Noise Figure & Associated Conversion Gain of a GaAs Heterojunction Bipolar Transistor Mixer

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Abstract-An analytical technique is developed to predict the noise performance of the GaAs Heterojunction Bipolar transistor (HBT) mixer. The measured versus modelled data shows good agreement. The measured noise figure of the HBT mixer is 15.7dB with an associated conversion gain of +13dB (RF=950MHz, IF=50MHz).

I. Introduction

The GaAs HBT is finding wide application in the areas of power amplifiers, wideband amplifiers and frequency multipliers [1]. It is generally acknowledged the HBT device has a poor noise performance when compared to MESFETs or HEMT devices, thus, the small signal applications of the device are limited.

The intermodulation and conversion gain performance of the single ended HBT mixer has been shown to be superior to similar circuits constructed using MESFET and HEMT technologies [2]. The object of this paper is to present the theoretical and measured noise figure of the HBT mixer and contrast these results with those obtainable using MESFET mixers.

In order to investigate and improve the noise figure of the HBT mixer, a model and an analytical technique are developed. This enables the noise figure of the HBT mixer to be determined as a function of circuit embedding impedances, device parameters and circuit configuration.

II. Classification of the HBT Noise Sources

The noise sources of the HBT consist of shot noise, flicker noise and Johnson noise. Flicker noise is inversely proportional to frequency and is thus disregarded in this analysis.

The non-linear model chosen to represent the noise behaviour of the HBT mixer is shown in fig 1.

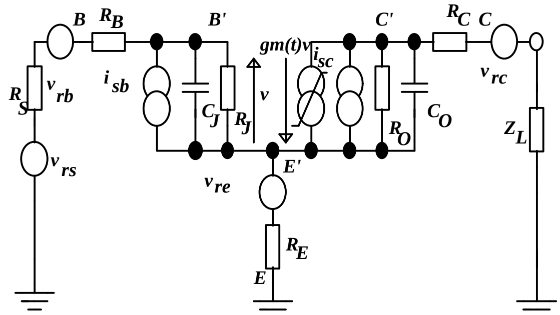

Fig. 1. Quasi-Linear Noise Model of the HBT

The quasi-linear model of the HBT has been shown to be an accurate representation of device behaviour at frequencies below 6GHz [2]. The shot noise of the device is modelled by current sources connected between the base-emitter junctions and the collector-emitter junctions of the device. The thermal noise sources are modelled by voltage sources connected in series with the devices ohmic resistors. The expression for the base-emitter and collector-emitter shot noise sources are given in eqn. 1 and eqn. 2 respectively [3].

$$\overline{i_{sb}^{\,2}} = \frac{2 \cdot k \cdot T \cdot B \cdot gm}{h_{fe}} \qquad (1)$$

$$\overline{i_{sc}^{\,2}} = 2 \cdot B \cdot k \cdot T \cdot gm \qquad (2)$$

where k is Boltzmann's constant (1.38×10^{-23}), T is temperature, gm is the HBT device transconductance, h_{fe} is common emitter current gain and B is bandwidth.

The thermal or Johnson noise sources of the device are represented by v_{re}, v_{rc} and v_{rb} in fig 1. The general expression for the thermal noise sources is given in eqn 3.

$$\overline{v_r^{\,2}} = 4 \cdot k \cdot T \cdot B \cdot R \qquad (3)$$

where R (Ω) is the resistance of interest.

The base-emitter shot noise current source may be modelled by two voltage noise sources connected in series at the input terminal of the device. The second voltage noise source is required to include the effect of the emitter resistance (R_E). The expression for the sum of these two shot noise voltage sources is given in eqn 4.

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$$\overline{v_b^{\,2}}(t)=\frac{2\cdot k\cdot T\cdot B\cdot gm(t)\cdot\left(R_B+R_E+Z_n\right)^2}{h_{fe}} \quad (4)$$

where Z_n is the impedance seen at the base terminal of the mixer, the resistors are defined in table I.

The transconductance of the HBT is a function of LO drive level and thus time, therefore the shot noise sources of the device are a function of transconductance and thus time. The small signal current gain of the device is assumed to be constant over the level of LO drive chosen (-20dBm:-6dBm).

The collector-emitter shot noise current source may be modelled as two voltage noise sources connected in series at the input of the device to include the effect of the emitter resistor as is shown in eqn 5.

$$\overline{v_{nc}^{\,2}}(t)=\frac{2\cdot k\cdot T\cdot B}{gm(t)}\left(1+\frac{\left(R_E+R_B+Z_n\right)^2}{Z^{\;2}}\right) \quad (5)$$

where Z is the parallel combination of R_J and C_J (see table I).

