Simulation of Physical Semiconductor Devices under Large and Small Signal Conditions

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Outline

(A) Physics-Based Analysis of a RF-Bipolar Transistor

- Simulation Frame
- DC, AC, Noise, Large Signal Transient Analysis

(B) Harmonic Balance for Mixed-Mode Simulations

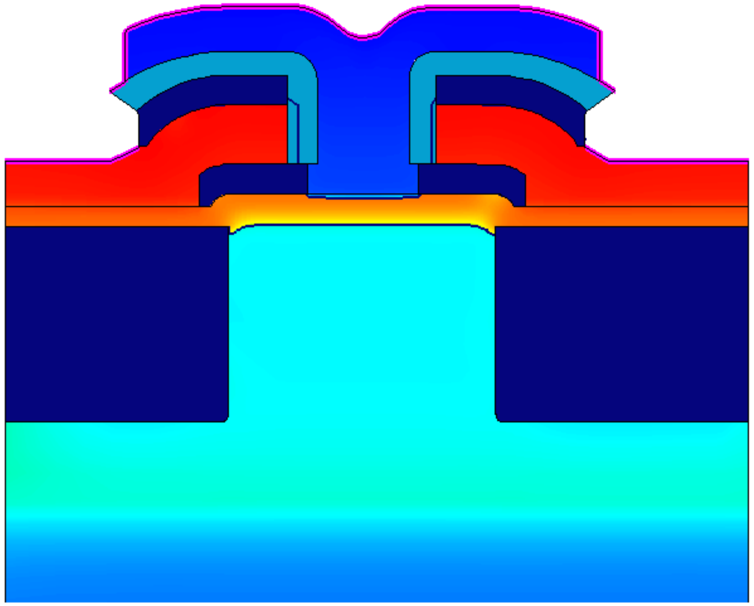
- HB Equation Solving Strategies
- Examples

  PN Diode, Varactor Frequency Doubler,
  MOSFET, Simple Bipolar

Conclusions

RF-Bipolar

Physics-Based Characterization
of the Intrinsic RF-Bipolar Transistor
and of Mixed-Mode Power Amplifier

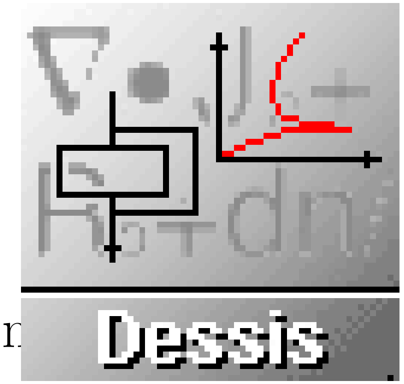


RF-Bipolar Structure (Segment)
with Doping

Figures of Merit:

- **DC:** Early and Gummel Plots
- **Small Signal:** S-Parameters, Power Gain, Current Gain
- **Noise:** Voltage and Current Noise Spectra
- **Large Signal:** Distortion, Compression Point CP_{1dB}, IP3

Simulation Frame



Transport:

DD, TD, HD, QDD, MC, ...

Physical Description:

Thermionic Emission, Tunnelin

Gate Currents, Schrödinger,

Optics, Physical Model Interface (PMI), ...

Computational Features:

1D - 3D, Hetero Structures,

DC Grid Adaptation,

Mixed-Mode (HSPICE),

Compact Model Interface (CMI)

Analysis:

DC, Transient, AC, Noise

Drift-Diffusion Model

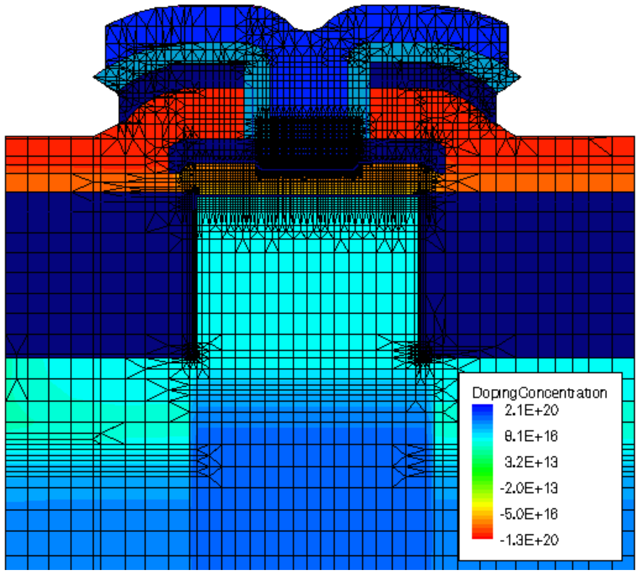
$$\begin{aligned} -\nabla \cdot (\epsilon \nabla \psi) &= q\,(p - n + C) \\ q\frac{\partial n}{\partial t} - \nabla \cdot \mathbf{j}_n &= -q\,R \\ q\frac{\partial p}{\partial t} + \nabla \cdot \mathbf{j}_p &= -q\,R \end{aligned}$$

$$\begin{aligned} \mathbf{j}_n &= q\,(D_n \nabla n - \mu_n n \nabla \psi) \\ \mathbf{j}_p &= -q\,(D_p \nabla p + \mu_p p \nabla \psi) \end{aligned}$$

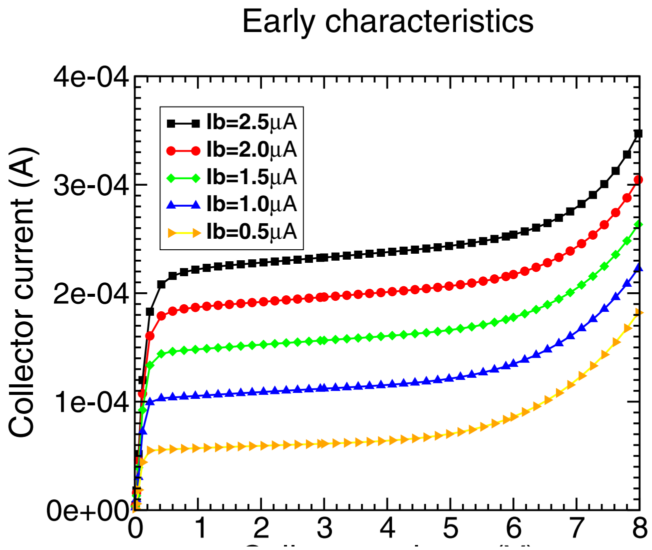
and boundary conditions

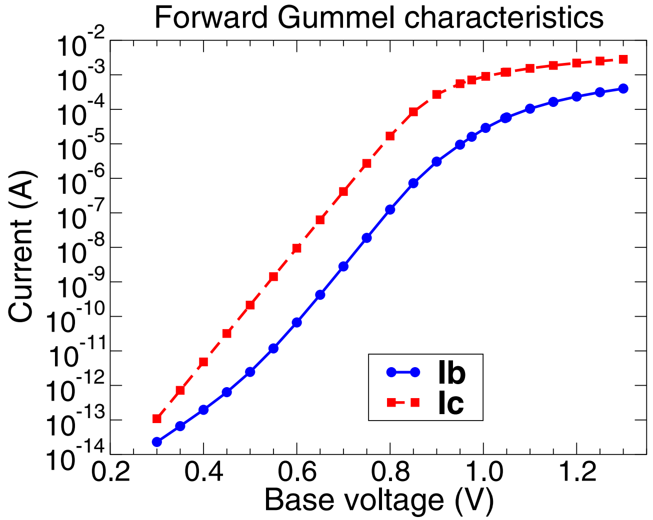
$$\frac{d}{dt} q(r, u(t)) + f(r, u(t), w(t)) = 0$$

RF-Bipolar: DC



Grid Size $N_V = 6654$





Physical Effects:

