HICUM - Productization and Support Update

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http://www.iee.et.tu-dresden.de/iee/eb/hic_new/hic_start.html

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OUTLINE

- HICUM/L2 Support Activities
- HICUM/L0 Support Activities
- Vertical NQS Effects and Implementation

HICUM/L2 Support Activities

fixes and improvements towards v2.23

- testing (changes see previous meeting slides and doc on www):
  - y-parameters (internal transistor) vs. analytical expressions match well with VA Code
  - ST's comparison of simulator performance see HICUM WS website => EDA relevant
- Possible to link convergence criterion of I_T iteration in VA code to simulator current tol criterion? (same for GMIN and other parameters)
  - example: reltol = $simparam("reltol",1e-6) as suggested by Laurent does not work with OUR Spectre version => need latest simulator versions for support work
- Requests from design houses (using a foundry) regarding model characteristics cannot be handled without model parameters
  issue: foundry contract prevents design houses from providing parameters
- NQS effects:
  - Bessel polynomial in frequency domain to be implemented with ddt operator due to bias dependence of τ_1 and τ_2 => see more details later
  - Note: this type of "delay" behavior is common to other devices, too!
    => solution will be of general benefit
  - VA implementation does not converge in Spectre for NQS with RBX=RCX=0 Ohm - cause?

HICUM/L0 Support Activities

Version 1.12

Current L0 version (released March 9, ’07) has been available at

(http://www.iee.et.tu-dresden.de/iee/eb/hic_new/hic_start.html)

- Detailed documentation for HicumL0V1.12 has been released
  - format similar to L2
  - first complete doc for L0 latest version
  - includes complete parameter list, OP list
- Parameter TFH (for high injection correction) has been allowed to take the value 0
- Parameter DT0H (base width modulation) does not have a range limitation anymore; i.e. negative values are also allowed

HICUM/L0 Support Activities

=> Version 1.13

Work in response to user requests

- High current region: negative slope in IC(VBE) has been observed (see HICUM WS 2007) for non-physical values of parameter IQFH (in relation to IQF)
  => high-current correction formulation needs to be investigated

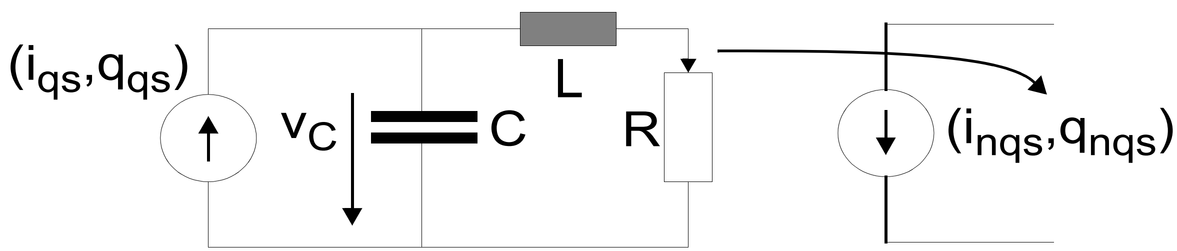
- Improve temperature dependent behavior of IC(VBE) slope (see HICUM WS 2007) caused by T independent emission factor MCf

=> partially development work

=> manpower limited

Vertical NQS Effects and Implementation

- HICUM/L2 v2.1 and lower: implementation via Weil's approach
- v2.2: attempt to use VA and model compiler
  => implementation via adjunct LCR-type Network (or equivalent network approach)



$C = \alpha\,\tau_f$
$L = \alpha\,\tau_f/3$
$R = 1\text{Ohm}$

bias dependent

time domain: $A_2 \frac{d^2 x_{nqs}}{dt^2} + A_1 \frac{dx_{nqs}}{dt} + x_{nqs} = x_{qs}(t)$ (A_1, A_2 generally bias dep.)

