Improved Noise Models for High-Speed SiGe HBT RF Circuit Design

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Task Overview

- Task Description
- Task Objectives / Deliverables
- Task Leader
- Students with Grad Date
- Industrial Liaisons
- Past year accomplishments
  - New extraction based model
  - Scalability modeling

Task Objectives

- Development of more accurate RF noise models for SiGe RFIC design
  - Methodologies of RF noise source extraction
  - Evaluation of existing models
  - New model and parameter extraction development
  - Model verification on 50 / 120 / 200 GHz HBTs for SRC member companies
- Tools for application of new model in circuit design
  - Matlab codes for model parameter extraction
  - Verilog-A based models (VBIC based) for application of the new model in circuit design

Personnel

- PI and Co-PI
  - Guofu Niu (Auburn) and John Cressler (Georgia Tech)
- Students
  - Kejun Xia (Auburn, PhD, to graduate Fall 2005, presenter)
  - Qingqing Liang (Georgia Tech, PhD, graduated Spring 2005, now at IBM)
- Industrial Liaisons
  - David Sheridan (IBM)
  - Shaikh F. Shams and Hernan A. Rueda (Freescale)

Industry Interaction and Knowledge Transfer

- Extensive collaboration and transfer of research result to IBM and Freescale
  - New model
  - Parameter extraction methods
- The PI visited Freescale in Dec 2004
  - Presentation of results
  - Transfer and demonstration of noise extraction and modeling matlab codes
- Numerous interactions with IBM Modeling group
- Student internship
  - Summer 2004 at IBM, Burlington – with Scott Parker

Past Year Accomplishments

- Noise source extraction / parameter extraction methods
- Major models evaluated
- Connections between different models established
- A new expression for noise crowding effect derived
- Noise crowding effect quantified experimentally
- A new model for all noise sources is developed
  - Explicit modeling of frequency dependence through w or w^2
  - Explicit modeling of current dependence through gm
  - Scalable over multiple geometries
  - Extensive verification using measured and simulated data on 50 GHz HBTs
  - Initial investigation on 200 GHz HBTs
Publications


Noise Figure: Definition and Importance

- Noise Figure (NF) = (Si/Ni)/(So/No) > 1 as amplifier adds noise
- NF determines Minimum Detectable Signal and hence sensitivity of a wireless system
- Cost and density of base station infrastructure are directly determined by receiver noise figure
- 1dB degradation in Noise Figure is a big deal – for cell phones, it means 26% more additional base stations

Minimization of noise through bandgap engineering as well as accurate modeling of noise are important!

Noise Sources In Transistor And Expected Modeling Improvement

- 4kT/q thermal noise for Rbx, Rcx and Re - well understood
- Thermal-like noise for intrinsic base resistance rbi
- Crowding effect, quantification needed
- 2q1 shot-like noise (white) for base and collector current
- Experimental extraction of Ib and Ic noise clearly needed!
- Our extraction has shown strong frequency dependence of IB noise, and strong correlation between IB and IC noises.

Intrinsic Base Resistance Noise With Crowding Effect

- Theoretical results are given by J. C. J. Paasschens in [2]
- Expressed with two parameter Vbxbi and Rb.
- Generally Vbxbi = several kT (=kT/q), difficult to extract
- Newly proposed approximation $\frac{1}{R_{np}} + \frac{4kTq}{2q1}$ [1]
- Based on [2], more convenient when using small signal ckt
- Exact for circular BJT, < 3 % error for rectangular BJT

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NF determined by transistor noise parameters and source
NF => NFmin when Ys = Ys, opt (noise matching)
Rn determines sensitivity to deviation from Ys, opt

$NF = NF_{min} + \frac{R_n}{G_s} |Y_s - Y_{s, opt}|^2$

What fundamentally determines transistor noise parameters?

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How Crowding Effect affects SiGe Intrinsic Base Resistance Noise?

- $S_{\text{Sib}} = 4kT/r_{\text{bi}} - 2qI_b$

Crowding effect on noise is negligible in SiGe HBTs
- Because of the heavily dope base
- Small base resistance $r_{\text{bi}}$
- Small base current $I_b$

Summary of Important Noise Models

- **van Vliet Model**
  \[ S_{\text{Sib}} = 4kT(Y_1 + Y_2) \]

- **Transport Noise Model**
  \[ S_{\text{Sib}} = 2qI_b (e^{V_{br}} - 1) \]

- **SPICE Model**
  \[ S_{\text{Sib}} = 2qI_b \]

- **Semi-empirical Model**
  SiB modeling is demonstrated here.

