Physics-based nonlinear noise modelling

Nonlinear Noise Modelling and Large-Signal Low-Noise Microwave Circuit Design

Organisers:
Matthias Rudolph, Ferdinand-Braun Institut (FBH), Berlin, Germany
Fabio Filicori, University of Bologna, Italy

Abstract:

This workshop is focussed on recent developments in the field of nonlinear noise models and design techniques for low-noise microwave circuits which are intrinsically subject to large-signal operating conditions. In fact, many of the fundamental building blocks for the development of high-performance communication systems, like low-phase-noise oscillators, mixers or interference-robust low-noise amplifiers, are subject to important noise generation phenomena which are strongly conditioned by the presence of large-amplitude signals. In such cases, normally characterized by periodic or almost periodic non-linear operation, noise modelling in electron devices becomes much more complex, in comparison with the linear steady-state case, since cyclostationary, instead of conventional, stationary equivalent noise sources must be considered in the device models or low noise circuit design.

In this workshop, after outlining the basics of noise generation in semiconductors and of numerical physics-based noise models, non linear, compact HBT and FET non-linear noise models will be described with examples of application to noise analysis in non linear microwave circuits. Design approaches for low-noise oscillators, mixers and amplifiers will also be presented and discussed.

Programme

8:45 - 9:20
Physics-Based Nonlinear Noise Modelling
Fabrizio Bonani, S. Donati Guerrieri, G. Ghione, Politecnico di Torino, Italy

9:20 - 9:55
Non-Linear HBT Noise Modelling and Applications
Christophe Nallatamby[1], E. Dupouy[1], J. Portilla[2], M. Prigent[1], J. Obregon1,
[1] University of Limoges, France
[2] University of the Basque country, Bilbao, Spain

9:55 - 10:30
Non-Linear FET Noise Modelling and Applications
C.Florian, P.A.Traverso, F. Filicori, Univ. Bologna, Italy

10:30 - 11:00
Coffee Break

11:00 - 11:35
Low Phase-Noise Oscillator Design Techniques, Applications and Future Trends
U. L. Rohde, Univ. Cottbus, Germany
Ajay K. Poddar, Synergy Microwave Corp., NJ, USA

11:35 - 12:10
Noise in Mixers
Steven Maas, AWR, USA

12:10 - 12:45
Highly Linear Low-noise Amplifiers
Matthias Rudolph, Ferdinand-Braun-Inst. (FBH), Germany

12:45 - 14:00
Lunch

Physics-Based Nonlinear Noise Modelling

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Outline

- **Motivation**
- **Overview on numerical noise modelling**
  - **Small-signal (stationary)**
  - ***Forced* large-signal (cyclostationary)**
  - ***Autonomous* large signal**
- **Modeling low frequency noise**
- **Evaluating the Large Signal working point**
- **Case studies**
- **Conclusions**

Motivation

- Low-noise circuits important in RF & microwave telecommunication systems
  - Linear circuits (e.g., low noise amplifiers)
  - "Nonlinear" circuits (e.g., mixers, frequency multipliers, oscillators)
- Physics-based (PB) simulation is a powerful tool for:
  - TCAD Device design and optimization
  - Development of compact, circuit-oriented model with sound physical basis
  - Understanding exotic noise mechanisms (1/f?)

A few basics on physics-based noise modelling - I

- Microscopic (carrier velocity or population) fluctuations are a *small perturbation* of
  - DC steady-state → *Small-signal, stationary noise*
  - Large-signal (quasi) - periodic steady state → *LS (quasi)-cyclostationary noise*
  - LS steady-state of autonomous system → *LS (oscillator) stationary (?) noise*

A few basics on physics-based noise modelling - II

- Terminal (*v*,*i*) fluctuations are evaluated through a (*linear*) Green's function approach from (spatially uncorrelated) ***microscopic (charge or current density) fluctuations*** distribuited in the device volume
  - SS conditions → Superposition + *Filtering of microscopic noise source spectra*
  - LS conditions →Superposition + *Filtering & frequency conversion*

A few basics on physics-based noise modelling - III

- The Green's function (→ "impedance field") can be derived through SS (small-signal) or SSLS (ss with respect to LS) linearization from any PDE based physical model:
  - Drift-diffusion (DD)
  - Energy balance
  - Full hydrodynamic, *N* moments from BE

Simulation steps

1. **Evaluate the noiseless working point**
   - Noise sources are switched off
   - Solution is (φ_0, n_0,p_0,$n_{t,k0}$)
   - The working point depends on the applied generators → might depend on time and require mixed-mode simulation → CPU-intensive for the large-signal case
2. **Add (model) the microscopic noise sources**
   - The working point is perturbed by fluctuations $\delta\alpha$
3. **Solve the (linear) perturbed system to evaluate the terminal electrical fluctuations (noise generators) through the Green's function approach**

Example: DD model, SS noise

$$\varepsilon\nabla^2\Psi = -\rho(n,p,\Psi)$$

$$\frac{\partial n}{\partial t} = -\frac{1}{q}\nabla\cdot\vec{J}_n - U_n$$

$$\frac{\partial p}{\partial t} = +\frac{1}{q}\nabla\cdot\vec{J}_p - U_p$$

Linearization around DC steady state, frequency domain & Langevin sources

$$\varepsilon\nabla^2 G_\alpha = -\Lambda_\Psi(\tilde{n},\tilde{p},G_\alpha)$$

$$j\omega\tilde{n} = -\Lambda_n(\tilde{n},\tilde{p},G_\alpha) + \delta_{\alpha,n}\delta(\vec{r}-\vec{r}_1)$$

$$j\omega\tilde{p} = -\Lambda_p(\tilde{n},\tilde{p},G_\alpha) + \delta_{\alpha,p}\delta(\vec{r}-\vec{r}_1)$$

