NOISE MEASURING TECHNIQUES
AT ULTRA-HIGH FREQUENCIES

by

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ABSTRACT

A method whereby the noise figure and the excess noise ratio of a device may be measured using succeeding-stage noise compensation is given. The procedure developed, measures the noise behavior of the first stage of a system and corrects for the noise contributions of the following stages.

Experimental results are presented for the noise figure and the excess noise ratio at UHF for a junction FET device. The existing noise models are also verified.

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CHAPTER I

NOISE CHARACTERIZATION

One-Port Noise-Equivalent Representations

For the noise analysis of one-port networks various characterizations of noise exist. Representations commonly used are: noise temperature, noise conductance, noise resistance, equivalent saturated diode current, and excess noise ratio.

Any noise that has a power spectrum containing all frequency components in equal proportion is referred to as "white noise".

For any white-noise source a noise temperature, T_e, can be defined which is a measure of the available power of that white-noise source:

$$T_e = N_A/kB, \qquad \text{1.1}$$

where N_A = available noise power of noise source measured in a bandwidth B.

As an example, consider the case when a temperature-limited diode is used as a white-noise source. For UHF purposes, the noise diode is terminated by the characteristic admittance of the system. The equivalent noise model of the diode noise source is shown in Figure 1.1.

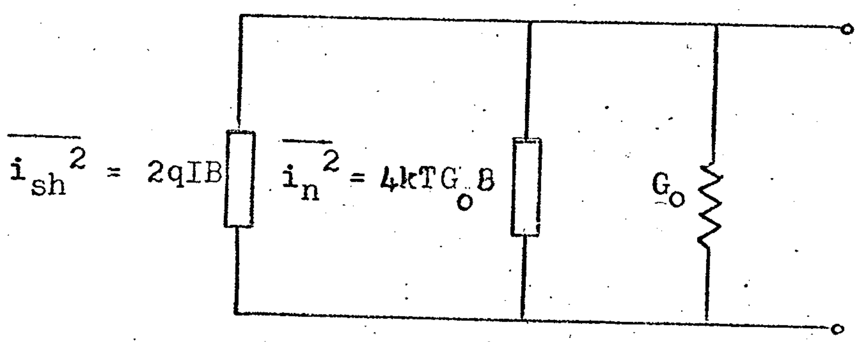


Figure 1.1 Noise-equivalent circuit of a diode noise generator

The diode generates shot noise which is proportional to the plate current, I. The terminating conductance generates thermal noise porportional to the physical temperature T of the conductor.

Short circuiting the generator's terminals, the mean-squared noise current becomes

$$\overline{i_{TOT}^2} = 2qIB + 4kTG_oB \quad \ldots\ldots\ldots\ldots\ldots \quad 1.2$$

This noise current can be expressed as a thermal noise source of conductance G_o with a physical temperature T_e. Rearranging equation 1.2,

$$\overline{i_{TOT}^2} = 4kT_eG_oB \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1.3$$

where $$T_e = qI/2kG_o + T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1.4$$

Equivalently, the available noise power from the generator is

$$N_A = 2qIBG_o/4G_o^2 + 4kTG_o/4G_o$$

$$= qIB/2G_o + kTB \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1.5$$

which can be rewritten,

$$N_A = kT_eB \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1.6$$

where T_e is given in Equation 1.4.

This example shows that the diode noise generator can be described by a thermal conductance G_o at a physical temperature T_e, without affecting the terminal properties of the generator.

White noise across any two terminals of a network, measured in a bandwidth B, can be described by a noise current generator, paralleling the terminals.[2] The mean-squared value of the generator is

$$\overline{i_n^2} = 4kTg_nB \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1.7$$

where g_n is the equivalent noise conductance across the terminals, and T is the physical temperature of the network.

The fictitious noise conductance g_n gives a measure of the noise across the two terminals. It does not necessarily represent an actual conductance in the network.

The dual to the equivalent noise conductance is the equivalent noise resistance. White noise may be described by its equivalent noise resistance R_n referred across any pair of terminals. This fictitious resistance generates an equivalent mean-squared voltage paralleling the two terminals:

$$\overline{v_n^2} = 4kTR_nB \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1.8$$

where T is the physical noise of the system.

Noise may also be represented by an equivalent mean-squared current generator

$$\overline{i_n^2} = 2qI_{EQ}B \quad \text{.......................} \quad 1.9$$

in parallel with the terminals of a network, where I_{EQ} is the equivalent saturated (temperature-limited) diode current of the network. In this case, the noise of the network is characterized by a generator having full shot noise, even though the true origin of the noise is not necessarily known.

The noise ratio, NR, of a two-terminal network is defined as

$$NR = N_A / kT_oB \quad \text{.....................} \quad 1.10$$

where N_A is the available output noise power measured in the bandwidth B, and kT_oB is the available thermal noise power of the network's passive termination at standard temperature (290^{o}K).

Noise ratio can also be expressed according to Equation 1.6 by

$$NR = T_e/T_o \quad \text{........................} \quad 1.11$$

where T_e is the equaivalent noise temperature of the network, and T_o is the standard noise temperature.

An excess noise ratio, ENR, can also be defined:

$$ENR = (T_e - T_o)/T_o = T_x/T_o \quad \text{..........} \quad 1.12$$

where T_x is the excess noise temperature.

Excess noise ratio is a measure of the noise produced by a one port network above the thermal noise contributed by its driving-point admittance.

Two-Port Noise-Equivalent Representations

Spot noise figure is a measure of the noise performance of two port networks. A definition of spot noise figure is the ratio of the noise power output of an actual two-port and its noise-free equivalent. Spot noise figure, at a specified frequency, has been defined by the IRE[3] as "the ratio of 1) the total noise power per unit bandwidth at a corresponding output frequency available at the output port when the noise temperature of the input termination is standard (290°K) to that of 1) engendered at the input frequency by the input termination. The standard noise temperature 290°K approximates the actual noise temperature of most terminations."

The important aspects of the previous definition should be pointed out. As defined, the spot noise figure is a point function of frequency. It is independent of output termination. The definition also states that the spot noise figure assumes that the input termination is at a physical temperature of 290°K.

When several networks are cascaded, each network contributes to the overall spot noise figure of the system according to [1]

$$F_{syst} = 1 + (F_1 - 1) + (F_2 - 1)/G_{A1} + (F_3 - 1)/G_{A1}G_{A2} + \cdots \qquad 1.13$$

where G_{A1}, G_{A2}, ... are available power gains of the individual stages, and F_1, F_2, ... are the spot noise figures of the individual stages. This expression holds for networks whether they amplify or attenuate.

The spot noise figure of an attenuating network at standard temperature is

$$F = 1/G_A \quad \text{.......................} \quad 1.14$$

where G_A is the available gain of the network.

Equation 1.13 demonstrates that if the first stage of the cascade has a high gain, and the second stage has a relatively low spot noise figure, the system spot noise figure becomes

$$F_{syst} \cong F_1 \quad \text{.....................} \quad 1.15$$

Thus, design of the first stage is an important consideration for optimizing the noise performance of a system. Equations 1.13 and 1.14 show that attenuation in the front end of any amplifying system must be avoided if a low spot noise figure is desired.

Often the noise properties of only the first stage in the system are wanted. If the equality in Equation 1.15 does not hold, the contribution to system spot noise figure due to the second-order terms in Equation 1.13 must be taken into account. These terms form the expression for what is called the background spot noise figure, F_{bkgd}, of the system:

$$F_{bkgd} = F_{syst} - F_1 \quad \text{.............} \quad 1.16$$

In most amplifier systems, the signal occupies a finite bandwidth, and the spot noise figure may vary with frequency over this bandwidth. This consideration has prompted an average noise figure to be defined, which takes into account the total noise power in the channel. The IRE defines average noise figure as[3] "the ratio of 1) the total noise power delivered into the output termination by the transducer when the noise temperature of the input termination is standard (290°K) at all frequencies to 2) that portion of 1) engendered by the input termination. For heterodyne systems, 2) includes only that portion of the noise from the input termination which appears in the output via the principle-frequency transformation of the system, and does not include spurious contributions such as those from an image-frequency transformation".

Spot noise figure can then be written as a power ratio:

$$F = (GkT_oB + N_n)/GkT_oB \quad \ldots\ldots\ldots\ldots\ldots \quad 1.17$$

where $G = \dfrac{\text{output power delivered into load}}{\text{power available at input}}$

kT_oB = available noise power from input termination

N_n = output noise power contributed by transducer

Average noise figure and spot noise figure can be related by[3]

$$\bar{F} = \int F(f)G(f)\,df \Big/ \int G(f)\,df \quad \ldots\ldots\ldots\ldots \quad 1.18$$

where $\bar{F}$ = average noise figure

$F(f)$ = spot noise figure

$G(f)$ = transducer gain

If F(f) and G(f) are assumed constant over the measurement bandwidth, the average noise figure equals the spot noise figure. These conditions can be achieved by making the measurement bandwidth very narrow compared to the bandwidth of F(f) and G(f). With this in mind, it will be assumed that noise figure measurements designate spot noise figure, even though in actuality an average noise figure is being measured.

CHAPTER II

NOISE IN JUNCTION FETS

The measurement techniques developed in Chapter three were tested experimentally by examining the noise parameters of a junction FET (JFET). A brief outline of the JFET noise model will be given herein.

Two-Port Representation of JFET Properties

In order to describe its behavior, the JFET must be considered as a linear two port having small signal voltages and currents as variables.

The admittance or y-parameters provide a useful characterization of two-ports at UHF. Figure 2.1 shows a linear network receiving a signal I_s from a generator with output admittance Y_s, and delivering it to a load Y_L.

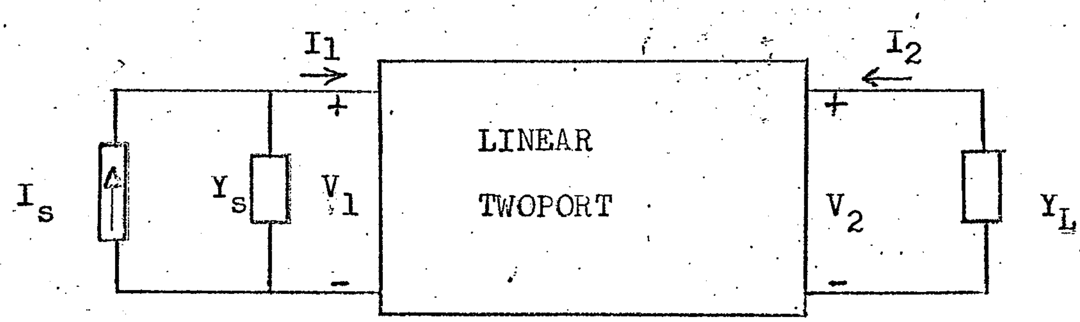


Figure 2.1 Two-port admittance representation of a network

The relationship between input and output variables is given by

$$I_1 = y_{11}V_1 + y_{12}V_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 2.1$$

$$I_2 = y_{21}V_1 + y_{22}V_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 2.2$$

The coefficients, or y parameters, are in general dependent on biasing and operating frequency.

