1974

Noise upconversion in Gunn diode oscillators /

Charles Barry Winn
Lehigh University

Recommended Citation

Winn, Charles Barry, "Noise upconversion in Gunn diode oscillators /" (1974). *Theses and Dissertations*. 4404.
https://preserve.lehigh.edu/etd/4404

NOISE UPCONVERSION
IN
GUNN DIODE OSCILLATORS

by

Charles Barry Winn

A Thesis
Presented to the Graduate Committee
of Lehigh University
in Candidacy for the Degree of
Master of Science
in Electrical Engineering

Lehigh University
1974

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

May 5, 1974
(Date)

D. Leenov
Professor in Charge

Chairman of Department

ACKNOWLEDGEMENT

The author wishes to acknowledge Dr. Daniel Leenov for his theoretical guidance and help in the preparation of this thesis. Special thanks are due to Hans R. Gnerlich for his advice and assistance with the experimental procedure. The author is grateful for the help of Vikram Kumar and Dr. John G. Ondria with regard to noise measurement technique and oscillator theory.

The author is indebted to his parents for their special interest and support of his education.

TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

A study has been made of the mechanisms leading to the generation of low frequency noise in Gunn diode oscillators and the effect of this noise on the microwave FM and AM noise spectra. The following results were obtained: (a) a low frequency equivalent circuit for the diode was developed; (b) the microwave noise spectra are dominated by up-converted noise in the range 20 Hz to 10 MHz; (c) microwave noise calculated using Sweet's theoretical formula [7] agreed with the measured microwave noise in the range 20 Hz to 10 MHz.

The low frequency equivalent circuit was investigated by varying the size of a resistor connected across the low frequency (bias circuit) terminals of the Gunn diode, and observing the resulting changes in the low frequency, the FM and the AM noise spectra. From these observations it was deduced that the Gunn diode low frequency equivalent circuit includes a series resistance of 10 to 50 ohms and a shunt resistance of about 300 ohms across a noise current source.

The upconversion process was studied by calculating the upconversion contribution to the FM noise spectrum of the low frequency noise voltage spectrum through the frequency pushing factor according to Sweet's formula [7] . The calculated results agreed quite well with the measured FM noise near the carrier.

INTRODUCTION

Electrical noise is generally classified according to its source. Each idealized source represents a mechanism by which random signals are generated and for which an idealized power density spectrum can be predicted. A number of these noise sources are important in semiconductor devices.

Thermal noise is a white noise caused by the random motion of thermally exited carriers. Shot noise is a white noise associated with junctions or barriers due to the quantization of charge. Since charge is carried by individual electrons, a current across a barrier is a random series of current impulses rather than a continuous flow. Generation-recombination noise results from the random capture and release of carriers by atomic traps. Although the actual capture or release of a carrier by a single trap is a random process, there is an average lifetime associated with the process and the noise is flat at low frequency rolling off as $1/f^2$ at high frequency. Flicker noise has a $1/f$ spectrum and is caused by a rather continuous distribution of generation-recombination time constants, being a summation of their associated spectra. Avalanche noise is caused by the randomness of the multiplication factor and the time between collisions in a particular avalanche.

The Gunn oscillator is a bulk effect semiconductor device, and as such it is subject to sources of noise as any piece of semiconductor material. The noise sources important in the Gunn oscillator are (a) in the microwave band, thermal noise and the noise associated with the jumping of carriers between the high and low mobility bands , (Haus et.al [3]); (b) at low frequencies, 1/f noise and generation-recombination noise. The low frequency noise was studied in this thesis. This noise, which is slow compared to the oscillation frequency, then acts as a modulating signal causing a certain amount of frequency modulation and amplitude modulation. It is this component of the RF noise spectrum, either AM or FM, that is correlated with the low frequency noise spectrum and is referred to as the upconverted noise.

The upconverted noise power is dependent upon both the amount of low frequency noise and the upconversion factor or modulation sensitivity. Sweet and MacKenzie [9] studied the effect of the upconversion factor on the microwave noise spectrum by varying the loaded Q of the oscillator cavity. The purpose of this paper is to investigate the change in the RF noise spectra due to a change in the low frequency noise signal caused by the diode. This low frequency noise signal is changed by varying the video resistance presented to the diode by the bias circuit. This relationship suggests a low frequency noise model for the diode. The upconversion factors are measured and the FM and AM spectra are calculated in good agreement with experiment.

II. THEORY

II-1. EQUIVALENT CIRCUIT

It is well known that the power and frequency of a Gunn oscillator are dependent on the bias voltage. The exact mechanism behind this is not well understood, although computer calculations on the non-linear device have yielded qualitative agreement with experiment. Part of the problem is in finding the mode of operation in terms of an equivalent circuit.

Sweet [7,8] used a parallel R L C circuit shown in Fig. 1. This model assumes the Gunn to be a parallel capacitance and conductance fed by a noise current generator. $\overline{C}_d$ is the domain capacitance, $-\overline{G}$ is the dynamic, negative resistance, and $\sqrt{\overline{i_n^2}}$ is the white noise current generated by accelerated electrons in the high-field domain and by intervalley scattering. The loaded cavity as seen from the diode terminals is represented by a parallel G L C over the narrow frequency range considered.

The domain width is a function of the applied voltage; therefore, the domain capacitance and hence the free-running frequency are bias dependent. The domain conductance must be just the negative of the load plus cavity conductance in order to sustain oscillations. Its magnitude must also decrease as the amplitude of the RF signal increases for the oscillation to be stable. Therefore, if a change in the bias voltage causes a change in the diode's negative conductance, that change will be transferred to a change in the RF power output. Sweet then expresses the oscillator frequency and power pushing factors as functions of the elements in this equivalent circuit. The frequency pushing factor is

$$\frac{\partial \omega_o}{\partial V_{bias}} = \frac{\omega_o^2 \left(\frac{\partial \bar{C}_d}{\partial V_{bias}}\right)}{2Q_L\ (G_i + G_L)} \qquad (1)$$

and the power pushing factor is

$$\frac{\partial P_o}{\partial V_{bias}} = 2\sqrt{P_o\ (G_i + G_L)}\ \frac{\left|\frac{\partial \bar{G}}{\partial V_{bias}}\right|}{\left|\frac{\partial \bar{G}}{\partial V_{rf}}\right|} \qquad (2)$$

where Q_L is the loaded Q, and P_o is the output power.

$$Q_L = \frac{\omega_o (C_c + \bar{C}_d)}{(G_L + G_i)}$$

$$P_o = \frac{V_{rf}^2\ (G_L + G_i)}{2}$$

$\bar{C}_d$ = Gunn diode capacitance

C_c = cavity capacitance

G_L = load conductance

G_i = cavity conductance

$-\bar{G}$ = Gunn diode's negative conductance

ω_o = Gunn diode operating frequency

V_{rf} = RF voltage

V_{bias} = Gunn diode bias voltage

II-2. NOISE SOURCES

Sweet describes three major sources of noise in Gunn oscillators. Flicker noise has a 1/f spectrum due to a distribution of trap energies causing a distribution of associated lifetimes. The nature of these trapping centers is not well known but Copeland [2] has suggested that they consist of interstitial copper atoms with a range of energy levels. Generation-recombination noise develops when a large number of recombination centers exhibit a common lifetime. The spectrum is flat at low frequencies and rolls off as $1/f^2$ at high frequencies. This is most likely a bulk effect where a common mechanism is dominant in capturing and releasing carriers. Both flicker noise and generation-recombination noise cause a noisy DC current to flow through the Gunn oscillator. The flow of this current through the circuit induces bias voltage which serves to amplitude-modulate and frequency-modulate the carrier through the power pushing and frequency pushing factors respectively. The third noise sourcesis the white source of field excited electrons and intervalley scattering in the domain itself. This is a noise current at microwave frequencies introduced directly as $\sqrt{\overline{i_n^2}}$ in Fig. 1 and does not involve interaction with the terminal voltage. Sweet calculates this noise to give a white AM component:

$$\frac{P_{AM}}{P_o} = \frac{kT_n B (G_L + G_i)^3 \Big/ P_o^2 \left|\frac{\partial \bar{G}}{\partial V_{bias}}\right|^2}{1 + \left(\frac{\omega}{\omega'}\right)^2} \qquad (3)$$

$$\omega'^2 = \frac{\omega_o^2 P_o \left| \frac{\partial \bar{G}}{\partial V_{rf}} \right|^2}{2Q^2 \quad (G_i + G_L)^3} \qquad (4)$$

T_n = equivalent noise temperature for $\sqrt{\overline{i_n^2}}$

and an FM component:

$$\overline{\Delta\omega^2} = \frac{\omega_o^2 k T_n B}{4Q_L^2 P_o} \qquad (5)$$

The three sources contributing to the RF noise spectrum are shown in the diagram in Fig. 2. Both AM and FM spectra have the same qualitative shape.

Sweet's final equations express the total AM and FM spectra as the sums of a component of the terminal voltage spectrum, $S_{\Delta V_{bias}}(\omega)$, upconverted through the respective pushing factors and a white microwave component.

$$\overline{\Delta\omega^2} = \frac{\omega_o^2 k T_n B}{4Q_L^2 P_o} + \left(\frac{\omega_o^2 \left(\frac{\partial \bar{C}_d}{\partial V_{bias}} \right)}{2Q_L \; (G_i + G_L)} \right)^2 S_{\Delta V_{bias}}(\omega) B \qquad (6)$$

$$\frac{P_{AM}}{P_c} = \frac{kT_n B (G_i + G_L)^3 \Big/ P_o^2 \left|\frac{\partial \bar{G}}{\partial V_{rf}}\right|}{1 + \left(\frac{\omega}{\omega'}\right)^2} + \left(\frac{2\sqrt{P_o (G_i + G_L)} \left|\frac{\partial \bar{G}}{\partial V_{bias}}\right|}{\left|\frac{\partial \bar{G}}{\partial V_{rf}}\right|} \right)^2 S_{\Delta V_{bias}}(\omega) B \qquad (7)$$

Since the flicker and generation-recombinationnnoise currents develop a voltage across the bias impedance which is upconverted through the voltage pushing factors, it is expected that the upconverted noise will be dependent upon the bias impedance that the Gunn sees at video frequencies. To the extent that the flicker and generation-recombination noises are current sources, the low frequency bias fluctuations, and hence upconverted AM and FM spectra, will be directly proportional to the bias impedance. On the other hand, $\sqrt{\overline{i_n^2}}$ causes a RF noise directly without influencing the terminal voltage and therefore will not show impedance dependence.