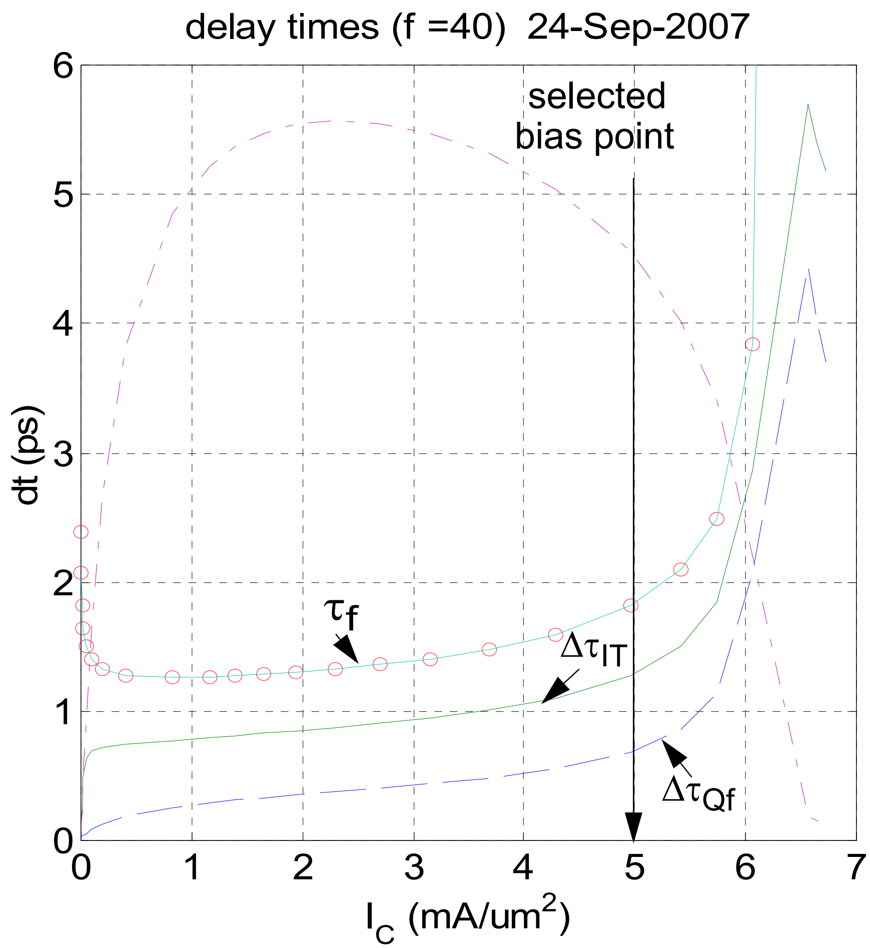
frequency domain: compiler creates derivatives due to bias dependent τ_f

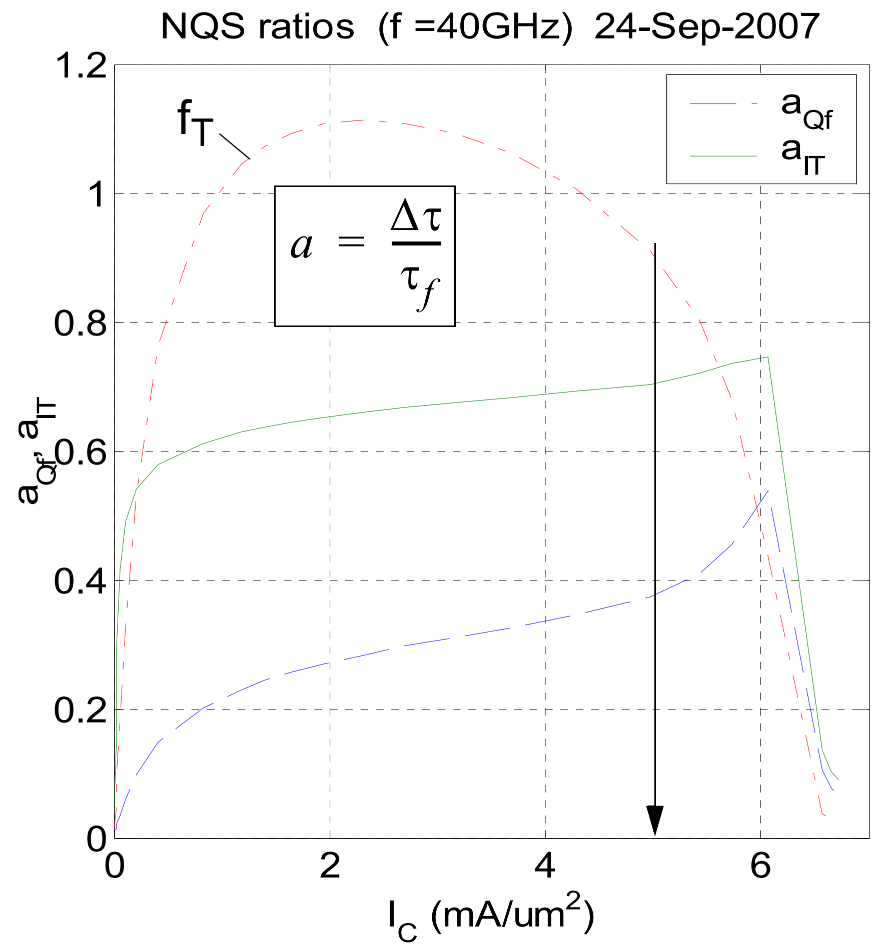
=> additional elements and disagreement with device simulation
(and with theory and previous model versions)

