequencies a plot of carrier concentration versus distance through the I layer, x, looks like the following:

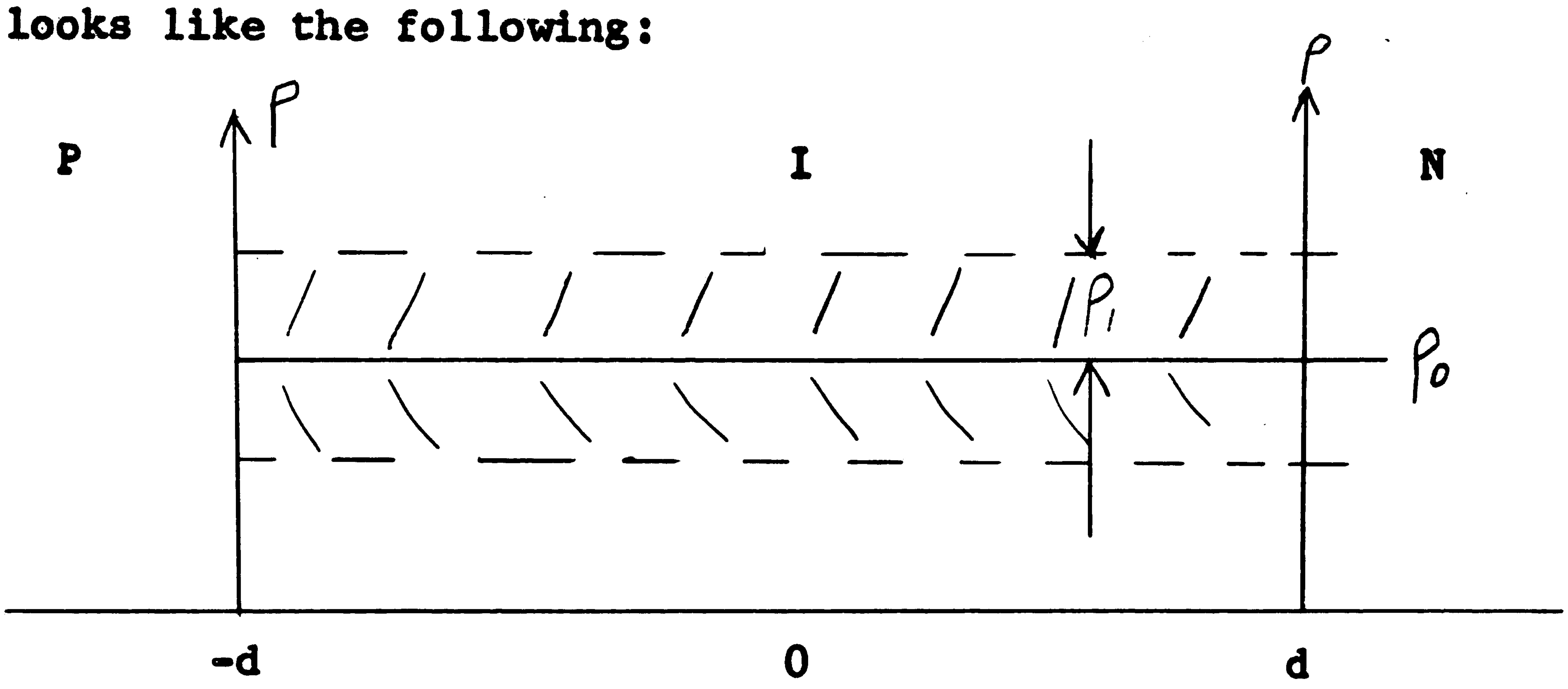


Figure 8. Sketch of carrier concentration, ρ, versus I layer distance, x. Low frequency

According to Leenov[5]

$$\rho_0 = I_0 \tau / qAw \qquad (14)$$

(symbols as defined earlier)

and

$$\rho_1 = I_1 \tau / qAw, \text{ where } I_1 \tau = Q_1 \text{ , } I_1 = I_m \qquad (15)$$

It is important to note that carrier concentration is assumed constant across the I layer. Hence a constant output from the modulator is expected at low frequencies.

(By low frequencies is meant audio to 200-300 kilocycles).

At higher frequencies carrier concentration looks more like the following:

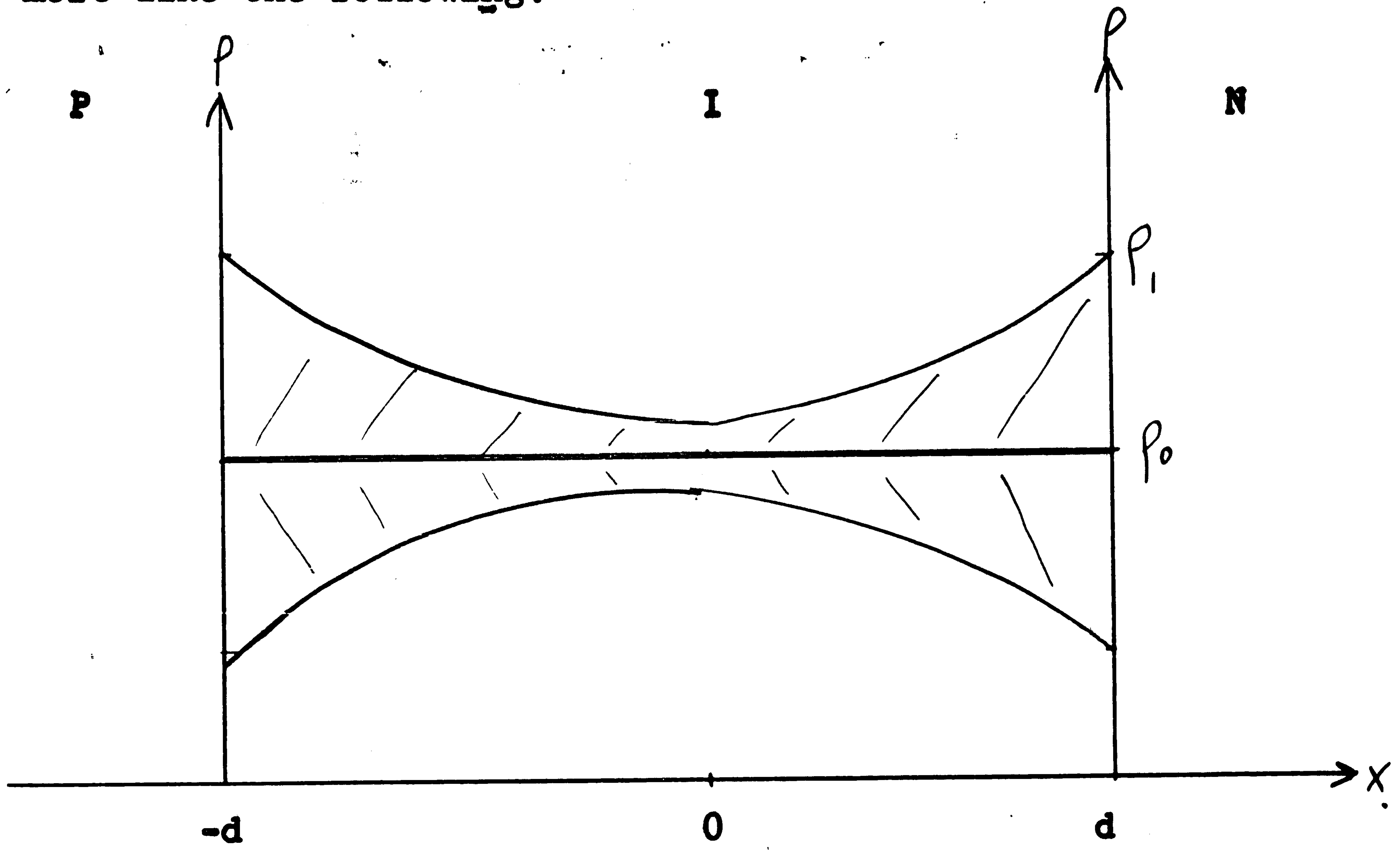


Figure 9. Carrier concentration, ρ, versus I layer distance, x. High frequencies

In this case $Q_1 = I_1/\omega$ (16)

hence $\rho_1 = Q_1/qAw = I_1/\omega qAw$ (17)

We see a $1/\omega$ dependence for carrier concentration. It is, therefore, reasonable to expect modulated output to decrease according to a $1/\omega$ (1/f) relationship if input current remains constant.

Thus, it is expected that output will be constant at low frequencies then decrease according to a 1/f relationship at higher modulation frequencies. It is impossible to accurately predict the frequency where this change will occur under the operating condition of large a.c. signal. However, we expect that

$$\omega_m \tau \approx 1 \qquad (18)$$

III. Experimental Techniques and Circuits

1. 600 Megacycle Series Circuit.[5,6]

It is desired to use the PIN diode now in an actual modulating circuit with carrier frequencies of 600 megacycles and 8.5 kilomegacycles. Modulating frequencies are to extend from 50 kilocycles to 5^+ megacycles.

The lower frequency circuit is set up first as shown in figure 10.

In this circuit the General Radio 1209B Unit Osscillator supplies the carrier at 600 megacycles with about 150 milliwatts output. The coupling capacitor prevents d.c. bias current and modulating current from flowing into the high frequency generator. The Tektronix 190B generator supplies modulation frequency current. Resistance in series with the output provides a constant modulating current output to the PIN diode. The low pass filter prevents high frequency current from entering the modulation generator. The capacitors at this point block the d.c. bias. D.C. bias is supplied by the Hewlett-Packard 721A power supply. A Simpson 373 ammeter measures the bias current and a 15 kilohm resistor serves to isolate d.c. bias from the radio frequency circuitry. The PIN diode is inserted in series in the coaxial line mounted in a General Radio coaxial insertion unit.