Scalar & vector Green's functions

$$\begin{cases} G_\alpha(\vec{r},\vec{r}_1) \\ \nabla_{r_1} G_\alpha(\vec{r},\vec{r}_1) \end{cases}$$

$$\alpha = n, p$$

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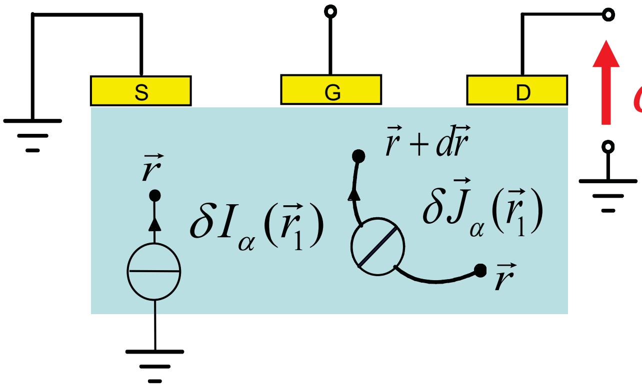
Propagating fluctuations to terminals



$$\delta V_{D,\alpha} = G_\alpha(\vec r_D,\vec r_1)\,\delta I_\alpha(\vec r_1) + \nabla_{r_1} G_\alpha(\vec r_D,\vec r_1)\cdot \delta \vec J_\alpha(\vec r_1)$$

$\delta I_\alpha(\vec r_1)$ →e/h *GR noise source* (*population fluctuations*)

$\delta \vec J_\alpha(\vec r_1)$ →e/h *diffusion noise source* (*velocity fluctuations*)

SS noise power spectra

- Correlation matrix of open-circuit voltage noise fluctuations:

$$S_{\delta V_i \delta V_j}(\omega) = \sum_{\alpha=n,p} \int_\Omega \vec G_\alpha(\vec r_i,\vec r,\omega)\cdot \mathbf{K}_{\delta \vec J_\alpha \delta \vec J_\alpha}(\vec r,\omega)\cdot \vec G^*_\alpha(\vec r_j,\vec r,\omega)\,d\vec r$$
$$+ \sum_{\alpha,\beta=n,p} \int_\Omega G_\alpha(\vec r_i,\vec r,\omega)\,K_{\gamma_\alpha\gamma_\beta}(\vec r,\omega)\,G^*_\beta(\vec r_j,\vec r,\omega)\,d\vec r$$

$\mathbf{K}_{\delta \vec J_\alpha \delta \vec J_\alpha} = 4q^2\alpha \mathbf{D}_\alpha$ →**e/h *diffusion <u>local noise source</u>***

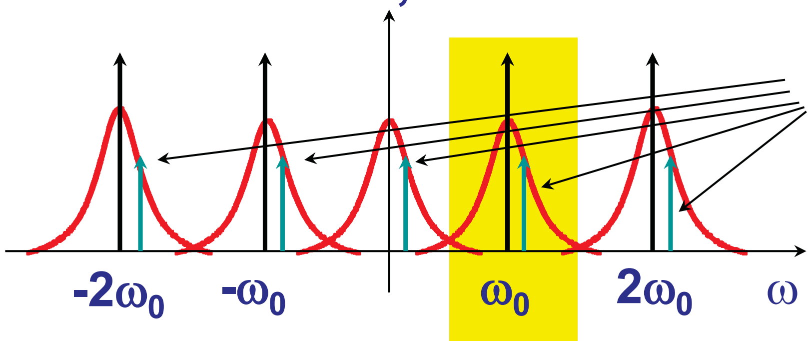
$K_{\gamma_\alpha\gamma_\beta}(\vec r,\omega)$ →**e/h *GR <u>local noise source</u>***

LS cyclostationary noise - I

- Analog applications often require **periodic** or **quasi-periodic** LS operation
- In LS operation microscopic noise sources are **amplitude modulated** by the periodic LS steady-state leading to → **cyclostationary microscopic sources** with **correlated** frequency components
- Those are described by the **Sideband Correlation Matrix (SCM)** formalism

Cyclostationary noise formalism

- Only the spectral components in each **sideband** having the **same distance** from the LS harmonics, are **correlated**



Correlated sidebands of noise process *y*

$\omega_k = k\omega_0$	LS harmonics
$\omega_k^+ = \omega_k + \omega$	*sidebands*

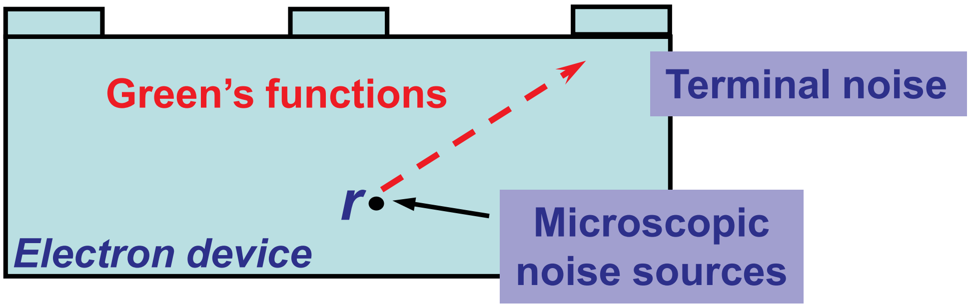
- 2nd order statistical properties through the ***sideband correlation matrix*** *(SCM)*:

$$\left(\mathbf{S}_{y,y}(\omega)\right)_{k,l} = \left\langle \tilde{y}\left(\omega_k^+\right)\tilde{y}^*\left(\omega_l^+\right)\right\rangle$$