The JFET, with its internal noise sources, can be considered as a linear noisy two-port network. The noise behavior within a narrow bandwidth B can be represented by two external noise generators connected to the network terminals, leaving the linear two-port noise free.[4] In general, the two noise generators are partially correlated with one another. One convenient way of describing JFET noise behavior is by lumping all noise contributions from within the device at the terminals as shown in Figure 2.2.[5]

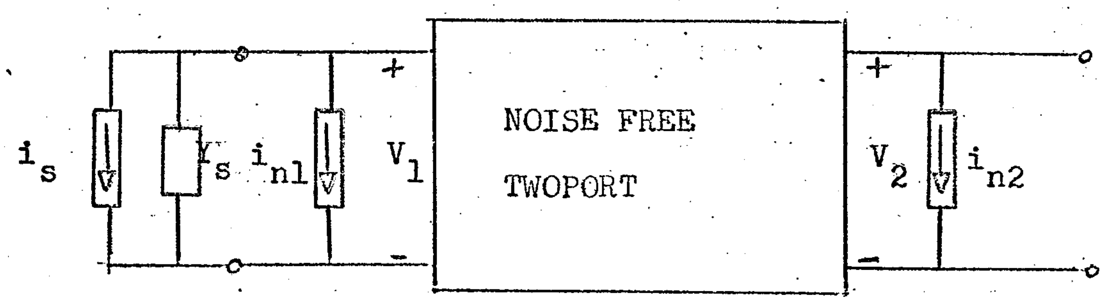


Figure 2.2 Representation of a noisy two-port connected to a signal source

The signal source with internal admittance is

$$Y_s = G_s + jB_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.3$$

connected to the input of the two port. The thermal noise of the signal generator is represented by the noise current generator i_s of mean-squared value

$$\overline{i_s^2} = 4kT_oG_sB \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.4$$

where T_o is standard temperature (290^oK). This noise generator is assumed to be uncorrelated with any noise generator of the noisy two-port.

Figure 2.2 can now be used for the determination of noise figure. The total noise power delivered to the output termination of a two port is proportional to the short-circuit mean-squared noise current of the output terminals. The noise power delivered to the output termination from any noise source in the network is proportional to the contribution made by that source to the output short-circuit current. The noise figure of the network in Figure 2.2, referring to Equation 1.17 then becomes[6]

$$F = 1 + \frac{1}{\overline{i_s^2}} \overline{\left| -i_{n1} + \frac{i_{n2}}{y_{21}} (Y_s + y_{11}) \right|^2} \quad \ldots \quad 2.5$$

where y_{11} and y_{21} are admittance parameters of the two port.

The noise current i_{n1} can be separated into two components, i_{n1}' and i_{n1}'', where the noise current i_{n1}' is perfectly correlated with i_{n2}, and i_{n1}'' is completely uncorrelated with i_{n2}. Therefore:

$$i_{n1} = i_{n1}' + i_{n1}'' \qquad \text{or}$$

$$\overline{i_{n1}^2} = \overline{i_{n1}'^2} + \overline{i_{n1}''^2} \quad \ldots\ldots\ldots\ldots\ldots \quad 2.6$$

A correlation admittance is defined, where

$$y_{cor} = g_{cor} + jb_{cor} = y_{21}i_{n1}'/i_{n2} \quad .. \quad 2.7$$

The correlated current generator i_{n1}'' is expressed in terms of an equivalent noise conductance g_n with the property

$$\overline{i_{n1}''^2} = 4kT_o g_n B \quad .... \quad 2.8$$

The output current generator i_{n2}, when transformed to the input terminals as an equivalent noise resistance R_n, has the value

$$\overline{i_{n2}^2} = 4kT_o R_n \left| y_{21} \right|^2 \quad .... \quad 2.9$$

From Equations 2.4 to 2.9, the noise figure of the network in Figure 2.2 can be re-written in the following form:

$$F = 1 + \frac{g_n}{G_s} + \frac{R_n}{G_s} \left| Y_s + y_{11} + y_{cor} \right|^2$$

$$= 1 + \frac{g_n}{G_s} + \frac{R_n}{G_s} \left[(G_s + g_{11} + g_{cor})^2 + (B_s + b_{11} + b_{cor})^2 \right] \quad .... \quad 2.10$$

The noise figure of the noisy two port can then be expressed as a function of four noise parameters: g_n, R_n, g_{cor}, and b_{cor}. In general, these quantities are a function of frequency and bias and do not depend on external circuitry.

<u>JFET Small Signal High Frequency Model</u>

Figure 2.3 shows an equivalent small signal model of an intrinsic JFET operated in the region beyond drain

pinch-off[7,8].

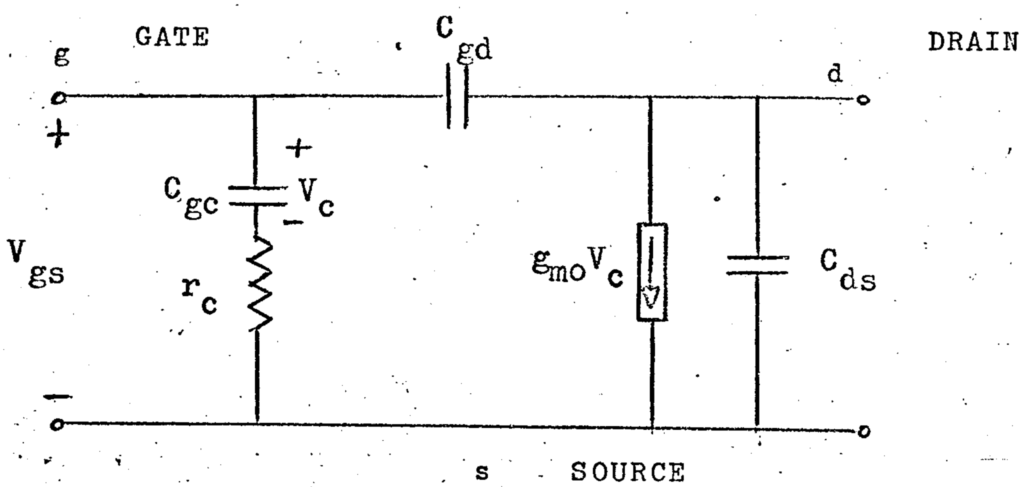


Figure 2.3 Small-signal model of intrinsic JFET

The series capacitor-resistor combination from gate to source is a lumped-element approximation of the distributed network formed between the gate and the active channel. C_{gc} is the capacitance of the space charge diode of the reverse-biased gate-to-channel diode. The resistance r_c is the effective resistance of the channel.

The intrinsic transconductance generator $g_{mo}V_c$ is controlled by the voltage across C_{gc}. This transconductance remains essentially constant with frequency; the high frequency performance being a function of the time constant r_cC_{gc}.

The capacitances C_{gd} and C_{ds} represent the intrinsic capacitances of the gate-drain and drain-source terminals, respectively.

Figure 2.4 shows a model of a physical UHF-JFET operating in the pinch-off region[9]. This model is useful well into the UHF region, until the lumped-element approximations are no longer valid and the lead inductance must be taken into account.

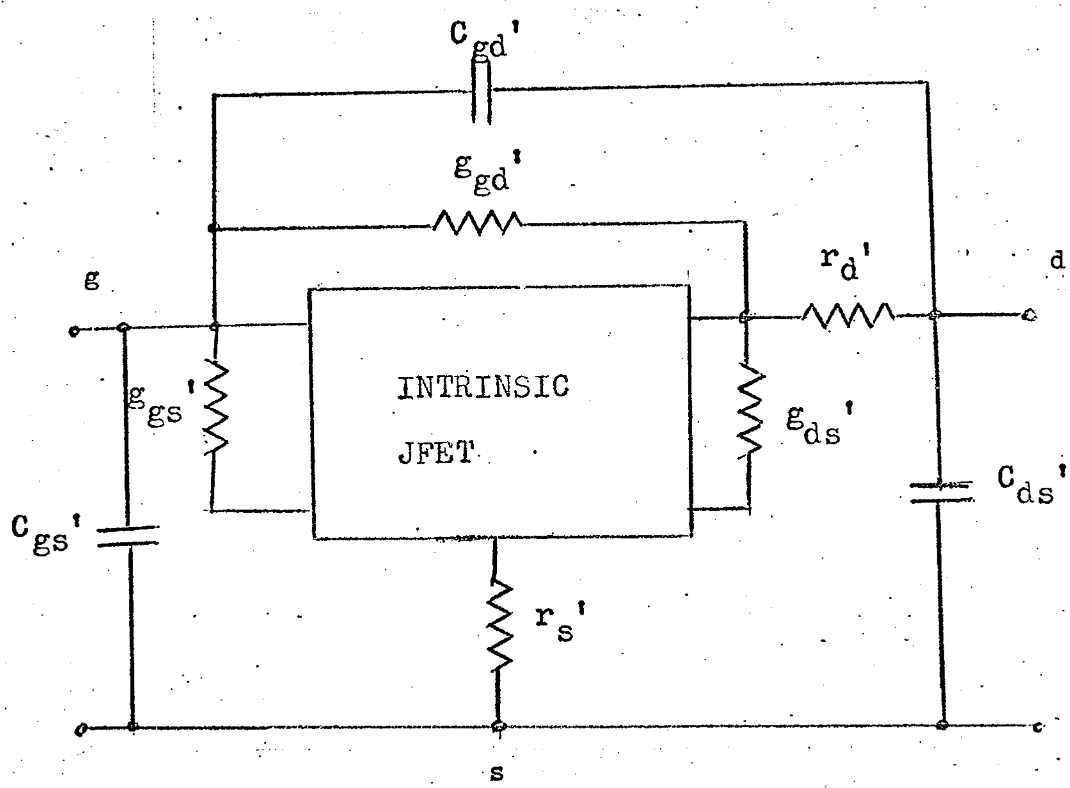


Figure 2.4 Practical JFET small-signal equivalent circuit for UHF

The conductance g_{ds}', which is very small for a good device, represents the dynamic output conductance of the JFET.

