Modeling of Correlated Noise in RF Bipolar Devices

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Abstract

An RF noise model is proposed for high-frequency bipolar transistors considering partial correlation of shot and thermal noise sources. For frequencies $f \geq f_T/\sqrt{\beta_0}$ expressions are derived for input noise voltage, noise current and correlation impedance. The model is verified with data obtained from a 0.5 μm BiCMOS technology developed for RF wireless applications.

Introduction

The high frequency noise exhibited by bipolar transistors (BJTs) affects the performance of several critical components in a typical RF circuit. Therefore, the measurement and modeling of RF noise in active devices is a subject of strong current interest. In RF applications it is important to consider not only the minimum noise figure of a transistor but also the optimum matching conditions. The noise analysis in standard circuit simulators (e.g. SPICE, ADVICE) assumes that the noise sources in the circuit are either uncorrelated or fully correlated with each other.[1] Typically, in an active device this assumption is reasonable only at frequencies and biases where the reactive components of the device are not dominant. For current RF wireless applications the signal frequencies are quite often nearly about a tenth of the transistor cutoff frequency. In this region the reactances play a major role in the device operation. Consequently, the partial correlation of intrinsic noise sources is realized.

An alternate approach to circuit analysis involves treating noise in terms of correlation matrices.[2] The main advantage of this method is that it enables us to take into account correlation between noise sources. It also provides the complete noise correlation matrix, i.e. the full set of noise parameters (noise figure, optimum source impedance, noise conductance). In advanced silicon bipolar technologies operating at high frequencies, the distributed nature of the various device parameters needs to be implemented. For instance, an accurate description of RF scattering parameters requires distributing the input base-emitter junction region and the base resistance. Similarly, the mutual correlation between the shot noise current and thermal noise voltage requires a lumped circuit model of the device which accurately represents the correlation. This correlation is expected since carriers crossing the junction region also contribute to thermal fluctuations in the base region.

An extension of this approach involves separating the noise behavior from the dc and ac model of the device. A lumped circuit model of the noiseless device is used for dc and ac analysis. The noise behavior is modeled by the equivalent input voltage and current noise sources, and their mutual correlation is implemented through a correlation impedance. In order not to affect the ac analysis, a negative correlation impedance can be additionally inserted at the input.[3] The major challenge of this approach is to obtain an expression for the correlation impedance which takes into account the intrinsic device properties. In this paper we present measurements of noise parameters on BJTs from the Modular BiCMOS (MBIC) process developed in Lucent Technologies. Using expressions for the equivalent input noise sources and correlation impedance, the noise parameters are modeled and compared with the data. It is found that a distribution of the dynamic input impedance is necessary to account quantitatively for the noise parameters. The model is verified by using a first order bias dependence of the circuit parameters and by comparing with noise data obtained from several different process runs.

Model description

In order to explicitly take into account the mutual correlation between the noise sources, the correlated part of the noise is separated from the individual noise sources and the latter are treated as uncorrelated. For example, the voltage noise source is expressed as :

$$v_n = v_{nu} + Z_\gamma \cdot i_n \qquad (1)$$

Here, the uncorrelated part of the voltage noise is denoted by v_{nu} and the correlated part is given by a correlation impedance Z_γ.

The formulation of a lumped circuit model for noise properties should take into account the effective noise correlation volumes in the device. We find that a reasonably simple decomposition of the capacitive and resistive components of the input impedance can be used to model the noise correlation parameters. This yields the following expressions:

$$\frac{< v_{nu}^2 >}{4kTB} = r_n = R_b \qquad (2a)$$

$$\frac{< i_n^2 >}{4kTB} = g_n = \frac{1}{2r_\pi} + \frac{r_\pi}{2\beta_0} \cdot \frac{1}{|Z_\pi|^2} \qquad (2b)$$

$$Z_\gamma = R_b + \left[\frac{1}{r_{\pi 0}} + j\omega \cdot C_{\pi 0} \right]^{-1} \qquad (2c)$$

Here the DC current gain is denoted by β_0 and the base resistance by R_b. The input impedance Z_π (π-model) is composed of the resistance $r_\pi = kT/qI_B$ and the capacitance $C_\pi = \tau g_m$, where τ is the carrier transit time. The decomposition of the input impedance is given by $r_{\pi 0} = \rho r_\pi$ and by $C_{\pi 0} = \sigma C_\pi$. Note that the basic procedure for quantitatively accounting for the noise parameters in terms of lumped RF components of the device is to decompose the input impedance, reflecting the distributed nature of the base-emitter junction region, and is characterized by the parameters ρ and σ. This property has been noted for high-frequency BJTs previously.[4]

Results

Fig.1 shows the frequency dependence of the noise parameters at a fixed bias of I_C = 8mA in common-emitter configuration.

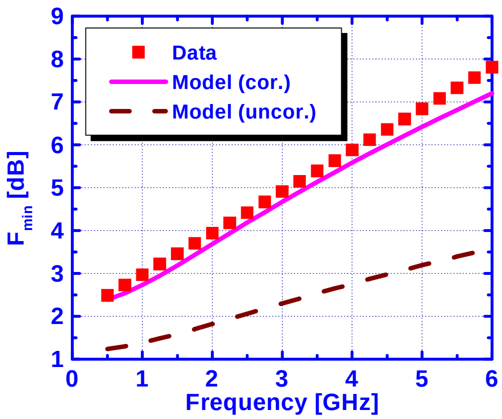

Fig.1a) *Measured minimum noise figure compared with results obtained from the model with and without correlations.*