ω is called ***sideband frequency***

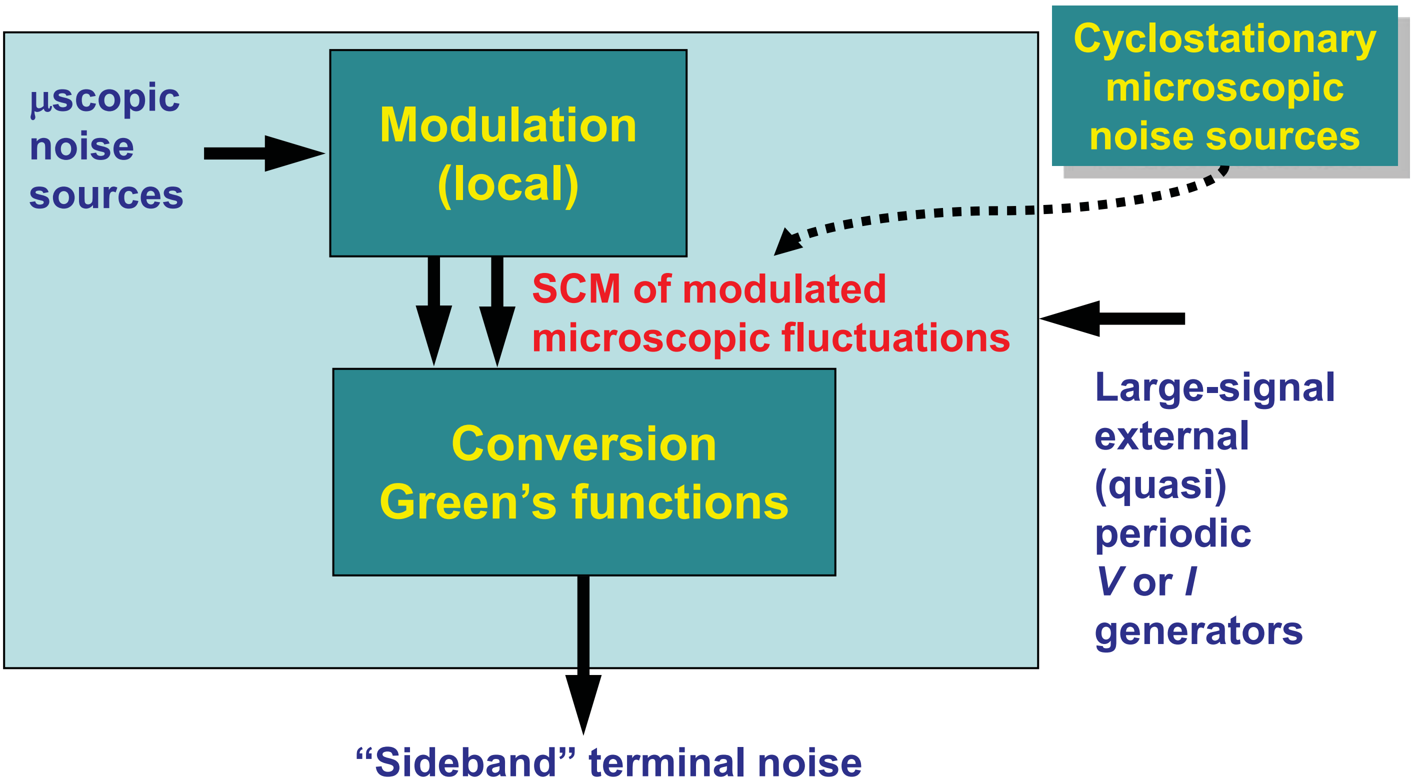
LS cyclostationary noise - II

LS extension of Green's function approach



- Green's functions → conversion Green's functions, implying noise frequency conversion into LS spectrum sidebands
- After propagation & conversion noise around each harmonic is due to
  - microscopic noise source at that sideband
  - source conversion from other sidebands

LS cyclostationary noise - III



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Noise in autonomous systems

- Oscillator noise → open research issue and object of debate even at circuit and system level
- A. Demir's approach (system level) accounting both for coloured and white noise sources → viable way for extension to device level
- Work by group of Seoul National University (white diffusion noise sources)

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Numerical implementation

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- Through standard (e.g. finite box – Scharfetter-Gummel) discretization the Green's function is derived from a linear system (← SS or SSLS)
- Efficient evaluation of the Green's functions at device terminals through adjoint and generalized adjoint techniques
- ☹ Bottleneck: LS (quasi) periodic solution through Harmonic Balance

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Low frequency noise modelling

- Low-frequency (coloured, 1/f or Lorentzian) noise important in many analog applications (mixers, multipliers, oscillators…) where noise frequency conversion takes place
- Low-frequency noise → superposition of bulk, surface or interface GR noise
- GR trap-assisted noise → theory developed by van Vliet in 1960 → trap level rate equations added to DD model

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Model + traps: bipolar drift-diffusion