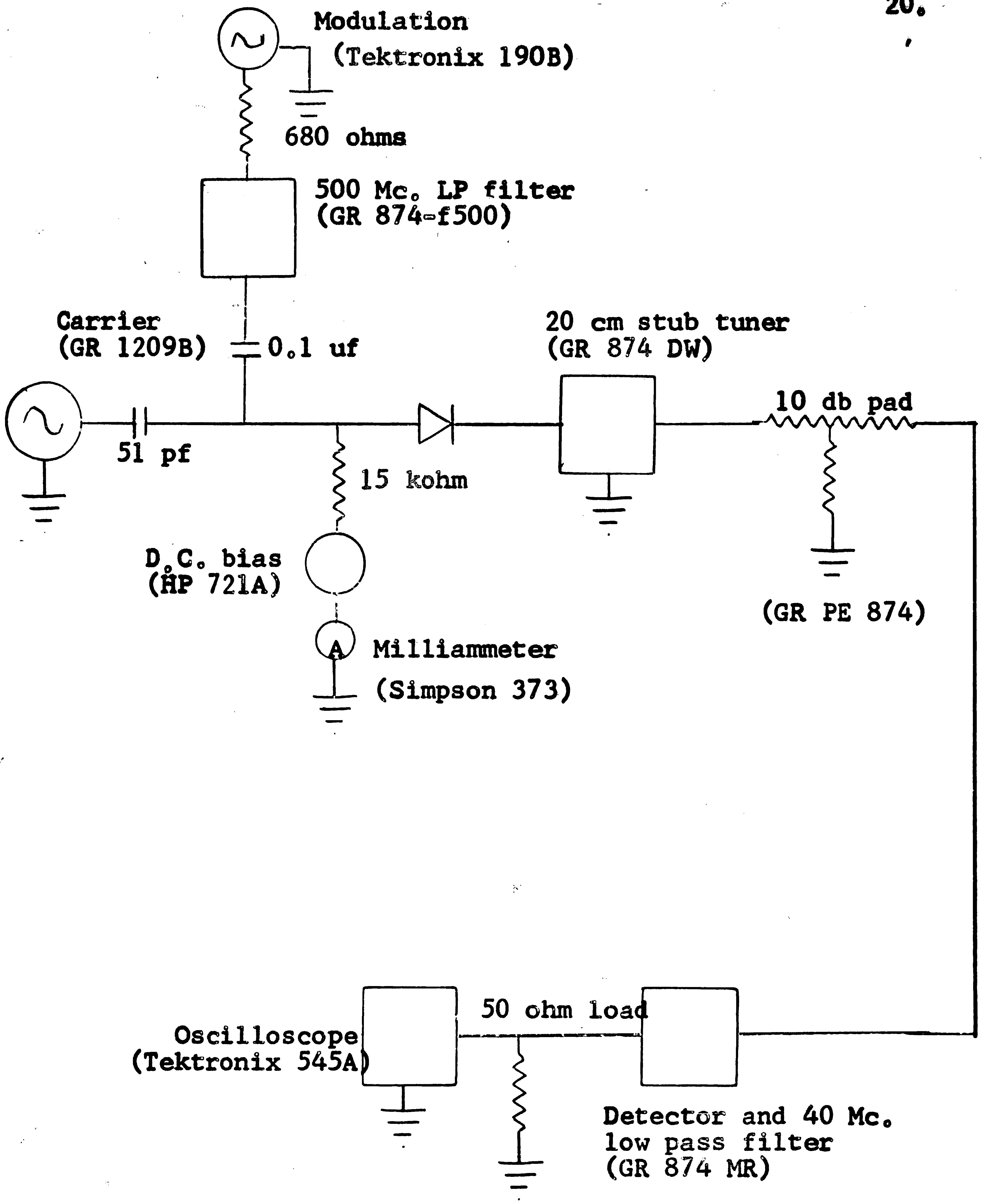


Figure 10. 600 Megacycle Series Modulation Circuit

The 20 centimeter stub tuner serves three purposes. It supplies a d.c. return path for the bias current; shorts any modulation current which passes through the diode as this is undesirable in the output; tunes the line to provide minimum loss of power in the coaxial transmission line. The 50 ohm pad serves to isolate the output and help keep the transmission line 'flat' (at constant impedance). The crystal detector serves to demodulate the signal and the unit's self-contained 40 megacycle low pass filter prevents any high frequency energy which may have passed through the crystal from reaching the output. The 50 ohm output load provides a matched load into which the demodulated signal is fed. The voltage generated across this load is observed and measured on the Tektronix 545A oscilloscope. A sensitive scope plug-in unit, providing 5 millivolt/centimeter sensitivity, is used.

This circuit evolved after much experimentation with variations of the circuit. At first a radio frequency bypass capacitor was provided for the d.c. bias supply. This proved to be a problem as the capacitor shunted radio frequency power to ground. A larger capacitance originally used in the carrier signal line proved to be a problem as modulating signal current was passing through it and being lost in the high frequency generator instead of the PIN diode. The 51 pf capacitor now being used eliminates that difficulty without signifigantly impeding high frequency current flow into the circuit.

Earlier circuits did not use a high resistance (high relative to diode resistance into which it feeds) in the modulating generator output. As a result, diode resistance changes caused changes in the output of the modulating source. A constant input current is desired so that output variations may be related to variations in diode modulating efficiency.

Originally the crystal detector output voltage was measured directly with the oscilloscope. This failure to provide a matched load prevented proper operation of the crystal. Failing, at the time, to realize the cause of the difficulties produced it was decided to provide variable attenuation preceding the crystal detector in order to allow use of the detector as a constant output device. It was felt that this technique would eliminate the problem of the apparent variation in detector efficiency. However, sufficiently accurate variable attenuators were not available hence the technique had to be abandoned. Fortunately, the use of a proper load in the output allows the detector to operate at constant efficiency thus eliminating the problem.

The above difficulties cleared up, the circuit described works very well. As carrier power is limited, that generator is operated at maximum output. The modulating source and d.c. bias are then adjusted to provide maximum undistorted output as observed and measured on the oscilloscope.

Several diodes were tested in this configuration. Results are as predicted and are tabulated and graphed on pages to follow. (See Results).

The operation of the circuit is found to be independent of modulating current. That is, any modulating current value below the distortion level will work equally well. However, the value of d.c. bias current is extremely critical as expected. Sometimes a variation in bias of as little as 20 microamperes will cause the circuit to become inoperative.

It is readily observed that detected output power (output modulation) is directly proportional to both modulating current and carrier power (i.e., carrier current squared). This is to be expected as modulating current regulates the resistance swing of the diode and any given swing can regulate any amount of carrier power up to the power limit of the diode. Thus, a relatively small modulating signal will regulate a much higher power carrier.

The diode package, which contains inherent inductance and capacitance, yields reactive effects at the carrier frequency. This causes some attenuation of carrier power across a range of carrier frequencies.

2. 600 Megacycle Parallel Circuit.

A modulating circuit using the diode in a parallel configuration is also of interest. The circuit configuration is shown in figure 11. This circuit is identical to the series configuration except that the diode is in parallel or 'across the line'. This is done, physically, by using a coaxial T section with the insertion unit containing the diode forming one leg. The free end of the insertion unit is short-circuited to provide a complete radio frequency and d.c. path through the diode. A 51 pf capacitor is used as a d.c. block as the d.c. short provided by the stub tuner is no longer desired.

Only one problem was encountered in the operation of this circuit. A 4700 pf insertion type capacitor was first used as a d.c. block at the carrier generator terminal. As this presents a low impedance to the 600 megacycle signal, no problem was expected. However, it was discovered that modulating current was being leaked through the capacitor and lost. This was not only undesirable from a power loss standpoint but defeats our purpose due to the frequency dependence of the effect. With the use of the 51 pf capacitor the problem is eliminated.