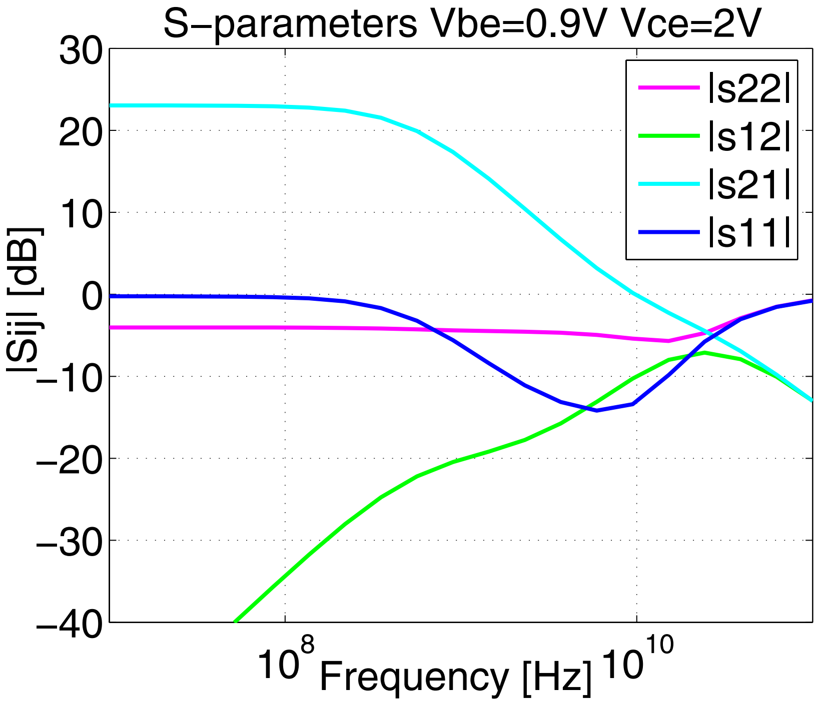
Bandgap Narrowing,
Minority Diffusion Length,
Saturation Velocity, Doping of Collector,
Pre-Breakdown, ...

AC Analysis

Linearization around DC Solution u_0

$$[j\omega q'(u_0) + f'(u_0)]\, U_1 = -W$$

U_1 Phasors of Solution Variables



S-Parameters

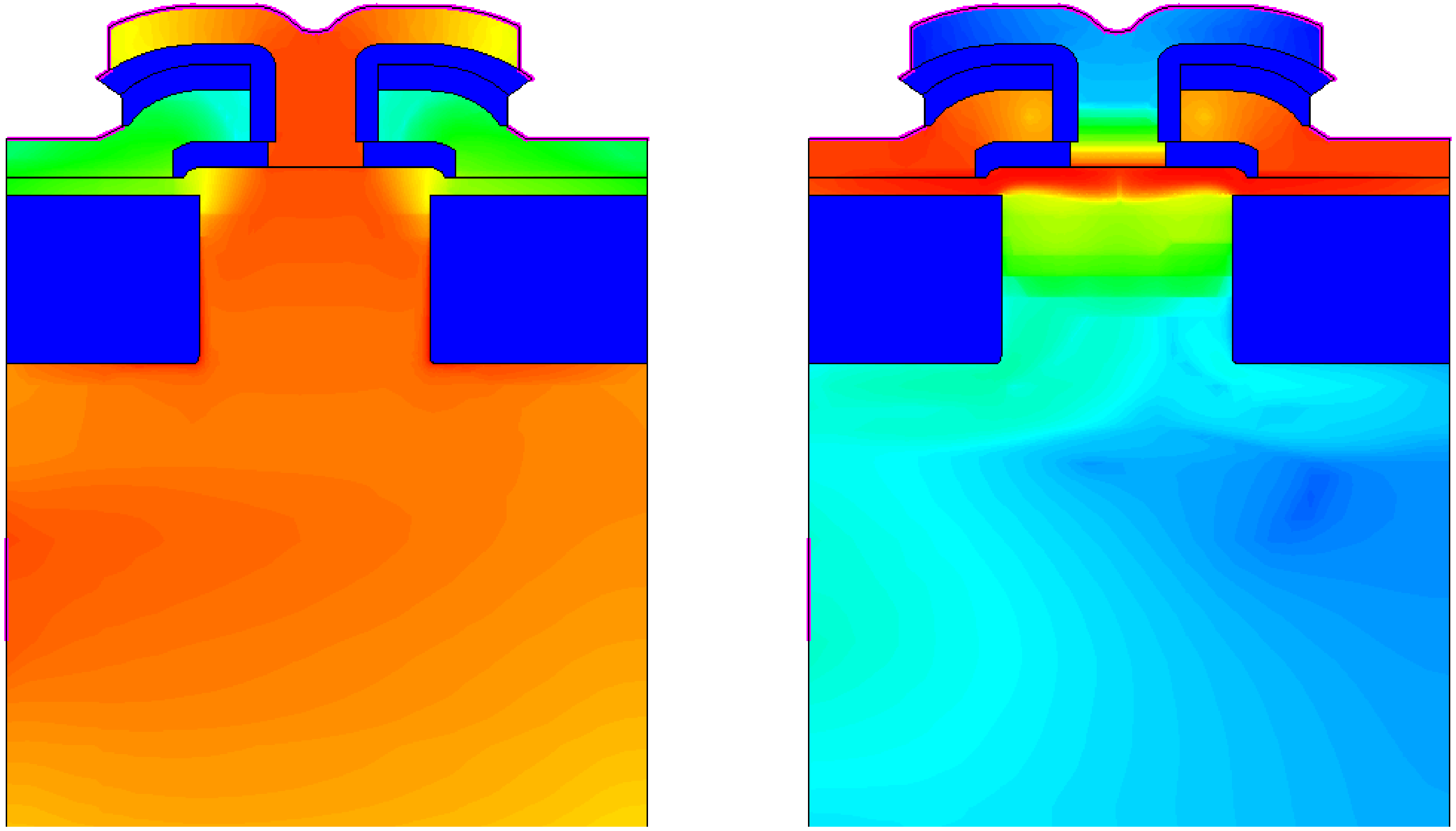
Results:

- **Y-Parameters**
- Locally Distributed Response
  of Potential, Densities, and Current Densities

Computational Aspects

- Solve Linear System in $\mathbb{C}$
- Requires **Direct Linear Solver** !