- N_t traps included
- Device mesh: N_i internal nodes and N_x external nodes on metallic contacts
- Device contacts: N_c+1, one grounded

$$\nabla^2\varphi = -\frac{q}{\varepsilon}\left(p - n - \sum_{k=1}^{N_t} n_{t,k}\right)$$

$$\frac{\partial n}{\partial t} = -\nabla\cdot\left(n\mu_n\nabla\varphi - D_n\nabla n\right) - U_n + \gamma_n$$

$$\frac{\partial p}{\partial t} = +\nabla\cdot\left(p\mu_p\nabla\varphi + D_p\nabla p\right) - U_p + \gamma_p$$

$$\frac{\partial n_{t,k}}{\partial t} = -U_k + \gamma_k \qquad k = 1,\dots,N_t$$

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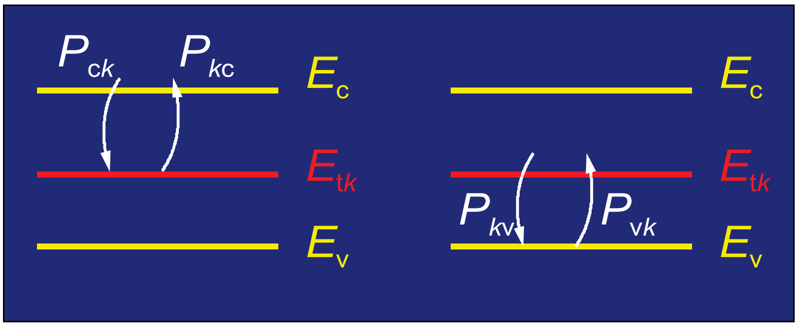
Trap level transition rates

- N_t (local) trap rate equations → SRH model
- Noninteracting traps considered; superposition → 1/f spectrum

total trap density c=(cross sect.) x v_{th}

$$P_{ck} = c_{n,k} n (N_{t,k} - n_{t,k}), \quad P_{kc} = c_{n,k} n_{1,k} n_{t,k},$$

$$P_{vk} = c_{p,k} p_{1,k} (N_{t,k} - n_{t,k}), \quad P_{kv} = c_{p,k} p\, n_{t,k}$$



$$n_{1,k} = N_c \exp\left(\frac{E_{t,k} - E_c}{k_B T}\right)$$

$$p_{1,k} = N_v \exp\left(\frac{E_v - E_{t,k}}{k_B T}\right)$$

SS - GR local noise source

$$K_{\gamma_n,\gamma_n} = 2(P_{ck0} + P_{kc0}),$$

$$K_{\gamma_p,\gamma_p} = 2(P_{vk0} + P_{kv0}),$$

$$K_{\gamma_n,\gamma_p} = 0,$$

$$K_{\gamma_k,\gamma_k} = 2(P_{ck0} + P_{kc0} + P_{vk0} + P_{kv0}),$$

$$K_{\gamma_n,\gamma_k} = -2(P_{ck0} + P_{kc0}),$$

$$K_{\gamma_p,\gamma_k} = 2(P_{vk0} + P_{kv0})$$

$\gamma_n \rightarrow$ Langevin source, e-continuity equation

$\gamma_p \rightarrow$ Langevin source, p-continuity equation

$\gamma_k \rightarrow$ Langevin source, kth trap rate equation

Trap transition probabilities ⇒

$$P_{ck} = c_{n,k} n (N_{t,k} - n_{t,k}),$$

$$P_{kc} = c_{n,k} n_{1,k} n_{t,k},$$

$$P_{vk} = c_{p,k} p_{1,k} (N_{t,k} - n_{t,k}),$$

$$P_{kv} = c_{p,k} p n_{t,k}$$

LS - GR local noise source SCM

- In LS conditions the white microscopic RG noise sources are (quasi) periodically modulated by the working point
- Noise source SCM, e.g.:

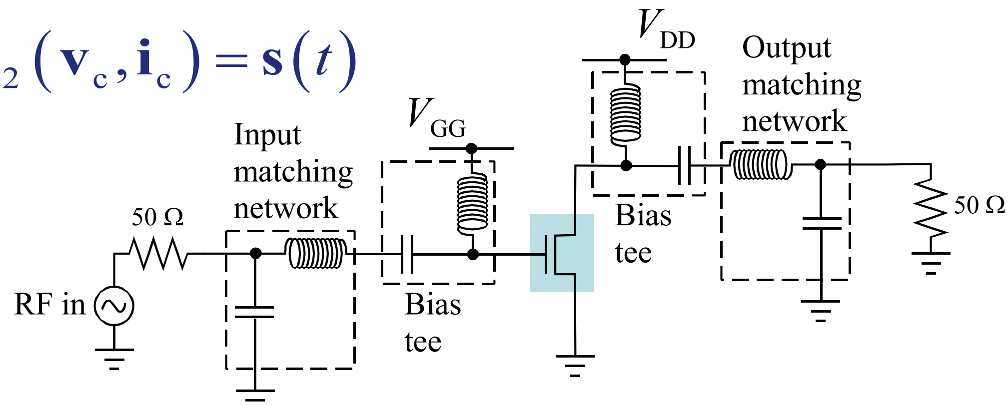
$$\left(\mathbf{K}_{\gamma_n,\gamma_n}\right)_{l,m} = 2\left(P_{\mathrm{ck}0,l-m} + P_{\mathrm{kc}0,l-m}\right)$$

(*l-m*)-th Fourier component of transition rate

Solving the PB model in LS: the embedding circuit

- Represented, in its simplest form, by a memory relationship between v_c, i_c and the applied generators s(*t*)
  - For periodic excitation, s(*t*+*T*)=s(*t*)
  - For autonomous circuit, s(*t*)=0

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{e}_1\left(\mathbf{v}_c,\mathbf{i}_c\right)+\mathbf{e}_2\left(\mathbf{v}_c,\mathbf{i}_c\right)=\mathbf{s}\left(t\right)$$



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Solving the PB model in LS: discretized model & solution

- (Space) discretized PB model + embedding circuit → differential algebraic equation (DAE)

System size: $$N_{\mathrm{eq}} = (3 + N_{\mathrm{t}})(N_{\mathrm{i}} + N_{\mathrm{x}}) + 2N_{\mathrm{c}}$$

For a 3-terminal device with 2000 mesh nodes and 3 traps N_{eq}=12,004!