III. MEASUREMENT PROCEDURE

III.-1. EQUIPMENT

The noise measurement system used was designed and built by J. Ondria [5]. It employs direct detection of AM and a cavity discriminator for FM. Low noise Philco back diodes are used for both AM and FM detection and are biased as described by Ondria.

The video signal from the diodes is amplified in a low-noise, high-gain, wide-band amplifier before being fed into a wave analyzer. Noise is measured at octave intervals in a bandwidth of 9.6 Hz between 20 Hz and 640 Hz and in a bandwidth of 88 Hz between 1.28 kHz and 640 kHz on a HP 3590A wave analyzer.

The Gunn diodes and cavities were supplied by Microwave Associates. The length of the active region of these samples is 9.25 μ with a donor concentration of .85 x 10^{15}cm^{-3}. The cavity is frequency tunable by inserting a dielectric screw, but the cavity coupling is not adjustable. The diodes are biased through the circuit of Fig. 3 where the component sizes are chosen so that an impedance R is presented to the Gunn in the frequency range 20 Hz to 640 kHz, the value being varied to allow the Gunn diode's bias current noise to develop a variable noise voltage component of upconverted noise to the RF noise spectrum.

III-2. MEASUREMENT OF PUSHING FACTORS

The power pushing and frequency pushing factors were measured as follows. A BFO current modulation signal is applied as in Fig. 3. This gives a voltage signal across the diode well above the noise to determine the voltage pushing factors as a function of modulation frequency. The pushing factors are also measured staticall ally as the slope of the power and frequency versus bias voltage curves. Power is measured directly with a power meter and frequency is measured by counting the output of a 185 MHz transfer oscillator.

III-3. MEASUREMENT OF Q

Q is measured according to the method of Ondria and Turlington [6] .

A BFO modulating signal is applied as in Fig. 3 and the frequency modulation, Δf_{free} , is measured. The frequency of this modulating signal must be well within the bandwidth of the modulation network. Power from a stable microwave source with frequency very close to the free running of the Gunn is injected into the Gunn oscillator. The Gunn locks to this source and the frequency modulation is correspondingly reduced to Δf_{lock} . The effectiveness of this lock is related to the Gunn cavity Q . The result of Ondria and Turlington is slightly modified to yield:

$$Q_L = \frac{S}{\sqrt{1-S^2}} \frac{f_o}{2f_m} \sqrt{\frac{P_i}{P_o}} \tag{8}$$

f_o = RF frequency

f_m = modulation frequency external circuit bandwidth

P_i = injection power

P_o = output power

S = suppression = $\Delta f_{lock} / \Delta f_{free}$

The feedback model used in their analysis assumes that the modulating signal is a voltage which is the same under locked or unlocked conditions. Since the modulation source has some impedance, the diode impedance dependence on injection power makes the modulation signal dependent on injection power. This can be accounted for by dividing the suppression by the ratio of the locked to unlocked modulation voltages:

$$S = \frac{\Delta f_{lock} / \Delta f_{free}}{\Delta v_{mod.\ lock} / \Delta v_{mod.\ free}}$$

IV. RESULTS AND DISCUSSION

The voltage pushing factor or modulation sensitivities depended on frequency for many of the samples. The reason for this is not known; however, AM and FM pushing factors had the same shape with frequency indicating that the cause affects both AM and FM equally.

The pushing factors were measured to be independent of bias impedance R, as expected, since R is in parallel with, and hence does not affect, the voltage across the Gunn device. The loaded Q was also measured to be independent of R; since the Q is determined by the microwave circuit loading, this assures that the bias circuit is isolated from the microwave signals.

The frequency and power versus bias voltage curves are shown in Fig. 4 and 5 for two diodes which exhibited nearly frequency independent pushing factors. The power pushing factor varied less than 10% from the statically measured value over five decades of frequency. The frequency pushing factor increased slightly with modulation frequency, but it was always within a factor of two of the statically measured value.

The AM, FM, and low frequency voltage noise spectra of these diodes are given in Fig. 6-11 with the resistance R as a parameter. The measured AM values are into the system noise level for low values of R and are consequently not as accurate. All of the spectra show an increase in noise with R; however, for high values of R, the noise voltage does not double for a doubling of R.

This indicates that the diode noise equivalent circuit includes a fixed shunt resistance.

Assuming that the noise current source is independent of R, the voltage versus R relationship at each frequency can be used to calculate the value of the parallel source impedance. For the two samples D103 and D104, the value is about 300 ohms.

In both diodes, there is AM and FM microwave noise present when the terminal voltage noise is shorted by making R=0. This spectrum consists of a component due to upconverted low frequency noise as well as a component of white noise.

The fact that the terminal voltage noise has an influence on the microwave noise when terminals are shorted suggests that the power and frequency controlling node is removed from the terminals by some impedance. A finite noise voltage can exist at this interval node when R=0 and this voltage will cause FM and AM microwave noise. The low frequency voltage noise spectrum corresponding to the residual FM and AM spectra can be determined by dividing the FM and AM spectra by the respective pushing factors. This noise voltage theoretically appears at the internal controlling node. Assuming the same current noise source as before, a value can be calculated for the impedance separating the control node from the terminal node. The calculated value for this impedance is 50 ohms for D103 and 10 ohms for D104. The low frequency equivalent noise model is shown in Fig. 12.

If the frequency and power are controlled by the voltage across the domain as suggested in section II.1., then this voltage is always separated from the terminal voltage by the below-threshold resistance of the rest of the Gunn diode. Sweet [8] finds this resistance to be on the order of 10 ohms which is consistent with these results.

The second component of microwave noise for R=0 is the white component which appears directly as a microwave source. It does not show an effect on the terminal voltage and is therefore independent of R. The noise temperature of this white noise source can be calculated using equation 5 and Δf = .054, Q_L = 805, B = 1 Hz, P_o = 14.2 mW and the result is T_n =193000 K. These noise temperatures are three to six times larger than reported by Sweet [7].

The breakpoint frequency of the generation-recombination noise in these samples is 6 kHz. This corresponds to a carrier lifetime for this process of 25 μs. Generation-recombination noise is not a strong component in most of the spectra measured.

Fig. 13 - 16 show the FM and AM noise spectra predicted for the two diodes by adding to the short circuit noise an upconverted component equal to the product of the voltage pushing squared and the measured bias voltage noise squared. These calculated results are in good agreement with the measured spectra of Fig. 6,7,9, and 10.

CONCLUSIONS

The video frequency terminal voltage noise of the Gunn diode oscillator is strongly dependent upon the biasing circuit impedance presented to the diode. A low frequency noise model is proposed which includes a small resistance between the active region of the device and the terminals, and a large shunt resistance across the device. This model accounts for the behavior of the low frequency noise voltage spectrum for the bias impedance in the range of 1 to 1500 ohms.

The frequency pushing and power pushing factors were measured both statically and as functions of modulation frequency. Both pushing factors were found to be relatively independent of modulation frequency and in good agreement with the statically measured values.

The microwave AM and FM noise spectra exhibited a component of white noise which was independent of the bias circuit impedance. This noise was much lower than the upconverted noise for low frequencies but was an important component of the spectra above 500 kHz. The magnitude of this white source was used to calculate an equivalent noise temperature which was significantly larger than reported by Sweet [7] or calculated by Haus et al [3] .

The microwave FM and AM noise spectra were calculated according to equations by Sweet [7] by adding the white measured component to an upconverted component equal to the product of the low frequency terminal voltage spectrum and the measured pushing factors. The results were in good agreement with the measured microwave spectra.