Are VA compiler generated derivatives physically correct?

Example: SiGe HBT delay times

1D device simulation results (peak f_T = 110GHz)





=> "delay" times are bias dependent

Device physics and compact model

Time domain solution (e.g., via TICCR)

- 1D diffusion transistor: $i_{T,nqs}(t) = i_{T,qs}(t) - \alpha \frac{\partial Q_{mB}^{qs}}{\partial t} + \tau \frac{\partial^2 Q_{mB}^{qs}}{\partial t^2}$ (from theory)

  => to be realized in large-signal model (TR simulation)

- at any point in time (bias) during TR simulation:
  => use time "constants" at given time /bias point (or within discrete time interval)

- in the limit of infinitesimally small signals in time domain:
  use time ***constant*** given by DC bias point

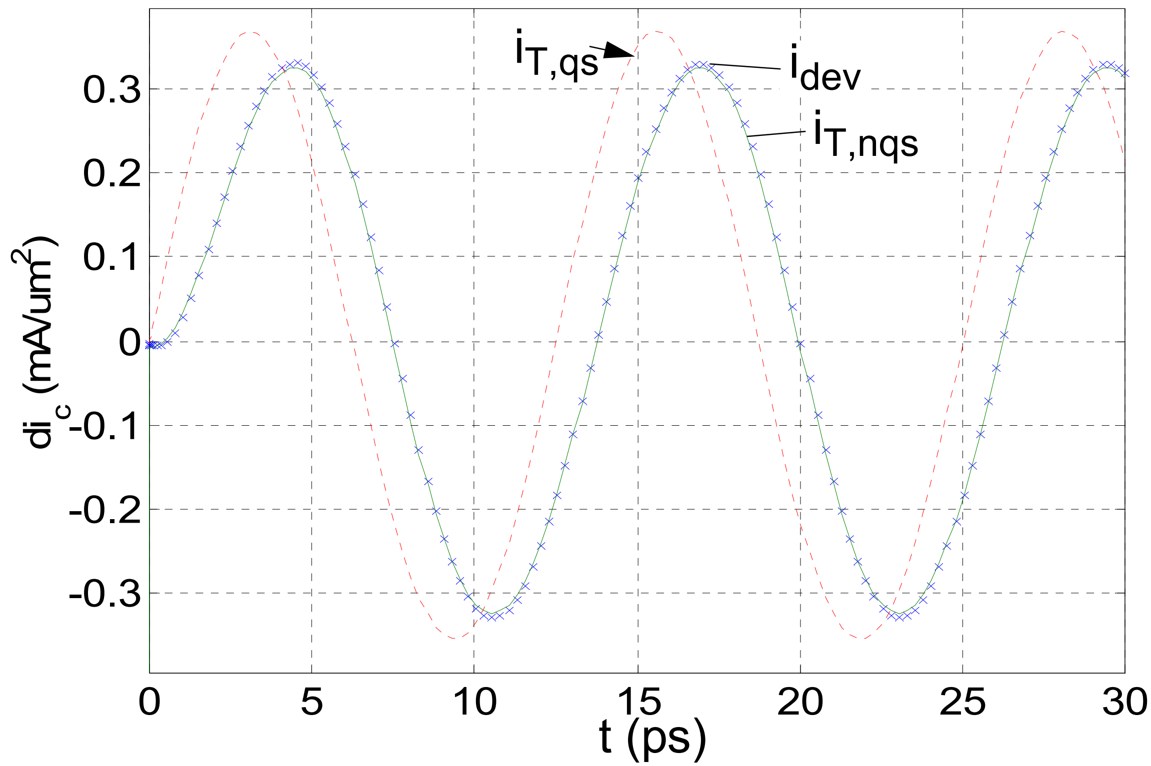
  => transformation to frequency domain contains no derivative of τ

- Note: NQS effects are not naturally included in SPICE-like approach
  => higher order terms (e.g. ω^2) require special coding, adjunct networks, etc.