- Direct computation of the steady-state response
  - Frequency-domain: Harmonic Balance (HB)
  - Time-domain: shooting method
  - Autonomous case?

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Case studies

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- 2D $n^{+}p$ diode
  - motivation: low-frequency noise compact modelling usually based on amplitude modulation of stationary SS noise generators → is this generally correct / accurate?

- GaAs MESFET and AlGaAs/GaAs HEMT Mixer
  - 2D LS mixed-mode noise simulation

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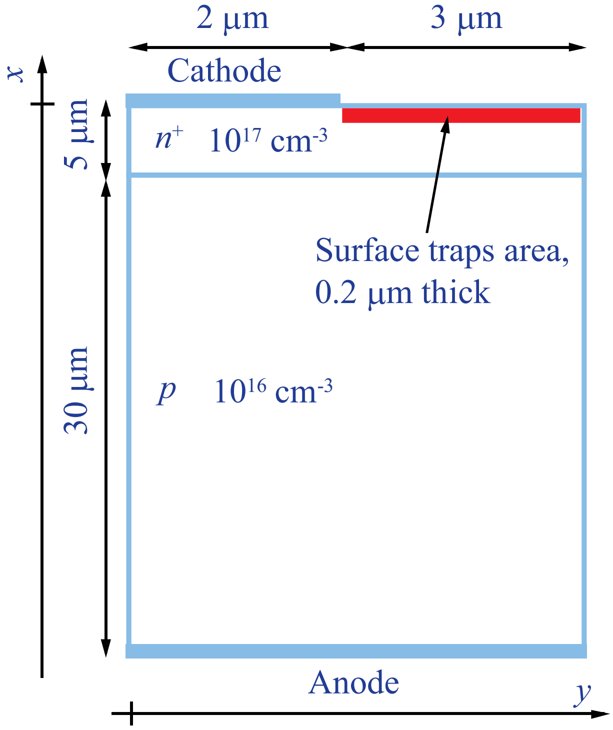
2D n^+p diode

- ***n*$^+$*p* junction diode → 1 bulk and 3 surface traps**

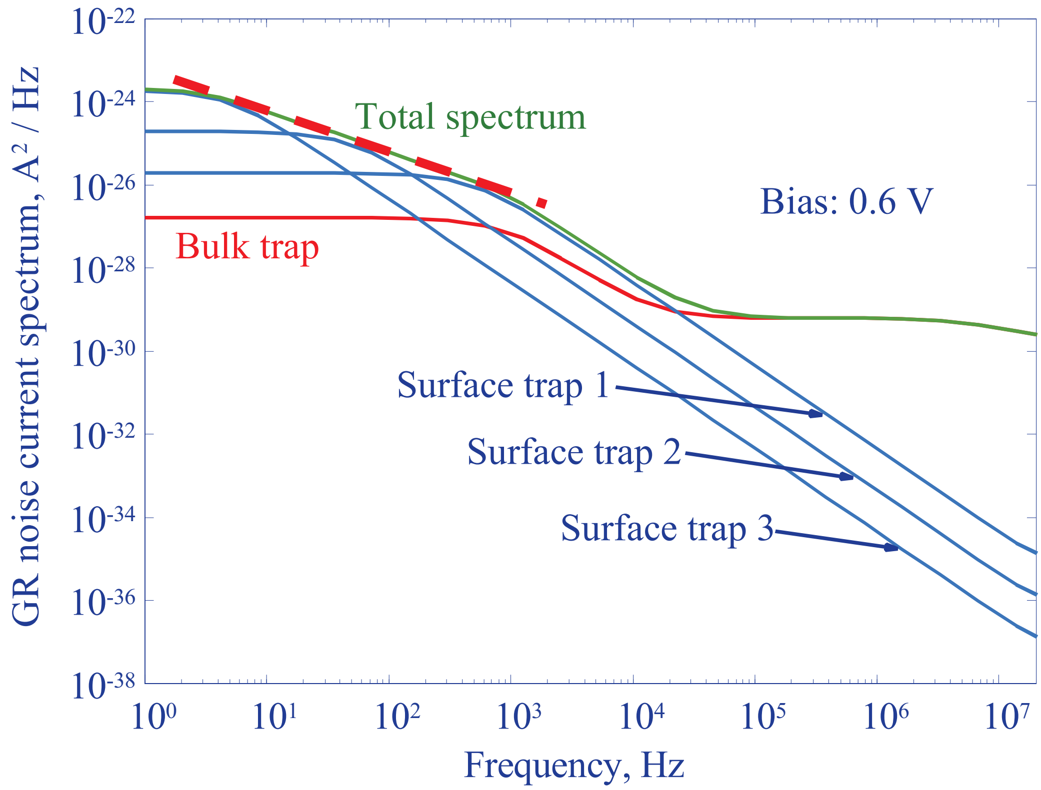


Bulk trap:
- $N_t = 5\times10^{12}$ cm^{-3}
- $c_n = c_p = 5.7\times10^{-13}$ cm^3/s
- energy level: 0.56 eV below E_c

