JEDEC STANDARD

Measurement of Transistor Noise Figure at MF, HF, and VHF

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NOVEMBER 1981 (Reaffirmed: April 1999, March 2009)

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EIA STANDARD

MEASUREMENT OF TRANSISTOR
NOISE FIGURE AND EFFECTIVE INPUT
NOISE TEMPERATURE AT
MF, HF AND VHF

RS-311-A

(Revision of RS-311)

and

(Rescission of RS-283)

NOVEMBER 1981

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Engineering Department

ELECTRONIC INDUSTRIES ASSOCIATION

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MEASUREMENT OF TRANSISTOR NOISE FIGURE AND EFFECTIVE INPUT NOISE TEMPERATURE AT MF, HF AND VHF

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FOREWORD

This Standard describes a test method for measurement of transistor noise figure and effective input noise temperature at MF, HF, and VHF. This method is a revision of RS-311 and incorporates material previously found in RS-283, and as such rescinds RS-283 since it was found deficient in test method details and definitions for noise figure measurements. Also, RS-311-A adds the necessary information to make "effective input noise temperature" measurements. The noise definitions are identical to that found in JEDEC Standard No. 77 and do not conflict with the IEC documents, found in 47(Secretariat)558/548 as approved in Tokyo, June 1975.

MEASUREMENT OF TRANSISTOR NOISE FIGURE AND EFFECTIVE INPUT NOISE TEMPERATURE AT MF, HF AND VHF

(From EIA Standards Proposal No. 1307, formulated under the cognizance of EIA/ JEDEC JC-25 Committee on Transistors.)

1.0 DEFINITIONS

1.1 Noise Temperature (symbol: T_n)

The uniform physical absolute temperature in degrees kelvin, at which a network (and all its sources, if a multiport) would have to be maintained if it (and its sources) were passive in order to make available (or deliver) the same random noise power per unit bandwidth (spectral density) at a given frequency as is actually available (or delivered) from the network.

1.2 Reference Noise Temperature (symbol: T_0)

A specified absolute temperature in degrees kelvin, to be assumed as a noise temperature at the input ports of a network when calculating certain noise parameters, and for normalizing purposes. When the reference noise temperature is 290 K, it is considered to be the standard reference noise temperature.

1.3 Average Noise Figure, Average Noise Factor (symbol: $\bar{F}$)

Rate of:

(1) the total output noise power within an output frequency band when the noise temperature of all input terminations is at the reference noise temperature, T_0, at all frequencies that contribute to the output noise

to:

(2) that part of (1) caused by the noise of the signal-input termination within the signal-input frequency band.

See Appendix I-A for specific definitions relating to mixer diodes.

1.4 Effective Average Input Noise Temperature (symbol: $\bar{T}_e$)

The noise temperature in degrees kelvin which, assigned to the input impedance termination(s) at all frequencies of a noise free equivalent of the transistor, would yield the same total noise power in an output termination as that of an actual transistor connected to noise free equivalents of the input termination(s).

See Appendix I-B for specific definitions relating to twoports or mixers.

1.5 Spot Noise Figure, Spot Noise Factor (symbol: F)

Ratio of:

(1) the total output noise power per unit bandwidth (spectral density) at a single output frequency when the noise temperature of all input *terminations is at the reference noise temperature,* T_0, at all frequencies that contribute to the output noise

to:

(2) that part of (1) caused by the noise of the signal-input termination at the signal-input frequency.

Reference JEDEC Standard No. 77, October, 1981. These definitions have been adopted by IEC/TC47.

2.0 INTRODUCTION

The noise figure and the effective input noise temperature of a transistor at MF, HF or VHF frequencies (300 kHz - 300 MHz) can be measured in a circuit as outlined in the block diagram below.