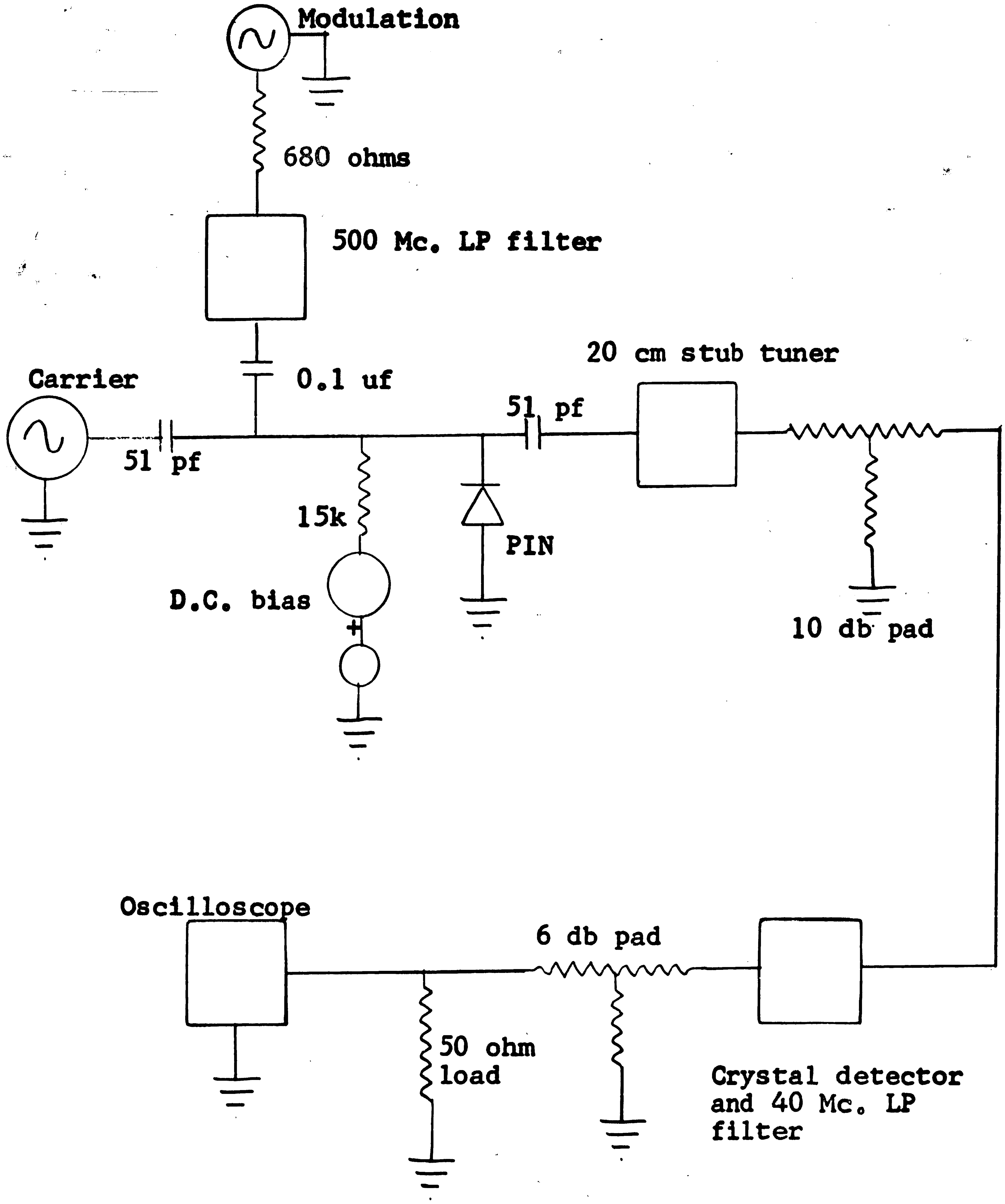


Figure 11. 600 Megacycle Parallel Modulation Circuit.

This circuit works equally as well as the series configuration, a result which is logically expected. D.C. bias current required is about four times that required for operation of the series circuit. This increased bias is due to the presence of shunt admittances in parallel with the d.c. supply (See figure 6). The circuit is much more sensitive to adjustment of modulation level and d.c. bias. Improper adjustment causes clipping and strong harmonic generation. This is not surprizing - the PIN diode is sometimes used as a harmonic generator.[7]

Modulation output versus frequency results are tabulated and graphed in the Results section. Results are essentially the same as for the series circuit. In general, the power output level of the modulation (i.e., detected sideband seen on the oscilloscope) is less with the parallel circuit than for the series configuration. This is no doubt due to the fact that the resistance swing of the parallel configuration is less than in the series case. (Resistance cannot go above ½ of the line impedance.)

3. 8.5 Kilomegacycle Series Circuit.

The next step in our work is to construct a modulating circuit operating at X band microwave frequencies (8 -12 kilomegacycles). The problems here are efficient use of the diode in a waveguide type transmission line and the resonance effects of the diode package.

The microwave circuit is shown in figure 12. The Alfred sweep generator provides carrier current at any frequency from eight to twelve kilomegacycles. The Hewlett-Packard X532B absorption wavemeter provides an accurate measurement of operating carrier frequency. The Hewlett-Packard X375A and X382A variable attenuators adjust power levels to either side of the PIN diode when and if desired. A Hewlett-Packard X870A slide screw tuner provides tuning of the transmission line which is usually quite critical. An H-P X478B thermister and 430C power meter are used at the output to measure microwave power output. An H-P X421A crystal detector and Tektronix 545A oscilloscope are substituted to provide detected output for measurement and observation.

The diode is mounted in a special waveguide specifically designed and constructed for this purpose. Essentially, the diode is across the waveguide so as to modulate the E field at the modulation frequency. Modulation current and d.c. bias are fed through the diode by means of connectors attached to the waveguide diode structure. Modulation current is returned to ground through a capacitor bypassing the d.c. bias circuitry. D.C. bias is returned through the modulating generator circuitry.

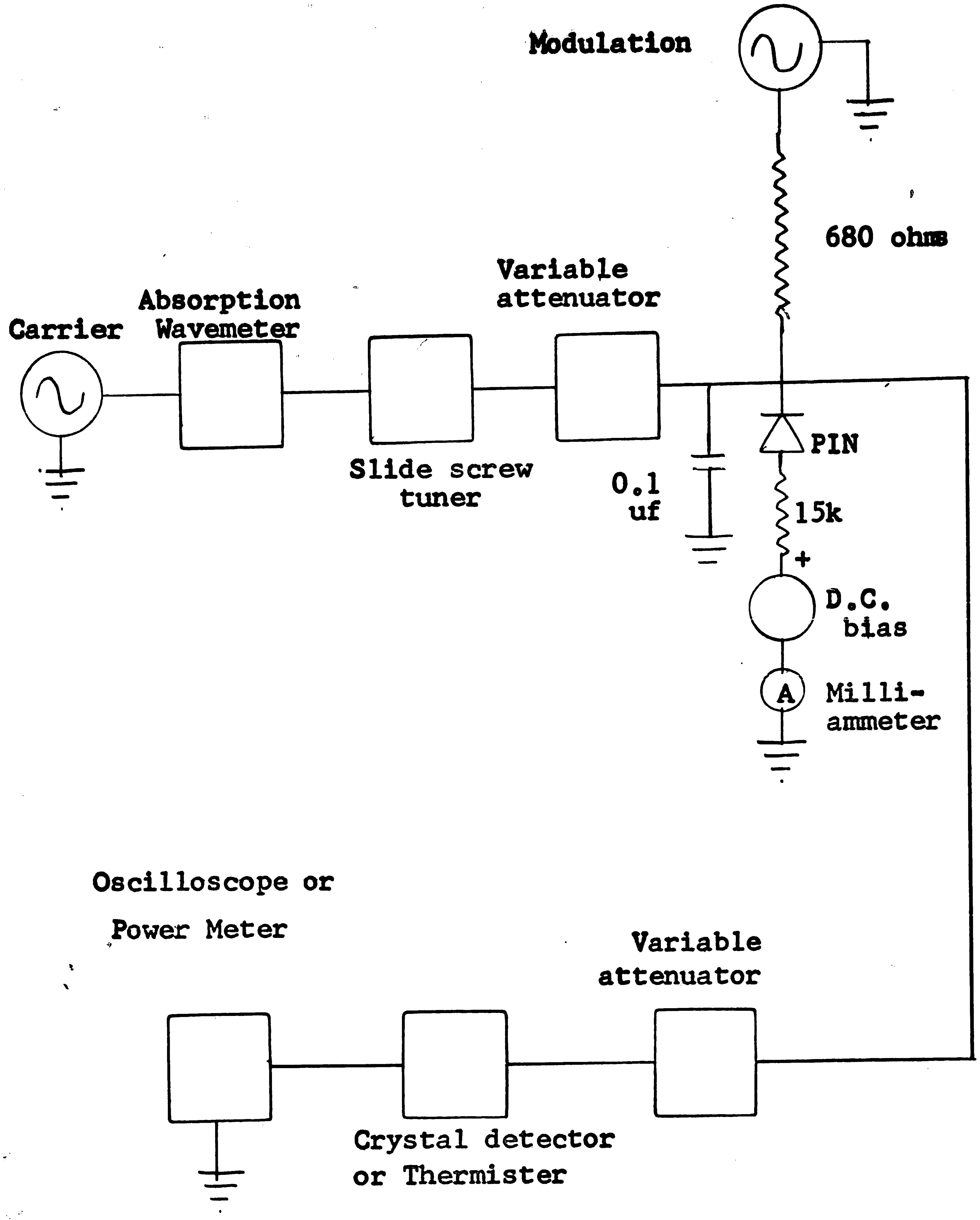


Figure 12. 8.5 Kilomegacycle Series Modulation Circuit

At microwave frequencies resonance effects due to diode and encapsulation inductance and capacitance are expected. These effects are, indeed, very pronounced with this circuit. With the particular diodes in use, circuit operation is possible only near 8.5 kilomegacycles. It is interesting to note that all diodes tested resonate or 'tune' very near 8.5 kilomegacycles. While the diodes themselves differ, their encapsulation is identical. Thus it appears that most resonance effects are due to the diode encapsulation rather than the semiconductor itself. It was expected that reverse biasing of the diode, thus increasing the diode capacitance, would alter the resonance frequency. However, if the effect occurred at all it is unmeasurable. It is likely that the diode capacitive effect is negligible compared to encapsulation capacitive effect.

Actual operation of the circuit is identical to lower frequency operations in terms of modulation and bias currents required. This is expected as the diode is doing exactly the same job it had been doing in the previous circuits. Results are the same as for our low frequency experiments and are presented in the Results section.

In order to determine the percentage of modulation obtainable the crystal detector and oscilloscope are used as a power indicator after calibration with the power meter. High frequency (carrier) power is seen as a change in d.c. level on the oscilloscope.