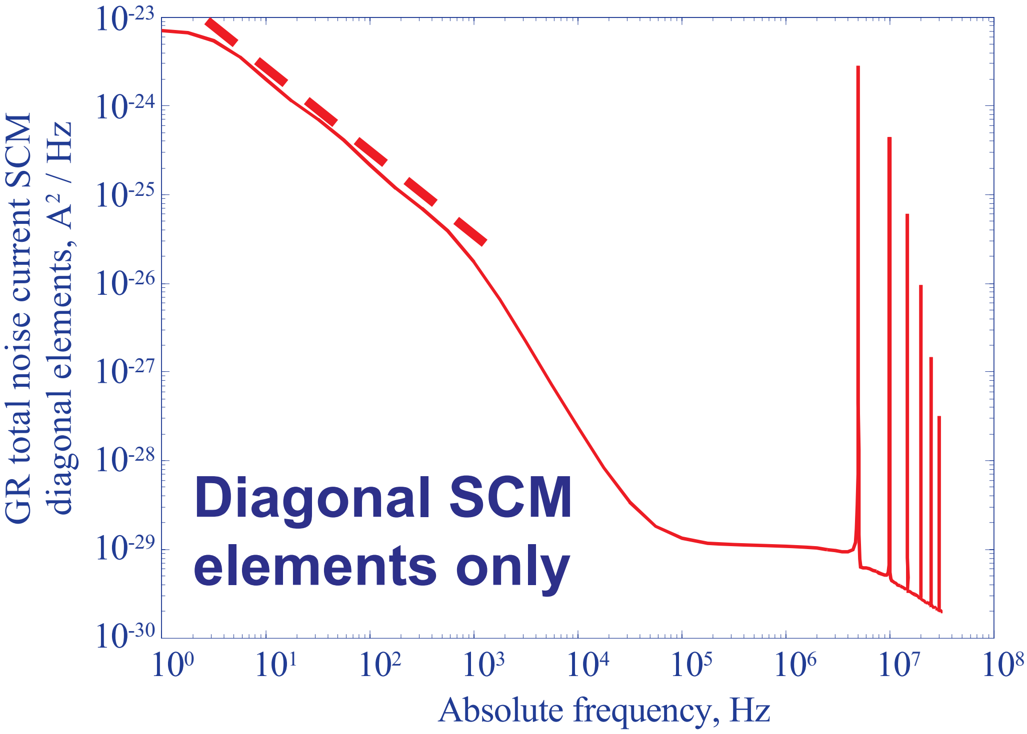
Surface traps:
- $N_t = 1.67\times10^{16}$ cm^{-3}
- $N_{t,surf} = 3.34\times10^{11}$ cm^{-2}
- energy level: 0.26 eV below Ec
- Trap 1: $c_n = c_p = 5.7\times10^{-14}$ cm^3/s
- Trap 2: $c_n = c_p = 5.7\times10^{-15}$ cm^3/s
- Trap 3: $c_n = c_p = 5.7\times10^{-16}$ cm^3/s

Large-signal simulation:
- 6 harmonics + DC
- working point: 0.6 V DC + 50 mV tone @ 5 MHz

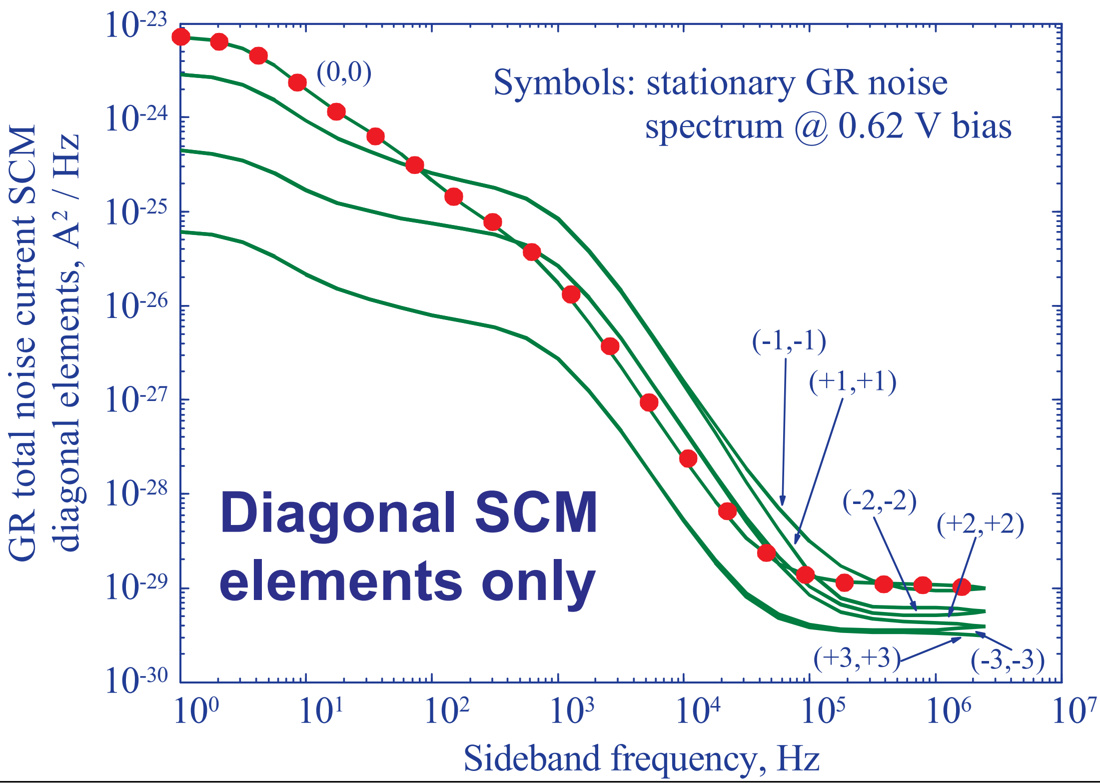
Stationary GR noise spectrum



Cyclostationary GR noise spectrum (absolute freq.)