- need implementation that satisfies theory and experimental data:
  => Weil's approach is suitable and has provided accurate results so far

Example: SiGe HBT time domain (TR) analysis

- 1D device simulation at $2.5*I_C$(peak f_T): 80GHz with 2.5mV amplitude (small-signal)
- MATLAB model: $i_T(t)$ from discretized solution of $A_2 \frac{d^2 i_{nqs}}{dt^2} + A_1 \frac{di_{nqs}}{dt} + i_{nqs} = i_{qs}(t)$



=> "Weil" approach yields accurate results

Device physics and compact model (2/2)

Frequency domain solution

- 1D drift/diffusion transistor: $\underline{I}_{T,nqs} \approx I_{T,qs} - (\omega\tau_2)^2 - j\omega\tau_1$

=> is valid at any bias point with τ ***at given bias point***

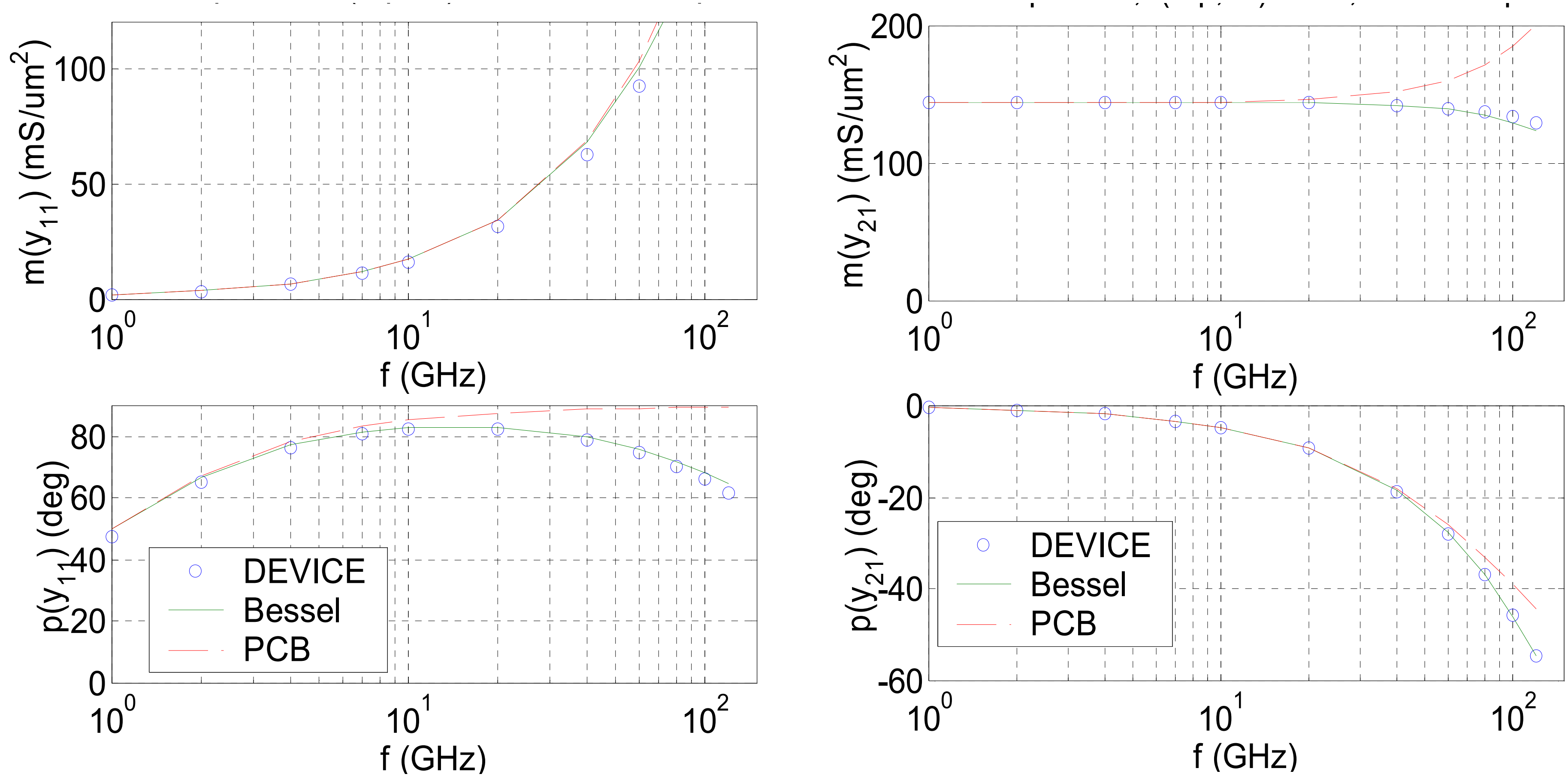
=> to be implemented in small-signal model (AC simulation)