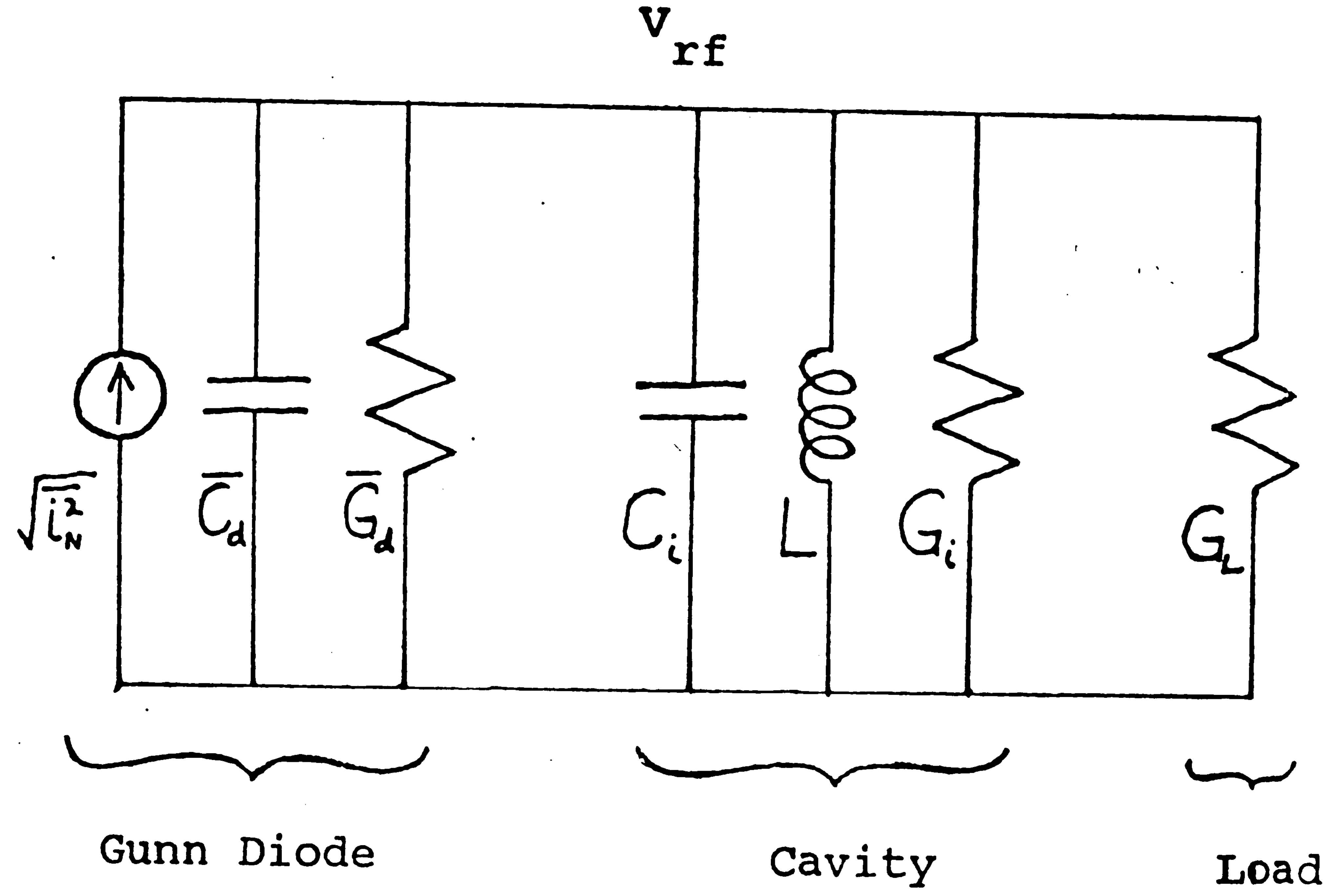

Figure 1 – Equivalent RF Circuit

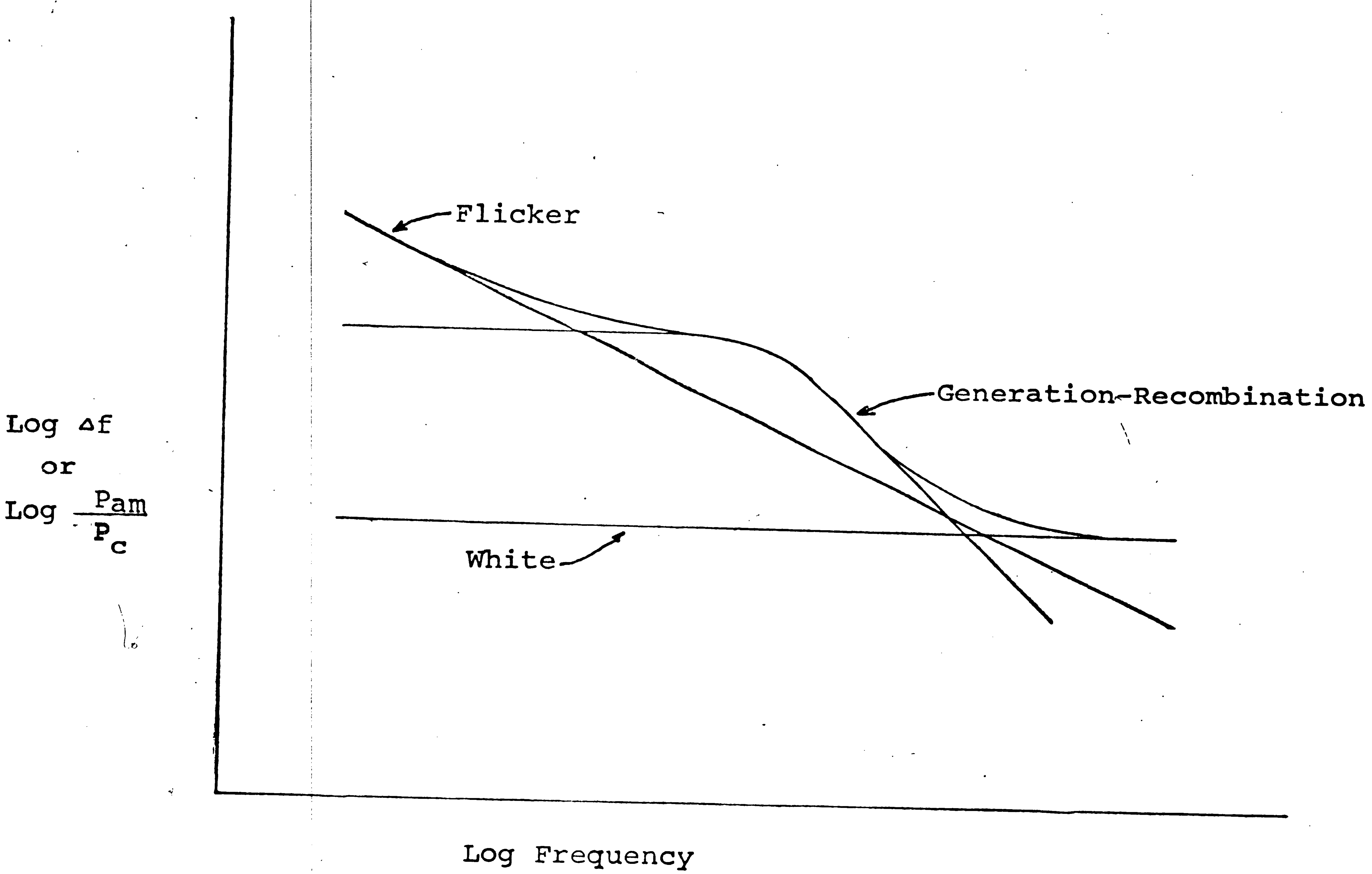

Figure 2 — Noise Sources in RF Spectra (AM or FM)