By this means it is possible to compare carrier and modulated power outputs. It is easily seen that 100% modulation, or very nearly 100%, is readily obtainable with all diodes. Thus, distortion caused by overdriving with modulation current is due to overmodulation. This is not surprising as the diode is biased through modulation from a low loss condition to a very high loss condition in which practically no carrier is passed. This corresponds to complete modulation.

A 10 db. directional coupler is added to the microwave circuit immediately preceding the diode. Using a power meter at this point and our calibrated detector at the output it is possible to determine insertion loss. Insertion loss is found to vary widely with bias of the diode and is very small (almost unmeasurable) when the diode is biased to provide good matching in the waveguide (or coaxial transmission line).

4. Carrier Rectification.

It is known that a small portion of the carrier current is rectified by the diode. A circuit, shown in figure 13, was constructed to attempt measurement of this phenomenon.

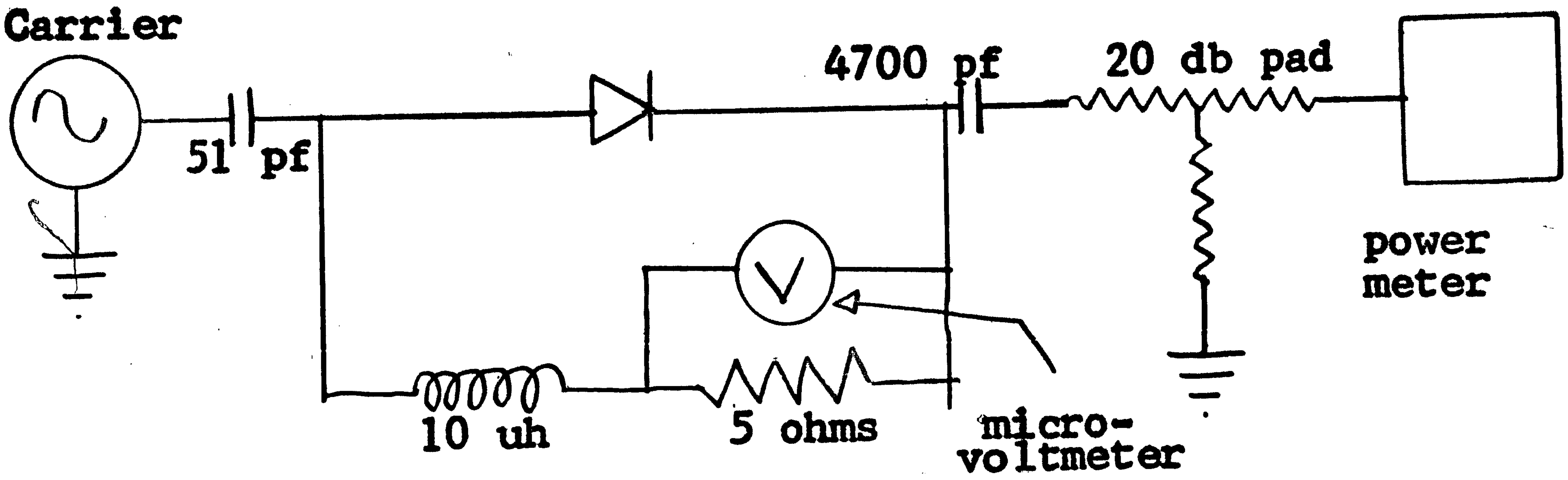


Figure 13. Circuit to Measure R.F. Rectification

The generator supplies energy from 65-900 megacycles for the test. The 51 pf capacitor is a d.c. block. A 10 uh choke and 5 ohm resistor form a d.c. path across the diode through which the rectified current flows. A 4700 pf capacitor acts as another d.c. block while a 20 db. pad provides loading and isolation. A power meter indicates radio frequency power through the diode.

The expected effect is easily seen on the microvoltmeter. However, lack of sensitivity and stability of the available instrument made accurate and signifigant measurements impossible. It is readily apparent, however, that rectified current decreases with increase in frequency as theory predicts. The ratio $I_{d.c.}/ I_{r.f.}$ varies from approximately 0.3 at 80 megacycles to 0.02 at 900 megacycles.

IV. Results

Each of the three circuits used to obtain the results, which appear graphically on the following pages, is operated as follows: Maximum available carrier power is supplied to the diode. D.C. bias current and modulating current are then jointly adjusted in order to provide maximum undistorted output as indicated on the oscilloscope. The detected output measured is a measure of the modulation amplitude, m, which appears in eq. (2). Tests of this technique show that it provides near 100% modulation as indicated in the previous section.

Results may be summarized into the following statements:

1. High level, accurate (undistorted) output modulation may be obtained with each of the three circuits used.
2. The PIN diode works equally well at low and high microwave frequencies.
3. Each modulated output versus frequency curve shows a break frequency f_b; for $f_m < f_b$ the detected signal is constant, while for $f_m > f_b$ the detected signal decreases according to a $1/f$ relationship. f_b is approximately equal to $1/\tau$.
4. Circuit operation is not affected by carrier signal

level within diode power limitations (which allows about 3 watts for the diodes used).

5. Best operation is obtained when modulating current is very slightly greater than d.c. bias current.

6. Low level modulation signals completely modulate much larger carrier signals. The gain in modulation is as high as 10^4.

τ = 1.1 usec

$\omega/2\pi \approx 1/2\pi\tau$ = 150 Kc.

f_b = 250 Kc.

Carrier: 600 Mc. Series

I_o = 70 ua.

I_m = 75 ua.

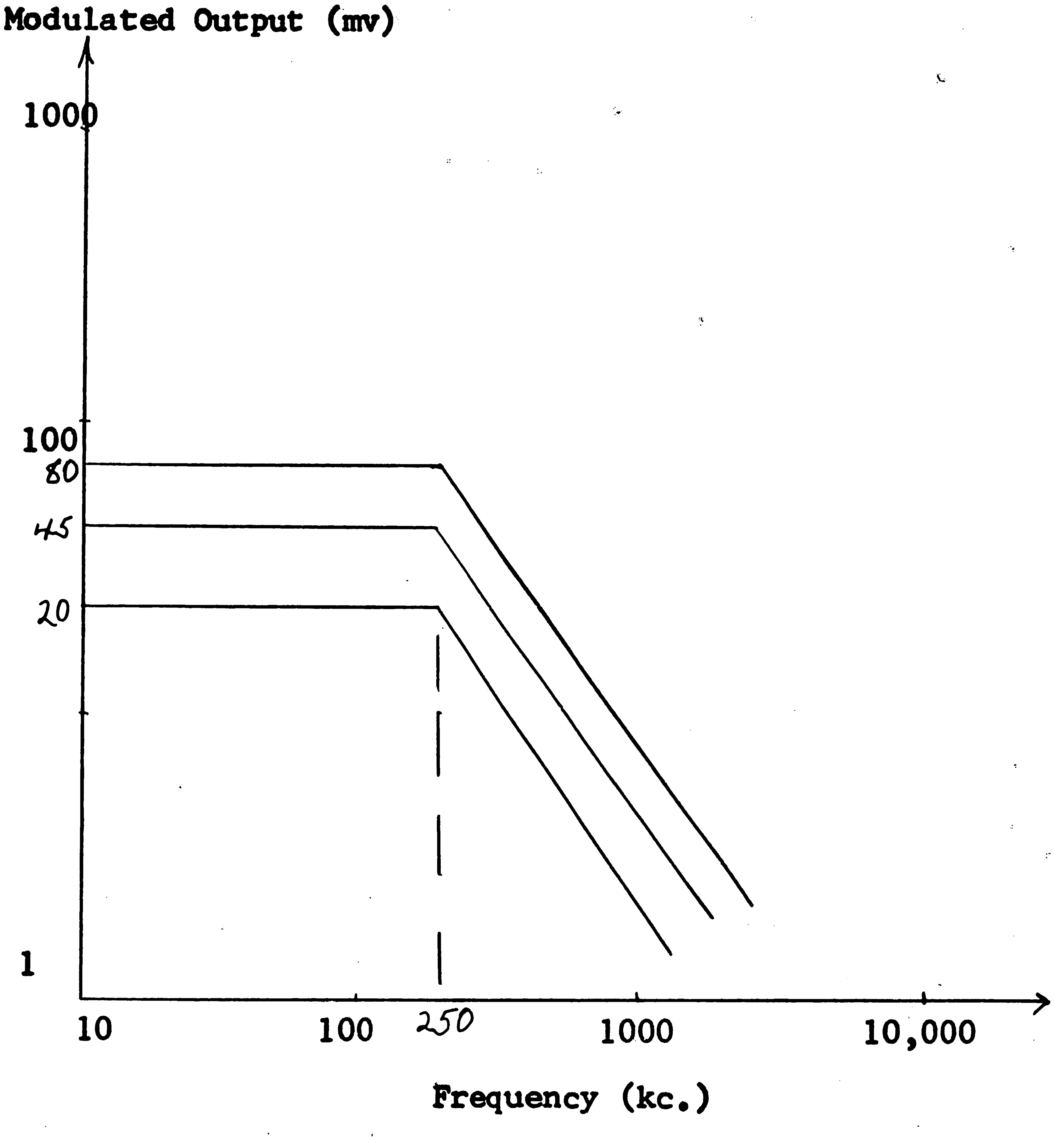


Figure 14. Modulated Output versus Frequency
Diode 1

$\tau = 0.28$ usec

$\omega/2\pi \approx 1/2\pi\tau = 575$ Kc.

$f_b = 550$ Kc.

Carrier: 600 Mc. Series

$I_o = 80$ ua.