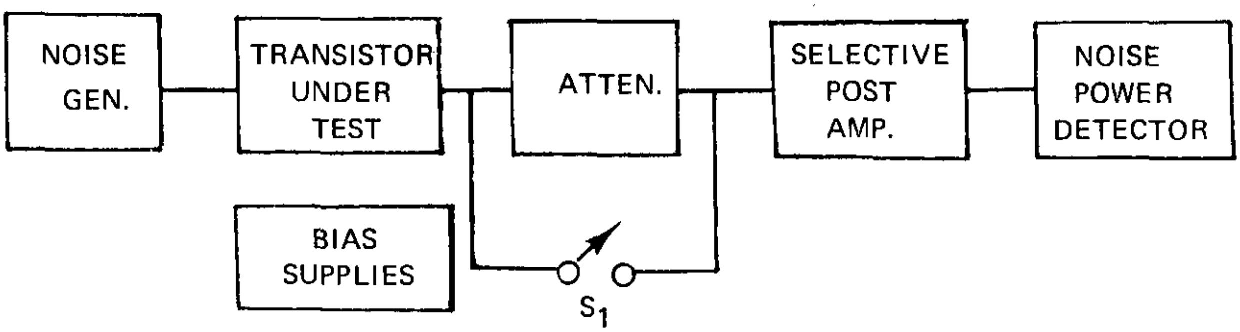

FIGURE 1

The values for the source resistance of the noise generator, the dc operating conditions and test frequency, should be as specified. These usually depend upon the application and the optimum conditions for any particular device. The transistor can be matched to give optimum gain, optimum noise figure, or a compromise between these two conditions.

Theoretical analysis and empirical experiments have shown that if the overall system relative bandwidth is 15% or less, the measured noise figure will be within a few percent of the true spot noise figure (where B = 1 Hz). For average (broad-band) noise figure measurements, noise bandwidth must be as specified.

3.0 NOISE GENERATOR

A suitably calibrated noise generator shall be used. Care should be taken to avoid errors due to series inductance in the noise generator which can be serious, particularly at high frequencies. All resistors which make up the effective noise source for the transistor under test shall be of a low noise type, such as deposited metal film resistors, in order to minimize contact and breakdown noise.

4.0 TRANSISTOR UNDER TEST

The transistor under test shall be inserted in an amplifier circuit having the general configuration for bipolar transistors shown in Figure 2, or a corresponding common-source circuit for field-effect transistors. A similar configuration in which the transistor is operated in the common-base (common-gate) or common-collector (common-drain) connections may be used.

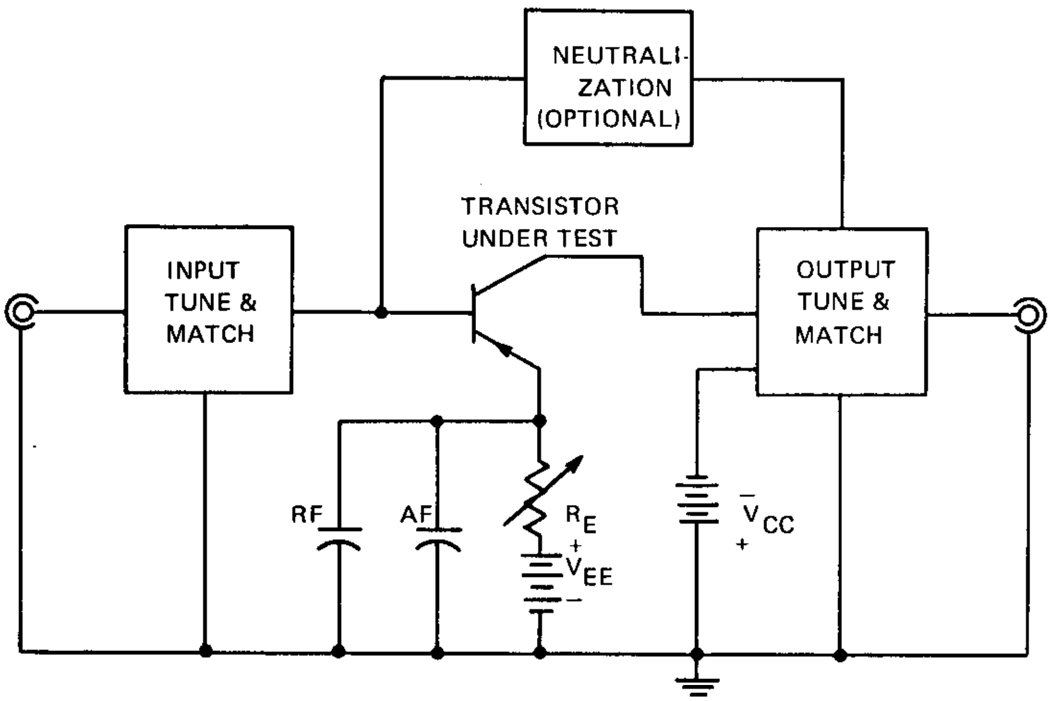

Figure 2

4.0 TRANSISTOR UNDER TEST (continued)

The input circuit should have a relative bandwidth of 50% or more, and low loss (an unloaded input coil Q of 50 or more is adequate), or the input bandwidth may be selected as desired and the contribution of the specified input network accounted for in the calculation of the noise figure. The input network should provide an effective bypass for audio frequencies. An input network which meets these requirements is shown in Figure 3.