Cyclostationary GR noise spectrum (sideband freq.)

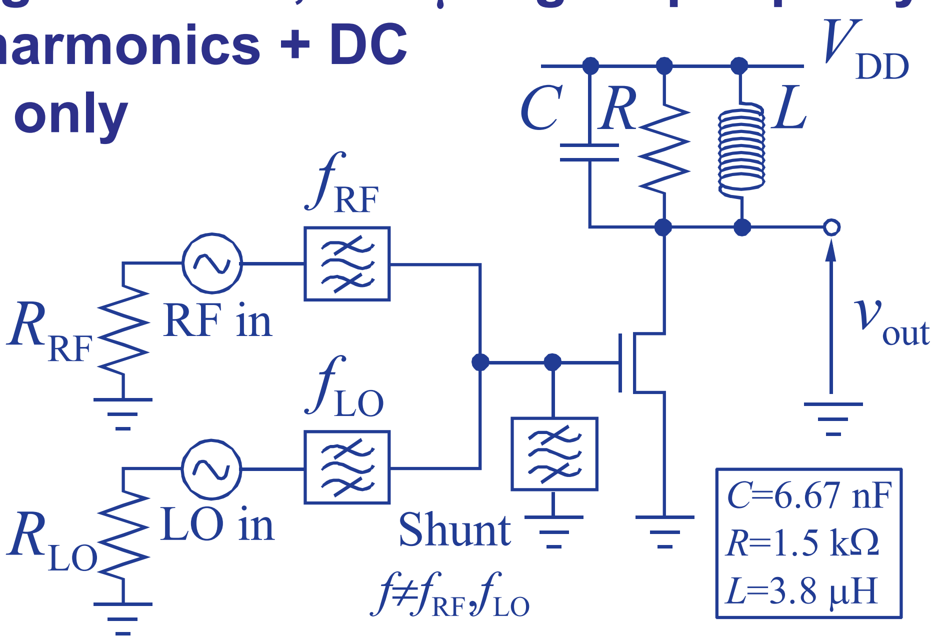


Remarks

- The SS 1/f like behaviour is **preserved in the (0,0) sideband**
- However, **conversion to upper sidebands** acts **differently** for **bulk** and **surface** traps
- Therefore, noise in upper sidebands is **markedly different from modulated SS noise** → which would have the same 1/f like behaviour for all sidebands
- Impact on **compact modelling!**

Mixer circuit

- Downconversion mixer, f_{LO}=1 GHz, f_{RF}=1.001 GHz
- Device: 0.3 μm gate HEMT, 100 μm gate periphery
- 1300 nodes, 4 harmonics + DC
- Diffusion noise only
- Noiseless LO