- need implementation approach that meets above requirements (related to theory and model formulation):
  => Bessel polynomial is suitable and has provided accurate results so far

=> direct implementation in AC code instead of adjunct network

Example: SiGe HBT frequency domain (AC) analysis

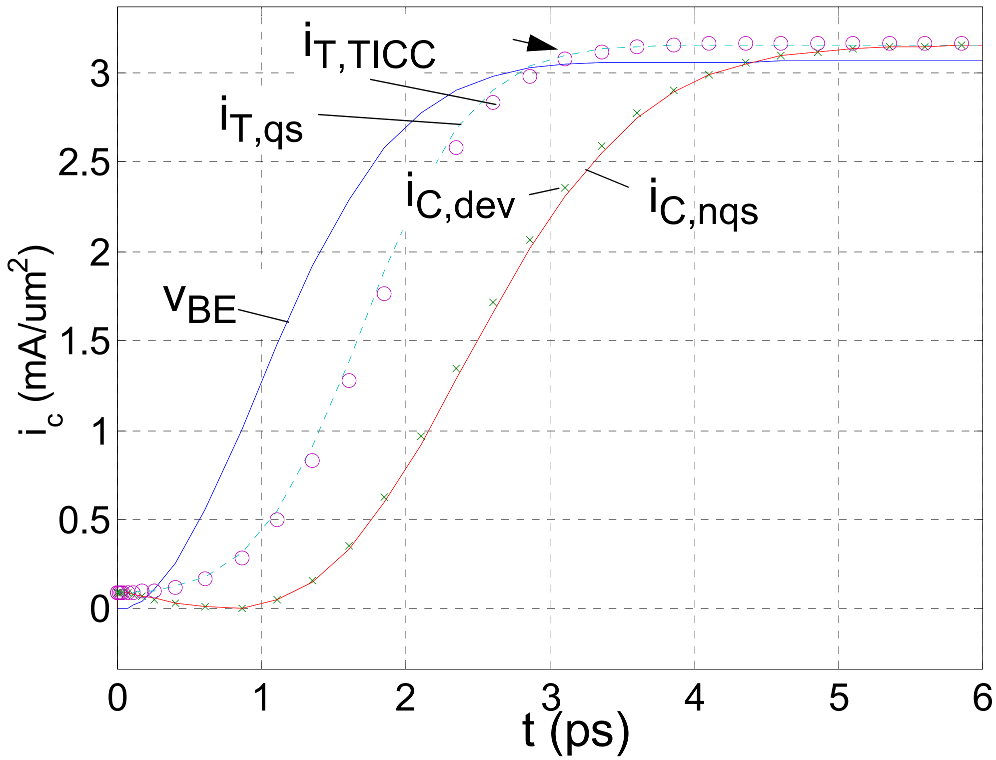
- 1D device simulation at $2.5 \cdot I_C$(peak f_T): 80GHz small-signal analysis
- MATLAB model: $\underline{I}_T(\omega)$ from analytical equations and Regional Approach (for C, G)