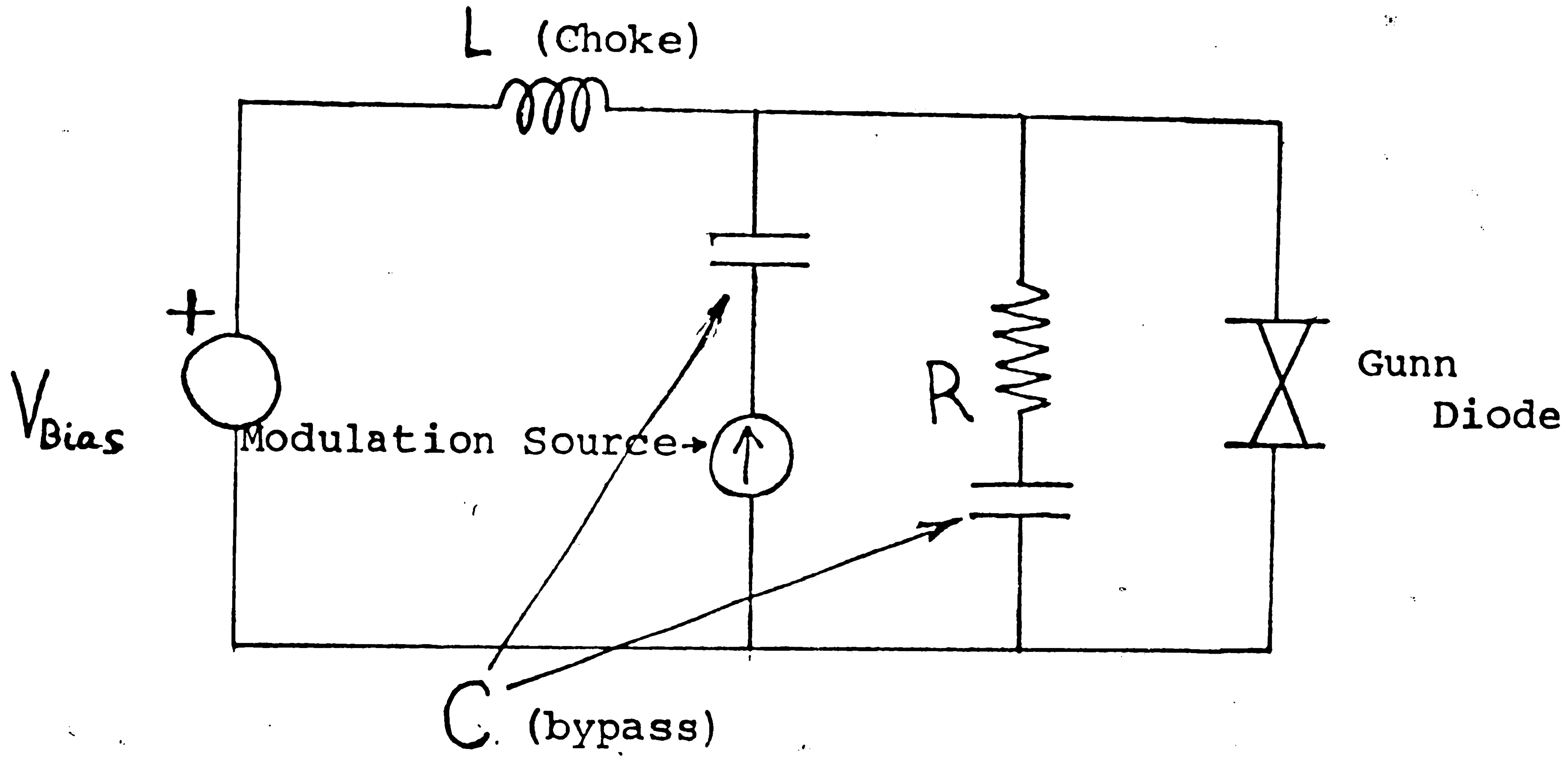

Figure 3 — Gunn Diode Biasing Circuit

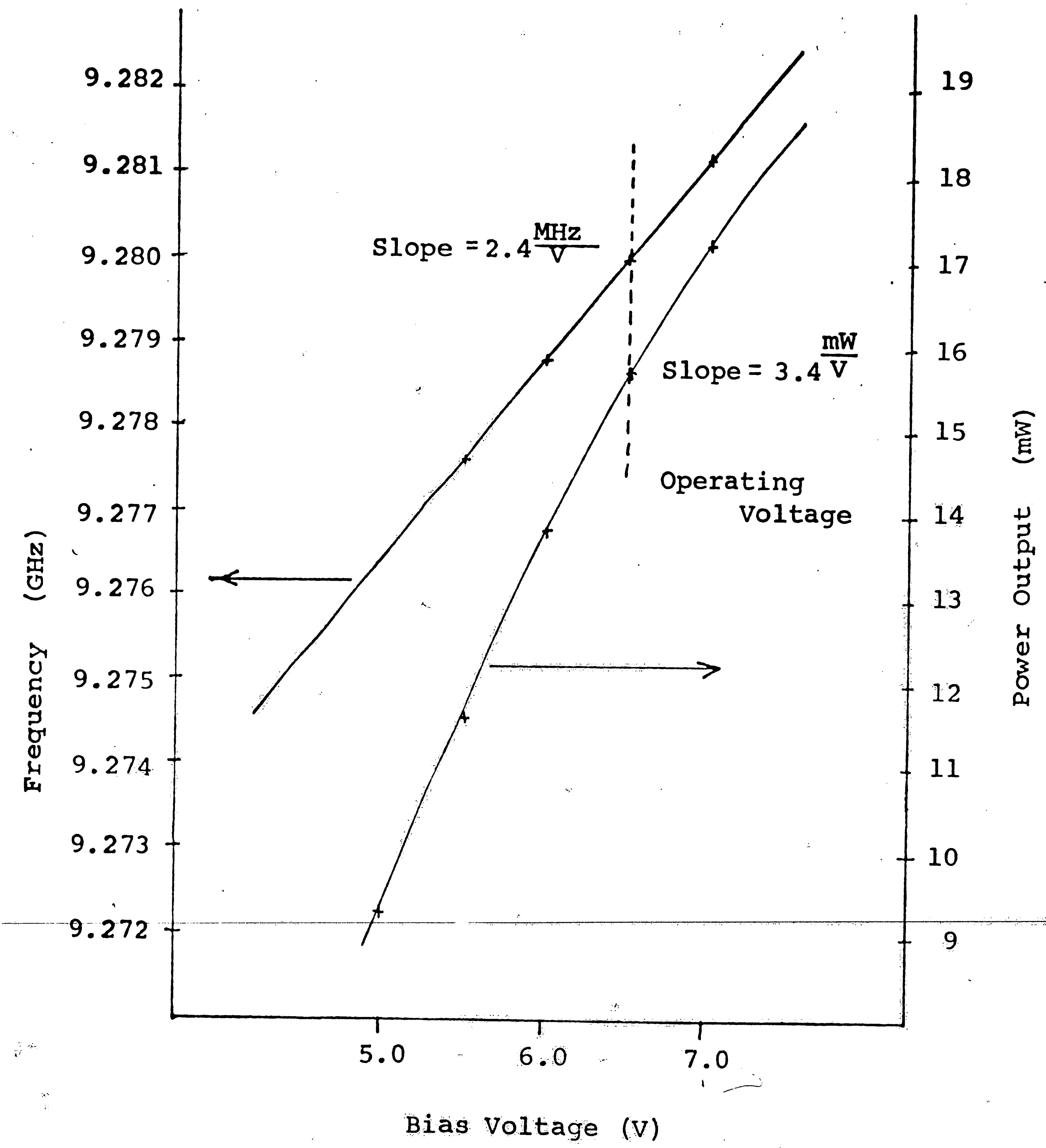

Figure 4 — Frequency and Power Versus DC Bias Voltage — D103

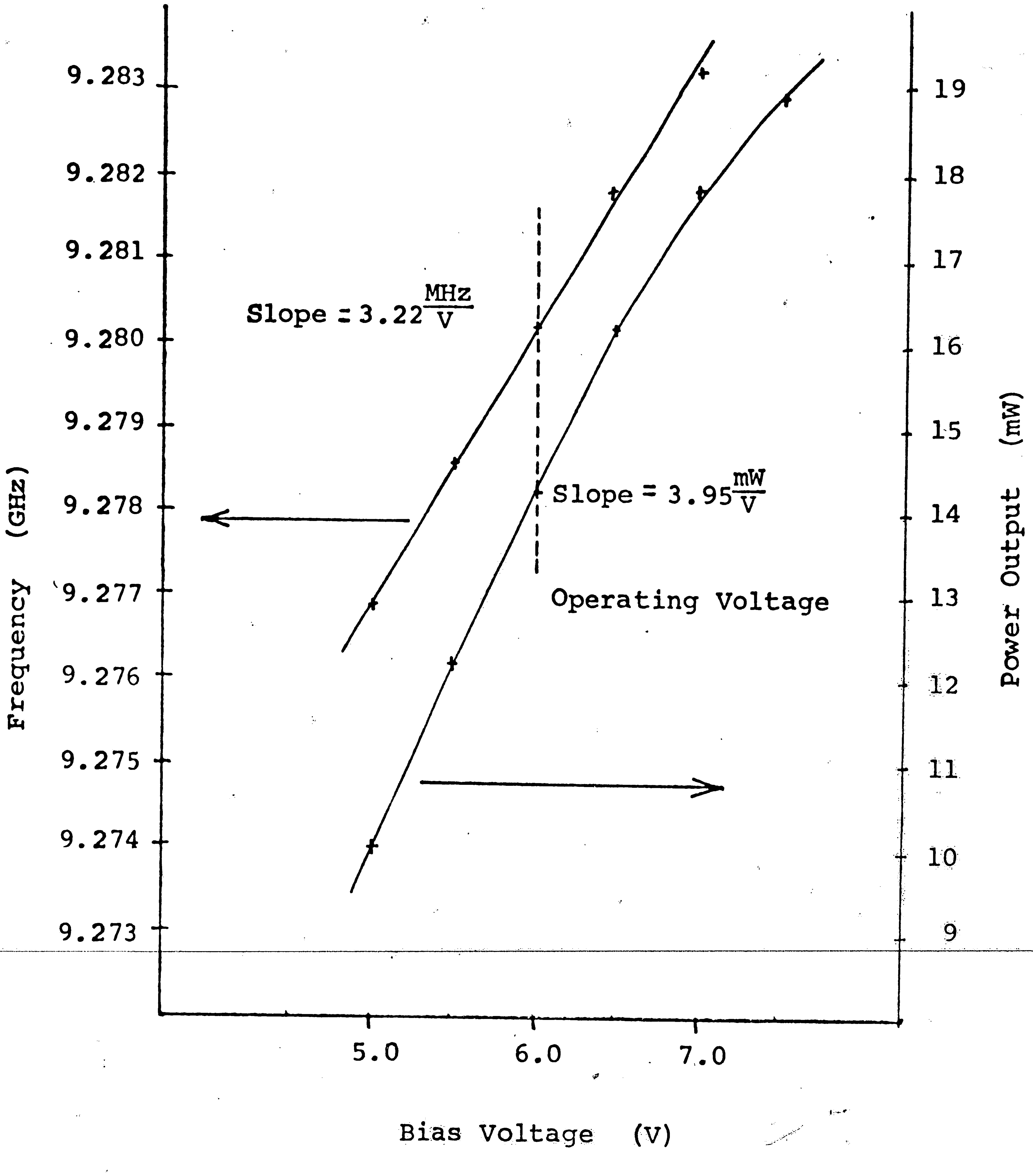

Figure 5 — Frequency and Power Versus DC Bias Voltage-D104

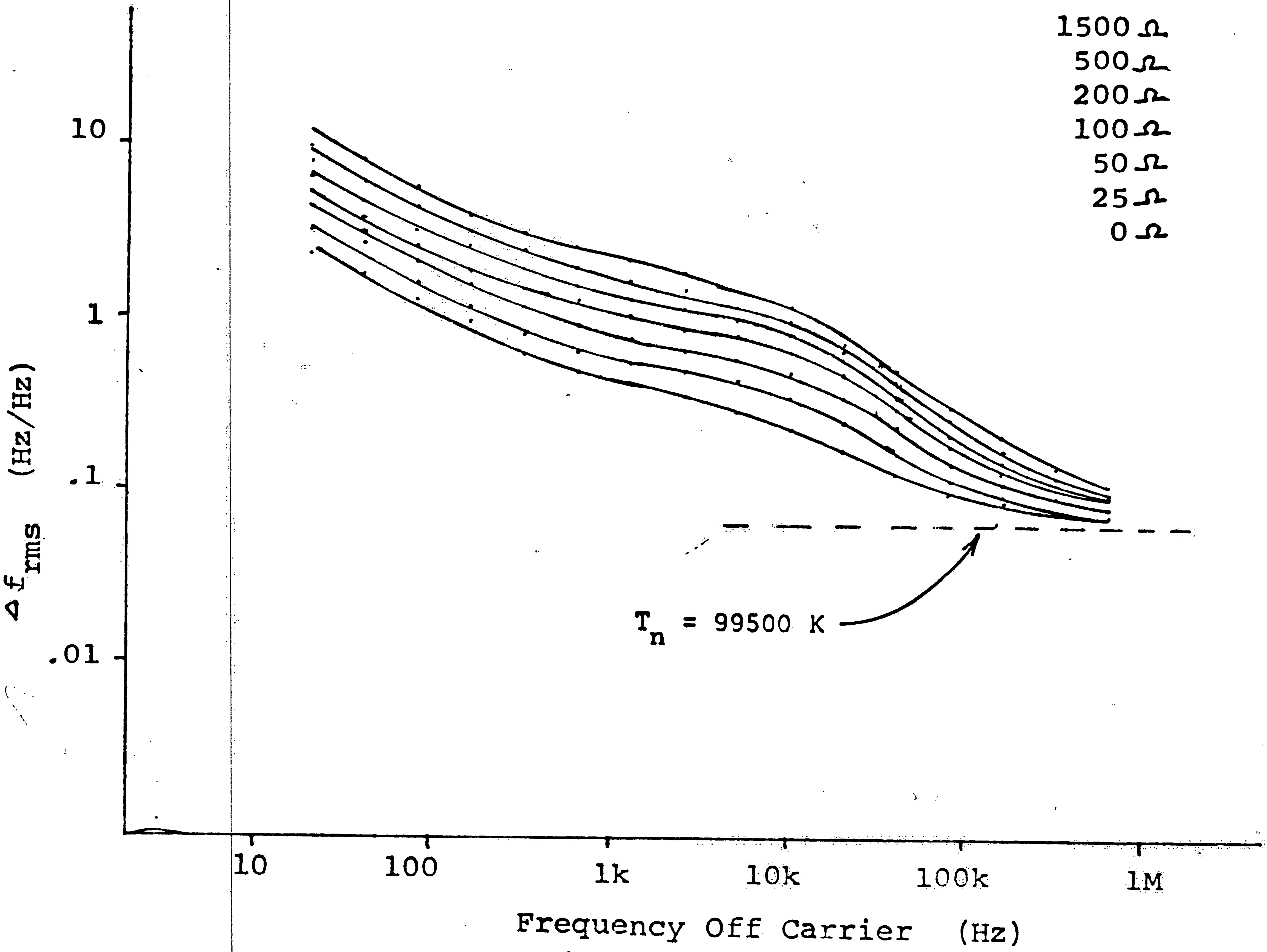