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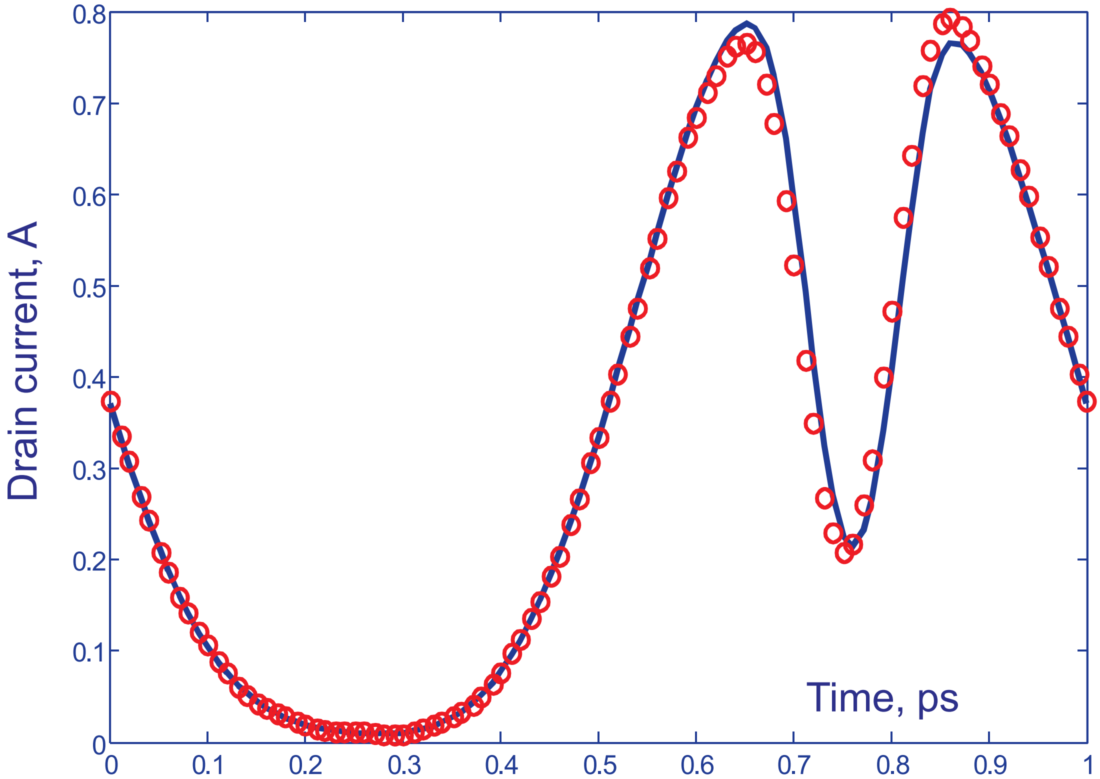
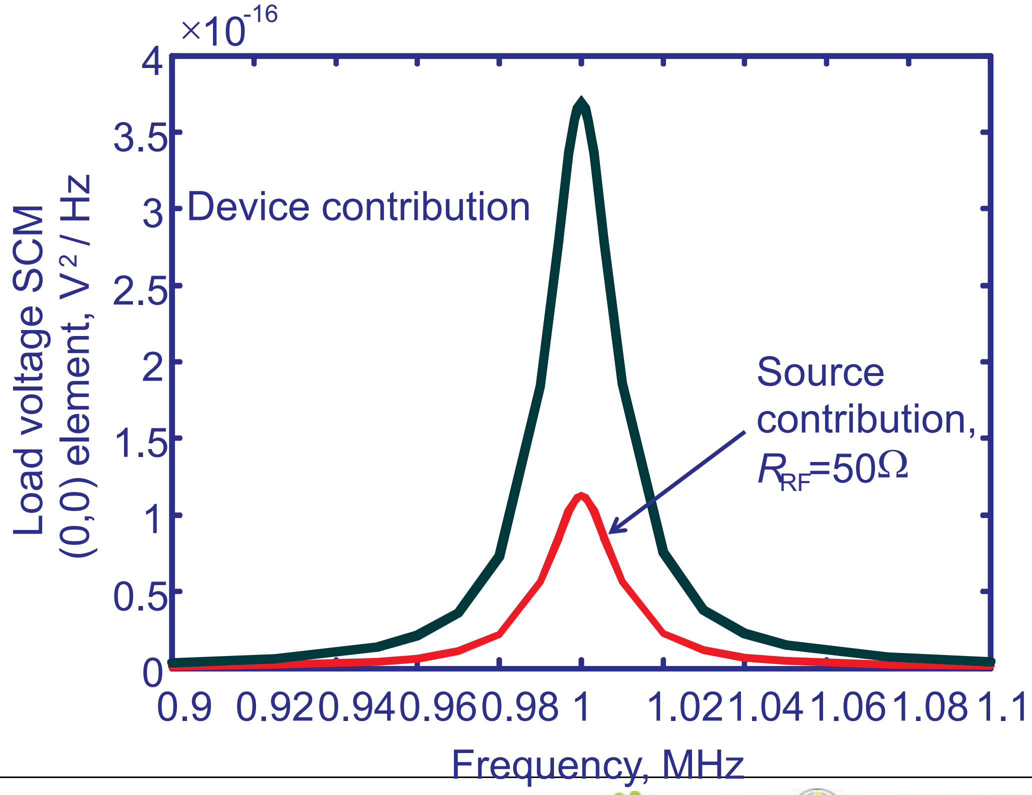
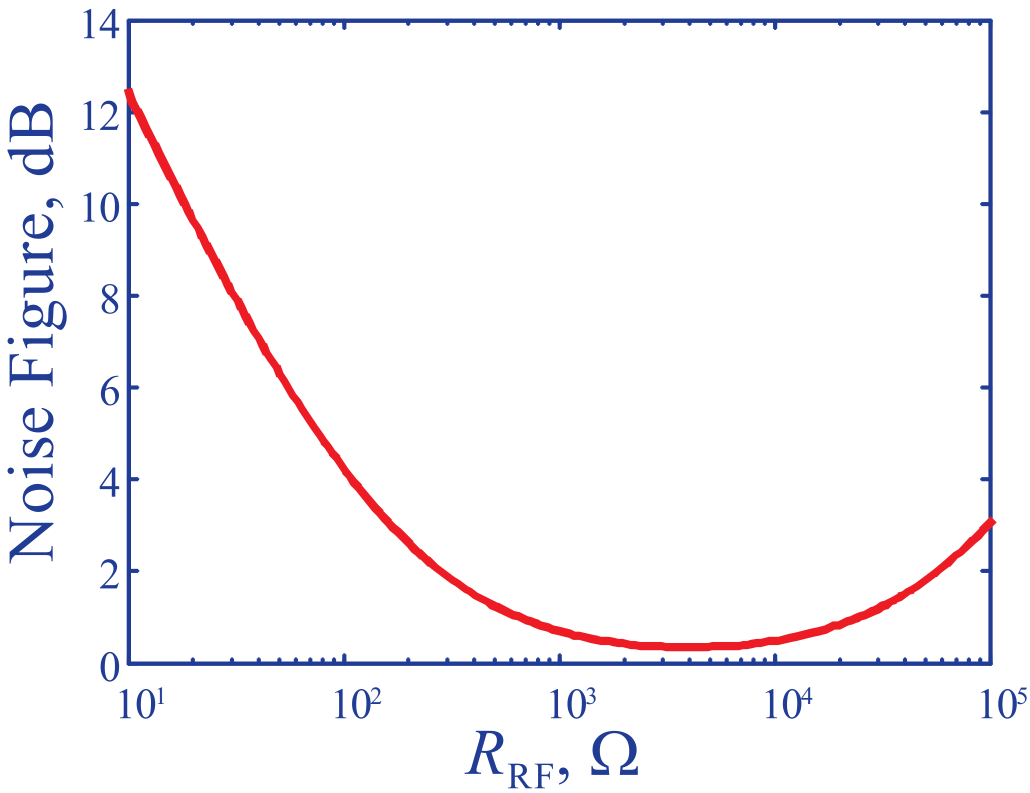
Mixer working point



Load noise voltage around IF



Intrinsic noise figure vs. RF source resistance



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Conclusions

- Numerical noise simulation has (hopefully) reached maturity
- Progress made in understanding low-frequency noise (→1/f) and its frequency conversion (also → compact modelling)
- Encouraging advances in oscillator PB modelling
- LS noise simulation requires more efficient WP solvers (time domain?)
- General strategy for LS compact modelling still an open problem – but this is another story!

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