New Semi-empirical Extraction Based Intrinsic Noise Model

- **Pros:**
  - Using conventional models without input NQS effect
  - Infrastructure of conventional models can be used

- **Cons:**
  - Resulting noise currents may not be completely physical
  - Involve several additional parameters dedicated to noise modeling

- **Technical approach:**
  - Small signal parameter extraction to obtain accurate and physically meaningful values
  - Intrinsic noise sources extraction using de-embedding of all circuit elements step by step using standard noise circuit analysis theory (Hilbrand and Russer)
  - Intrinsic noise sources modeling
  - Geometry scaling examination

Small Signal CKT – No Input NQS

Devices and Parameter Extraction

- 50 GHz peak ft SiGe HBTs with different geometries are used to develop noise model and examine noise scaling
  - 0.24x20x2 um² (reference device)
  - 0.24x10x2 um² (emitter length scaling)
  - 0.24x20x1 um² (finger number scaling)
  - 0.48x10x1 um² (emitter width scaling)

- SiGe HBT noise simulations are used to provide guidance to model equation development
- Excellent Y-parameters fitting is obtained
  - For all devices
  - Parameters are well consistent with geometry scaling

Intrinsic Sib and Sic Extracted

- Extracted Sib > 2qIb and strongly frequency dependent
  - The van Vliet model Sib=2qIb, the same as the SPICE model, when the input NQS effect is not modeled.
  - The transport noise model Sib is fitted to the extraction result with parameter $r_{\text{bi}}$
- Extracted Sic > 2qIc and frequency dependent
  - All models give 2qIc and hence overlap with each other.
Intrinsic $\text{Sicib}^*$ Extracted

- Extracted $\text{Sicib}^*$ is significant and frequency dependent
  - SPICE model, $\text{Sicib}^*$ not used
  - van Vliet model, much underestimate the value
  - Transport model, $\text{Sicib}^*$ improves the frequency dependence a lot. However, its $\text{Im}($$\text{Sicib}^*)$ is not well modeled, as $r_n$ has been used to fit $\text{Sib}$ only.

![Graph showing frequency dependence and bias dependence comparison]

- For each of $\text{Sib}$, $\text{Sic}$, $\text{Im}($$\text{Sicib}^*)$ and $\text{Re}($$\text{Sicib}^*)$
  - Examine the frequency dependence through $g_m$
  - Examine the bias dependence of coefficients through $g_m$
  - Develop new equations guided by noise physics
  - Insight from noise simulation
  - Analysis of transport and van Vliet (with input NOS) models

- Normalized correlation $c$
  - Schwartz inequality
  - How much is $c$ for SiGe HBTs examined?

- Geometry scaling
- Rule derivation
- Verification

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Sib and "induced" base current noise

**Frequency dependence:**
$$S_{ib} = 2qI_b + K_{bb}g_m\omega^2$$

**Bias dependence:**
$$C_{ib} = K_{ib}g_m$$

![Graph of frequency dependence and bias dependence comparison]

Understanding "Induced" Base Current Noise

- $1 = dq/dt$
- Frequent dependence is consistent with van Vliet model and transport model
- Bias dependence different

$$S_{ib}^{\text{Exp}} \approx 2qI_b + 4kTC_{ib}g_m^2\omega^2$$

Frequency Dependence of Sic

$$S_{ic}^2 = C_{ic}R(Y_{21})$$

- Firstly, the bias dependence of Sic $C_{ic} = K_{ic}g_m + B_{ic}$.

- Therefore
$$S_{ic} = (K_{ic}g_m + B_{ic})R(Y_{21})$$

Sic – Collector Current Noise

- Experimental data
- More accurate at low frequencies, system noise plays a bigger role

- Simulation data

Im(S_{icb}*) – Imaginary Correlation

Frequency dependence:
\[ \Im(S_{icb}^*) = -C_{icb}^1 \omega \]

Bias dependence:
\[ C_{icb} = K_{icb} G_m^2 \]

Re(S_{icb}*) – Real Correlation

The bias dependence of coefficients are
\[ C_{icb}^1 = k_{icb} G_m \]
\[ C_{icb}^2 = k_{icb} G_m^2 \]

Therefore
\[ \Re(S_{icb}^*) = K_{icb} G_m - K_{icb} G_m^2 \omega^2 \]

Normalized Correlation c

By definition
\[ c = \frac{S_{icb}^*}{\sqrt{S_{ss}} S_{icb}} \]

Schwartz inequality must be satisfied:
\[ |c| \leq 1 \]

If this is not satisfied
- Double check Y-parameters extraction
- Double check noise extraction

Extracted c And Modeling Results

\(|c|\) is about 0.9 at high lc. The correlation is important for SiGe HBTs examined.