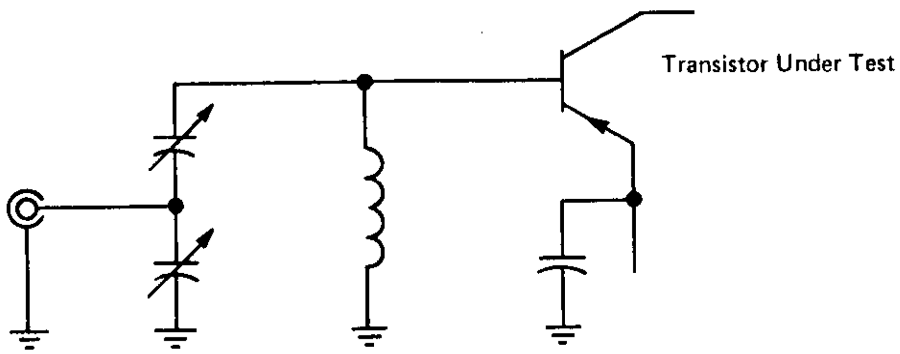

Figure 3

The use of neutralization network is optional. It may be used if desired to maintain stability.

5.0 BIAS SUPPLIES

Batteries of low-ripple dc supplies should be used. All bias applied should be bypassed for both RF and audio frequencies. The test setup must be very well shielded and grounded in order to prevent pickup of unwanted signals.

6.0 ATTENUATOR

An attenuator is used to minimize the effect of nonlinearities in the post amplifier and the noise power detector by controlling the gain of the system. The input and output impedances of the attenuator should be matched to the system in order that the attentuation factor can be accurately known. The attenuator can also be used at higher frequencies to determine the effect of second stage noise when the transistor gain is low. The attenuator may be made equal to 3 dB and a switch, S_1, connected around it as shown in Figure 1. The use of this connection will be described under "Y-Factor Method of Test".

Some amplification can be inserted between the transistor under test and the attenuator if desired as is the case in measuring low noise figures. If this is done, this preamplifier must be essentially linear in order to prevent errors in the noise figure measurement. The requirements pertaining to second-stage noise given below must still be met.

7.0 SELECTIVE POST AMPLIFIER

The amplifier noise should be such that with the noise generator turned off any transistor under test gives at least an increase of 15 dB above the reading due to the post amplifier itself with no transistor in the circuit. If this is not true, the effect of the amplifier on the overall noise figure must be determined. This can be done conveniently by use of the attenuator (see "Effect of Second Stage Noise").

Heterodyne-type post amplifiers may be used, but careful attention must be paid to the image* and other spurious responses which can be encountered with such amplifiers. These spurious responses must be made negligible, or must be accounted for in the measurement.

The post amplifier should have an input impedance which matches the attenuator, in order that the attenuation factor will be accurately known.

To provide for the crest factor of the noise, the amplifier must be essentially linear from the rms level used to a minimum of 20 dB above the rms level. Additional flexibility may be provided by making the gain of the amplifier variable.

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*See also "IEEE Standards on Methods of Measuring Noise on Linear Two Ports, 1959" Proc. IEEE, vol. 48, pp. 60-68, January, 1960.