=> delay time at given bias point yields accurate results

Example: SiGe HBT *large-signal* time domain (TR) analysis

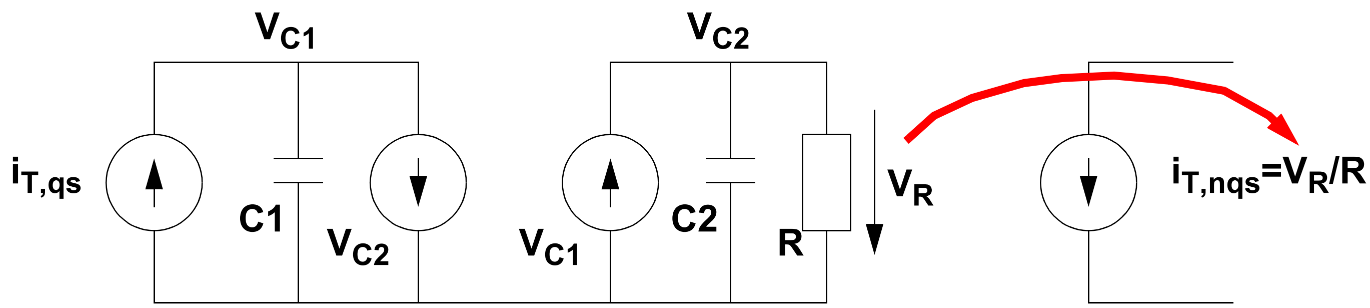
- 1D device simulation: pulse (100GHz slope) with 100mV amplitude
- MATLAB model: i_T(t) from $A_2\frac{d^2 i_{nqs}}{dt^2} + A_1\frac{di_{nqs}}{dt} + i_{nqs} = i_{qs}(t)$ => $i_C(t) = i_{T,NQS} - \frac{dQ_{jC}}{dt}$



=> "Weil" approach yields accurate ***large-signal*** results

VA adjunct network implementation

- gyrator equivalent of adjunct LCR-type network



coupled equations for traditional implementation with bias-independent τ_f

$$i_{T,qs} - \frac{d}{dt}(\alpha_{IT}\tau_f V_{C1}) - V_{C2} = 0 \quad \text{and} \quad V_{C1} - \frac{V_R}{R} - \frac{d}{dt}\left(\alpha_{IT}\frac{\tau_f}{3}V_{C2}\right) = 0$$

with R=1, C1=$\alpha_f\tau_f$ and C2=$\alpha_f\tau_f/3$

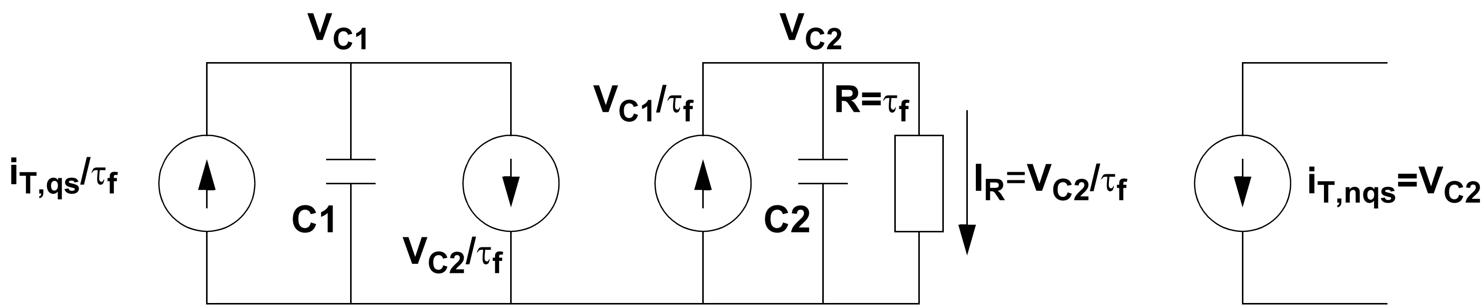
- represents 2nd order polynomial in frequency and time domain
- used in VBIC with bias-independent τ_f
- for bias-dependent τ_f
  => VA compiler generates undesired derivatives in small-signal EC
- need an implementation that provides no undesired derivatives even with $\tau_f(V,I)$

VA adjunct network implementation (2/2)

- proposed implementation with modified expressions for network elements

coupled equations for proposed implementation with bias-dependent τ_f

$$\frac{(i_{T,qs} - V_{C2})}{\tau_f} = \frac{d}{dt}(\alpha_{IT} V_{C1}) \quad \text{and} \quad \frac{V_{C1} - V_{C2}}{\tau_f} = \frac{d}{dt}\left(\frac{\alpha_{IT}}{3} V_{C2}\right)$$