Figure 6 - FM Noise Spectrum with Bias Impedance Parameter - D103

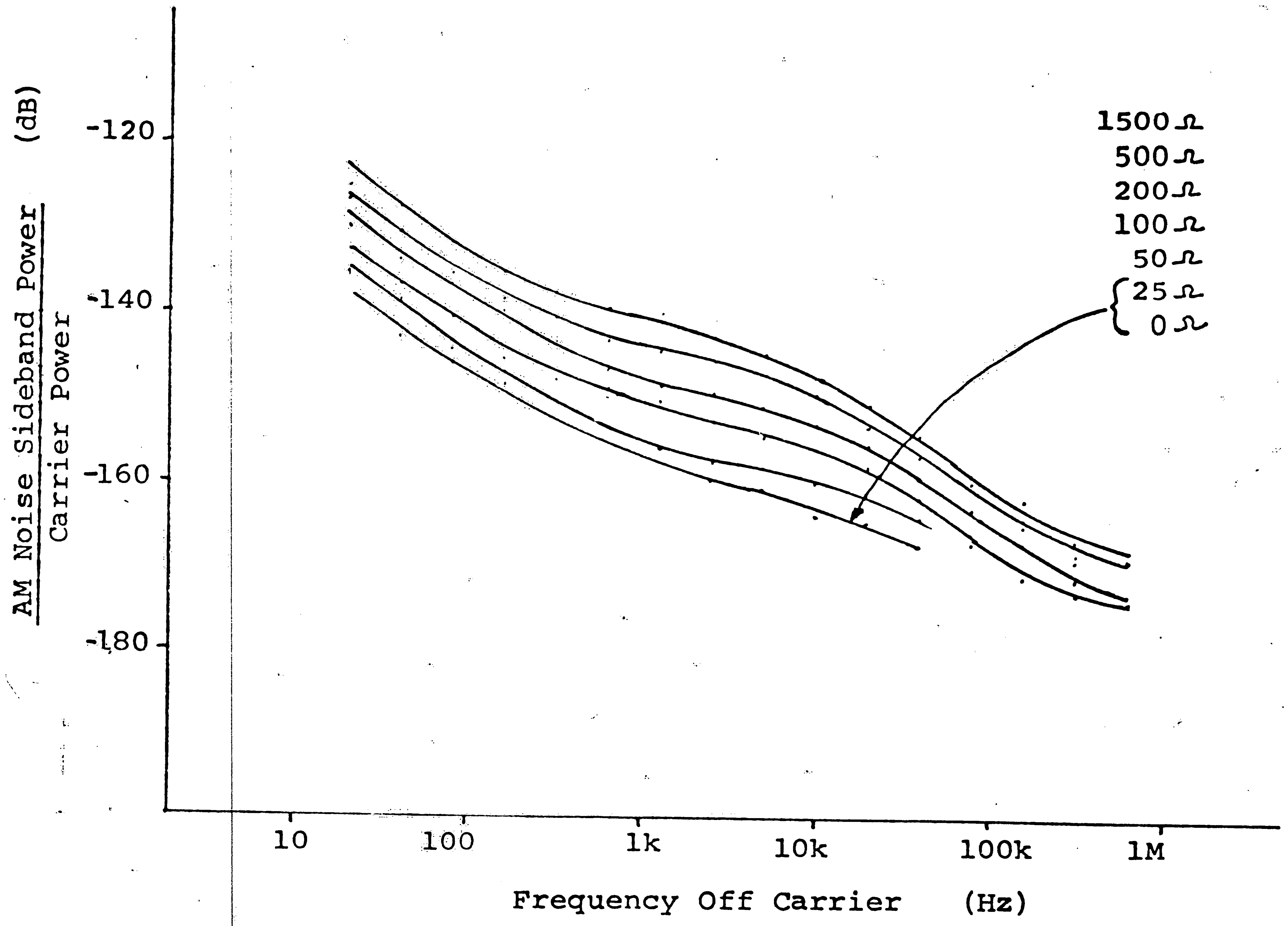

Figure 7 – AM Noise Spectrum with Bias Impedance Parameter – D103

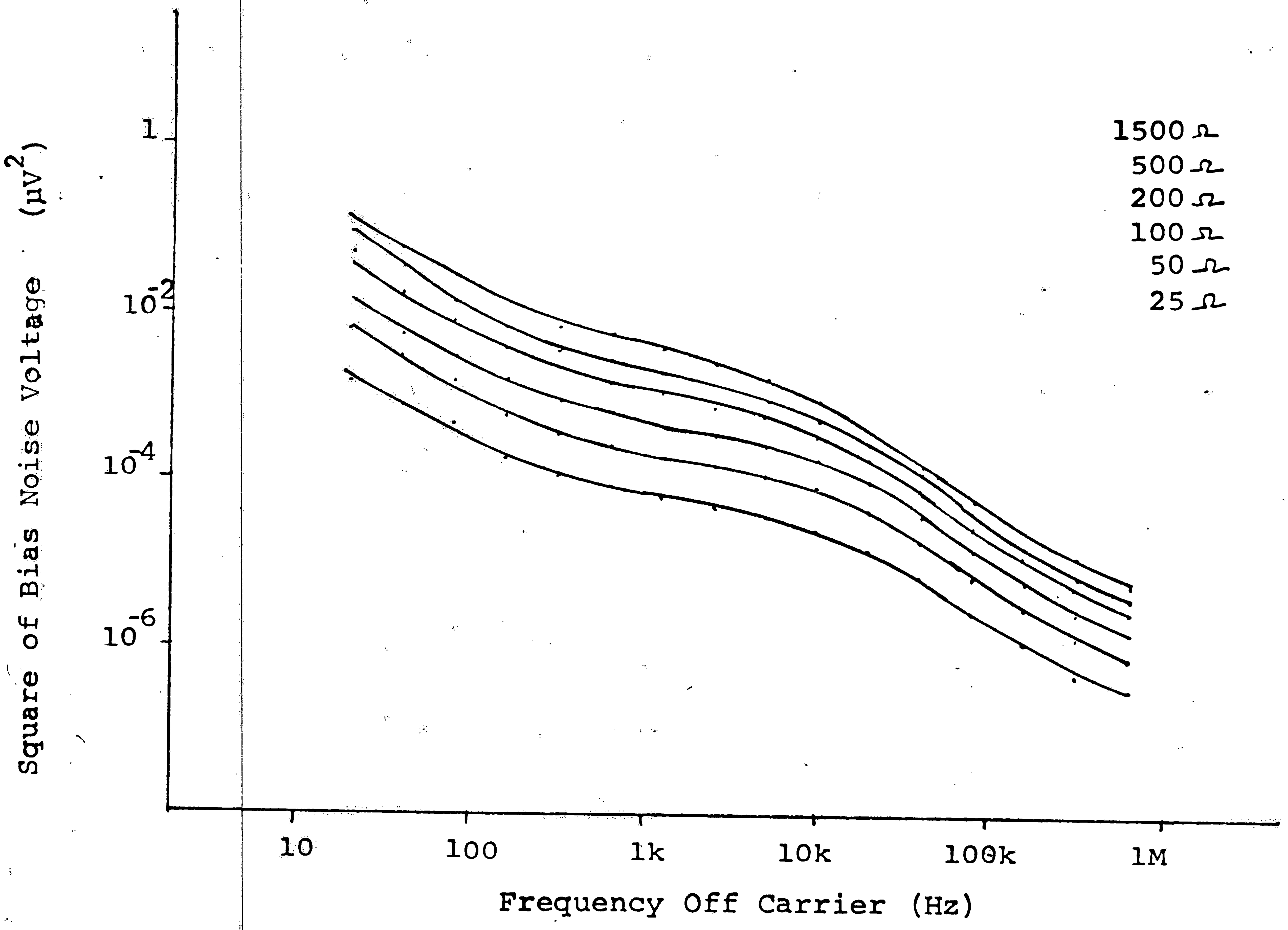

Figure 8 - Square of Terminal Voltage Spectrum with Bias Impedance Parameter-D103