8.0 Y-FACTOR METHOD OF TEST**

The transistor biases are adjusted to the value specified. With the noise generator output set to 0 and with the attentuator set to 0 dB, a reference level is obtained on the noise indicator. The attenuator is then switched into the *circuit. Next, the noise generator* is turned on and its output increased until the noise indicator returns to its original reading which was taken without the attenuator. The recorded value of the output of the noise generator is then used to compute the noise figure. For example, if a noise diode is used as the noise generator at T_g, the average noise Figure $\bar{F}$, and effective average input noise temperature $\bar{T}_e$, in kelvin (K) are:

$$\bar{F}(db) = 10 \log \left[\left(\frac{q}{2k.290}\right) \left(\frac{I_D R_g}{Y - 1}\right) - \frac{T_g}{290} + 1 \right] = 10 \log \left[20\,(\text{volts}^{-1}) \left(\frac{I_D R_g}{Y - 1}\right) - \frac{T_g}{290} + 1 \right] \quad \text{(Eq1)}$$

$$\bar{T}_e = \frac{(q/2k)\; I_D R_g + T_g - YT_g}{(Y-1)} = \frac{5800\,(\text{kelvins/volt})\; I_D R_g + T_g - YT_g}{(Y-1)}, \quad \text{(Eq2)}$$

respectively.

** See Appendices II and III

Where:

I_D is the dc plate current of the noise diode in amperes,

R_g is the noise generator resistance,

T_g is the noise generator temperature in degrees kelvin (K),

$Y = \text{antilog}\left(\frac{\text{attenuator reading in dB}}{10}\right)$

q is the elementary charge,

k is Boltzmann's constant.

A value of Y=2 (corresponding to an attenuator setting of 3 dB) is often used. In this case, the noise output of the diode is equal to the equivalent input noise power of the transistor under test.

Example:

Using Eq1 with

$T_g = (35^o\ C) = 308.18\ K$, $I_D = 0.0016$ A, R=50 ohms, Y = 3 dB (2 ratio),

$$\bar{F}(dB) = 10 \log \left[20(\text{volts}^{-1}) \left(\frac{I_D R_g}{Y-1}\right) - \frac{T_g}{290} + 1\right] = 10 \log \left[\frac{(20)(0.0016)(50)}{(2-1)} - \frac{308.18}{290} + 1\right],$$

$\bar{F} = 10 \log 1.537 = 1.87$ dB.

But with $T_g = 20^o$ C (293.18 K) instead of 35^o C, then

$\bar{F} = 10 \log 1.589 = 2.01$ dB.

Using Eq2 with $T_g = 35^oC$,

$$\bar{T}_e = \frac{5800\ (\text{kelvins/volt})\ I_D R_g + T_g - YT_g}{(Y-1)} = \frac{(5800)(0.0016)(50) + 308.18 - 2(308.18)}{(2-1)},$$

$\bar{T}_e = 155.82$ K

or with $T_g = 20^o$ C

$\bar{T}_e = 170.82$ K.