Imaginary part is much more important than real part!
Generalized Model Equations

- $\alpha_m = 2$, $\alpha_w = 1$ and $\alpha'_{s} \approx 1$ and $\alpha'_{s}^{*}$ is between 1 and 2
- $B_{bb}^{*}$ and $B_{cb}^{*}$ are close to zero, $B_{cc}^{*}$ is about $2KT$
- Only a slight accuracy loss in $B_{opt}$ by setting $Re(S_{icib}^{*})=0$,
  reduce to nine parameters
- Schwartz inequality is not satisfied automatically.

\[
S_{th} = 2qI_s + (K_{bb}^{*}g_m^{*} + B_{bb}^{*})\omega^2
\]
\[
S_{th} = (K_{cc}^{*}g_m^{*} + B_{cc}^{*})\Re(Y_{21})
\]
\[
\Re(S_{icib}^{*}) = K_{ic}^{*}g_m^{*} - K_{ic}^{*}g_m^{*}B_{ic}^{*}\omega^2
\]
\[
\Im(S_{icib}^{*}) = -K_{ic}^{*}g_m^{*} + B_{ic}^{*}\omega
\]

Extracted Model Parameters

- $AE=0.24\times20\times2\ \text{um}^2$ (the reference transistor)
- Parameters are in MKS unit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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<td>$B_{ic}^{*}$</td>
<td>$8.2843 \times 10^{-2}$</td>
<td>$B_{ic}^{*}$</td>
<td>$8.2843 \times 10^{-21}$</td>
</tr>
</tbody>
</table>

Noise Parameters Versus Frequency

Noise Parameters Versus $I_C$

Geometry Scaling Rule For Ideal Transistor With Same Profile

- dc, ac currents and Y-parameters are proportional to emitter area $AE$ (same profile if biased at same $J_c$).
- $B_{bb}$, $B_{cb}$ and $Re(Y_{21})$ can be calculated using scaling factor $M=AE/AE_0$.
- $s$, $t$, $m$, $g$ and $Re(Y_{21})$ can be calculated using scaling factor $M=AE/AE_0$, $AE_0$ is selected as a reference.

- $S_{ib}$, $S_{ic}$ and $Re(S_{icib})$ scale linearly with $AE$ of a reference transistor.

Geometry Scaling Rule Derived

- $S_{ib}$, $S_{ic}$ and $Re(S_{icib})$ of different geometries overlap well.
- Noise figures are not sensitive to $Re(S_{icib})$, thus difficult to extract.

\[
K_{bb}^{*} = K_{bb}^{*}M^{-a_{w}} \quad B_{bb}^{*} = B_{bb}^{*}M
\]
\[
K_{cc}^{*} = K_{cc}^{*}M^{-a_{w}} \quad B_{cc}^{*} = B_{cc}^{*}M
\]
\[
K_{ic}^{*} = K_{ic}^{*}M^{-a_{w}} \quad B_{ic}^{*} = B_{ic}^{*}M
\]
**Summary of Results**

- SiGe HBT noise sources extracted experimentally
- Alternative models evaluated
- Connections between various models established
- New expression obtained for base noise crowding effect
- Noise crowding effect quantified for the first time
- A new noise model has been developed
  - Explicit frequency dependence for $S_{ib}$ and $S_{ib}^*$
  - Explicit bias dependence for all through $g_m$
  - Scalable over emitter width, length, and number of fingers
- The new model has been verified on 50/60 GHz HBTs
  - From 2-25 GHz over a wide biasing range beyond peak $f_T$
  - Scalability verified for width, length and finger number

**Next Year Plan**

- Extensive model verification on 200 GHz HBTs
- Develop more efficient parameter extraction
- Develop a simpler model with fewer parameters if at all possible
- New noise test structures for improved measurement accuracy
- Implement the proposed model in our Matlab code
- Explore implementation using Verilog-A