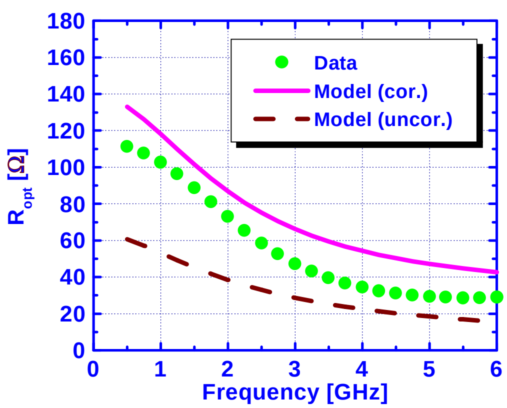

Fig.1b) *Measured optimum source resistance compared with results obtained from the model with and without correlations.*

The symbols are data obtained from an MBIC BJT composed of eight emitter fingers with each stripe being 0.6 x 3.6 μm^2. The solid lines show the results using the noise model including correlations (ρ = 0.45 and σ = 0.2), the dashed lines show the results of the model calculation without considering correlations.

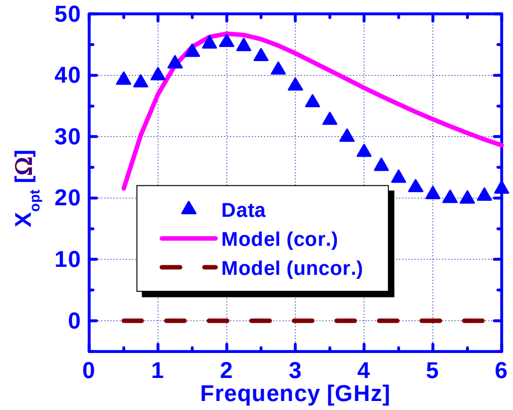

Fig.1c) *Measured optimum source reactance compared with results obtained from the model with and without correlations.*

Note that a significant improvement is seen for the minimum noise figure and optimum source reactance by including intrinsic current-voltage correlations.

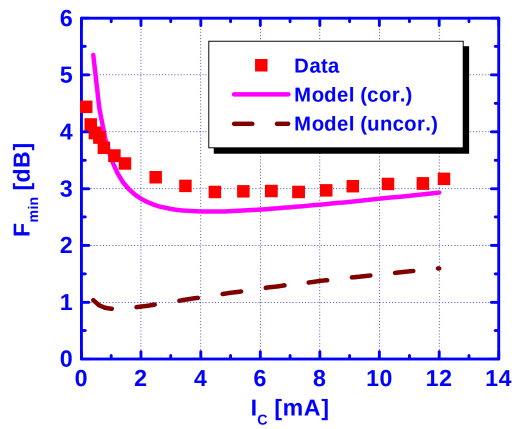

Fig.2a) *Measured and modeled bias dependence of minimum noise figure.*

Fig.2 shows the corresponding quantities for the bias dependence at a fixed frequency of 1 GHz. In this case also the improvement in noise parameter modeling with correlations is apparent. The noise conductance g_n is not affected as it is determined only by the shot noise mechanisms.

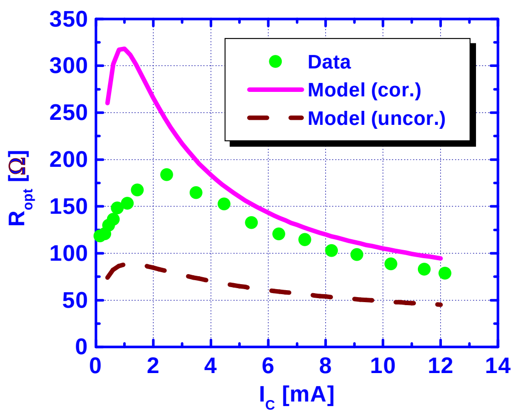

Fig.2b) *Measured and modeled bias dependence of optimum source resistance.*

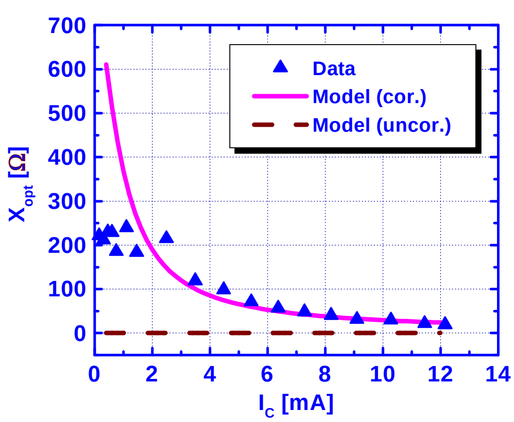

Fig.2c) *Measured and modeled bias dependence of optimum source reactance.*

Finally, Fig.3 shows that the model calculations can account for a wide variety of processing conditions by choosing a range for the parameters describing the distributed nature of the input impedance of the device (ρ and σ).

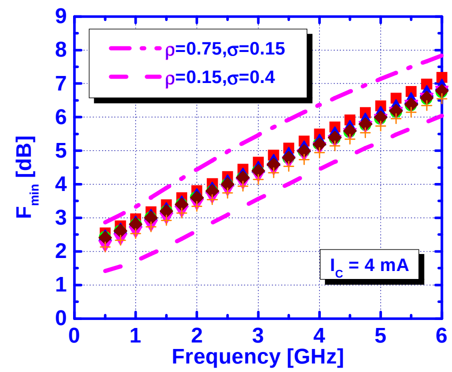

Fig.3) *The distribution of noise figure from different process runs is accounted for by varying the model parameters.*

The data were obtained on devices from different process runs and illustrate the variation of the minimum noise figure.

References

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