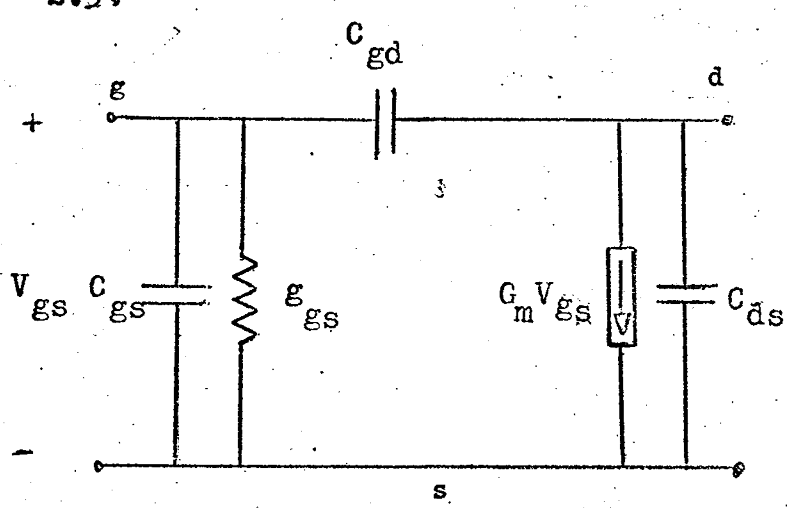
The conductances g_{gs}' and g_{gd}' represent the reverse-biased diodes between the gate and the drain, and also between the gate and the source.

Since the gate contacts of the JFET do not cover the entire channel, the series resistances r_s' and r_d' at the channel ends must be taken into account. The capacitances C_{gd}', C_{gs}', and C_{ds}' include the effects of the case and inter-lead capacitances between the terminals of the device.

<u>JFET Noise Model at UHF</u>

At frequencies above the audio spectrum, thermal noise is the dominant noise in the JFET. Shot noise appears as a second-order effect due to a reverse leakage current in the gate-channel diode. Since this current is very small, the shot noise is usually negligible.

The equivalent circuit for the intrinsic JFET operating in the pinch-off region, and shown in Figure 2.3, can be transformed into the representation shown in Figure 2.5.



$$g_{gs} = \frac{r_c \omega^2 C_{gc}}{1 + (\omega/\omega_o)^2}$$

$$C_{gs} = C_{gc} \frac{\omega}{1 + (\omega/\omega_o)^2}$$

$$G_m = g_{mo} / (1 + j\frac{\omega}{\omega_o})$$

$$\omega_o = 1 / r_c C_{gc}$$

Figure 2.5 A small-signal model of the intrinsic JFET

The noise model of the intrinsic JFET contains two noise sources, both of thermal origin. The dominant one is the source representing the noise of the channel conductance. This noise is represented by a current generator i_d, paralleling the drain-source terminals,[10] where

$$\overline{i_d{}^2} = 4kT_o a g_{mo} B \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 2.11$$

The constant (a) is a function of the biasing parameters of the device. In the pinch-off region, $.6 < a < .7$. The transconductance g_{mo} is the low frequency value. This channel noise generator is independent of frequency.

At high frequencies, the input conductance, g_{gs}, must be taken into account in the noise model. The input conductance exhibts almost full thermal noise and its effect may be represented by a current generator

$$\overline{i_g{}^2} = 4kT_o g_{gs} B \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.12$$

paralleling the gate-source terminals[11]. In fact, the input conductance gives rise to exactly full thermal noise if the gate-source junction is biased at 0 volts.[8]

These two noise generators, i_g and i_d, can now be added to the small signal model resulting in a noise model as shown in Figure 2.6.

The resistance r_c, from the equivalent model in Figure 2.3, is physically part of the channel. Thus the noise sources, i_d and i_g, can be expected to be partially correlated since noise fluctuations in the channel are coupled both to the gate and the drain. The result of this correlation is an ultimate decrease in the noise figure of the device. For the JFET, correlation decreases

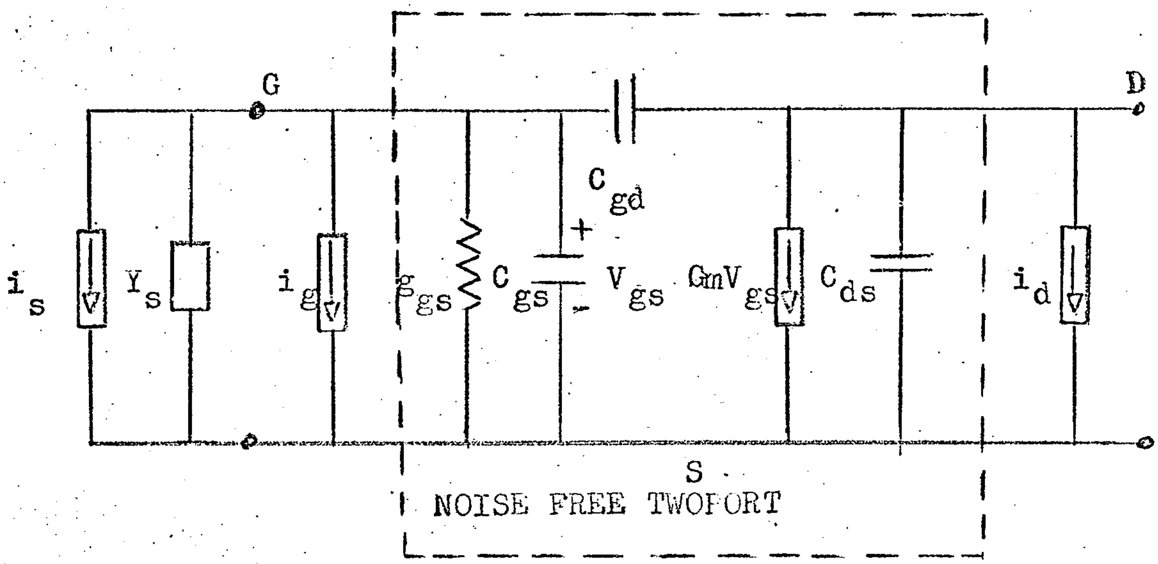


Figure 2.6 Intrinsic noise model of JFET in common-source configuration

noise figure by a factor of less than twenty percent[12] for all frequencies when the device behaves as the amplifier. Thus, it is a reasonable approximation to neglect the effect of correlation.

If correlation is neglected, a very simple expression results for the noise figure of the JFET. From Equations 2.10 to 2.12,

$$F = 1 + \frac{g_{gs}}{g_s} + \frac{R_{ns}}{g_s} \left| Y_s + y_{11s} \right|^2 \quad \ldots\ldots\ldots \quad 2.13$$

where $R_{ns} = ag_{mo} / \left| y_{21s} \right|^2$ 2.14

and y_{11s} and y_{21s} are admittance parameters of the common-source configuration.

In addition to the noise sources in the intrinsic JFET, thermal noise sources exist due to the parasitic resistances and conductances of the physical JFET. Lossy parasitic elements tend to increase the noise figure of a practical device. Parasitic susceptances, because they are loss-free, will not change the minimum obtainable noise figure at any one frequency.

Usually, parasitic elements have little effect on noise figure.[10] Also the effects of correlation and lossy parasitic elements tend to cancel the effect of one another. Correlation decreases noise figure and the parasitics increase it. Therefore Equation 2.13 can be expected to give reasonably accurate results for noise figure over a wide range of frequencies for the physical JFET in the common-source mode.

For JFET use at UHF, common-gate operation is preferred for presently available devices.[13] Common-gate operation allows reasonable power gains to be obtained in amplifier circuits. This configuration is unconditionally stable at all frequencies.

From the model of Figure 2.7, the following noise figure expression can be deduced[6]

$$F = 1 + \frac{1}{i_s^2} \overline{\left| -i_g + \frac{i_d}{y_{21g}} (Y_s + y_{11g} + y_{21g}) \right|^2} \quad .. \quad 2.15$$

where y_{11g}, y_{21g} are common-gate admittance parameters.

Neglecting correlation and parasitics, the noise figure for the JFET becomes

$$F \cong 1 + \frac{g_{gs}}{G_s} + \frac{R_{ng}}{G_s} \left| Y_s + y_{11g} + y_{21g} \right|^2 \quad ...... \quad 2.16$$

where $R_{ng} = ag_{mo} / \left| y_{21g} \right|^2$ 2.17

referring to the arguments for the common-source mode.

It should be noted that

$$y_{11g} + y_{21g} = y_{11s} + y_{12s} = g_{gs} + j \; C_{gs} \quad ... \quad 2.18$$

Comparing Equation 2.16 with Equation 2.13, it follows that there is little difference in noise figures of these two configurations (common-gate and common-source).

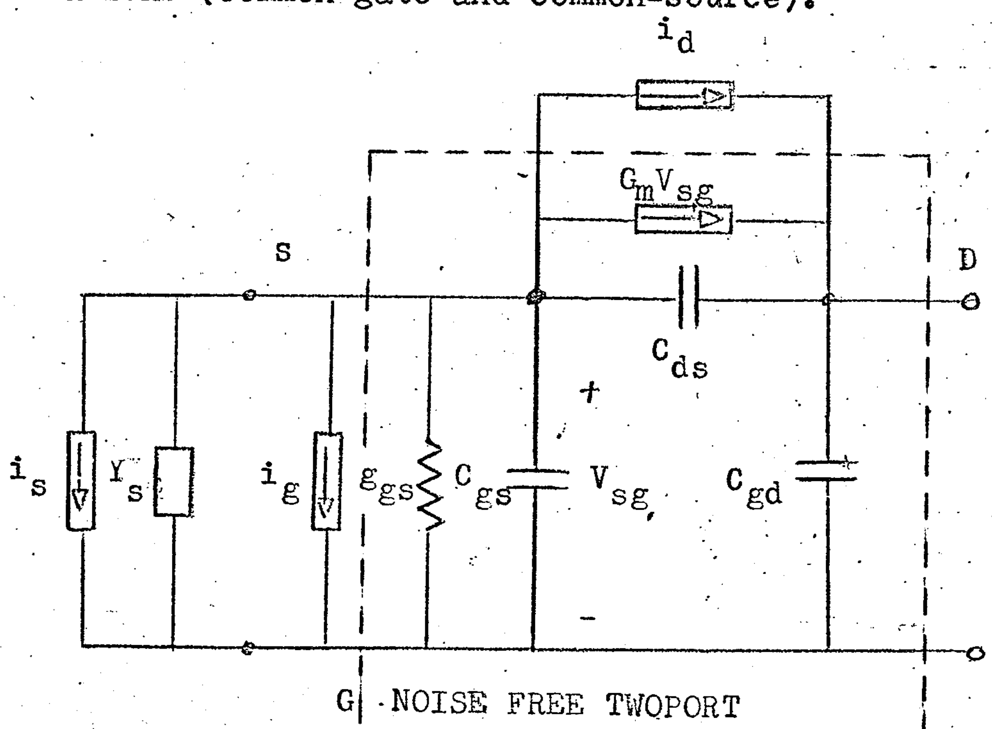


Figure 2.7 Intrinsic noise model of JFET in common-gate configuration (derived from Figure 2.6)

Excess Noise Ratio Relations - Common-Gate Mode

The excess noise ratio of the output of the JFET in the common-gate configuration may be determined for a variety of input terminations. Interesting results may be obtained for a short circuit input termination.