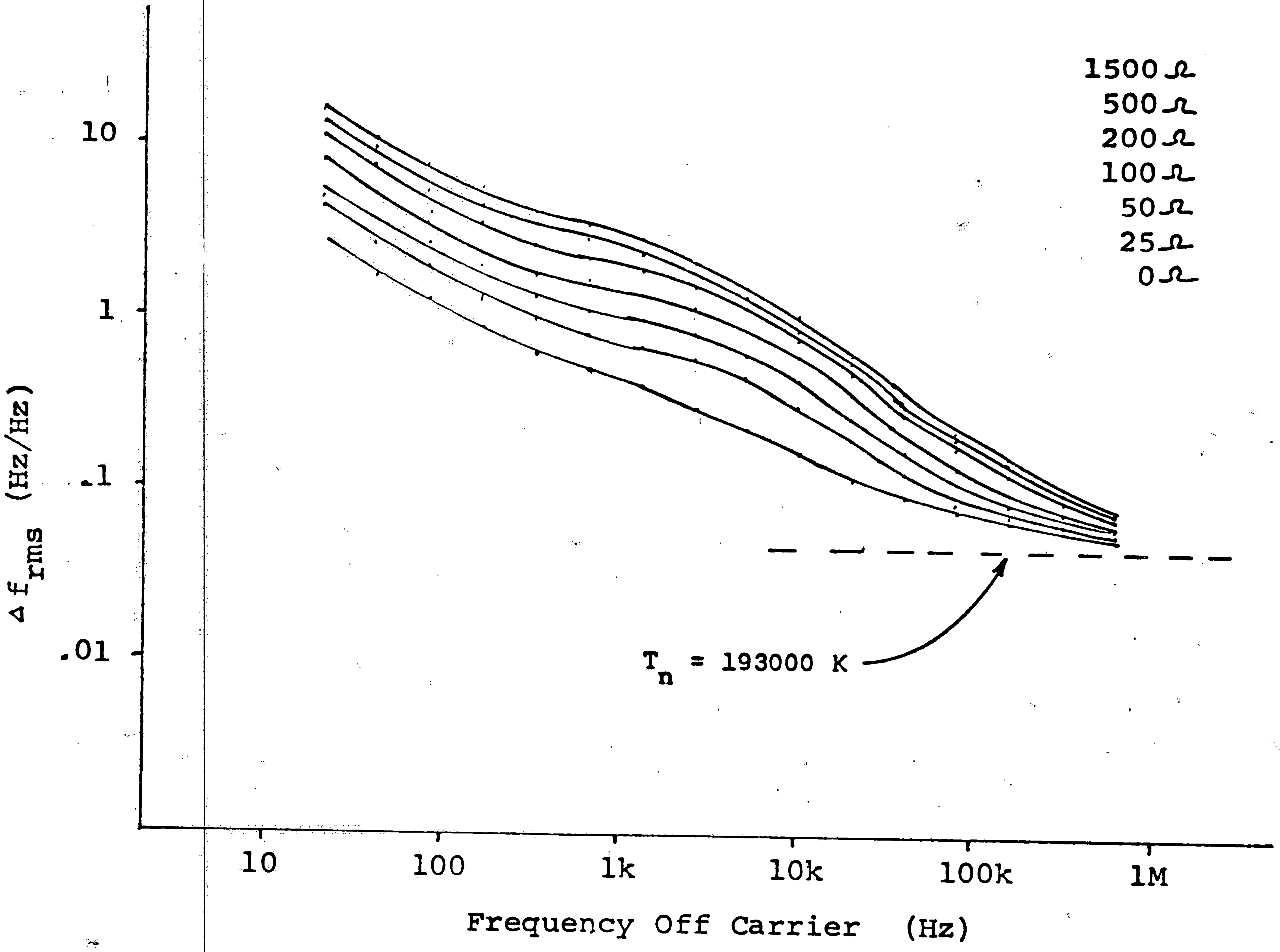

Figure 9 — FM Noise Spectrum with Bias Impedance Parameter-D104

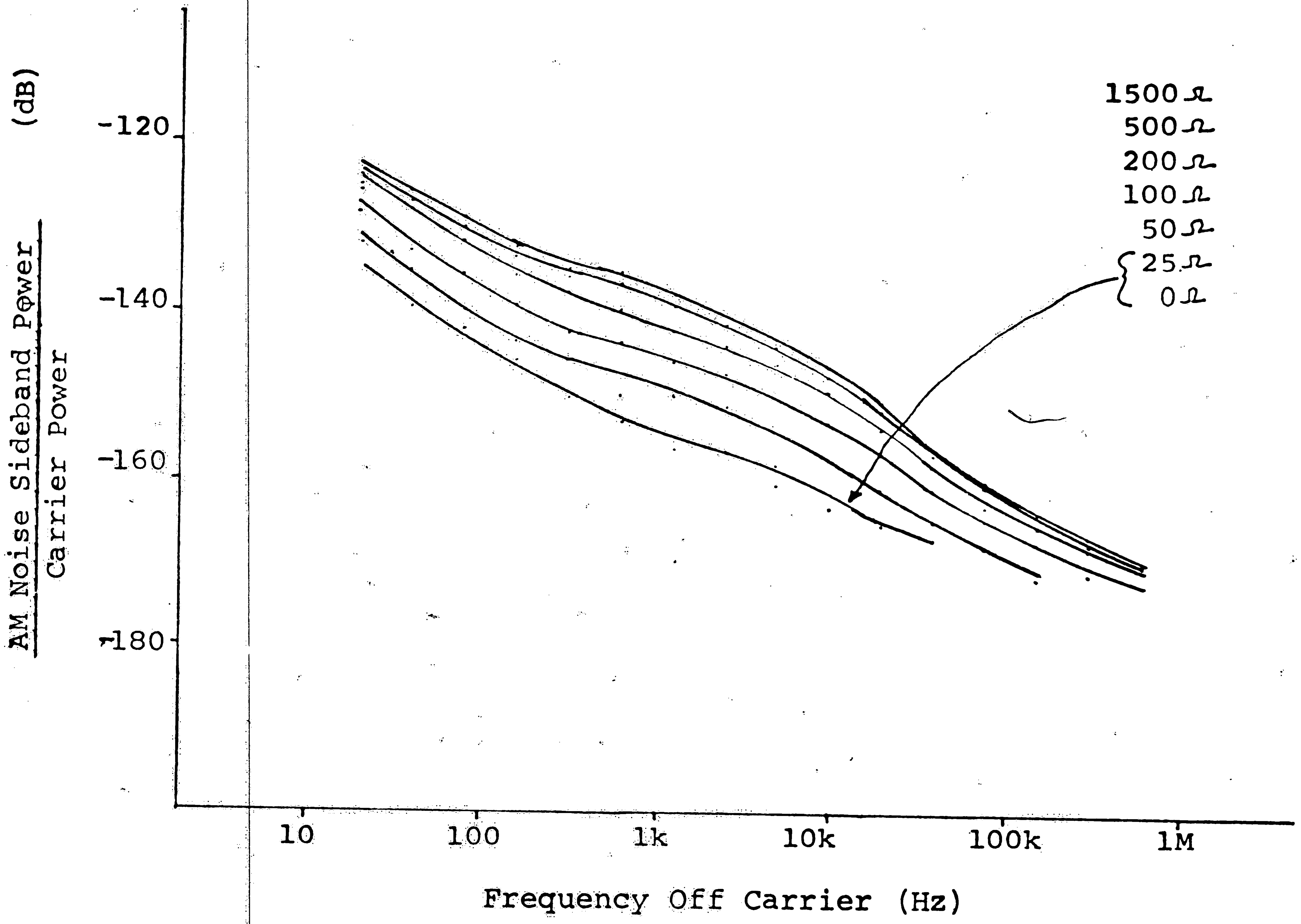

Figure 10 - AM Noise Spectrum with Bias Impedance Parameter-D104

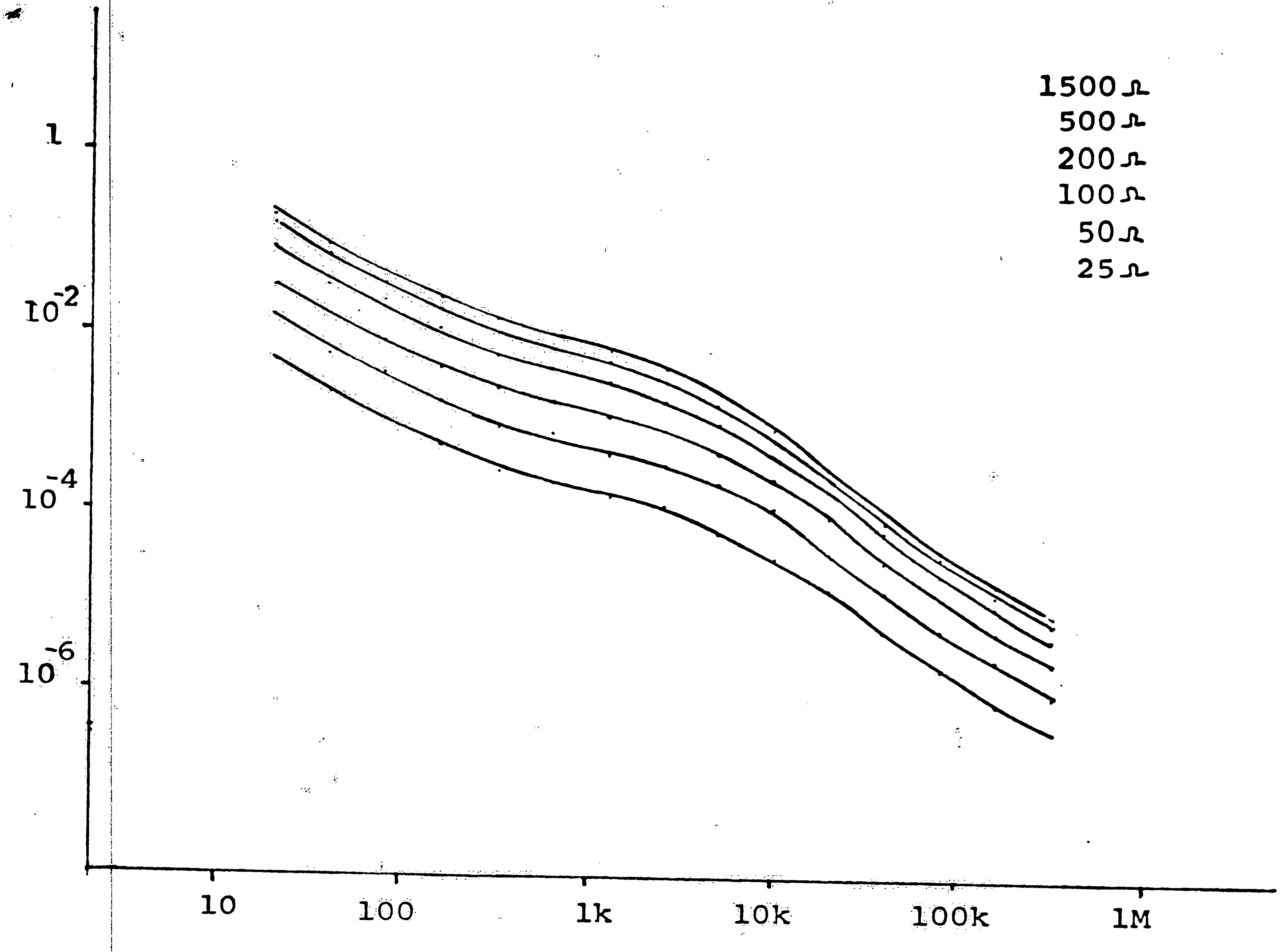

Figure 11 - Square of Terminal Voltage Spectrum with Bias Impedance Parameter - D104