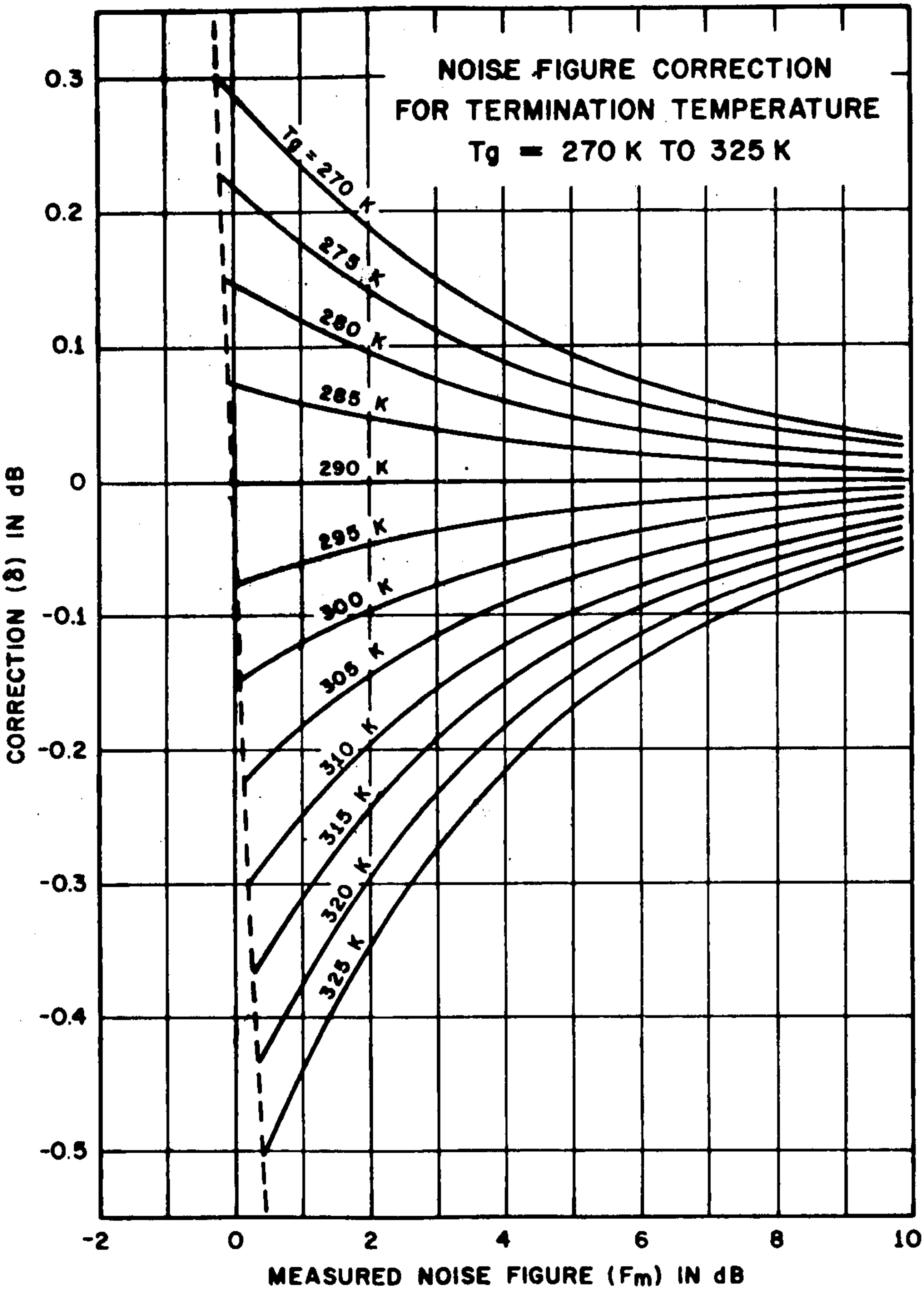
9.0 EFFECT OF SECOND-STAGE NOISE

At higher frequencies where the noise output of the transistor under test is not 15 dB above the selective amplifier noise, an attenuator may be used to obtain a correction for F_1, the noise figure of the transistor alone in terms of the overall noise figure F_{12}. To do this, the input impedance of the post amplifier must be matched to the attenuator. (See Appendix IV).

10.0 EFFECT OF NOISE GENERATOR TERMINATION TEMPERATURE

Equation 1 contains a correction for the effect of T_g being at a temperature other than 290 K. The amount of this correction can be read from the curve on the following page.

Eq1 contains a provision for the effect of T_g being at a temperature other than 290 K. The amount of this correction to be applied to F(db) in Eq1 provided a T_g of 290 is used in Eq1.



APPENDIX I

(A) ADDITIONAL DEFINITIONS RELATING TO MIXER DIODES

(1) Overall Average Noise Figure (of a mixer diode) (symbol: F_o)

The average noise figure of the cascaded combination of a mixer and an IF amplifier.

(2) Standard Overall Average Noise Figure (of a mixer diode) (symbol: F_{os})

The overall average noise figure when the average noise figure of the IF amplifier is a specified standard value (usually 1.5 dB) and the passband of the IF amplifier is sufficiently narrower than that of the mixer so that the mixer conversion loss and output noise temperature are essentially constant over the IF passband.

(B) ADDITIONAL DEFINITIONS RELATING TO TWOPORTS AND MIXERS

(1) Equivalent Input Noise Voltage (of a twoport) (symbol: V_n)

The voltage of an ideal voltage source (having an internal impedance equal to zero) in series with the input terminals of the device that represents the part of the internally generated noise that can properly be represented by a voltage source.

NOTE: In the definition, the equivalent input noise current, which would be needed for a complete and precise description of the device noise, is neglected. If the external source impedance is zero, the noise voltage represents the total noise.

(2) Equivalent Input Noise Current (of a twoport) (symbol: I_n)

The current of an ideal current source (having an internal impedance equal to infinity) in parallel with the input terminals of the device that represents the part of the internally generated noise that can properly be represented by a current source.