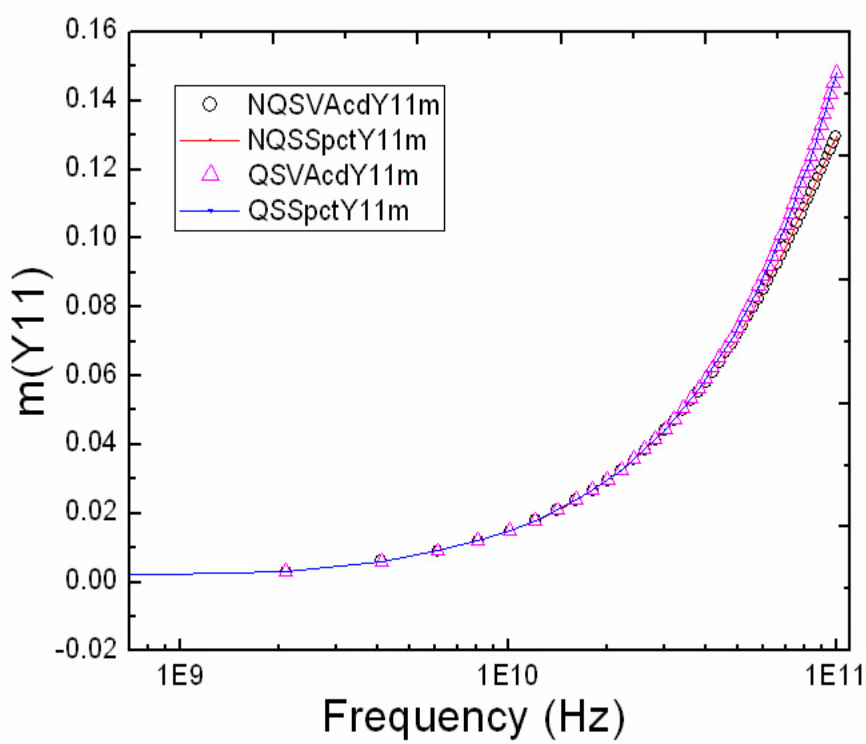
R=1
$C1=\alpha_{IT}$
$C2=\alpha_{IT}/3$

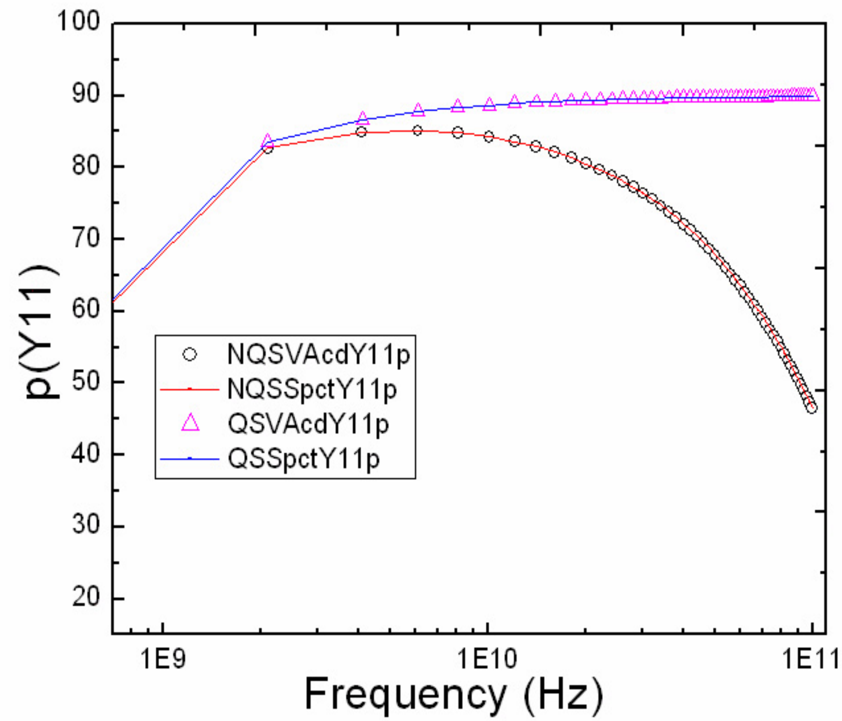
- "C" elements become bias-independent => no undesired derivatives anymore
- seems to yield desired results
  - division by $\tau_f = 0$ avoided through turning off NQS effects when input of zero value
  - charge conservation issue should be of no consequence for actual model equivalent circuit
  - presently testing

Results of VA NQS effect implementation (1/3)

HICUM comparison: v2.1(Weil) vs v2.3 (adj. network)