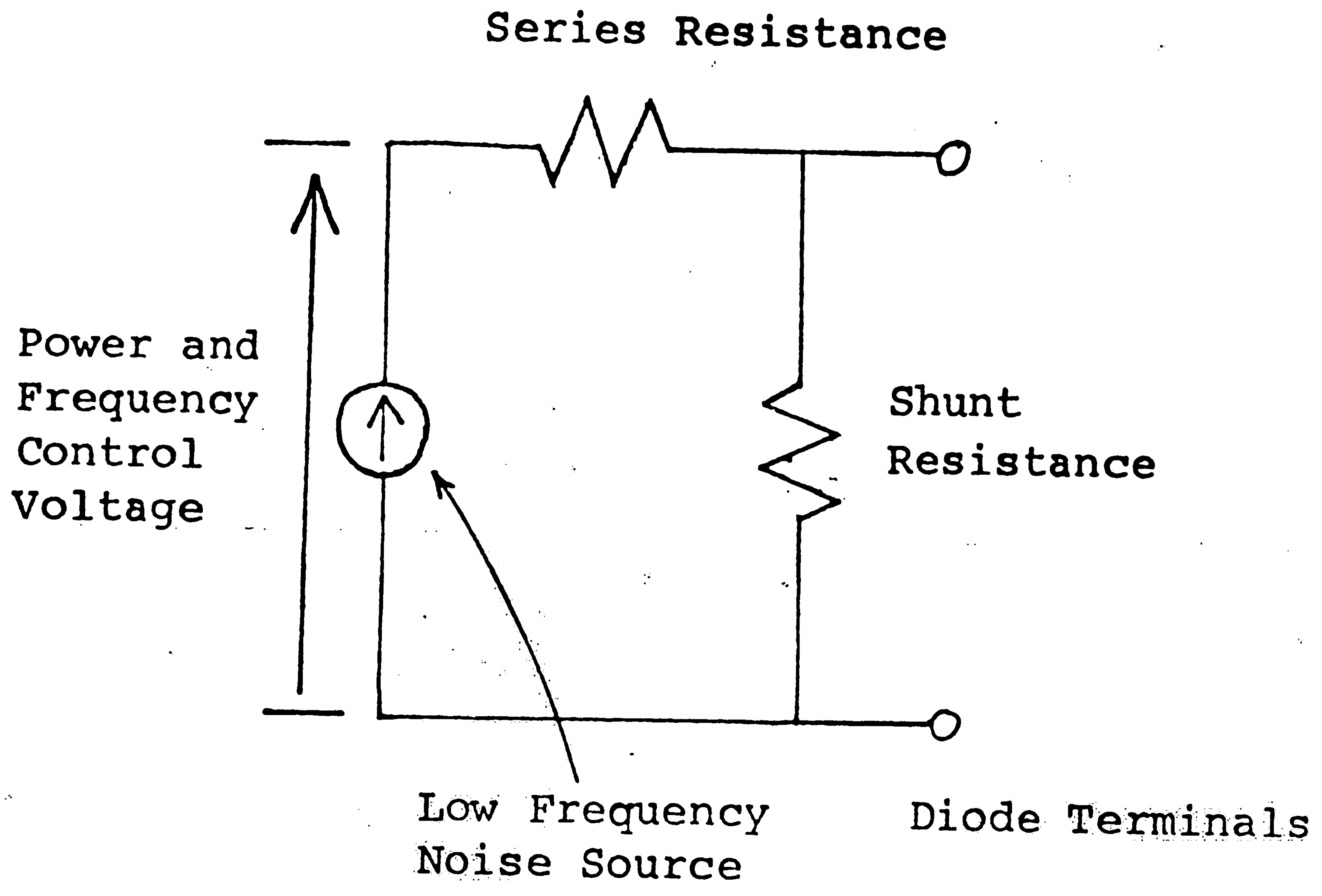

Figure 12 — Low Frequency Noise Model

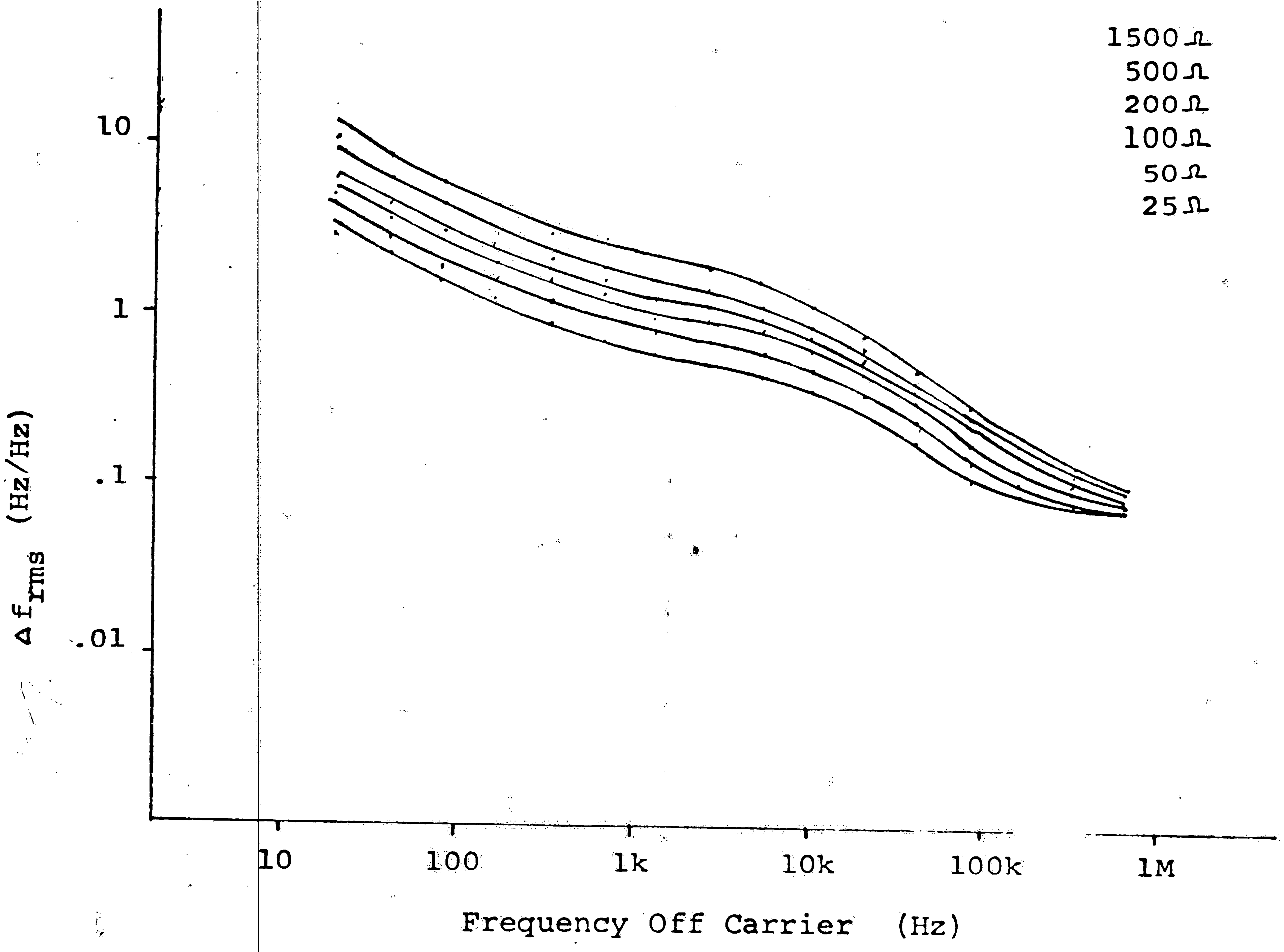

Figure 13 - Comparison of Predicted and Measured FM Noise-D103

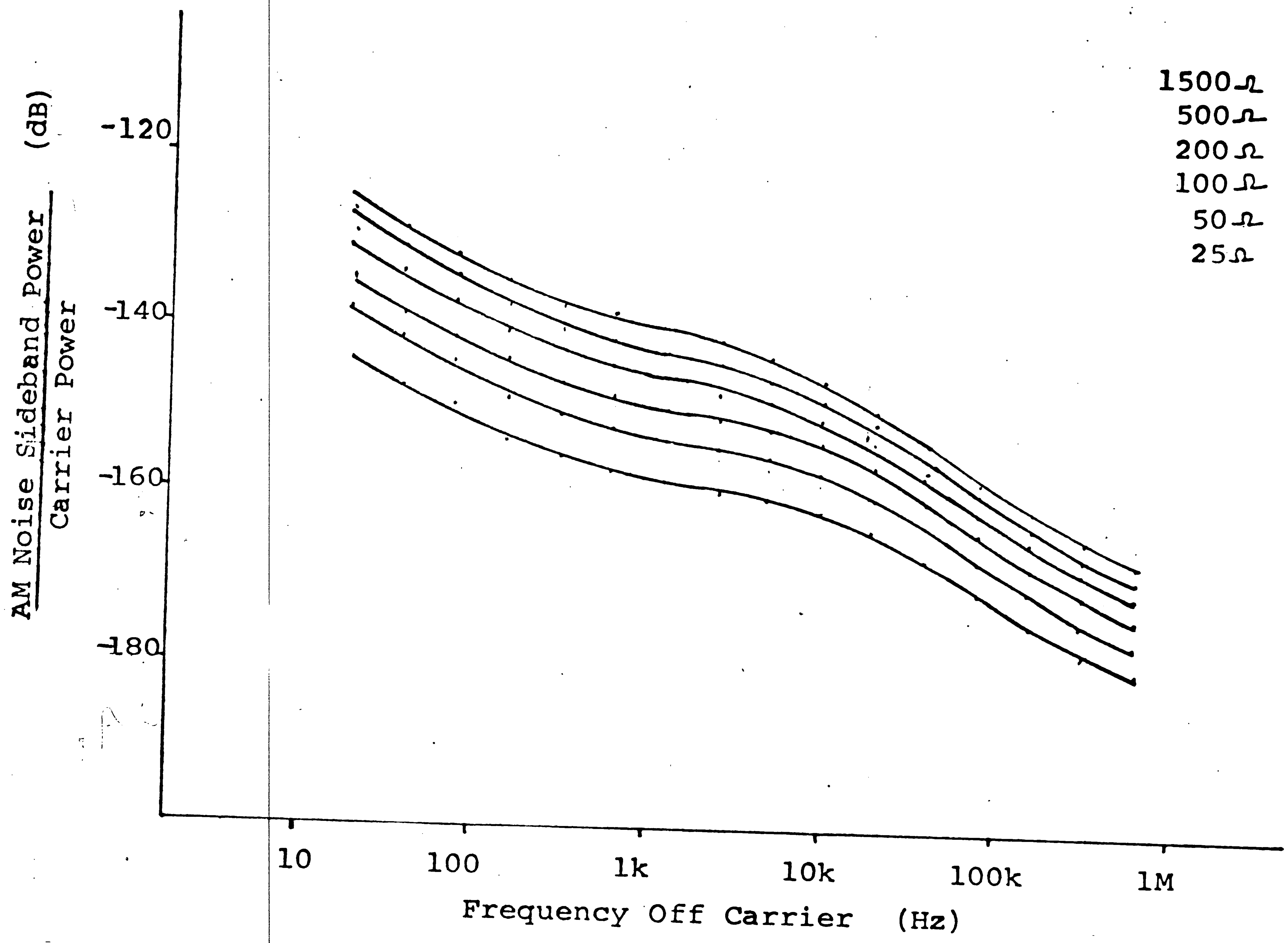

Figure 14 - Comparison of Predicted and Measured AM Noise - D103

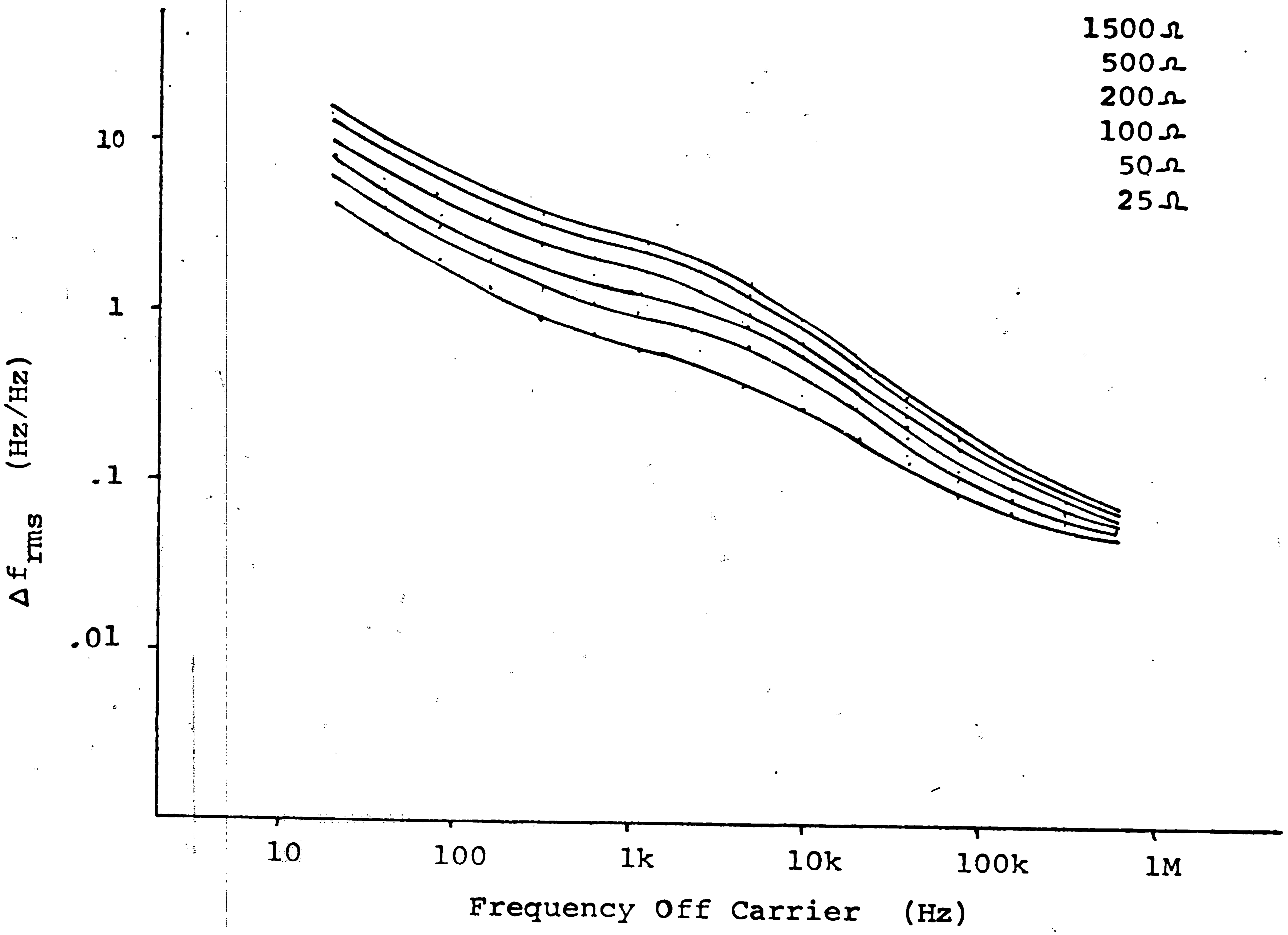

Figure 15 - Comparison of Predicted and Measured FM Noise - D104

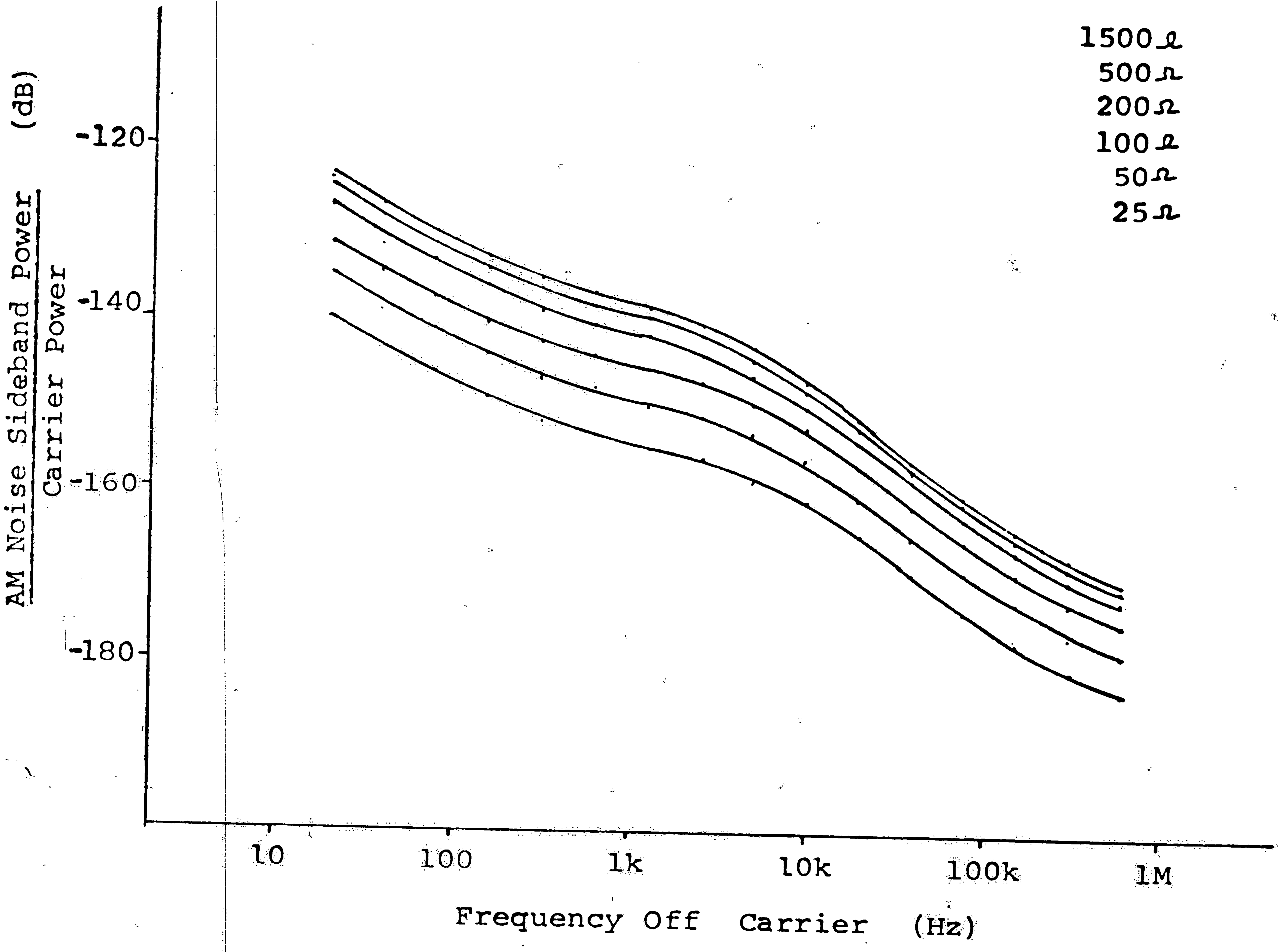

Figure 16 - Comparison of Predicted and Measured AM Noise - D104

BIBLIOGRAPHY

(1) Adler, R., "A Study of Locking Phenomena in Oscillators", Proc. IRE, Vol. 34, pp 351-357, June 1946.

(2) Copeland, J.A., "Semiconductor Impurity Analysis from Low-Frequency Noise Spectra", IEEE Trans. on Elec. Dev., Vol. ED-18, pp 50-53, January 1971.

(3) Haus, H.A., Statz, H., and Pucel, R.A., "Noise in Gunn Oscillators", Trans ED, Vol ED-20, pp 368-370, April 1973.

(4) Kurokawa, K., "Noise in Synchronized Oscillators", IEEE Trans., M.T.T., Vol. MTT-16, pp 234-240, April 1968.