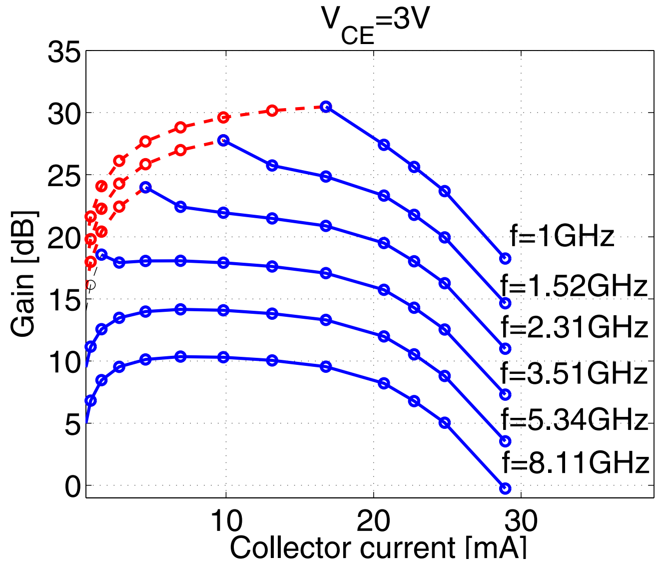
RF-Bipolar: Small Signal

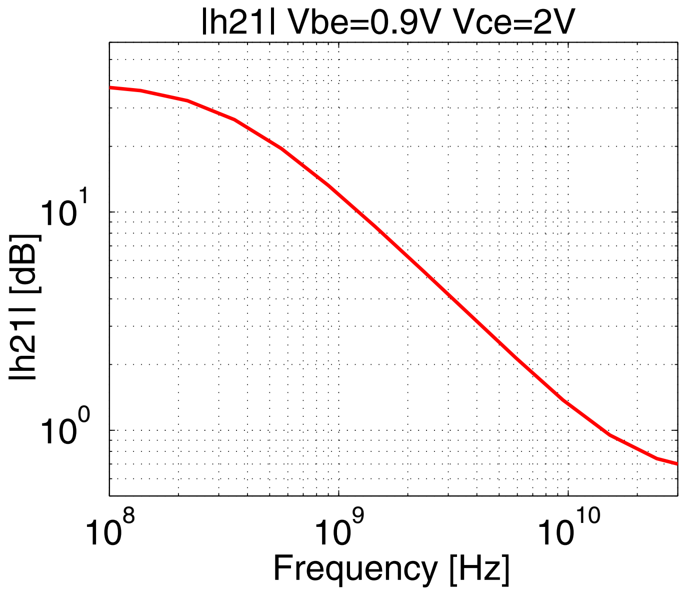


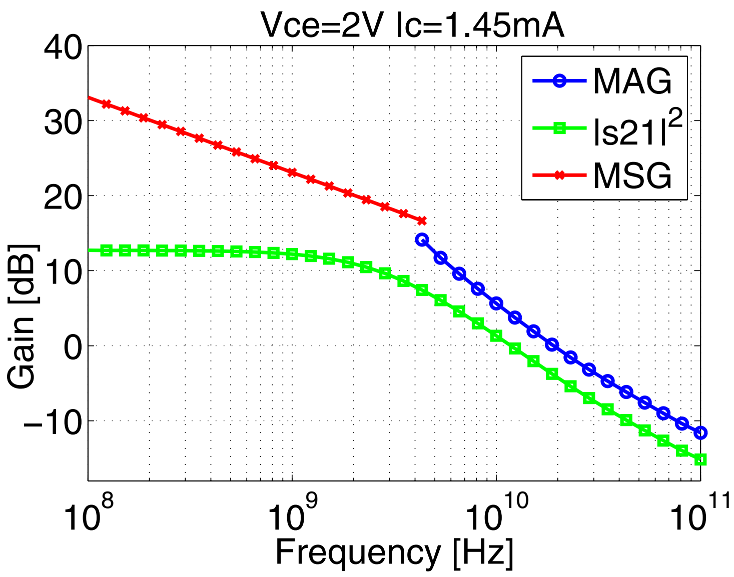
Electron Current Hole Current

Local AC Current Densities ($\left|Re(\mathbf{J}^1)\right|$)

RF-Bipolar: Small Signal







Noise Analysis

Shockley's Impedance Field Method

Langevin Equation

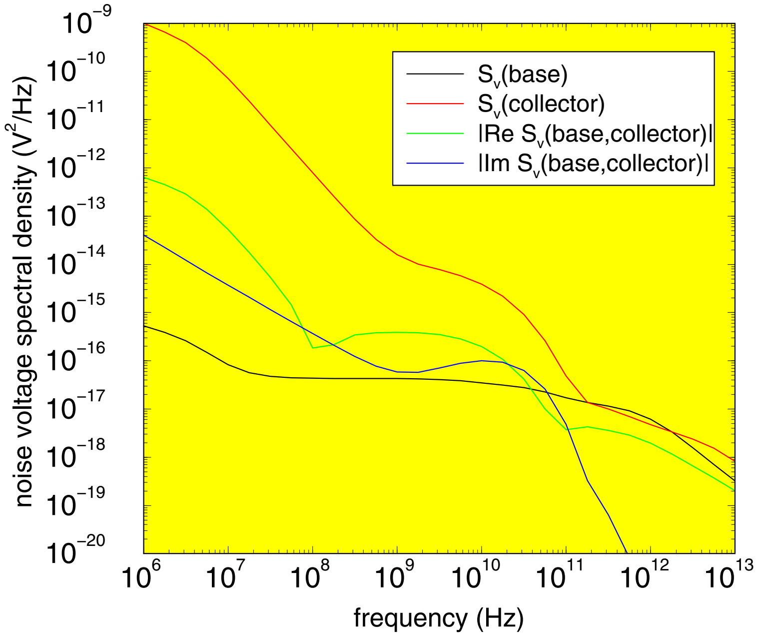
$$L(D, u_0)\delta u = s$$

Noise Voltage Spectral Density

$$S_{V,V}(r, r'; \omega) =$$

$$= \sum_{\alpha,\beta} \int_{\Omega} \Gamma_\alpha(r, r_1; \omega) K_{\alpha,\beta}(r_1; \omega) \Gamma^*_\beta(r', r_1; \omega) d\, r_1 +$$

$$+ \sum_{\alpha,\beta} \int_{X} \underline{\Gamma}_\alpha(r, r_1; \omega)\, \underline{\underline{K}}_{j_\alpha, j_\beta}(r_1; \omega)\, \underline{\Gamma}^*_\beta(r', r_1; \omega) d\, r_1$$



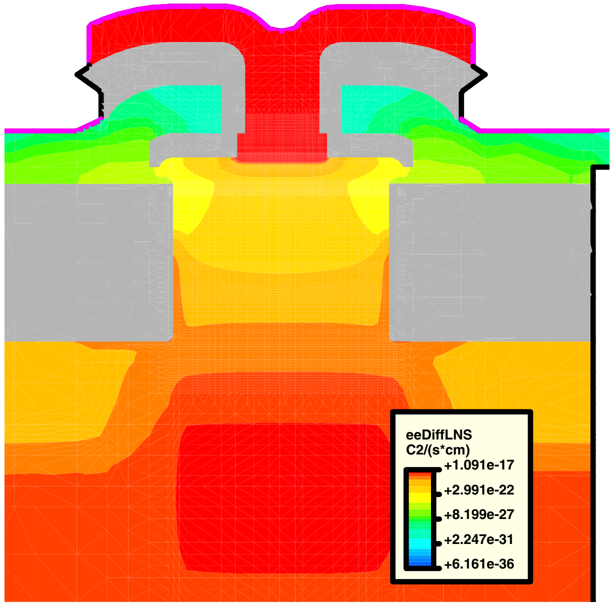
Noise Voltage Spectral Densities
of the Bipolar

Diffusion Noise Source

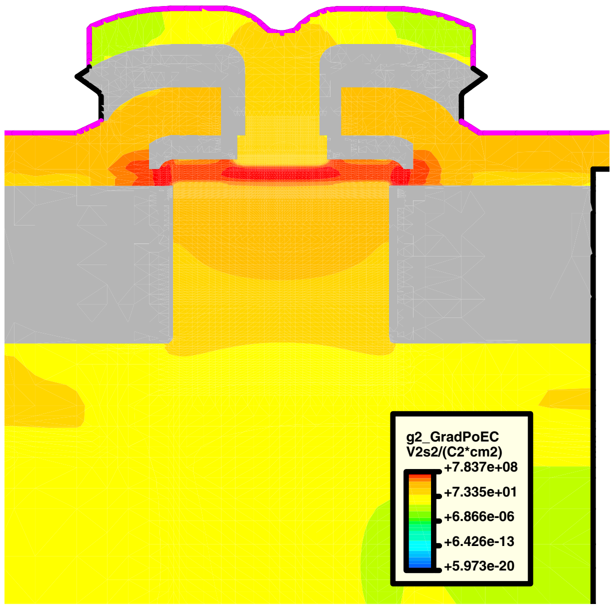
$$\underline{\underline{K}}_{j_n, j_n}(r) = 4q^2 n(r) \mu_{\mathrm{n}}(r)$$