$I_m = 85$ ua.

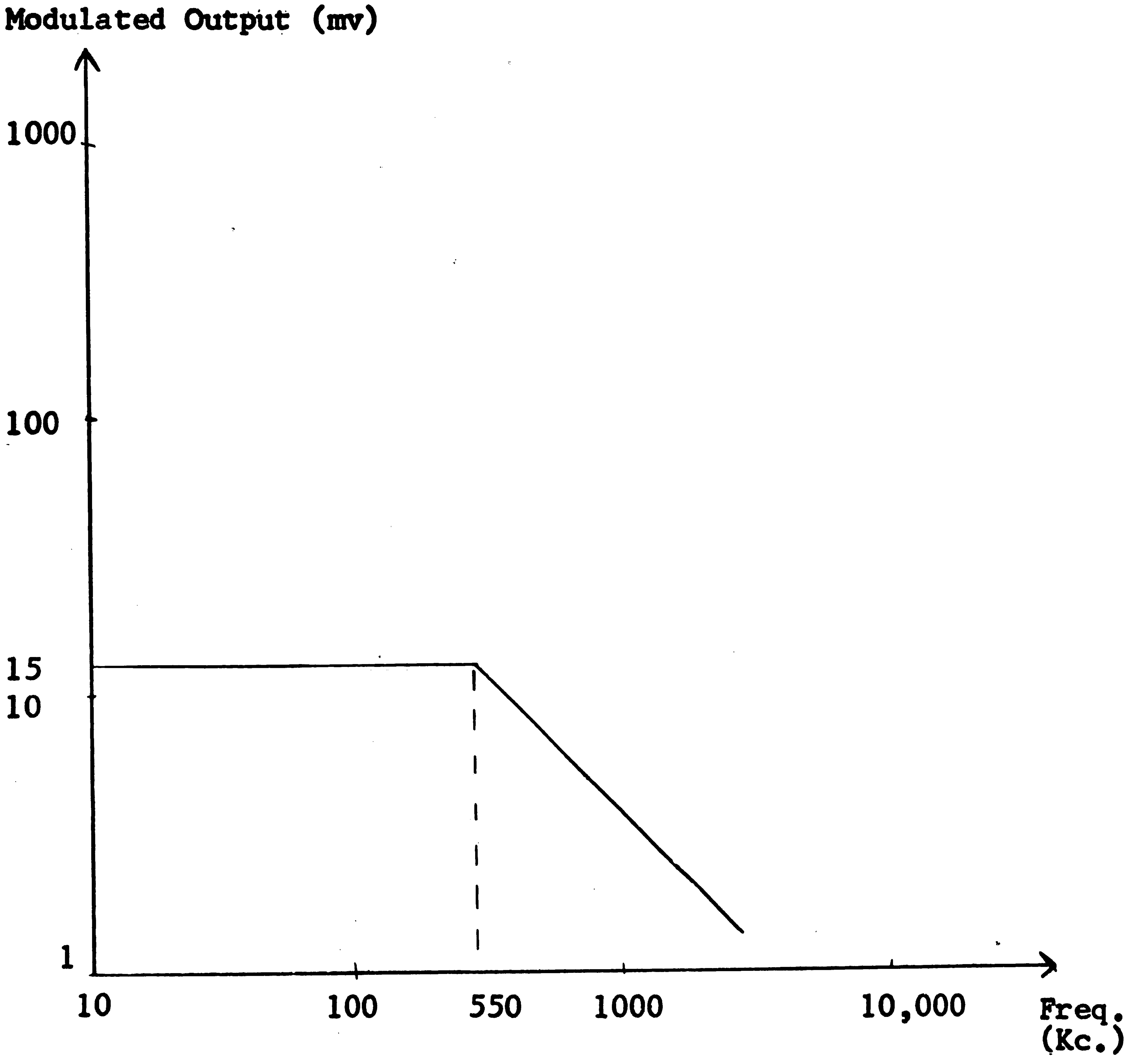


Figure 15. Modulated Output versus Frequency.
Diode 2

$\tau = 0.13$ usec.

$\omega/2\pi \approx 1/2\pi\tau = 1.2$ Mc.

$f_b = 900$ Kc.

Carrier: 600 Mc. Series

$I_o = 50$ ua.

$I_m = 55$ ua.

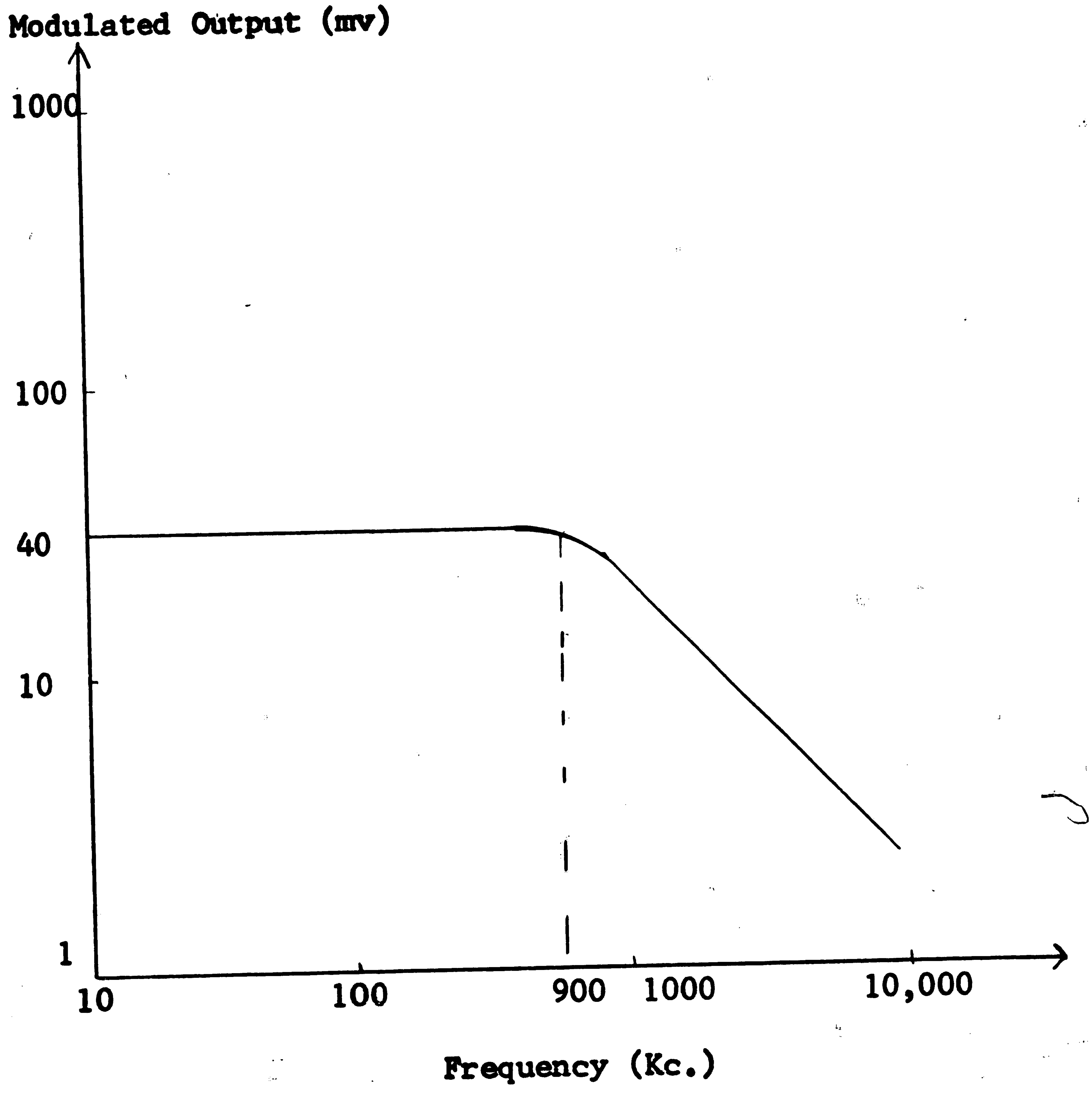


Figure 16. Modulated Output versus Frequency.
Diode 3

τ = 0.19 usec.

$\omega/2\pi \approx 1/2\pi\tau$ = 840 Kc.

f_b = 750 Kc.

Carrier: 600 Mc. Series

I_o = 100 ua.

I_m = 110 ua.