From the Figures 2.4 and 2.7, the following noise model may be drawn, assuming that the lossy parasitics r_s and r_d are very small.

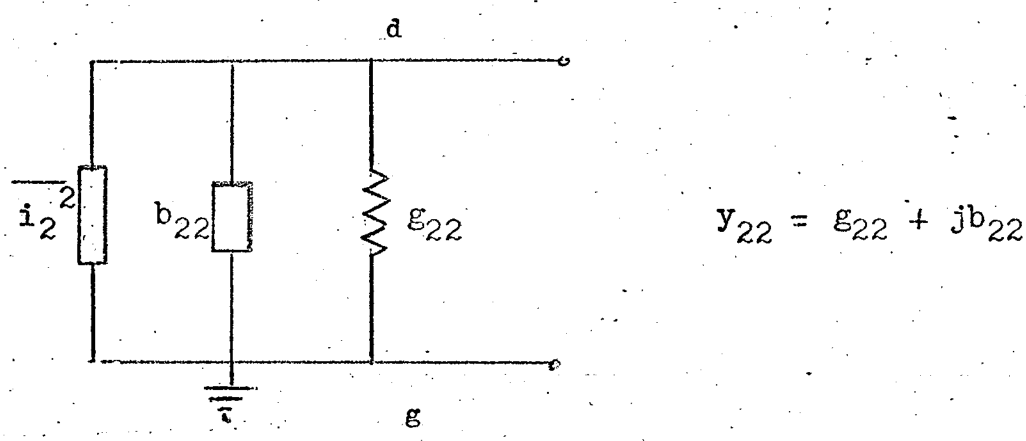


Figure 2.8 A simplified UHF noise model of JFET device with gate-source terminals short-circuited

This time the thermal noise of the parasitic elements, represented by y_{22}, cannot be neglected. Therefore the noise generator $\overline{i_2^2}$ will take into account both the channel noise and the noise from the lossy parasitic elements:

$$\overline{i_2^2} = \overline{i_d^2} + \overline{i_p^2} = 4kT_o a g_{mo} B + 4kT_o g_{22} B \quad \ldots\ldots \quad 2.19$$

When the gate-source junction of the JFET is reverse-biased, the transconductance g_{mo} approaches zero but to a good approximation y_{22} of Figure 2.8 does not change. With the device on the output, the noise power available from the JFET is

$$N_A = \frac{4kT_o a g_{mo} B + 4kT_o g_{22} B}{4g_{22}}$$

$$= (kT_o a g_{mo}/g_{22}) + kT_o B \quad \ldots\ldots\ldots\ldots \quad 2.20$$

The thermal noise power available from the passive termination is kT_oB. The noise ratio from the definition in Equation 1.10 becomes

$$N_R = N_A/kT_oB = (a g_{mo}/g_{22}) + 1 \quad \ldots\ldots\ldots\ldots \quad 2.21$$

From Equation 1.12, the excess noise ratio for the short-circuited input is

$$ENR = a g_{mo}/g_{22} \quad \ldots\ldots\ldots\ldots \quad 2.22$$

Since both g_{mo} and g_{22} are directly measurable, the constant (a) can be obtained directly from experimentally determining the excess noise ratio.

CHAPTER III

NOISE MEASUREMENT TECHNIQUES

Traditionally, noise figure measurements have been used to evaluate noise performance of devices at UHF. Noise figure is an integral measure, expressing the combined effect of all noise sources in the device. It does not, however, permit isolation of a particular source.

Measurement of Noise Figure at UHF

There are many methods of measuring the noise figure of a system[1,2,3]. A noise generator method, commonly called the Y-factor method, is the simplest and most often used. The simplicity of this method can be attributed to the fact that it can be adapted for automatic noise figure measurement, allowing system noise figure to be displayed directly on an indicating instrument.

The Y-factor method[14] requires a noise source with two output noise power levels. The ratio of these two output noise powers must be accurately known. A vacuum reference diode is used for frequencies below five hundred megahertz. The upper frequency limit of a particular diode is determined by its anode-to-cathode capacitance and the transit time in the anode- cathode region.

This type of noise source generates a large amount of excess noise power above the thermal noise of its termination in the "on" condition. The noise source is then said to have an effective noise temperature, T_D. In the "off" condition, just thermal noise from the output termination is generated. The termination is assumed to be at standard temperature.

The system noise figure is determined by connecting the input of the system to the "off" source and then to the "on" source at its elevated effective noise temperature. The ratio of the output noise powers is then measured. This ratio is called the Y-factor.

In the "off" case, the output noise power is, referring to Equation 1.17,

$$N_1 = GkT_oB + N_n \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 3.1$$

It is

$$N_2 = GkT_DB + N_n \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 3.2$$

in the "on" condition, where N_n is the output noise power contributed by the system. The Y-factor is thus

$$Y = \frac{N_2}{N_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 3.3$$

By rearranging Equations 1.17, and 3.1 to 3.3, the noise figure reduces to the following form:

$$F = \frac{(T_D - T_o)/T_o}{Y - 1} \quad \ldots\ldots\ldots\ldots\ldots \quad 3.4$$

where $(T_D - T_o)/T_o$ is the excess noise ratio of the noise source. The numerator is a known parameter of the noise source. The denominator is a function of the Y-factor. System gain and bandwidth do not appear in the noise figure expression.

The determination of noise figure involves the measurement of the ratio of two output powers, under the condition that the ratio of the input powers is known. It is then possible for noise figure to be displayed automatically and continuously on an indicating instrument known as an automatic noise figure meter.

To measure the noise figure of a system the automatic noise figure meter[14] is connected as indicated in Figure 3.1.

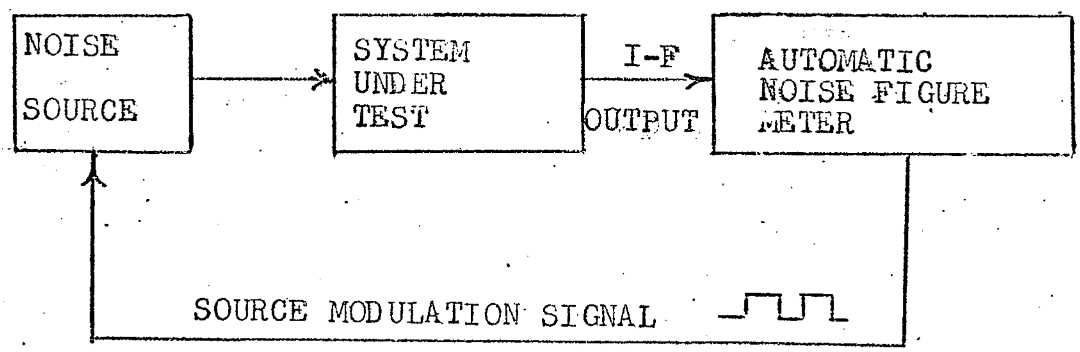


Figure 3.1 Equipment arrangement for automatic noise figure metering

The automatic noise figure meter switches the noise source "on" and "off" so that the output consists of noise pulses. A pulse of excess noise alternates with a pulse at the thermal level of the noise source termination.

The output of the system is applied to the automatic noise figure meter at an intermediate frequency. The "on" pulses of the output are amplified to a constant level in the meter by a gated automatic gain control action. The resulting signal is square-law detected, the detected signal being related to the Y-factor of the system. Since the excess noise ratio of the noise generator is known, the instrument can be calibrated directly in noise figure using Equation 3.4.

The continuous display of noise figure makes the meter a useful instrument for optimizing the noise performance of systems for minimum noise figure. Also, since the "on" and "off" measurements are taken quite frequently, the effect of system gain variation between measurements is minimized.

If the indicated measurement is to be equal to the system spot noise figure, the following precautions must be made. As mentioned previously in Chapter I, the bandwidth of the measuring instrument must be small compared to the bandwidth of the noise contributed by the input termination and the noise contributed by the system.

If the temperature of the input termination is different from the standard temperature of $290^{\circ}K$, a correction factor must be applied to the measured noise figure, in accordance with the noise figure definition.[14]

All expressions derived for noise figure have assumed linearity of the entire system. For low noise systems, the Y-factor is large and the system must have a wide dynamic range.[14] The required dynamic range can be decreased by using a noise generator with a lower excess noise ratio. The excess noise of the noise generator can be decreased by the insertion loss factor of a matched attenuator placed after the noise generator.

Measurement of Noise Figure with Succeeding-Stage Noise Compensation

Often in the laboratory or on the production line, it is desirable to measure the noise figure of a single device rather than of the entire system, including the noise figure meter. The system noise figure will be equal to the device figure if the following conditions, dictated by Equation 1.13, are met. The device must have a high available gain, and the second stage succeeding the device a low noise figure. At UHF, however, these conditions are not always met, and an appreciable background contribution is part of the measured system noise figure.

It is possible to compensate for this background noise contribution by a modification of the conventional automatic noise figure meter. Then only the noise figure of the first stage is measured, with the convenience of automatic noise figure metering still applying.

The equipment setup for the measurement of noise figure with background noise compensation is indicated in block form in Figure 3.2.

In the usual measuring procedure (by modulating the standard noise source), the automatic noise figure meter indicates the noise figure of the entire measuring system. However, by modulating the device appearing as the first stage,

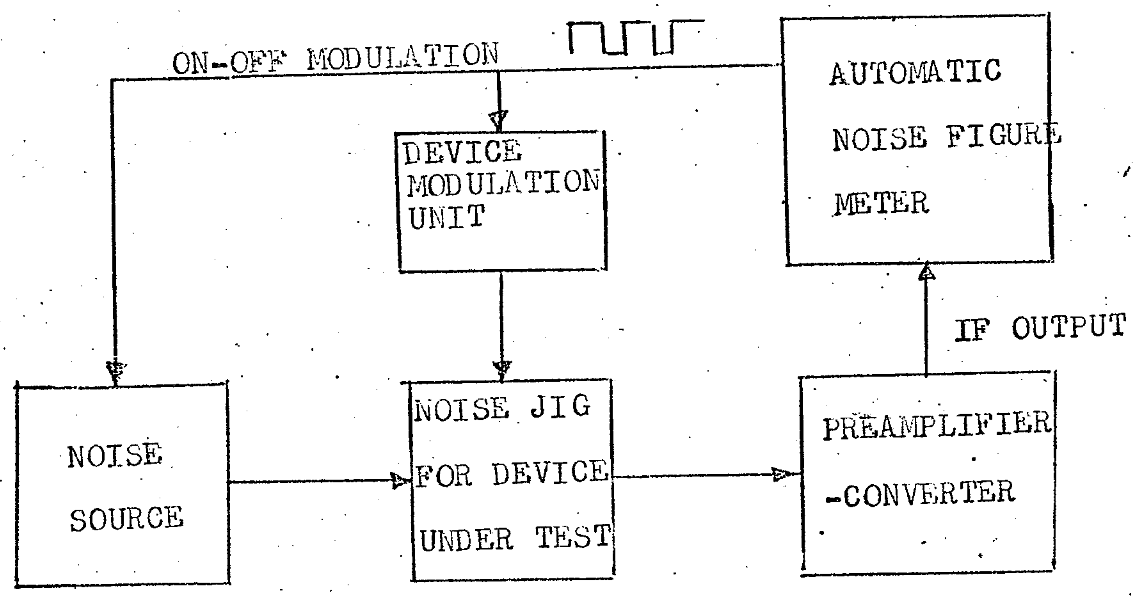


Figure 3.2 Equipment arrangement for compensating noise figure readings of background noise

it is possible to compensate for the background noise of the stage following the device under test.