RF-Bipolar: Noise

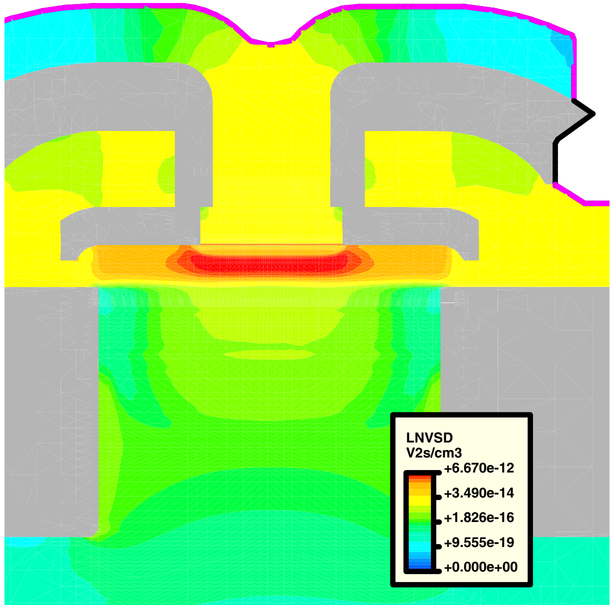
Bias: $V_{BE} = 0.84$ V, $V_{CE} = 2$V, f = 10 GHz



Diffusion Noise Source
for Collector Node (Electrons)

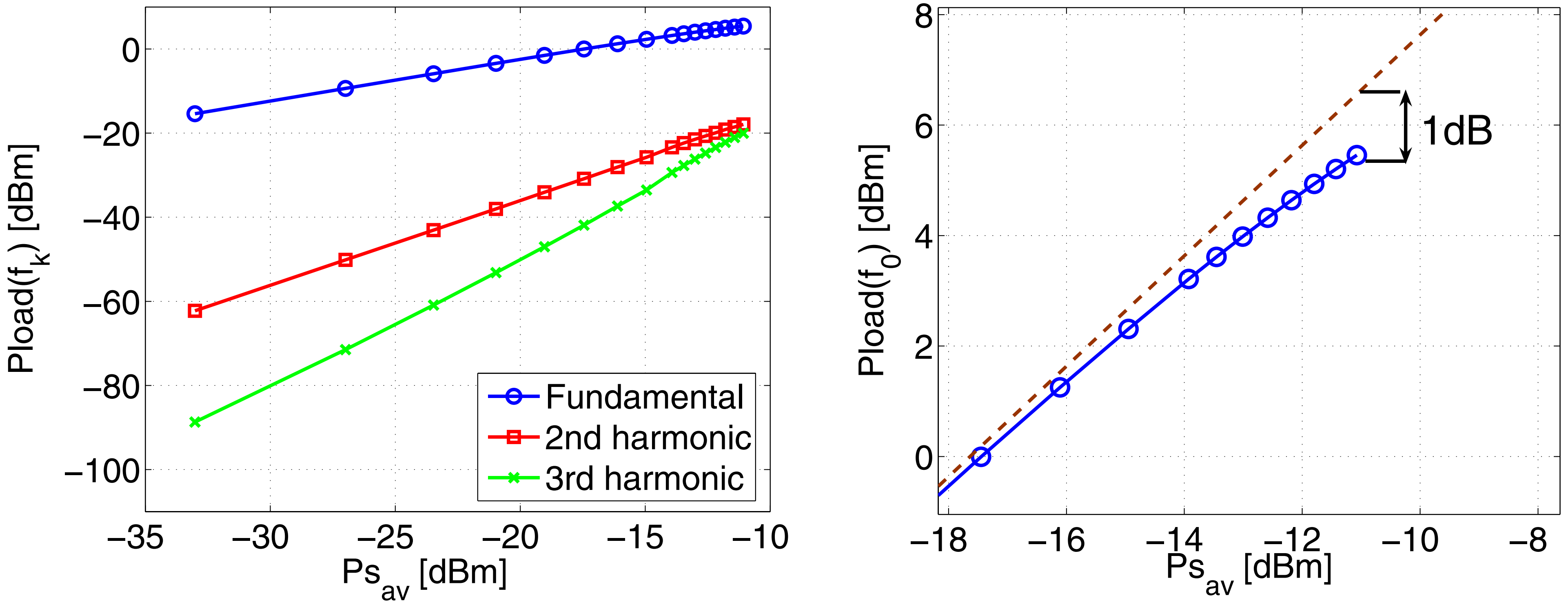


Square of Green's Function
for Potential (Electrons)



Total Noise Spectral Density
for Voltage at Collector Node

RF-Bipolar: Large Signal Transient



Simulation: $R_L = 22.5$ kOhm, f = 1 GHz, **Compression Point Reached**

Harmonic Balance (HB)

Periodic/Almost-Periodic Excitated Systems

Standard Method for RF Circuits

Time Domain:

$$\frac{d}{dt}q\left(r,x(t)\right)+f\left(r,x(t),w(t)\right)=0$$

Fourier Ansatz (One-Tone):

$$x(t)=\sum_{k=-H}^{H}X^{k}\exp(j\omega kt)$$

HB Equation:

$$H(X)=\Omega^{N}\Gamma q(\cdot)\Gamma^{-1}X+\Gamma f(\cdot)\Gamma^{-1}X=0$$

Optimization of RF Devices

Device Level HB

- Geometry and Materials
- Physics-Based
- No Quasistatic Assumption
- **Benefits:** **Faster** in case of Widespread Time Constants, **View Inside**
- **Bottlenecks:** Memory Consumption, Time Consumption, Convergence, Aliasing

DESSIS HB: Status of Implementation

(Under Development)

One-Tone HB for Mixed-Mode Simulations

Nonlinear Solving Strategies:

- **Continuation** of Amplitude, Frequency, Parameters, and Bias
- **Newton** Algorithm
  - Direct Solver **PARDISO**
  - Iterative Solver **ILS**: e.g. BiCGStab with Standard ILU Preconditioners
  - **BBP-GMRES(m,b)**: Block-Band-Preconditioned GMRES(m) with **Memory-Free** Jacobian
- **H-Decoupled**: Decoupling of Harmonics

Use of Densities or Quasi-Fermi Potentials

Problems: Memory, Time, Nonlinear Convergence, Linear Systems.

HB: Iterative Linear Solvers

Krylow Subspace Methods

Matrix-Vector Products → Memory-Less Matrix

HB Equation

- BiCGStab with ILUT Preconditioner: **Fails** with Reasonable Thresholds
- Block-Band Preconditioned GMRES(m):
  - Fine for Small Amplitudes
  - FFT per Matrix
  - Preconditioning with Direct Solver
  - **Surprisingly Robust**
  - Local Solutions

Newton:

$$\left[\Omega\Gamma q\Gamma^{-1} + \Gamma f\Gamma^{-1}\right]\,\delta U = -H(U)$$