NOTE: In the definition, the equivalent input noise voltage which would be needed for a complete and precise description of the device noise is neglected. If the external source impedance is infinite, the noise current represents the total noise.

(3) Conversion Loss (of a mixer, mixer diode or harmonic generator) (symbol: L_c)

The ratio of available input power at a single frequency to the available signal-output power, not including intrinsic mixer noise or power converted from other than the signal-input frequency.

NOTE: Delivered signal-output power may be used, in which case the loss is referred to as "conversion insertion loss".

APPENDIX II

MEASUREMENT OF NOISE FIGURE OF A DEVICE BY THE Y-FACTOR, NOISE GENERATOR METHOD

Definition

$\bar{T}_e$ = Effective Input Noise Temperature

Introduction

To measure $\bar{T}_e$ of a device, the input termination temperature is changed from T_g (hot) to T_g (cold) at all frequencies.

The relative output noise powers are N_{Tgh} and N_{Tgc}, respectively.

Letting $Y = N_{Tgh}/N_{Tgc}$,

we can express

$$\bar{T}_e = \frac{T_{gh} - YT_{gc}}{Y-1} \tag{1}$$

(2)

where $T_{gh} = T_g$ (hot) and $T_{gc} = T_g$ (cold).

This is commonly called the Y-Factor Method for measuring the effective input noise temperature, $\bar{T}_e$.

APPENDIX II (continued)

Noise Sources

Noise Diode

Total noise power available from a practical noise diode generator is the sum of the shot noise power and the resistor noise power.

P_{na} = Available noise power

Then for a noise diode

$$P_{na} = \frac{2qIBR^2}{4R} \text{ (shot noise)} + \frac{V_n^{\ 2}}{4R} \text{ (resistor noise).} \qquad (3)$$

But from Nyquist's Noise Theorem

$$V_n^{\ 2} = \frac{4hf}{e^{hf/kT}-1}$$

where h = Planck's constant.

When $f << \frac{kT}{h} = 2 \times 10^{10}$ T hertz, then

$$V_n^{\ 2} = 4kRBT. \qquad (4)$$

Therefore combining equations (3) and (4) we get

$$P_{na} = kB \left[\left(\frac{q}{2k}\right) IR + T \right]. \qquad (5)$$

Finally, the equivalent noise temperature of a noise diode (generator) at a current I_D with a termination resistance R_g at a temperature T_g is

$$T_g \text{(hot)} = \left[\left(\frac{q}{2k}\right) I_D R_g + T_g \right]. \qquad (6)$$

Noise temperature of a noise diode when $I_D = 0$ is the noise temperature T_g of the generator termination resistance R_g. Thus,

$$T_g \text{(cold)} = T_g. \qquad (7)$$

The effective input noise temperature, $\bar{T}_e$, of the device under test is

$$\bar{T}_e = \frac{(q/2k) I_D R_g + T_g - YT_g}{(Y-1)} \qquad (8)$$

APPENDIX III

MEASUREMENT OF NOISE FIGURE OF A DEVICE BY THE Y-FACTOR, NOISE GENERATOR METHOD

Introduction

If the effective average input noise temperature, $\bar{T}_e$, is known, the average noise figure, $\bar{F}$, can be calculated from the following relationship for single response amplifiers.[1]

$$\bar{F} = \frac{\bar{T}_e}{290} + 1, \text{ where } \bar{T}_e \text{ is expressed in K.}^2 \qquad (9)$$

Combining (8) and (9)

$$\bar{F} = \frac{(q/2k290)\ I_D R_g}{Y-1} - \frac{T_g}{290} + 1, \qquad (10)$$

where $\bar{F}$ is the average noise figure of a device whose input noise diode termination R_g, is at a temperature T_g in K, and when the noise diode is hot, its current is I_D.