To compensate accurately for the background noise, some stipulations must be put on the device to be measured. The device when modulated "off" must have a very low forward gain. Ideally, there should be no forward transmission. This insures that the device when "off" presents a passive termination to the second stage of the system, because all excess noise sources will have been shut off. Output admittance must remain constant as the device is modulated "on" and "off". If not, the background noise of the following stages, as well as the transmission of power from the first stage to the proceeding ones, will be affected.

Many devices such as FET's, bipolar transistors, and pentodes, where the quiescent operating point lies in the saturated region of the device characteristic, obey the above conditions. They all exhibit a low forward power gain and a negligible change in output admittance when their control junctions are reverse-biased.

The modulation signal for the device is a square-wave voltage which is synchronized to the noise source modulation. This signal, applied to the control junction of the device, switches the device between a normal operating condition ("on") and a current cut-off condition ("off"). All other biasing potentials must not be disturbed.

The measurement procedure with compensation consists of taking two noise figure readings while the device is being modulated: one with the noise source "off" and the other with the noise source modulated synchronously with the device. The former noise figure reading is termed F_{10}, the latter is called F_{20}.

The noise figure readings F_{10} and F_{20} by themselves have little significance. They merely represent power ratios that are displayed as noise figures on the noise figure meter.

From Equation 3.4 F_{10} is given by

$$F_{10} = ENR/(Y_{10}-1) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 3.5$$

where ENR is the excess noise ratio of the standard noise source, and

$$Y_{10} = \frac{\text{output noise power, noise source "off", device "on"}}{\text{output noise power, noise source "off", device "off"}}$$

$$= M_1/M_o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 3.6$$

M_o represents the noise power delivered to the output when the device is biased "off", and is termed the background noise of the system. M_1 is the noise power measured with the noise source "off" and the device "on":

$$M_1 = GkT_oB + N_A + M_O \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 3.7$$

where N_A = output noise power due to sources within the device, where

$$G = \frac{\text{output noise power engendered by input termination}}{\text{available noise power from the input termination}} \quad 3.8$$

By substituting Equation 3.6 into 3.5

$$F_{10} = ENR\ M_o/(N_A + GkT_oB) \quad \ldots\ldots\ldots\ldots \quad 3.9$$

The second noise figure reading, F_{20}, is defined as:

$$F_{20} = ENR/(Y_{20}-1) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 3.10$$

where

$$Y_{20} = \frac{\text{output noise power, noise source "on", device "on"}}{\text{output noise power, noise source "off", device "off"}}$$

$$= M_2/M_o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 3.11$$

$$M_2 = GkT_DB + N_A + M_0 \quad \ldots\ldots\ldots\ldots\ldots \quad 3.12$$

where GkT_DB is the output noise power engendered by input termination with the noise source "on".

Substituting Equation 3.12 into 3.10:

$$F_{20} = ENR\ M_0/(GkT_DB + N_A) \quad \ldots\ldots\ldots \quad 3.13$$

Taking the ratio F_{10}/F_{20},

$$\frac{F_{10}}{F_{20}} = \frac{GkT_DB + N_A}{GkT_oB + N_A} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 3.14$$

it is seen that ENR and the background noise power cancel. If F_{10}/F_{20} is treated as a Y-factor and then substituted into Equation 3.4, the result is:

$$\left[\frac{T_D - T_o}{T_o}\right] \frac{N_A + GkT_oB}{Gk(T_D-T_o)B} = \frac{N_A + GkT_oB}{GkT_oB} = F_1 \quad \ldots \quad 3.15$$

This expression, comparing it with Equation 1.17 is the noise figure of the first stage (since $ENR = (T_D-T_o)/T_o$). This is the desired result.

The above method of compensating for background noise is convenient since it utilizes, in the main part, commercially available and accurate noise measuring apparatus. The compensation for background noise includes a calculation step in the procedure, which makes the method semi-automatic. It would be possible though, with additional circuitry, to convert the presently available automatic noise figure meters to display noise figure, F_1, automatically and continuously.

From a search of the literature, a synchronous detection system has been used to effect a compensation for background noise.[15] This system is identical in concept to the method proposed above but has two disadvantages. It does not use readily available noise measuring apparatus such as the automatic noise figure meter. Also a calibration curve of the detection device must be made.

Measurement of Excess Noise Ratio with Succeeding-Stage Noise Compensation

A more fundamental noise parameter than noise figure is excess noise ratio. It is a measure of the amount of noise power above thermal level that can be delivered from two terminals of a device. By comparison of one port of a device against a noise source with a known excess noise ratio it is possible to determine the excess noise ratio of the device in question.

If the measuring system has negligible background noise, the measuring procedure would be straight-forward. For UHF measuring systems, noise from the system is usually appreciable, and the background contribution must be considered. By shutting "off" the excess noise of the device to be tested, a procedure involving the basic automatic noise figure meter can be used to determine the device excess noise ratio.

Principle of Operation

A block diagram of the equipment used for the excess noise ratio measurement with background compensation is shown in Figure 3.3.

The device and the noise source are coupled to the preamplifier by a three-port directional coupler. To compensate for background noise from the preamplifier stage and onwards, the device to be tested must be able to have its excess noise source extinguished. This is accomplished by biasing the active device "off". It is important that the driving point admittance of the device remain a constant value in both the "on" and "off" states.

The three-port directional coupler has reflectionless conditions at all ports. All transforming networks are assumed to be lossless. This assures that both the device and the standard noise source will supply their available noise power into the directional coupler. The available power from the noise source is isolated from the preamplifier by the coupling factor, C, of the directional coupler. The coupling factor is -10 to -20 dB. The available device noise power is attenuated from the preamplifier by the insertion gain, A; typically -.1 to -.5 dB.

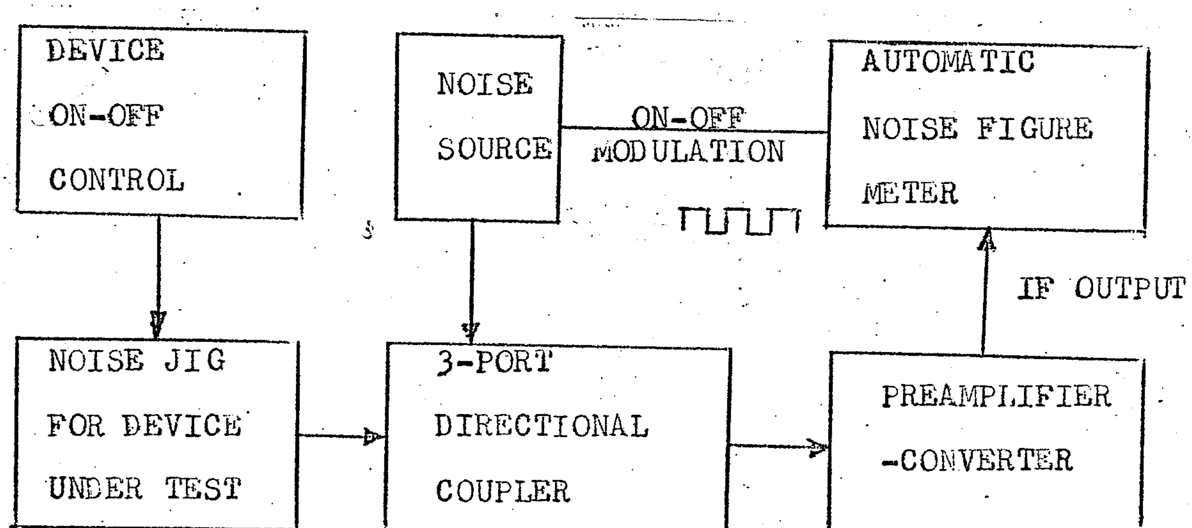


Figure 3.3 Equipment arrangement for using the automatic noise figure meter

It is advantageous to use a directional coupler as a power combiner rather than a simple "tee" network, the reason being that tuning the system for a conjugate match on both arms of the "tee" would be difficult since each arm would interact with one another. The directional coupler provides isolation between the noise source and the device, making interaction negligible. The penalty paid, though, is a decrease in the effective excess noise ratio of the noise source by the coupling factor of the directional coupler.

The measurement technique consists of taking two normal system noise figure readings with the automatic noise figure meter (F_f and F_n). One reading is with the device turned "off" (F_f); the other is with the device in its normal "on" state (F_n). The difference of these two readings is shown to be proportional to the excess noise ratio of the device.

From Equation 3.4, F_f is defined as:

$$F_f = ENR/(Y_f - 1) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 3.16$$

where ENR is the excess noise ratio of the standard noise generator, and

$$Y_f = \frac{\text{output noise power; device "off", noise source "on"}}{\text{output noise power; device "off", noise source "off"}}$$

$$= N_2/N_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 3.17$$

N_0 represents the background noise of the measuring system consisting of noise from the preamplifier and following networks, plus the thermal noise from the input termination of the preamplifier. N_2 consists of the background noise plus the excess noise of the standard noise source.

$$N_2 = CG_T kT_{xs}B + N_0 \quad \text{.................} \quad 3.18$$

where C is the coupling factor of the directional coupler, G_T is the transducer gain of system from the output of the directional coupler, and $kT_{xs}B$ is the excess available noise power from the standard noise source.