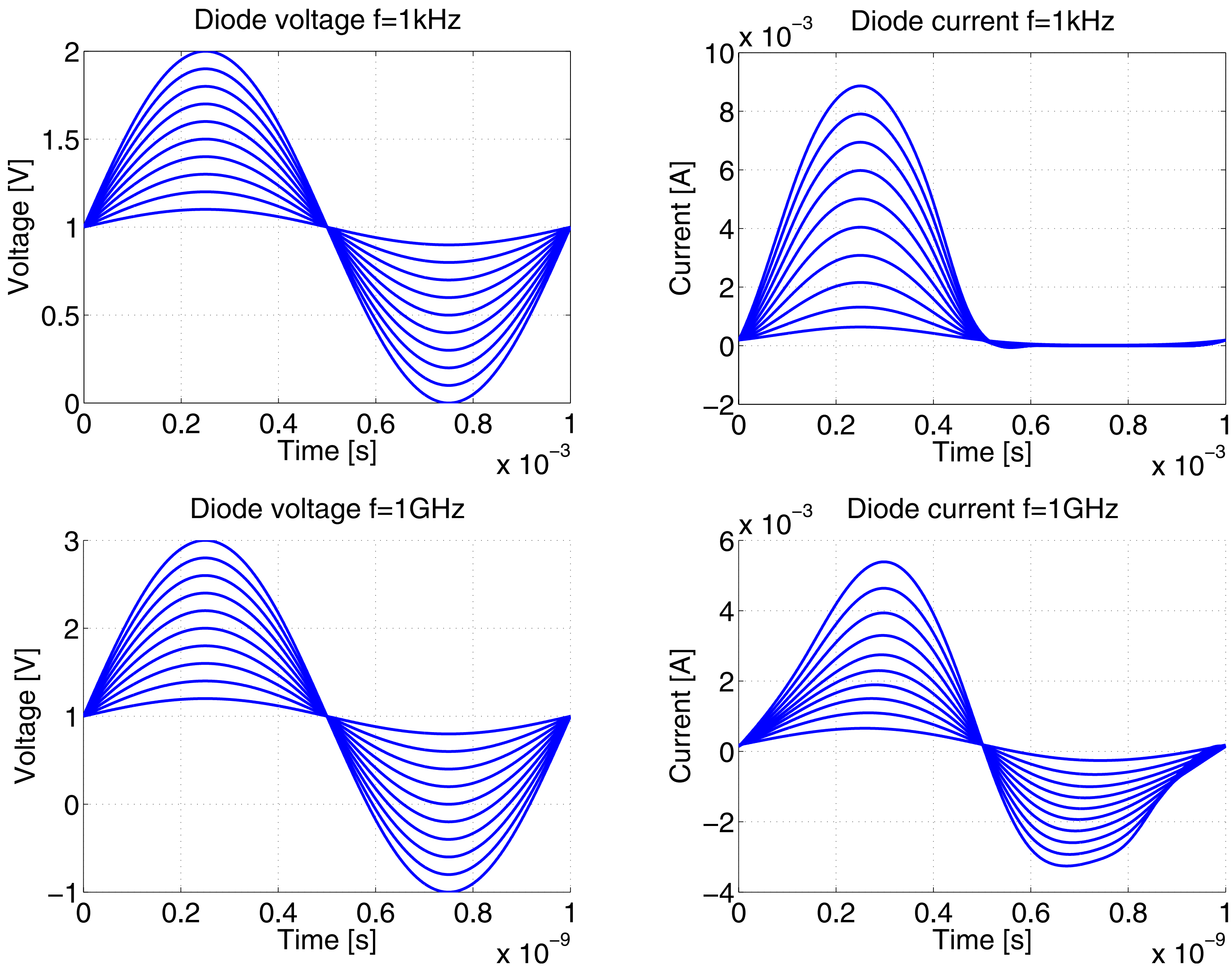
Preconditioner:

$$\begin{aligned} P &\approx A \\ P^{-1}Ax &= P^{-1}b \end{aligned}$$

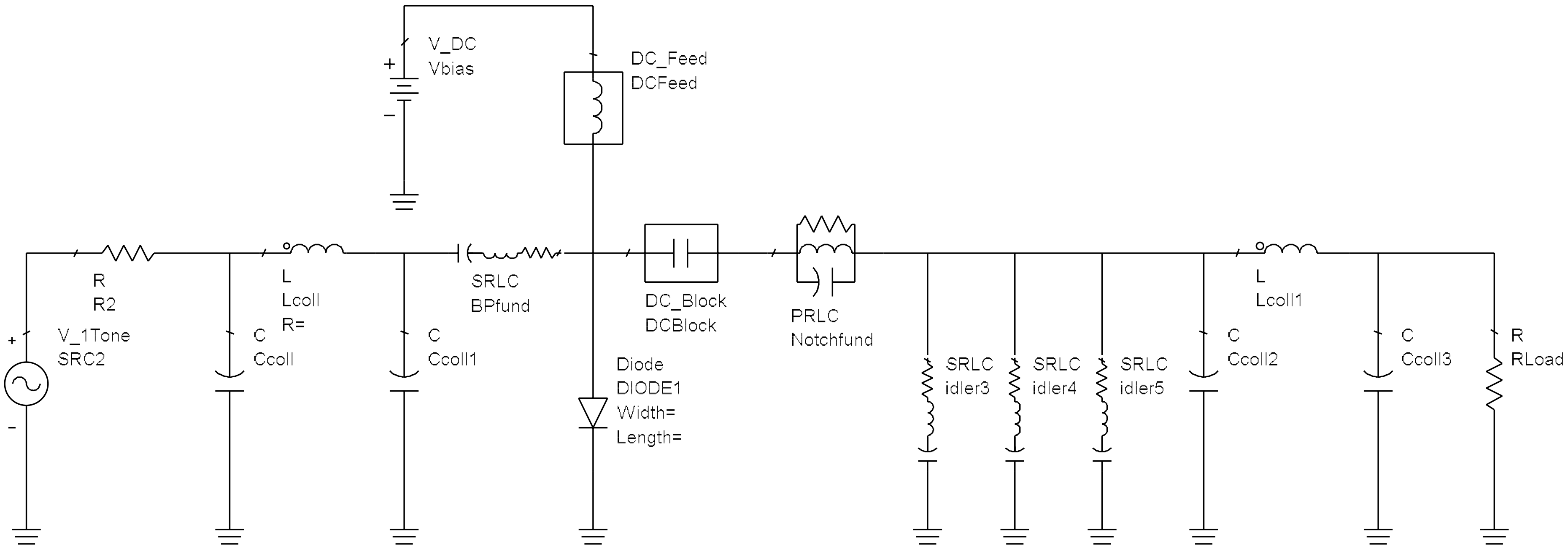
Block-Band Preconditioner:

$$\Gamma f\Gamma^{-1} \approx \begin{pmatrix} A_{0,0} & A_{1,1} & & \\ A_{1,0} & A_{1,1} & \ddots & \\ & \ddots & \ddots & A_{H-1,H} \\ & & A_{H,H-1} & A_{H,H} \end{pmatrix}$$

PN Diode: Harmonic Balance



Varactor frequency doubler



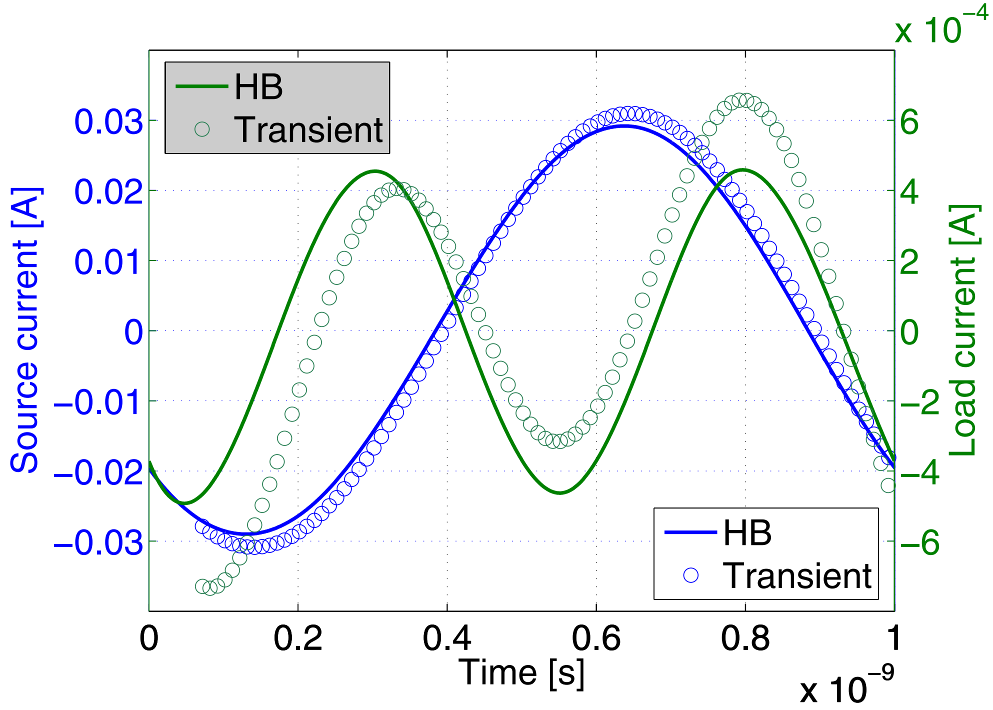
HB Simulation:

Voltage Source f = 1 GHz, H = 4, Grid Size $N_V = 478$, Direct Solver.