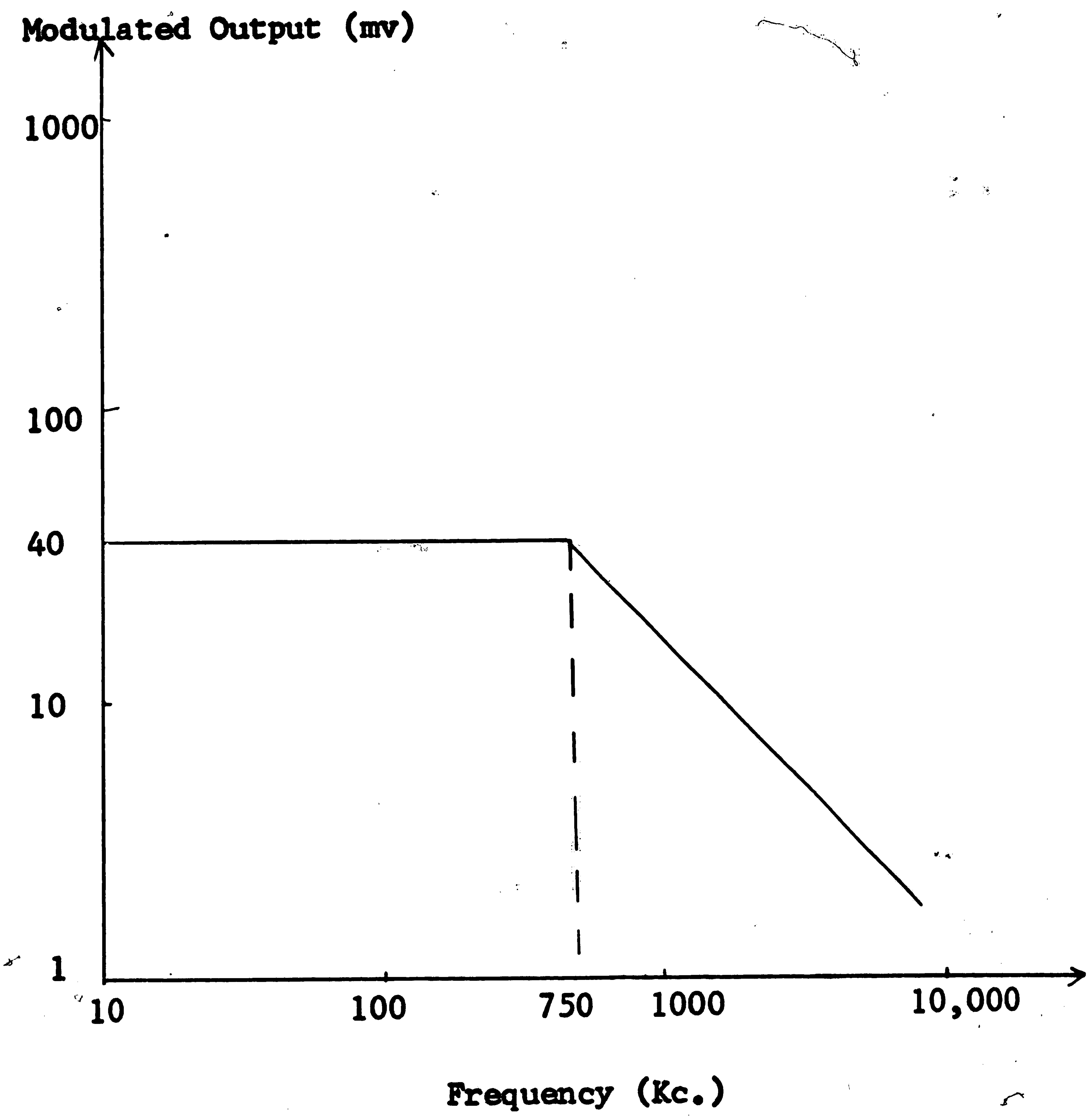


Figure 17. Modulated Output versus Frequency. Diode 4.

τ = 1.1 usec.

$\omega/2\pi \approx 1/2\pi\tau$ = 150 Kc.

f_b = 250 Kc.

Carrier: 600 Mc. Parallel

I_o = 350 ua.

I_m = 360 ua.

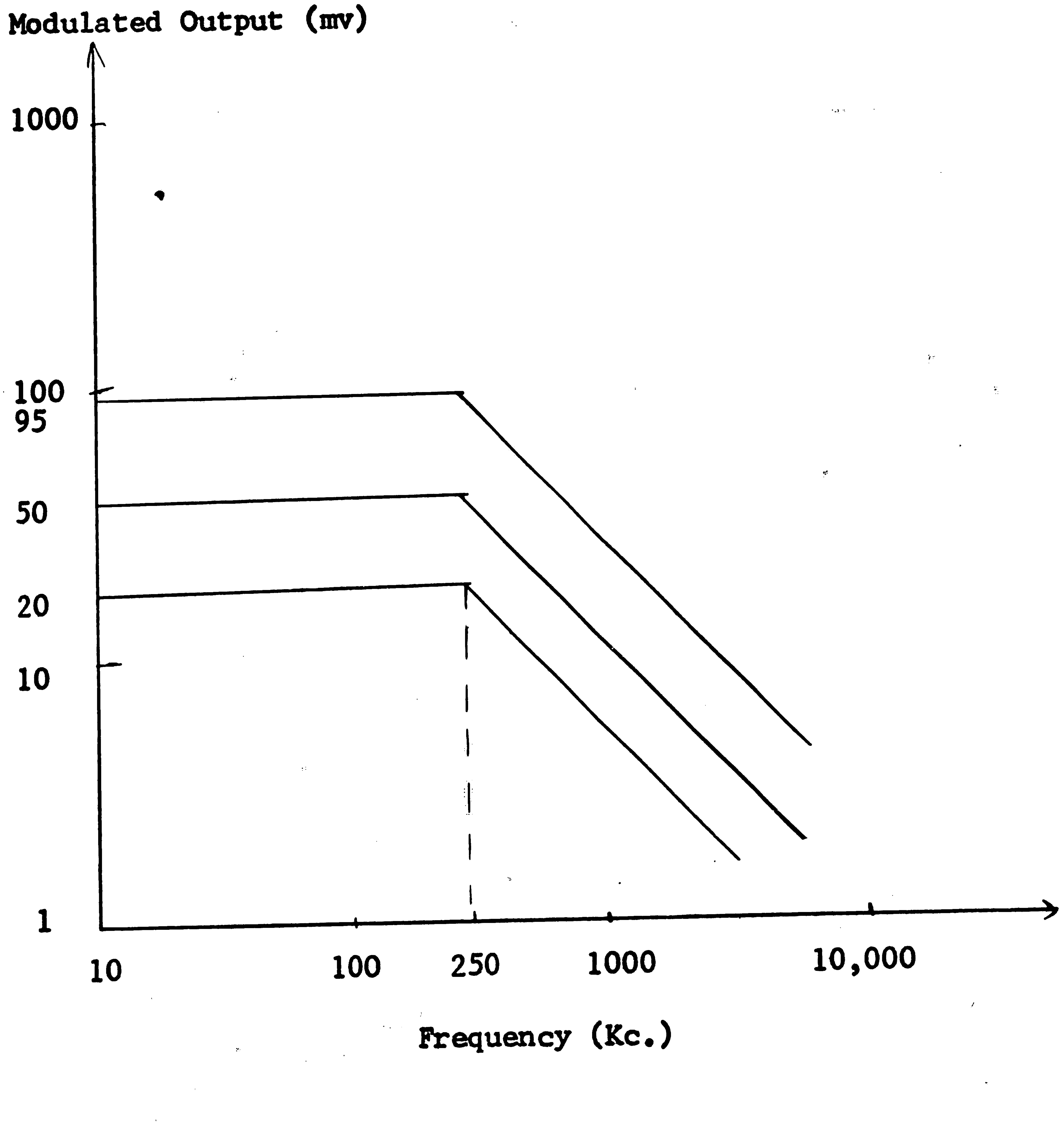


Figure 18. Modulated Output versus Frequency. Diode 1.

τ = 0.13 usec.

$\omega/2\pi \approx 1/2\pi\tau$ = 1.2 Mc.

f_b = 900 Kc.

Carrier: 600 Mc. Parallel

I_o = 600 ua.

I_m = 640 ua.