Substituting Equation 3.18 into 3.16,

$$F_f = \text{EMR } N_0/CG_T kT_{xs}B = N_0/CG_T kT_oB \quad \text{..........} \quad 3.19$$

The noise figure reading, F_n, is defined:

$$F_n = \text{ENR}/(Y_n - 1) \quad \text{..................} \quad 3.20$$

where

$$Y_n = \frac{\text{output noise power; device "on" noise source "on"}}{\text{output noise power; device "on", noise source "off"}}$$

$$= M_3/M_1 \quad \text{..} \quad 3.21$$

$$M_1 = AG_T kT_{xx}B + N_0 \quad \text{................} \quad 3.22$$

and

$$M_3 = AG_T kT_{xx}B + CG_T kT_{xs}B + N_0 \quad \text{...........} \quad 3.23$$

where A is the insertion gain of directional coupler, T_{xx} is the excess noise temperature of device, and $kT_{xx}B$ is the excess available noise power from the device. Substituting Equations 3.23 and 3.22 into Equation 3.20, the result is:

$$F_n = \text{ENR}(AG_T kT_{xx}B + N_0)/CG_T kT_{xs}B$$

$$= (AG_T kT_{xx}B + N_0)/CG_T kT_oB \quad \text{...............} \quad 3.24$$

Subtracting the two noise figures from Equations 3.24 and 3.19,

$$F_n - F_f = (A/C)\, T_{xx}/T_o \quad \text{.............} \quad 3.25$$

The ratio T_{xx}/T_o is the excess noise ratio of the device (ENR_x) so that

$$ENR_x = (C/A)\,(F_n - F_f) \qquad \text{3.26}$$

CHAPTER IV

EXPERIMENTAL VERIFICATION

Experimental Arrangement

Small Signal

The two-port common-gate admittance parameters of a Texas Instrument 2N3823 n-channel JFET were measured using a General Radio Company Transfer-Function and Immittance Bridge, Type 1607-A. This bridge has a frequency range of 25 - 1500 MHz and has provisions for DC biasing. These small signal measurements determine the value of the elements which appear in the noise model.

Device Noise Figure

It was desired to measure the noise figure of the JFET as a function of source admittance at an ultra-high frequency. The device noise figure measuring apparatus is shown in Figure 4.1

The noise generator is a General Microwave Corporation Model 504 Diode Noise Generator designed to operate with the General Microwave Corporation Model 551A Automatic Noise Figure Meter. The noise generator has a useful frequency range up to five hundred Megahertz, and maintains an excess noise ratio of 15.2 dB.

The GMC 551A is an automatic noise figure indicator, which also powers the 504. The 551A operates

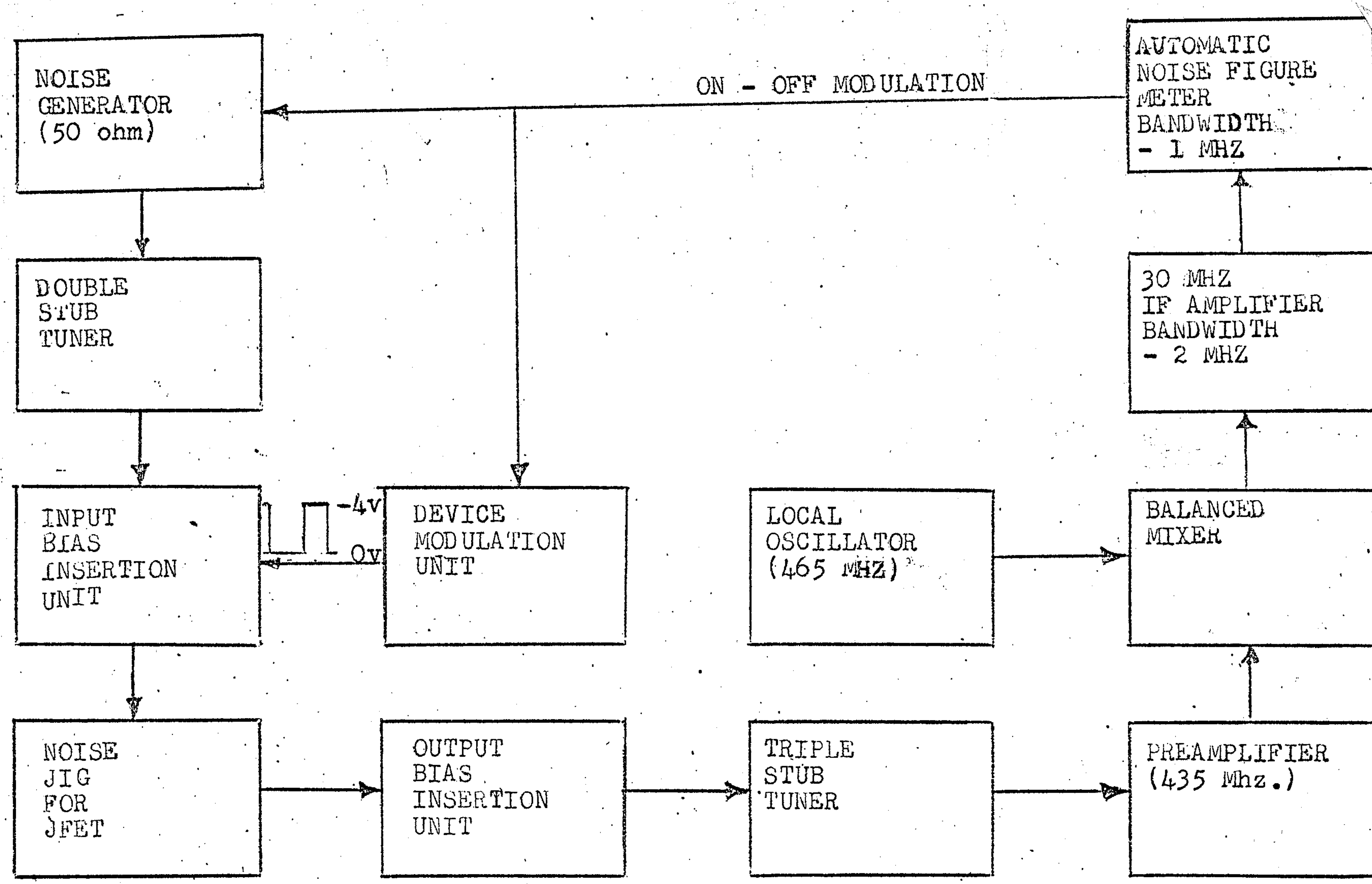


Figure 4.1 Block diagram of noise figure measurement with background compensation

using the Y-factor method of determining system noise figure. The noise jig is a General Radio Type 1607-P44 Transistor Mount. The mount allows the transistor to be connected by coaxial lines to the transistor header. General Radio Company Type 874-FBL Bias Insertion Units bias the devices installed in the coaxial-line system.

A double-stub tuner transforms the 20 millimho admittance of the noise generator to the desired admittance required by the input port of the device. This admittance is measured with the General Radio Company Immitance Bridge, Type 1607-A. A triple-stub tuner matches the output of the JFET to the input of the 435 MHz preamplifier.

The preamplifier is a one-stage tuned-output bipolar transistor amplifier with a center frequency of 435 MHz. The high frequency transistor used is operated in the common-base mode. The preamplifier feeds a balanced mixer which down-converts the signal to an intermediate frequency of 30 MHz. An Airborne Instruments Laboratory Type 132 adjustable-gain intermediate-frequency amplifier raises the converted signal to a level acceptable for the automatic noise figure meter.

The device modulation unit is a multivibrator circuit that is triggered by the "on"-"off" modulation of the noise diode. It delivers a square-wave switching waveform, 0 volt to -4 volt, to the gate-source junction of the JFET.

Precautions have to be taken to ensure that the image of the measurement frequency does not contribute to the preamplifier input. The image frequency was found to be 35 dB below the frequency of measurement, making the image-response negligible.

Device Excess Noise Ratio

It was desired to measure the excess noise ratio of the 2N3823 JFET at the same frequency (435 MHz) as the noise figure measurements. The device excess noise ratio measuring apparatus is shown in Figure 4.2.

The device and the diode noise generator are coupled to the measuring system by a 10 dB directional coupler. The device is matched conjugately to the directional coupler by a double-stub tuner. The input port of the device is connected to a known termination, which is a sliding transmission line short adjusted for half the wave-length condition. Thus the input port "sees" a short circuit.

The device "on" condition is achieved by shorting the terminals of the input bias insertion unit so that the device is operated with maximum gain. The "off" condition is produced by reverse-biasing the device with a -4 volt potential from gate to source.

The directional coupler is matched conjugately to the preamplifier. A 10 dB attenuator is inserted ahead of the directional coupler to make the gains of the device channel and the noise source channel approximately equal.

The setup from the preamplifier onwards is identical to the noise figure measuring apparatus in the

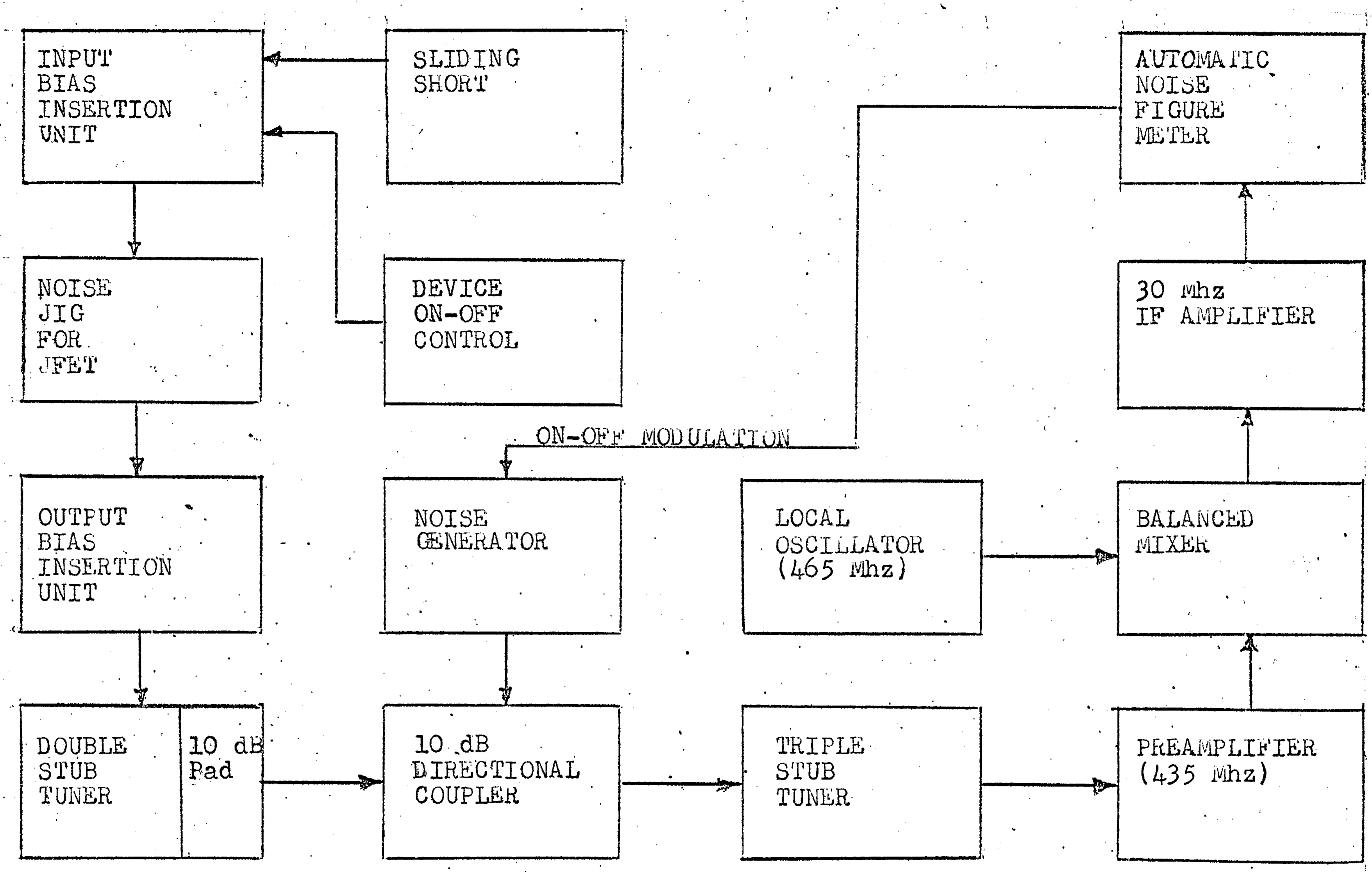


Figure 4.2 Block diagram of excess noise ratio measurement with background noise compensation

previous section.