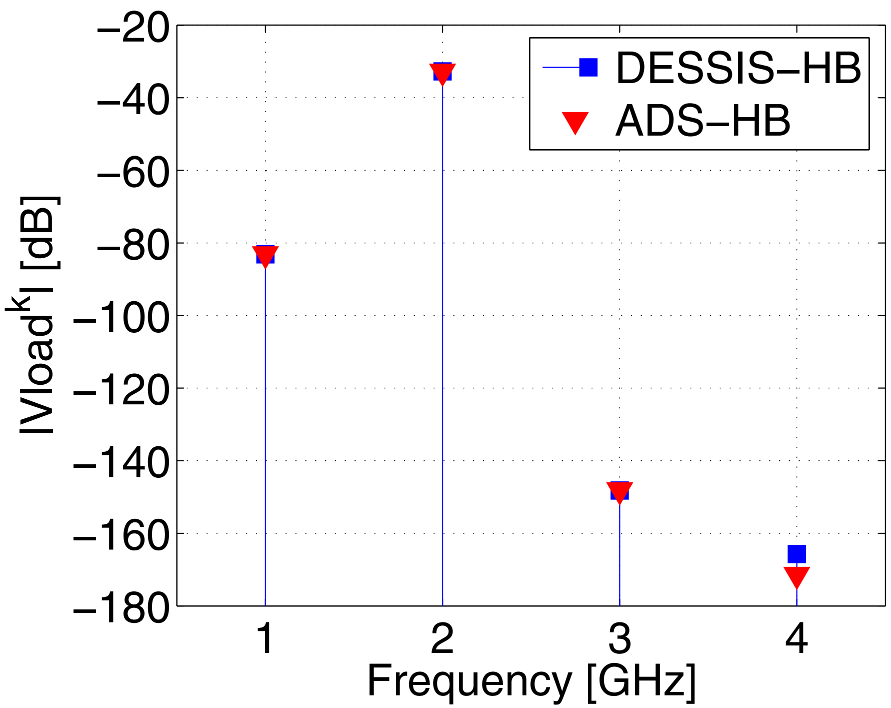
Resources: 500 MB Memory, CPU Time 20 min.

Convergence: **Error Oscillations** between Idler and Diode.