The noise figure expression of a device is defined as the ratio of the total noise at the output of the device divided by the noise engendered by the source termination alone, as is given in eqn (6). If *gm* is not time varying i.e. the HBT is configured as a small signal amplifier then, using typical quasi-linear model parameters @1GHz, a source termination of 50Ω, and a collector current of 5mA yields a predicted noise figure of 3.1dB; the measured noise figure of an HBT amplifier was 3dB.

$$F=\frac{G\cdot\overline{v_s^{\,2}}+G\cdot\overline{v_a^{\,2}}}{G\cdot\overline{v_s^{\,2}}} \quad (6)$$

where G is power gain, v_S is the noise engendered by the source, v_a is the device noise, the G terms cancel in eqn 6.

The HBT device noise is equal to the sum of the input refered collector and base shot noise and the thermal noise due to the ohmic resistors of the device. Thus, substituting eqn's 3, 4 & 5 into eqn 6 yields the time varying expression for noise figure of the HBT mixer, eqn 7. The thermal noise of the collector resistor (R_C) is typically 8.23×10^{-19} V^2/Hz whereas the voltage noise of the collector-emitter shot noise source is typically 2.63×10^{-14} V^2/Hz, thus, the thermal noise contribution of R_C isdisregarded.

$$F(t)=1+\frac{R_B+R_E}{R_S}+\frac{1}{2\cdot R_S\cdot gm(t)}+\frac{gm(t)\cdot(R_S+R_B+R_E)^2}{2\cdot h_{fe}\cdot R_S}+\frac{(R_S+R_B+R_E)^2}{2\cdot gm(t)\cdot R_S\cdot Z^{\,2}} \quad (7)$$

III. Conversion Matrix Analysis

Eqn's 3, 4, 5 represent voltage noise sources and are a function of transconductance and the real part of the embedding impedance seen by the HBT device. Thus, these sources may be represented as a column vector of phasor quantities in the frequency domain as is shown in eqn 8 for the specific case of the base-emitter shot noise source (eqn 4).

$$\left[\overline{v_b^{\,2}}\right]=\frac{4\cdot k\cdot T\cdot B}{2}\cdot\left(\begin{bmatrix}g_{-1} & g_0 & g_1\end{bmatrix}\cdot\left(\begin{bmatrix}R_B\\R_B\\R_B\end{bmatrix}+\begin{bmatrix}R_E\\R_E\\R_E\end{bmatrix}+\begin{bmatrix}Z_{-1}\\Z_2\\Z_1\end{bmatrix}\right)^2\right)\cdot\begin{bmatrix}\frac{1}{h_{fe}}\\ \frac{1}{h_{fe}}\\ \frac{1}{h_{fe}}\end{bmatrix} \quad (8)$$

where Z_n is the embedding impedance seen by the HBT device at the n^{th} LO harmonic frequency, g_n are the Fourier coefficients of the device transconductance, n is the harmonic of the LO drive, the $\left[\overline{v_b^{\,2}}\right]$ term in eqn 8 indicates the variable is a column vector in this text. Column vectors of the collector-emitter shot noise and the thermal noise are derived in a similar fashion to eqn 8. The sum of these voltage noise vectors represents the total time varying device noise referenced to the input of the device. Thus far, the effect of correlation between the various noise sources due to the mixing mechanism [4] have not been accounted for. This is achieved by evaluating the noise figure of the HBT mixer at the output of the device in terms of noise currents. Since the input noise is represented by voltage noise vectors, the admittance transfer function of the quasi-linear model (fig 1) can be used to determine the current noise at the collector port of the HBT mixer. The admittance transfer function of the quasi-linear HBT model is given in eqn 9.

$$\overline{Y21}=\overline{gm}\cdot\overline{Z}\;\cdot\overline{Y11} \quad (9)$$

where $$\overline{Y11}=\frac{1}{\overline{R_B}+\overline{Z}\;+\overline{R_E}\cdot(1+\overline{gm})}$$

The $\overline{X}$ notation in eqn 9 indicates the variables are n×n conversion matrices, where n is the n^{th} harmonic of the LO.

Multiplying the vector of input voltage noise sources by the conversion matrix [4] admittance

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transfer function (eqn 9) yields a vector of noise currents at the IF port of the mixer. The vector is the frequency domain representation of the output noise currents of the HBT mixer. The vector contains 2n+1 elements, where n is the number of LO harmonics considered in the Fourier analysis of the device transconductance. We are interested in the IF noise figure which corresponds to $\sum_{-n}^{n} n \times n = 0$ i.e. the input voltage noise vector multiplied by the n+1 row of the square of the conversion matrix of the admittance transfer function (eqn 9). The n+1 row of the square of the admittance transfer function matrix is defined in eqn 10.

$$\overline{Y21}^2 = \begin{bmatrix} Y_{-1} & Y_0 & Y_1 \end{bmatrix} \quad (10)$$

Performing the multiplication of eqn 10 and the input voltage noise vectors yields the IF noise figure of the HBT mixer, if the number of LO harmonics considered is limited to one then eqn 11 defines the noise figure of the HBT mixer.