Considering the latest NBS interim set of values of the physical constants[3]

$$\frac{q}{2K290} = 20.0074\ (\text{volts}^{-1}) \text{ where } q = 1.6021917 \times 10^{-19}\text{C} \qquad (11)$$

$$K = 1.380692 \times 10^{-23} \text{J/K}.$$

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1 W.W. Munford and E.H. Scheibe, "Noise Performance Factors in Communication Systems", Dedham, MA., Horizon House - Microwave, Inc., 1968

2 *This noise ratio is sometimes referred to as noise factor.*

3 Chapter 2, NBS Applied Mathematic Series 55, Handbook of Mathematical Functions, Ninth Printing, February, 1971.

APPENDIX III (continued)

Therefore, the average noise figure is

$$\bar{F} = \frac{20\ (\text{volts}^{-1})\ I_D R_g}{Y-1} - \frac{T_g}{290} + 1. \qquad (12)$$

Also, the average noise figure in dB is

$$\bar{F} = 10 \log\ [20(\text{volts}^{-1})\ I_D R_g\ -(Y-1)\ (T_g/290\ -1)]\ \ -10\ \log(Y-1). \qquad (13)$$

When T_g = 290 K,

$$\bar{F} = 10 \log\ [20\ (\text{volts}^{-1})\ I_D R_g]\ -10\ \log(Y-1)$$

for a diode noise generator; and, in general,

$$\bar{F} = \text{Excess Noise Temperature Ratio in dB}\ - 10\ \log\ (Y-1).$$

APPENDIX IV

The correction for second-stage noise is based on the well known equation for the noise figure of cascaded amplifiers

$$F_{12} = F_1 + (F_a - 1)\frac{1}{G_1} + (F_2 - 1)\frac{1}{G_1 G_a} \quad , \qquad (1)$$

where

F_1 is the noise figure of the test amplifier (the transistor and its circuitry),

G_1 is the power gain of the test amplifier,

F_a is the noise figure of the attenuator (equals L),

G_a is the power gain of the attenuator (equals 1/L),

F_2 is the noise figure of the post amplifier, all expressed as ratios.

To avoid having to measure G_1, two measurements of overall noise figure, F_{12}, can be made. First, F_{12} is measured with S_1 closed. Then S_1 is opened, the attenuator is set to an arbitrary loss, L, and a second measurement of overall noise figure, F_{12}, is made. In the first case the overall noise figure is given by the equation:

$$F_{12} = F_1 + (F_2 - 1)\frac{1}{G_1}. \qquad (2)$$

In the second case the overall noise figure is given by the equation:

$$F_{12} = F_1 + (LF_2 - 1)\frac{1}{G_1}. \qquad (3)$$

where the output resistances of the test amplifier and the attenuator are equal to each other and to the source resistance of the test amplifier.

Eliminating G_1 between these two equations leads to:

$$F_1 = \frac{F_{12}(LF_2 - 1) - F'_{12}(F_2 - 1)}{F_2(L - 1)}. \qquad (4)$$

APPENDIX IV (continued)

In terms of decibel representation of the noise figure this equation for F becomes

$$F_1(\text{db}) = F_{12}(\text{db}) - F_2(\text{db}) + 10 \log \frac{LF_2 - 1 - \dfrac{F'_{12}}{F_{12}}(F_2 - 1)}{L - 1} \qquad (5)$$

Example:

A transistor has a noise figure $F_{12} = 4.5$ dB with the attenuator out. With a 10-dB attenuator in, the noise figure $F'_{12} = 7.5$ dB. The noise figure of the post amplifier is $F_2 = 6$ dB. What is the true transistor noise figure:

$$L = 10 \text{ dB} = 10.00,$$

$$F_2 = 6 \text{ dB} = 3.98,$$

$$F_{12} = 4.5 \text{ dB} = 2.82,$$

$$F'_{12} = 7.5 \text{ dB} = 5.62.$$

Then true F_1 is

$$F_1 = 4.5 \text{ dB} - 6 \text{ dB} + 10 \log \frac{(10.00)(3.98) - 1 - \dfrac{5.62}{2.82}(3.98 - 1)}{10.00 - 1}$$

$$= 4.5 \text{ dB} - 6 \text{ dB} + 10 \log \frac{32.86}{9.00},$$

$$= 4.5 \text{ dB} - 6 \text{ dB} + 5.62 \text{ dB},$$

$$= 4.12 \text{ dB}.$$

Equation (4) can be adapted for graphical solution by a slight manipulation to give the correction to F_{12} ; i.e.,

$$\frac{F_1}{F_{12}} = \frac{(LF_2 - 1) - (F'_{12}/F_{12})(F_2 - 1)}{F_2(L - 1)} \qquad (6)$$

Since L and F_2 can be constants, a simple graph of F_1/F_{12} vs F'_{12}/F_{12} will give the required correction.

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