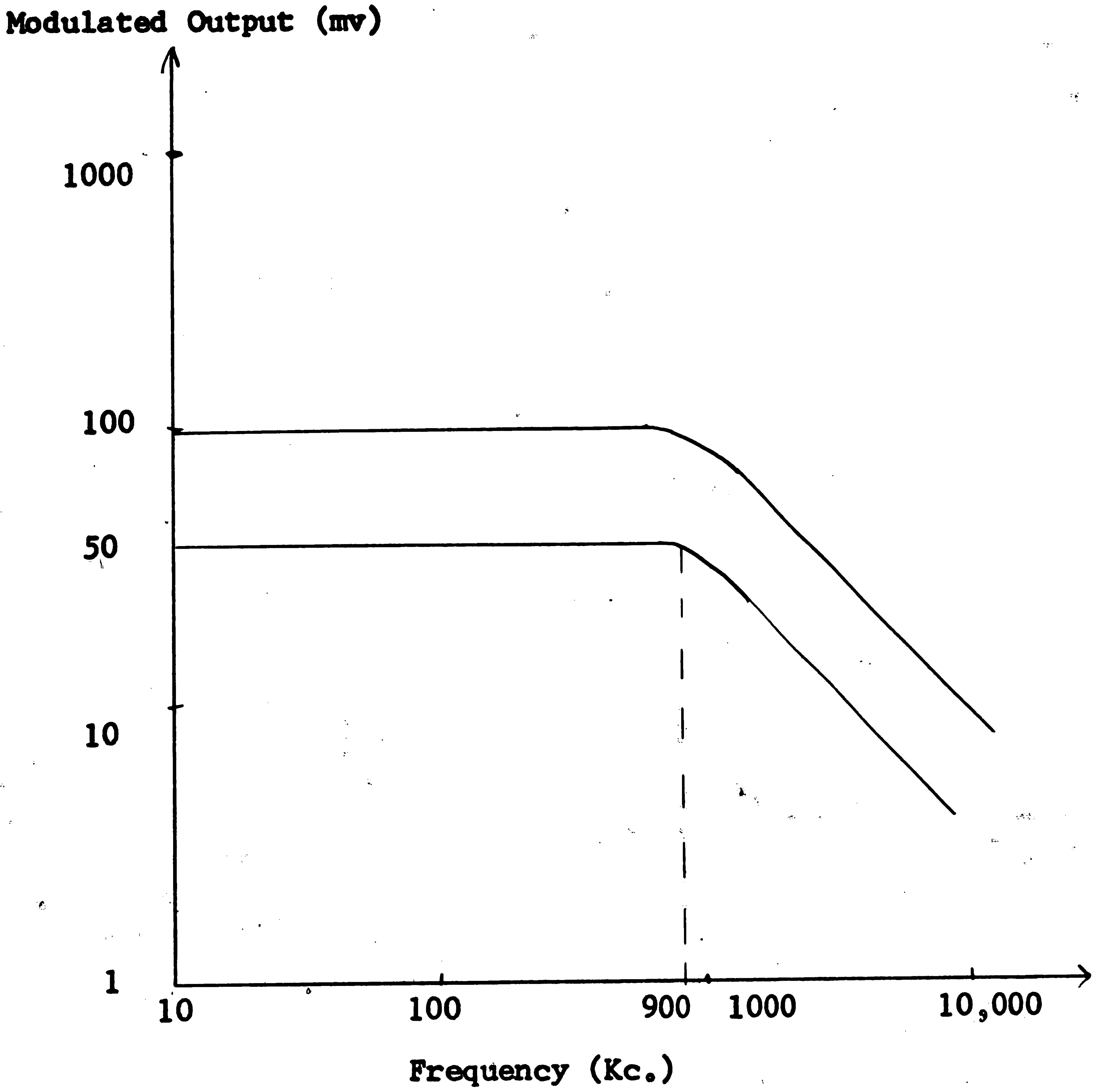


Figure 19. Modulated Output versus Frequency. Diode 3.

τ = 0.19 usec.

$\omega/2\pi \approx 1/2\pi\tau$ = 840 Kc.

f_b = 750 Kc.

Carrier: 600 Mc. Parallel

I_o = 450 ua.

I_m = 480 ua.

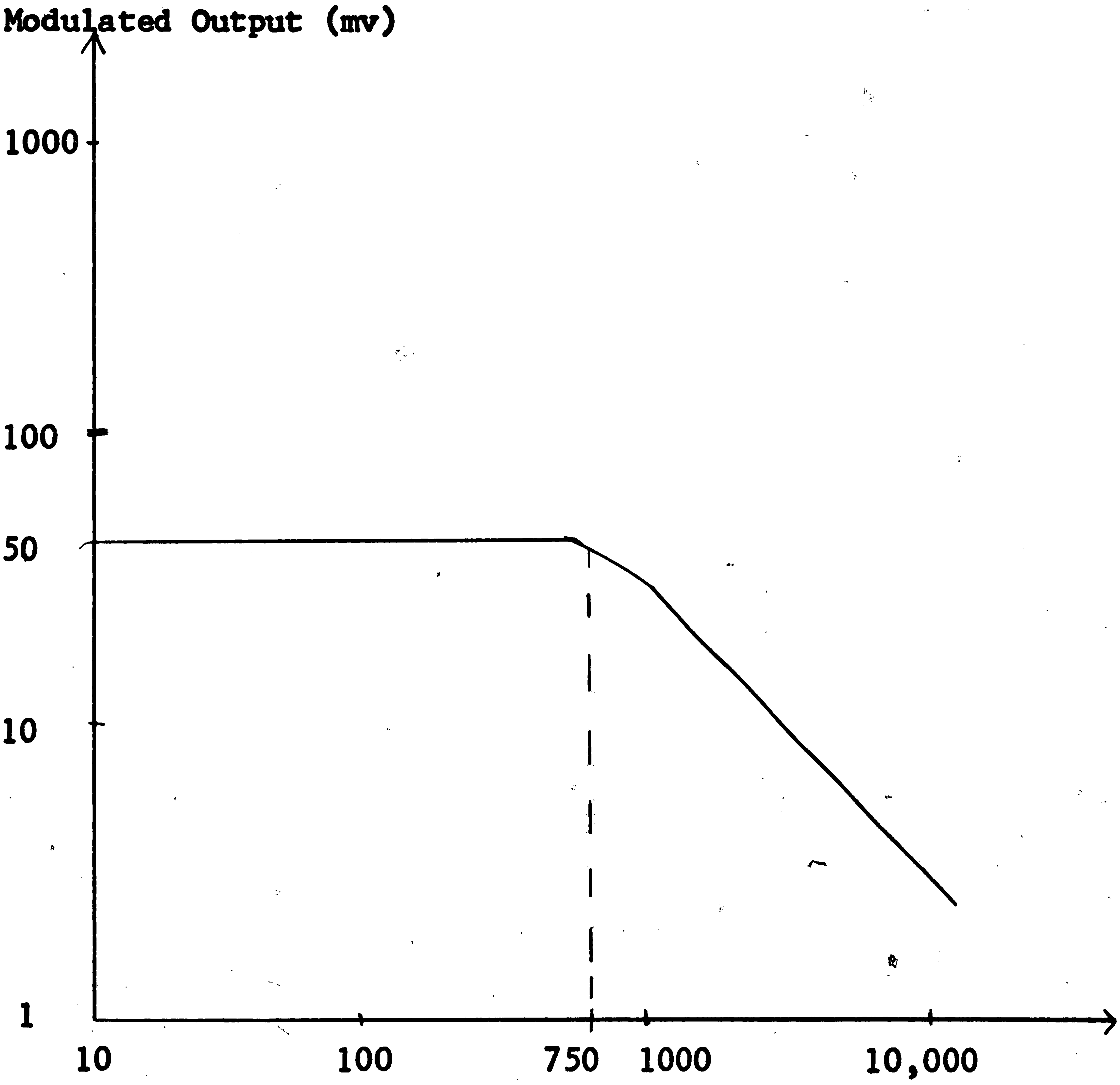


Figure 20. Modulated Output versus Frequency.
Diode 4

τ = 0.6 usec.

$\omega/2\pi \approx 1/2\pi\tau$ = 265 Kc.

f_b = 250 Kc.

Carrier: 8.5 Kmc. Series

I_o = 140 ua.

I_m = 150 ua.

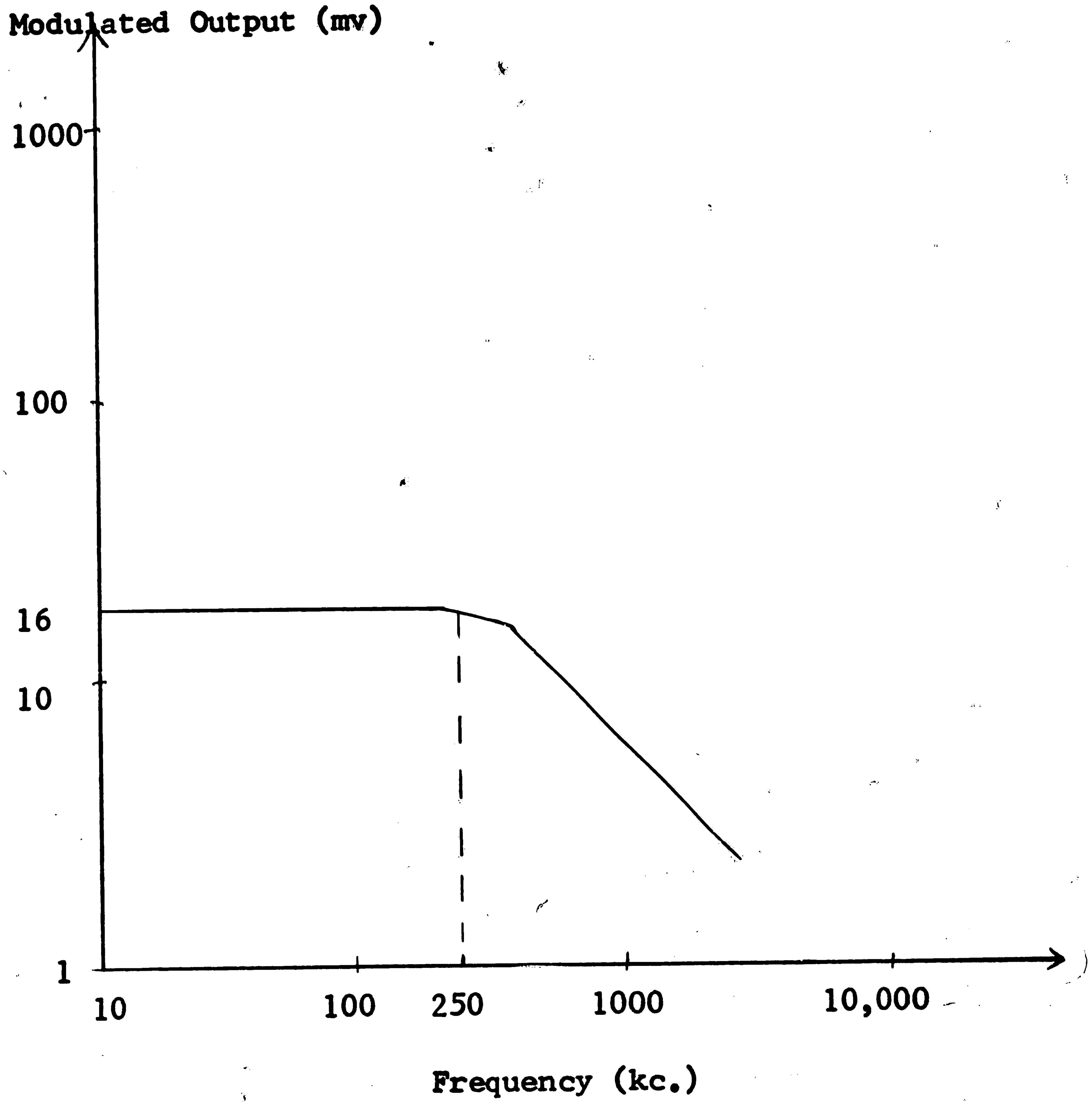


Figure 21. Modulated Output versus Frequency
Diode 5

τ = 1.3 usec.