The excess noise ratio was measured between the drain-source terminals in the device's pinch-off region.

Experimental Results

Small Signal

The admittance parameters of the 2N3823 measured at 435 MHz with drain-source voltage, 15 volts and gate-source voltage, 0 volts are:

$$y_{11g} = g_{11g} + jb_{11g} = 5.9 + j7.5 \text{ mmho}$$

$$y_{12g} = g_{12g} + jb_{12g} = -.04 - j.03 \text{ mmho}$$

$$y_{21g} = g_{21g} + jb_{21g} = -4.4 + j2.3 \text{ mmho}$$

$$y_{22g} = g_{22g} + jb_{22g} = .24 + j4.4 \text{ mmho}$$

The small signal, low frequency transconductance g_{mo} measured at the above bias condition was found to be:

$$g_{mo} = 5.2 \text{ ma./volt}$$

Device Noise Figure

From Equation 2.16 an approximate expression for noise figure is

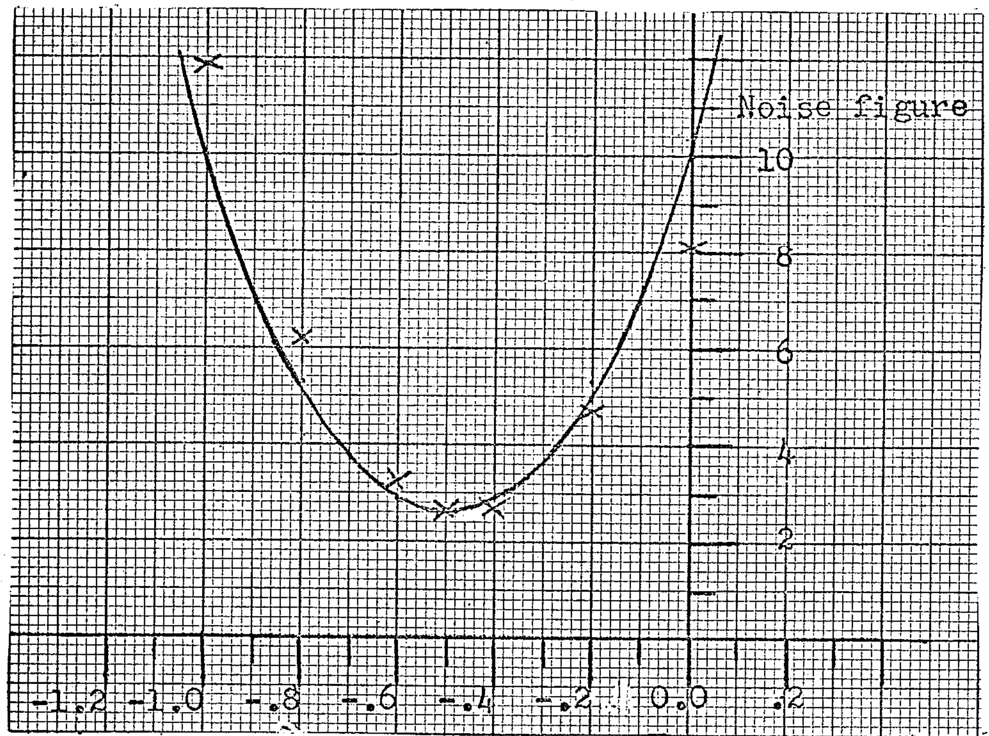
$$F \cong 1 + \frac{g_{gs}}{G_s} + \frac{R_{ng}}{G_s}\left[(G_s + g_{gs})^2 + (B_s + b_{gs})^2\right] \quad \ldots \quad 4.1$$

From the small signal measurements:

$$g_{gs} + jb_{gs} = (g_{11g} + g_{21g}) + j(b_{11g} + b_{21g})$$

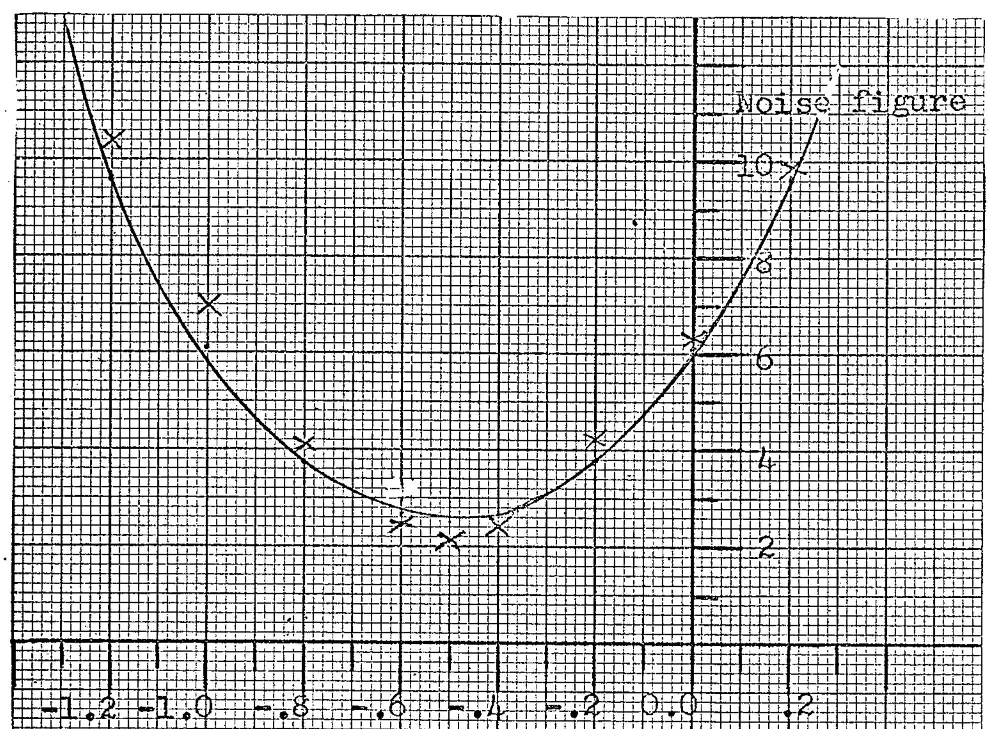
$$= 1.50 + j9.8 \text{ mmho} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 4.2$$

$$R_{ng} = ag_{mo}/\left|y_{21g}\right|^2 = 143 \text{ ohms, if } a = .67 \quad \ldots \quad 4.3$$



Source susceptance X 20 millimhos

Figure 4.3 Measured and computed noise figure versus source susceptance for g_s = .1 X 20 millimhos



Source susceptance X 20 millimhos

Figure 4.4 Measured and computed noise figure versus source susceptance for g_s = .2 X 20 millimhos

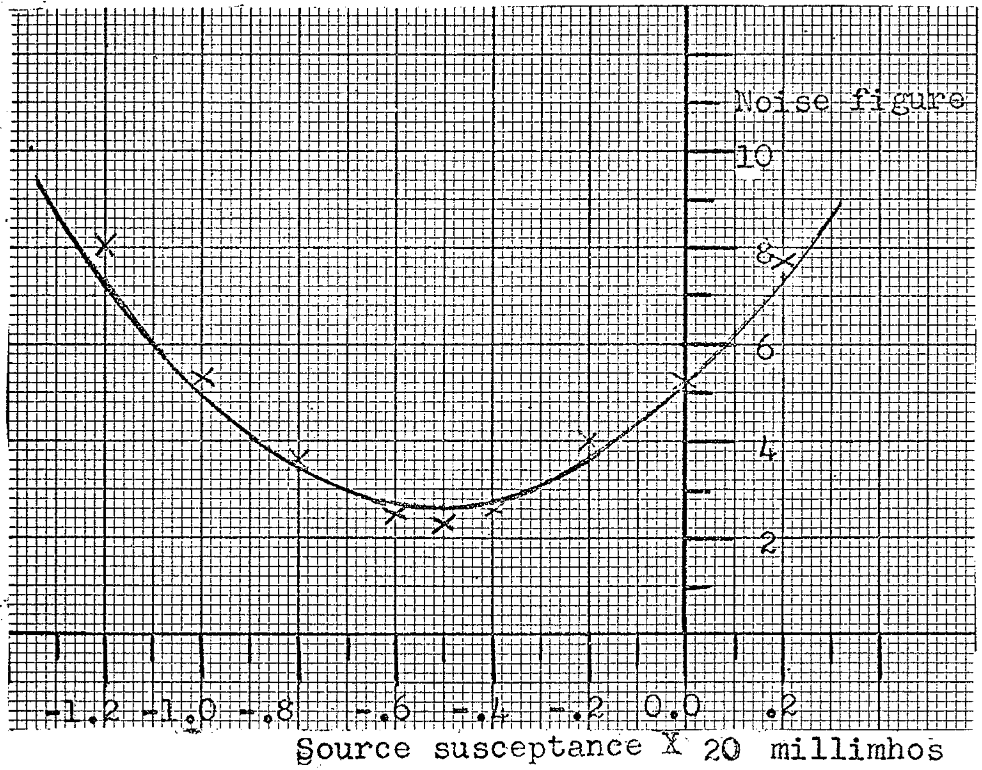


Figure 4.5 Measured and computed noise figure versus source susceptance for g_s = .3 X 20 millimhos