(5) Ondria, J.G., "A Microwave System for Measurement of AM and FM Noise Spectra", IEEE Trans., M.T.T., Vol MTT-16, pp 767-781, September 1968.

(6) Ondria, J.G. and Turlington, T.R., "Impatt and Gunn Oscillator Injection Lock Dynamic Behavior", Proc. Third Biennial Cornell Elec.Eng. Conf., Vol. 3, pp 233-243, 1971.

(7) Sweet, A.A., " A General Analysis of Noise in Gunn Oscillators", Proc. IEEE Letters, Vol. 60, pp 999-1000, August 1972.

(8) Sweet, A.A., "A study of Noise in Gunn Effect Oscillators", Ph.D. Dissertation, Cornell University, Ithaca, N.Y., 1970.

(9) Sweet, A.A. and MacKenzie, L.A., "The FM Noise of a CW Gunn Oscillator", Proc. IEEE, Vol. 58, pp 822-823, May 1970.

VITA

Charles B. Winn was born on July 29, 1950 in Syracuse, New York. He did his undergraduate work at Lehigh University and received the Bachelor of Science Degree in Electrical Engineering in 1972.

His professional experience includes work with General Electric in Hudson Falls, New York in 1969 and in Syracuse, New York in 1970.

The author was a teaching assistant in the Department of Electrical Engineering throughout his graduate program.