Varactor frequency doubler



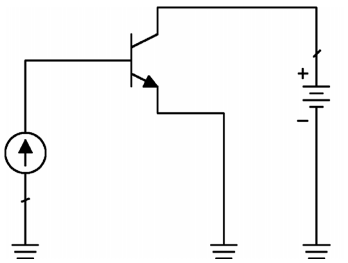
Comparison HB-Transient

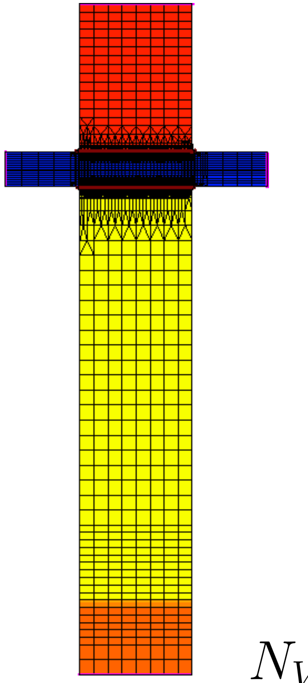


Comparison DESSIS-HB vs. ADS-HB

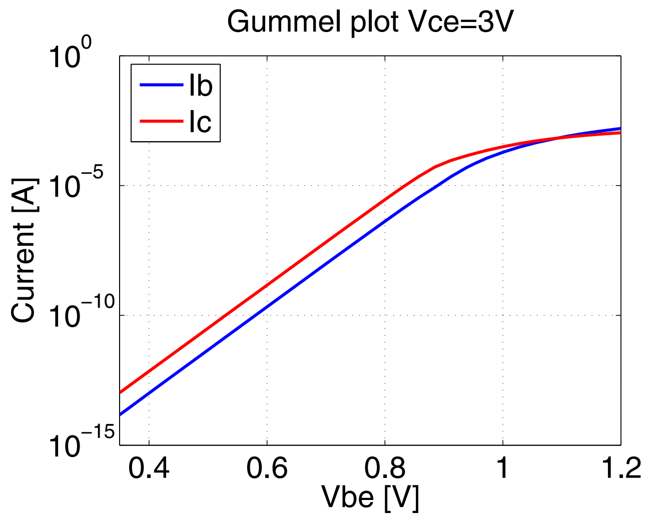
Simplified Bipolar

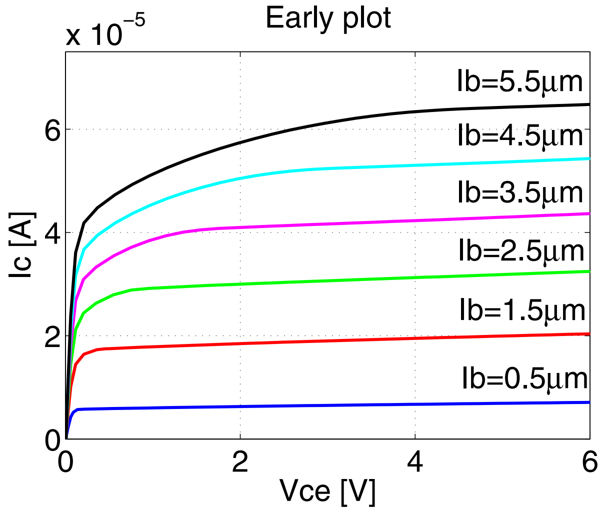
Simulation

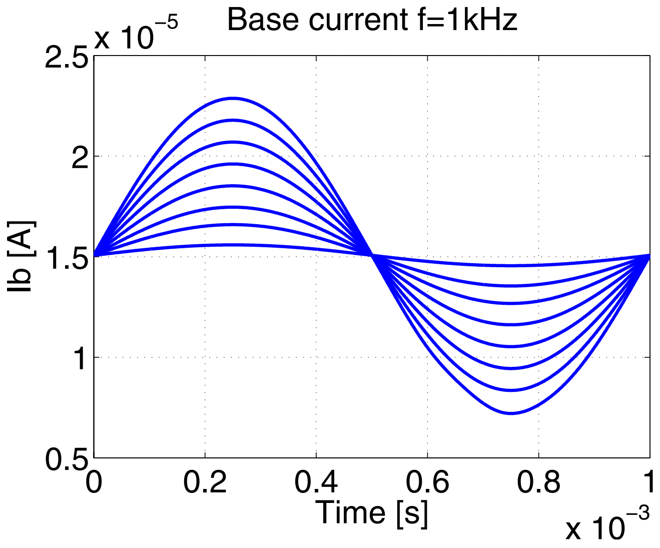


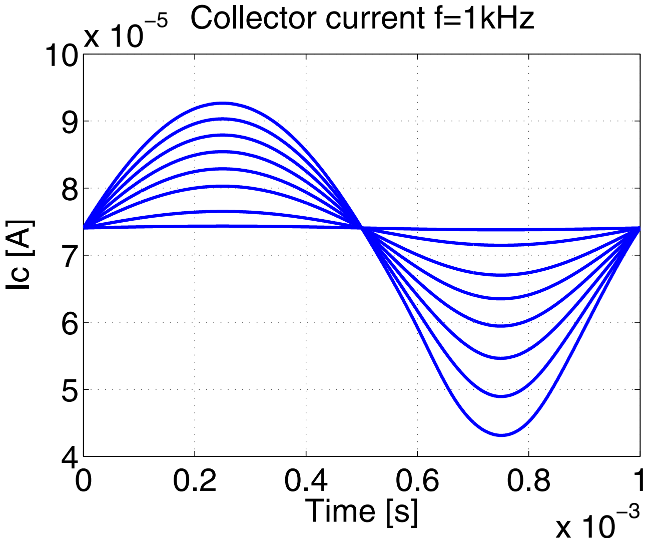


$N_V = 1191$

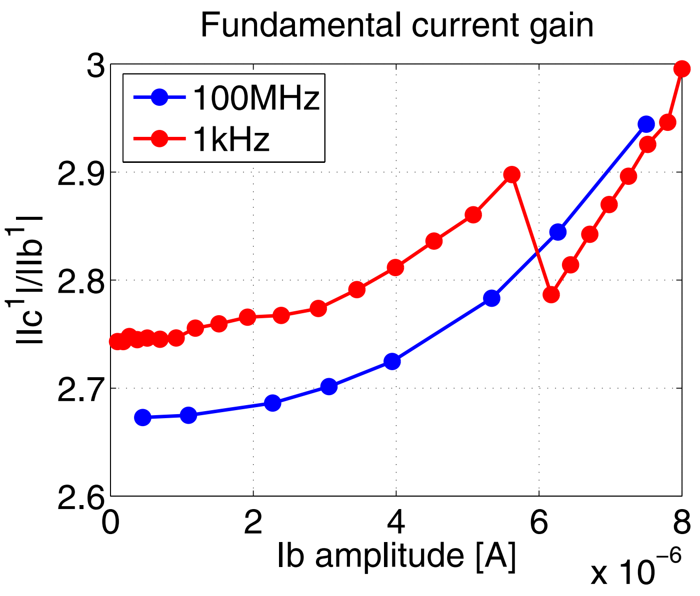


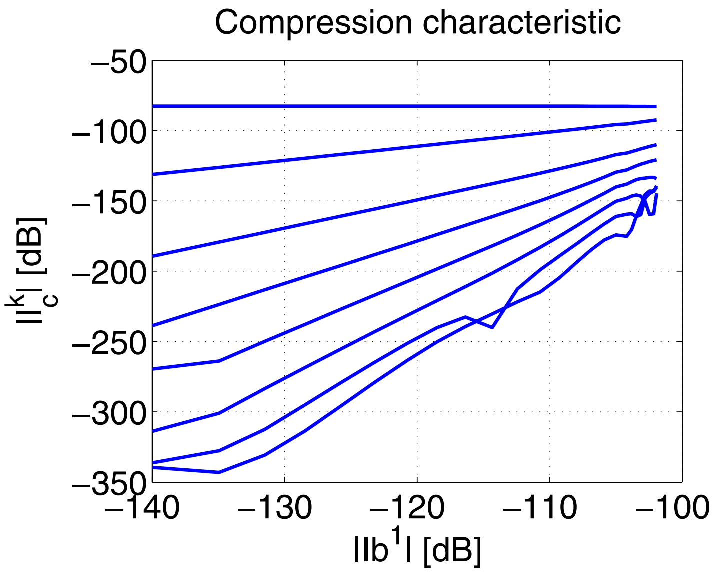


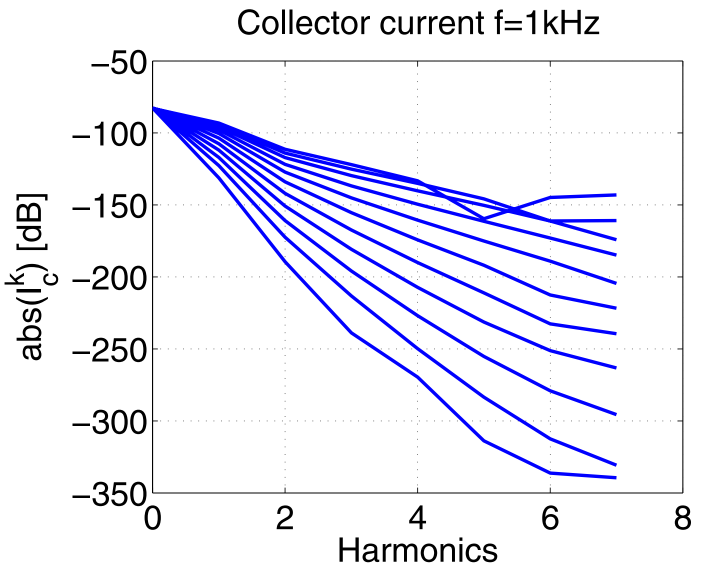




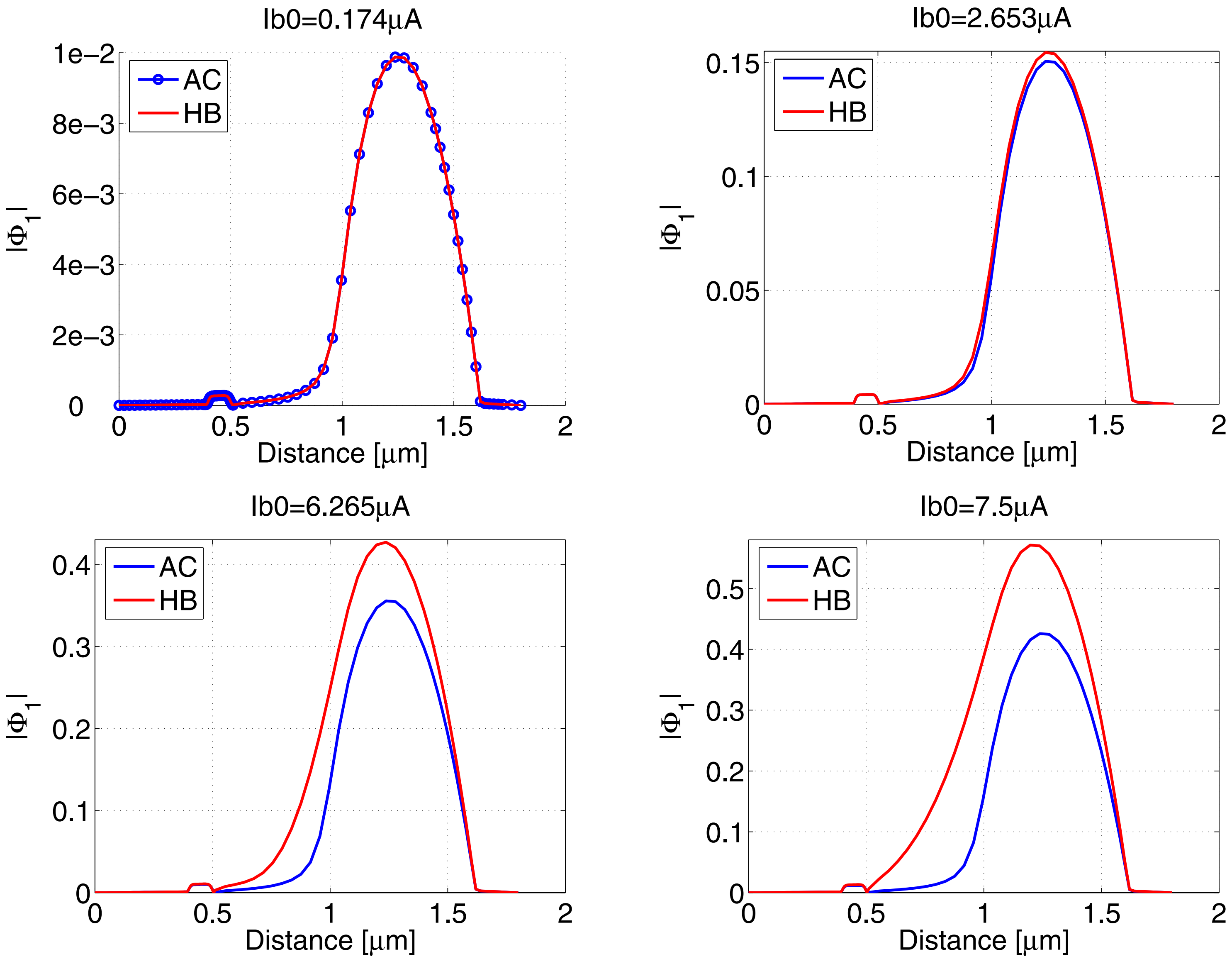
Simplified Bipolar: Harmonic Balance


Fundamental current gain


Compression characteristic

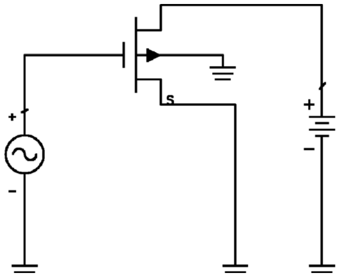

Collector current f=1kHz

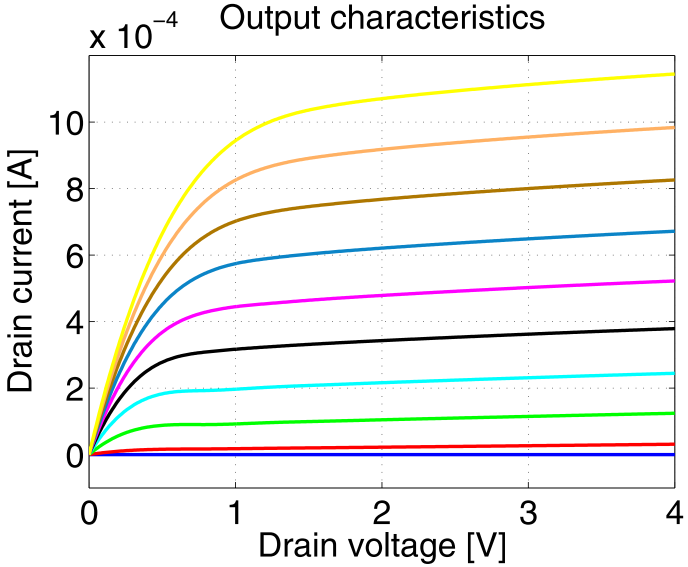
Simplified Bipolar: Harmonic Balance

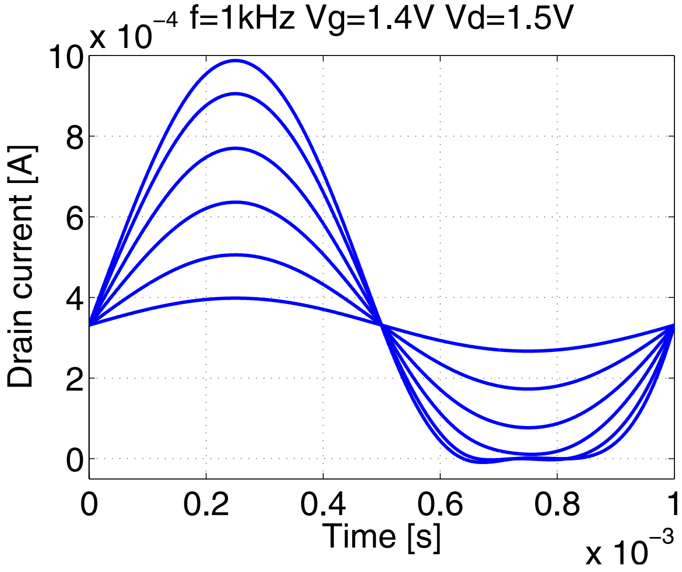


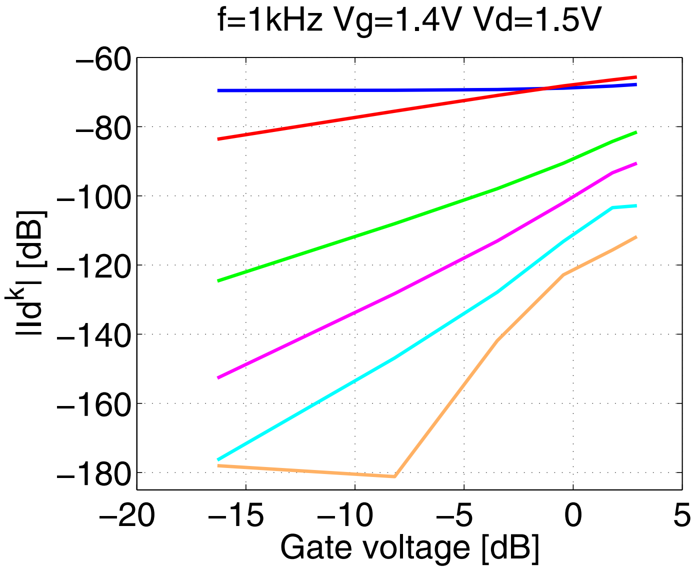
MOSFET

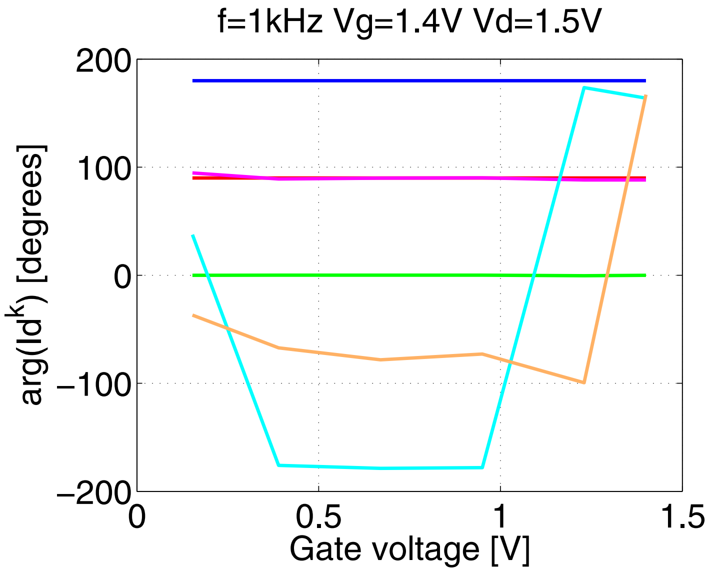
Simulation




Output characteristics


f=1kHz Vg=1.4V Vd=1.5V


f=1kHz Vg=1.4V Vd=1.5V


f=1kHz Vg=1.4V Vd=1.5V

RF-Bipolar: Harmonic Balance

Failed !

HB Simulations:

- Voltage or Current Source
- With/Without Network

Observations:

- Very Ill-Conditioned Linear Systems
- ILUT Precondioner works only "Direct"
- Convergence only Linear
- Large Voltage Amplitudes within Device → Accuracy Problem ?

Possible Reasons:

- Difficult Convergence already for DC
- Very High Doping ?
- Solution Singularities (Corners) ?
- DFT of Positive Variables $n, p > 0$?

Concluding Remarks

Simulation Platform DESSIS

- **Suitable for Characterization of RF Devices**
- **Optimization of Central Devices in RF Building Blocks**

Device/Mixed-Mode Harmonic Balance

- **Requires Significant Improvement to Compete with Transient Simulations**
- **Main Bottleneck is Lack of Robustness in Convergence**