$$F = 1 + \frac{R_B + R_E}{\mathrm{Re}(Z_{-1})} + \frac{1}{2 \cdot g_1 \cdot \mathrm{Re}(Z_{-1})} + \frac{(R_B + R_E + Z_{-1})^2}{2 \cdot R_J^{\,2} \cdot \mathrm{Re}(Z_{-1})} \cdot \frac{1}{g_1} + \frac{(R_B + R_E + Z_{-1})^2}{2 \cdot h_{fe} \cdot \mathrm{Re}(Z_{-1})} \cdot g_{-1} +$$
$$\frac{Y_0}{Y_1 \cdot \mathrm{Re}(Z_{-1})} \cdot \left(\frac{1}{2 \cdot g_0} + \frac{(R_B + R_E + Z_2)^2}{2 \cdot R_J^{\,2}} \cdot \frac{1}{g_0} + \frac{(R_B + R_E + Z_2)^2}{2 \cdot h_{fe}} \cdot g_0 + (R_B + R_E + \mathrm{Re}(Z_2)) \right) +$$
$$\frac{Y_{-1}}{Y_1 \cdot \mathrm{Re}(Z_{-1})} \cdot \left(\frac{1}{2 \cdot g_{-1}} + \frac{(R_B + R_E + Z_1)^2}{2 \cdot R_J^{\,2}} \cdot \frac{1}{g_{-1}} + \frac{(R_B + R_E + Z_1)^2}{2 \cdot h_{fe}} \cdot g_1 + (R_B + R_E + \mathrm{Re}(Z_1)) \right)$$

IV-Predicted Noise Figure of a HBT Mixer

The predicted single sideband noise figure of the HBT mixer is given in fig 2 (I_C=4mA V_{CE}=5.8V, LO=1GHz, IF=49MHz & V_{BE}=1.31V). All noise figures quoted in this text are single sideband.

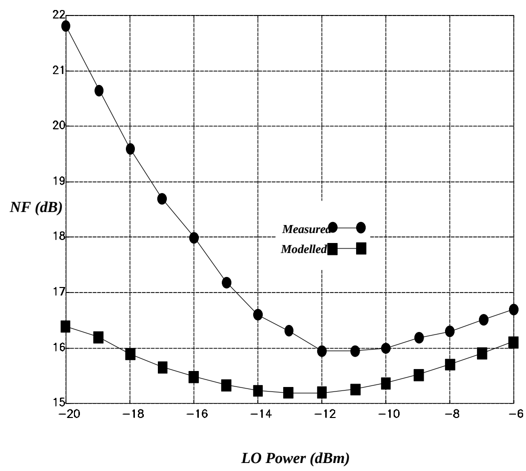

Fig. 2. Measured v Predicted Noise Figure of a HBT Mixer

From fig 2, the predicted noise figure of the HBT mixer varies from 15.2-16.4dB.

The optimum noise figure achieved (RF source impedance optimised) was 13dB (V_{CE}=5.8V, I_C=4mA, LO=1GHz, IF=49MHz) with a LO drive of -4dBm and RF (951MHz) source impedance of 37-j17Ω. The noise figure of the HBT mixer as a function of LO power, measured in a non-resonant system, is presented in fig 2, the best case measured noise figure was 15.8dB (V_{CE}=5.8V, I_C=4mA, LO=1GHz, IF=50MHz, G_C=8.5dB) for an LO power of -3dB, the worst case noise figure was 21.8dB for an LO power of -20dBm.

VI-Comments: Predicted v Measured Noise Figure

The difference between the predicted optimum noise figure and the measured noise figure of the HBT mixer is 0.7dB and the difference in LO drive is 1dB. As LO power is increased beyond that required for optimum noise performance the predicted versus measured data typically show a 0.7dB disparity. The general trend of the measured versus modelled data is very good at LO powers in excess of -16dBm.

VII-Comments: MESFET v HBT

The HBT mixer achieves a measured noise figure of 13dB with an associated conversion gain of 9dB, typically MESFET mixers achieve noise figures of between 5-8dB with an associated conversion gain of 6dB [7], thus, the HBT mixer is significantly worse than its MESFET counterpart in terms of noise performance.

VIII-Conclusions

The HBT mixer offers an optimum noise figure of 13dB and an associated conversion gain of 9dB. This result compares poorly with that achievable using MESFET technology. Measured versus predicted data shows good agreement for LO powers in excess of -16dBm.

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-Appendix I: Typical Quasi-Linear Model Parameters

Parameter	**Physical Meaning**	**Value**
gm	Transconductance	non-linear
C_J	Base-Emitter Junction Capacitance	6.06pF
C_O	Early Effect Capacitance	3.8pF
R_J	Base-Emitter Junction Resistance	2.86Ω
R_O	Output Resistance	8.08MΩ
R_E	Emitter Contact Resistance	7.468Ω
R_B	Base Contact Resistance	28Ω
R_C	Collector Contact Resistance	54Ω
C_J	Collector-Emitter Capacitor	3.84pF
C_O	Collector-Base Capacitor	0.08pF

Table A.I: Measured Quasi-Linear Model Parameters

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