$\omega/2\pi \approx 1/2\pi\tau$ = 125 Kc.

f_b = 150 Kc.

Carrier: 8.5 Kmc. Series

I_o = 80 ua.

I_m = 85 ua.

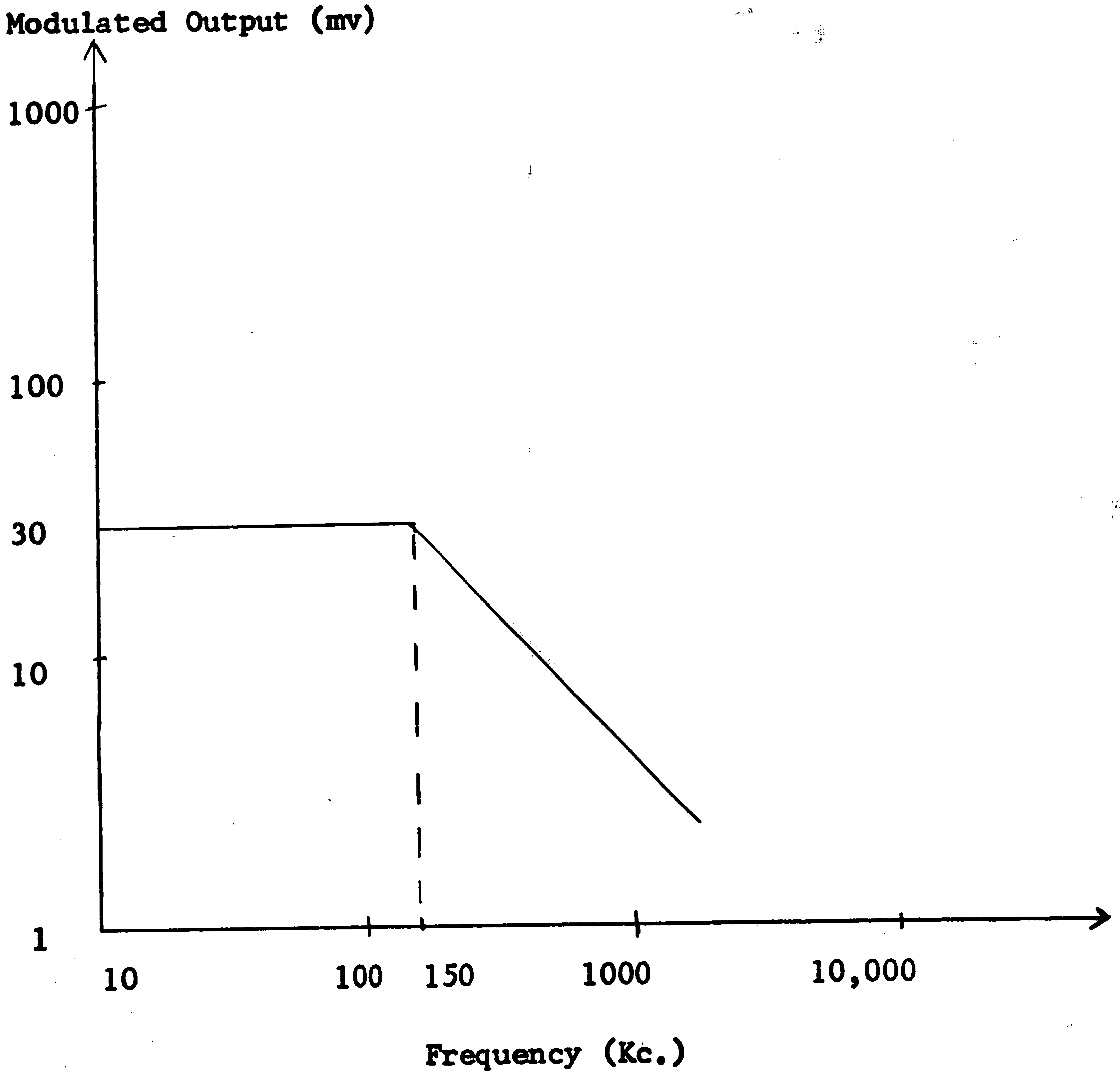


Figure 22. Modulated Output versus Frequency.
Diode 6

τ = 0.8 usec.

$\omega/2\pi \approx 1/2\pi\tau$ = 200 Kc.

f_b = 180 Kc.

Carrier: 8.5 Kmc. Series

I_o = 80 ua.

I_m = 90 ua.

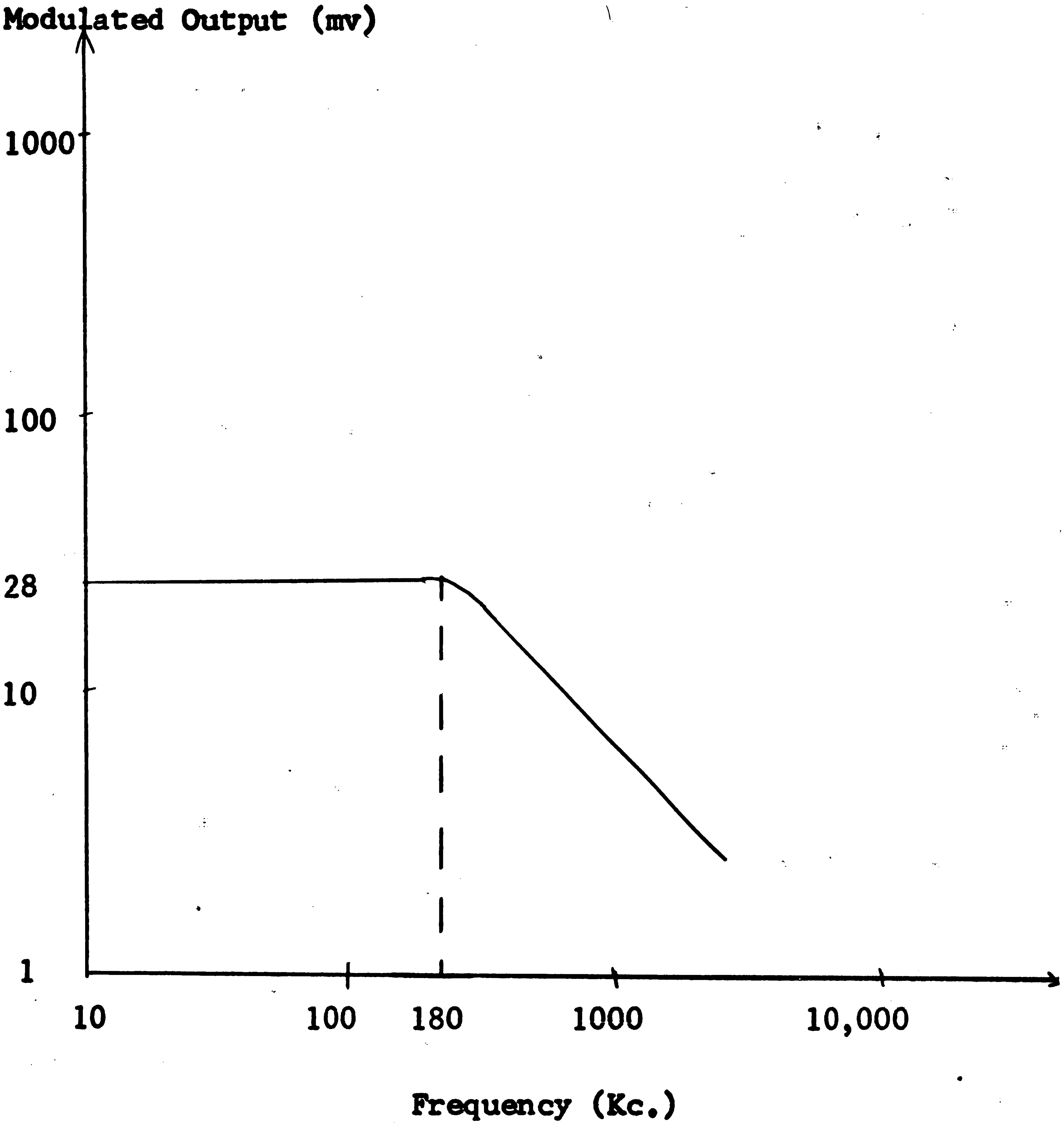


Figure 23. Modulated Output versus Frequency.
Diode 7

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Vita

Martin Clark Faga was born in Bethlehem, Pennsylvania on June 11, 1941 the son of Edgar M. and Corolyn C. Faga. He was raised in Bethlehem where he attended Penn Elementary School and Northeast Junior High School. In June of 1959 he graduated from Bethlehem High School with an academic standing of sixth in a class of 665. He attended Lehigh University receiving the degree of Bachelor of Science in Electrical Engineering with Honors in June of 1963. He is presently enrolled in the Graduate School at Lehigh.

Mr. Faga is a member of Phi Eta Sigma, Eta Kappa Nu, and Tau Beta Pi. He is a student member of the Institute of Electrical and Electronics Engineers.

Mr. Faga is a Second Lieutenant in the United States Air Force. His graduate work has been under the auspices of the Civilian Institutions Division of the Air Force Institute of Technology.