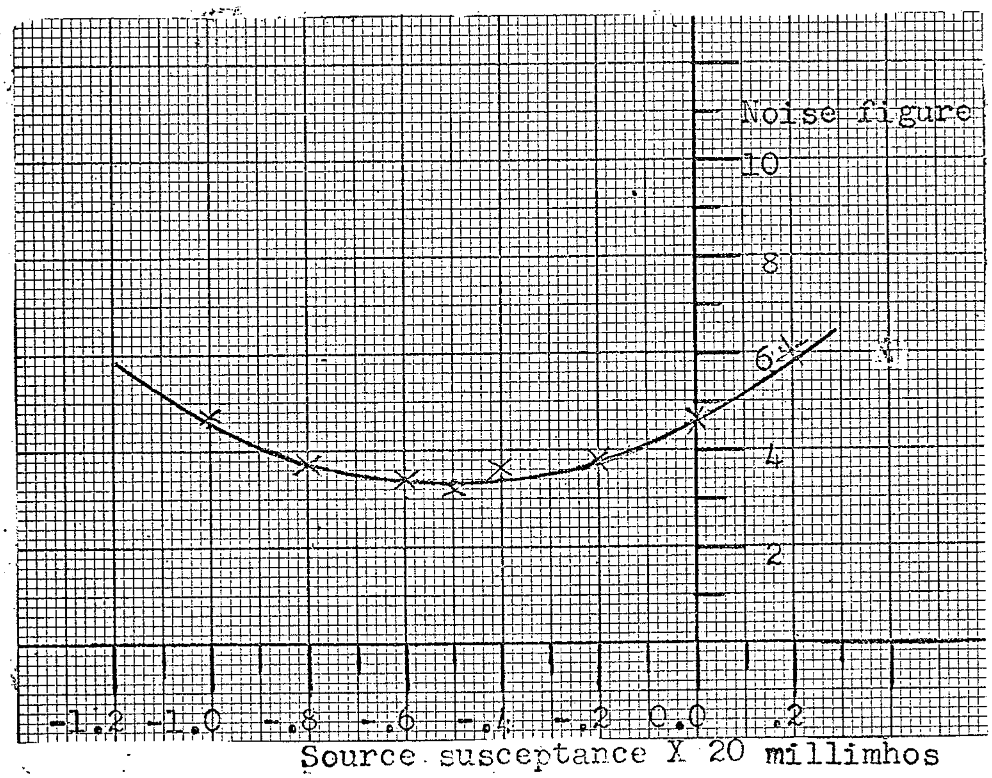


Figure 4.6 Measured and computed noise figure versus source susceptance for g_s = .6 X 20 millimhos

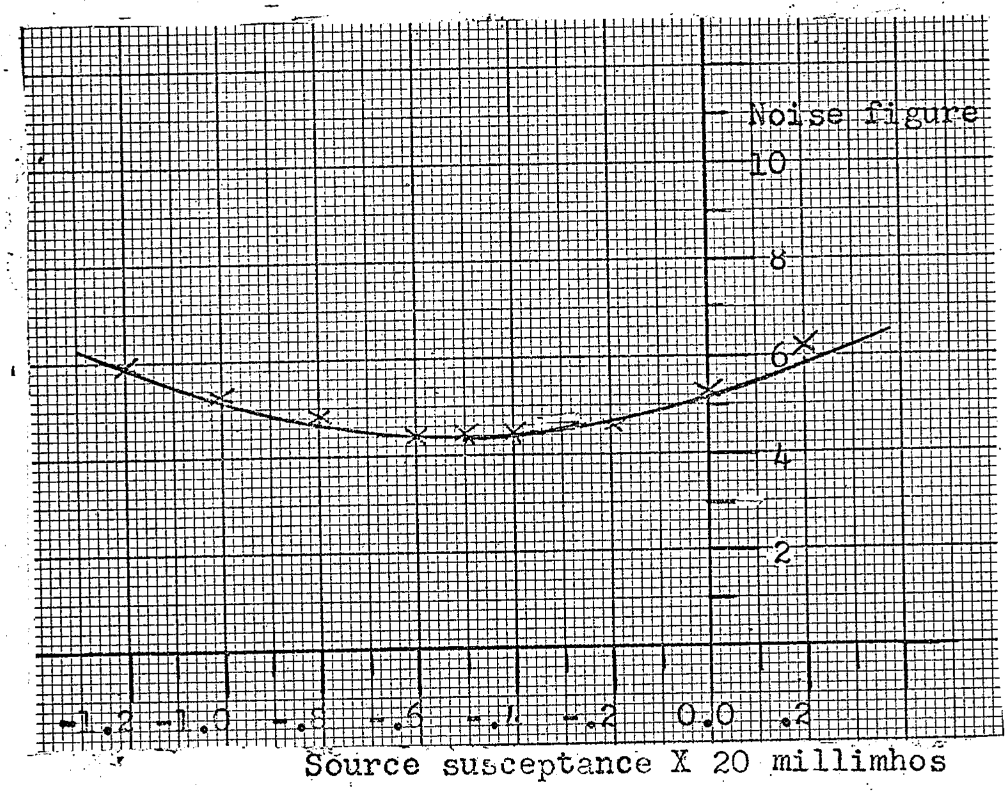


Figure 4.7 Measured and computed noise figure versus source susceptance for $g_s = 1.0 \times 20$ millimhos

The crosses (X) refer to measured values of noise figure, and the solid line gives the theoretical dependance of noise figure for the stated conditions.

Figures 4.3 to 4.7 show the measured and theoretical values of noise figure for the device. Most experimental noise figure readings agree with the calculated values within ± .5 of a noise figure.

Device Excess Noise Ratio

The coupling factor of the directional coupler was measured as a gain of -10.1 dB. The insertion gain of the directional coupler including the 10 dB pad was -10.55 dB. The ratio C/A is equal to .45 dB or a ratio of 1.1. With the drain-source voltage of 15 volts,

$$F_n = 53.7 \text{ or } 17.3 \text{ dB}$$

$$F_o = 42.2 \text{ or } 16.25 \text{ dB} \quad \ldots\ldots\ldots\ldots \quad 4.4$$

From Equation 3.26,

$$ENR_x = 12.7 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 4.5$$

Determining the constant a;

$$a = g_{22}ENR_x/g_{mo} = 0.575 \quad \ldots\ldots\ldots\ldots \quad 4.6$$

This is compared to the generally accepted value of a which is 0.67.[10]

Figure 4.8 shows the measured dependance of the constant (a) with the drain-source biasing potential. As expected, it remains essentially constant[10], since none of the parameters that it is dependant on, vary in the pinch-off region. This method will not give valid results in the triode region of the JFET (V_{DS} = 3 volt), since the output conductance will not remain constant during the device modulation process.

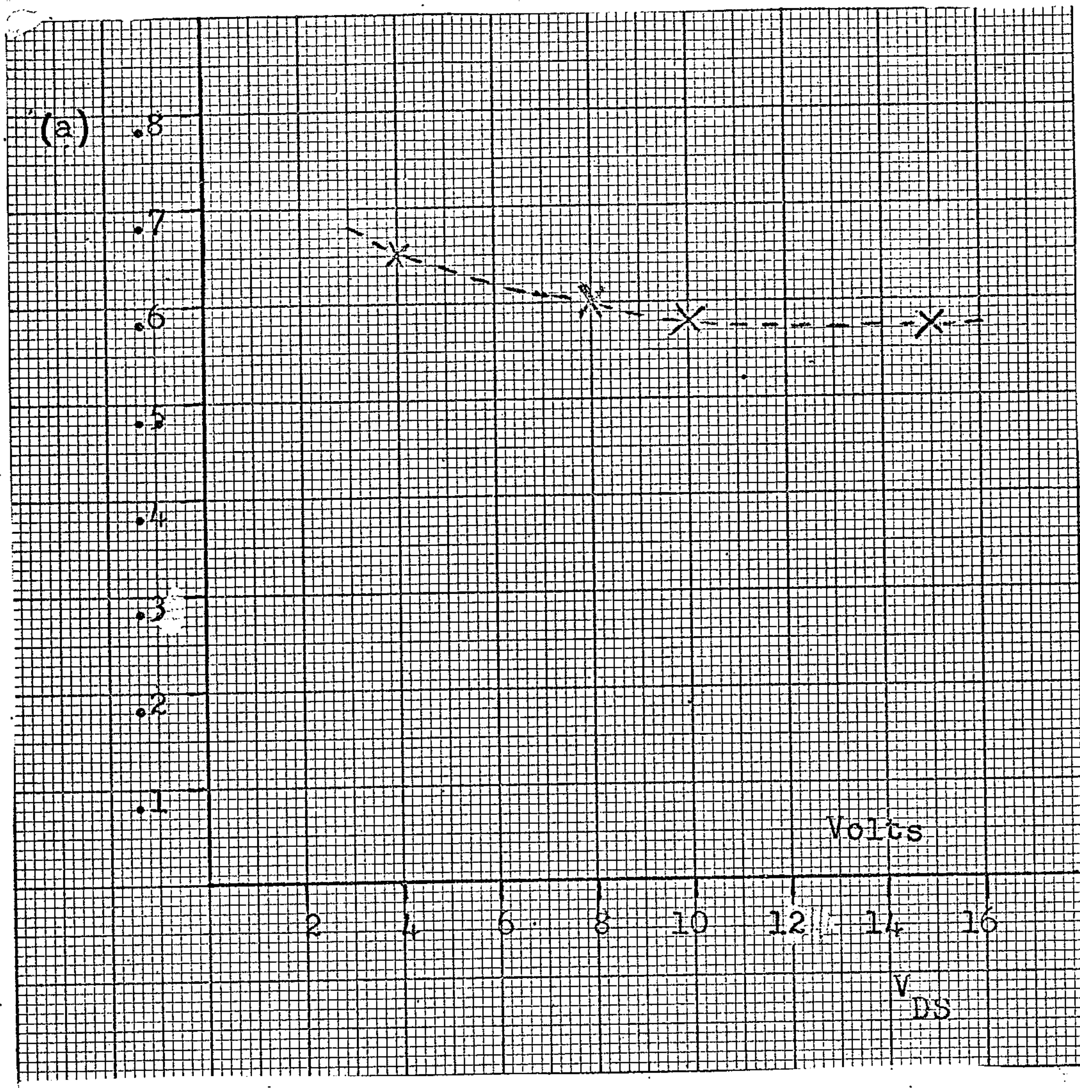


Figure 4.8 Measured values of a versus V_{DS}
(V_{GS} = 0.0 volt)

Possible sources of error in this measurement are: uncertainty in the noise figure readings of the noise figure meter of $\pm$ .25 dB, and the difficulty of matching the low admittance of the output of the JFET to the 50 ohms of the directional coupler.

CHAPTER V

CONCLUSIONS

The succeeding-stage noise compensation techniques used for measuring the noise figure and excess noise ratio of a single device have been described. Such compensation techniques can be applied to UHF measurement systems where the device gain is not high enough and/or the noise of the measurement system is not low enough, for the direct measurement of noise figure.

A one-port succeeding-stage noise compensation technique has been described and verified for ultra-high frequencies. The devices that may be measured with this method method are restricted. The device must permit modulation to extinguish its excess noise without affecting its admittance at the measured port.

An approximate noise model has been used to characterize the noise behavior of a junction FET at UHF. Experiments using succeeding-stage noise compensation show reasonable agreement with this noise model.

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