Small-signal frequency-domain simulation: Y11



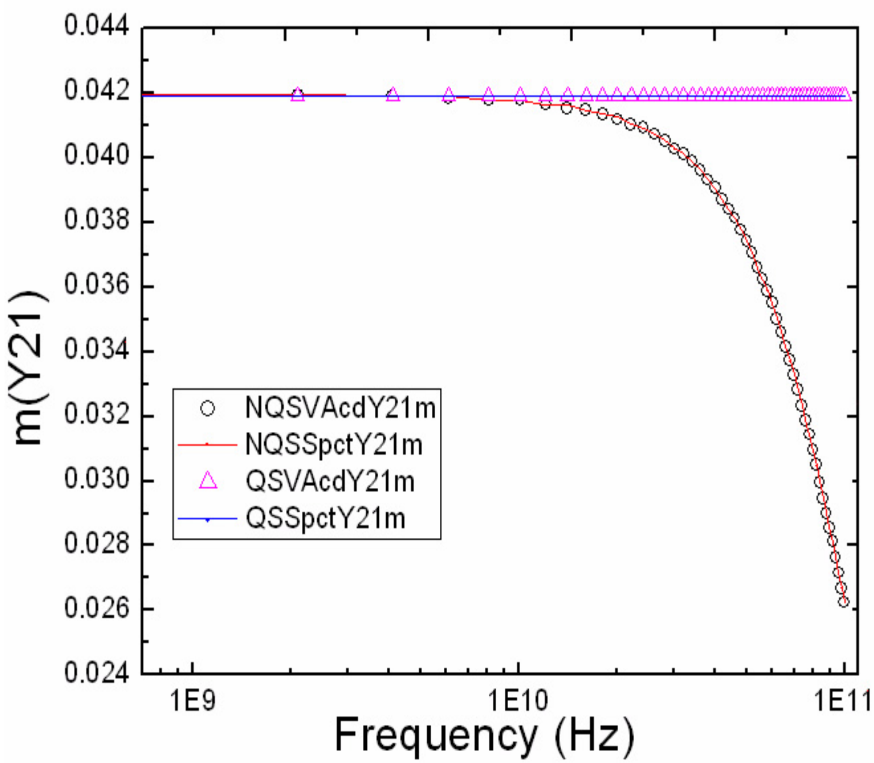


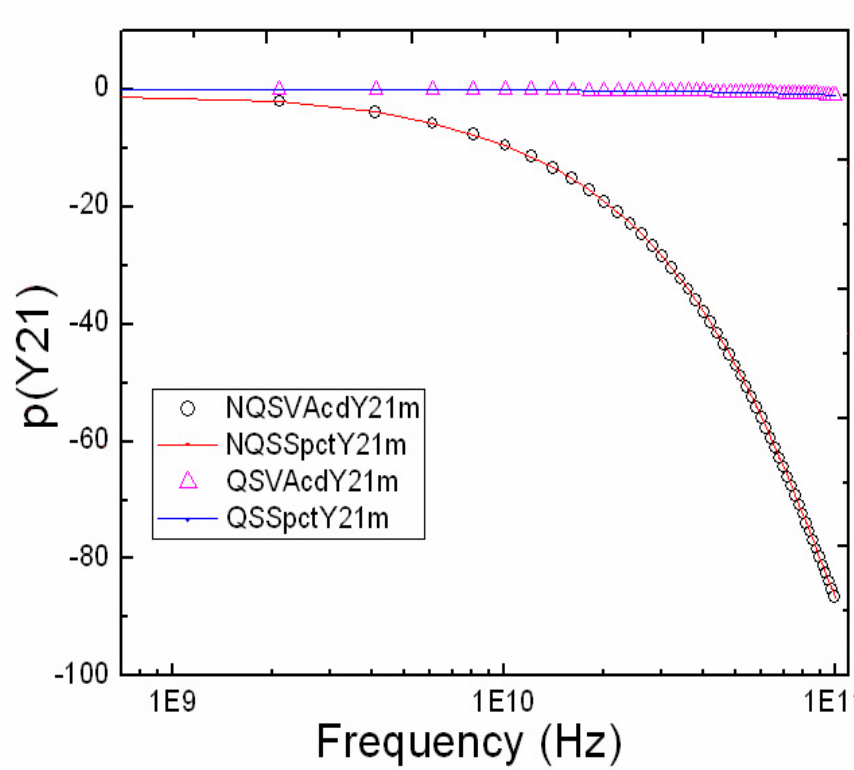
=> Excellent agreement

Results of VA NQS effect implementation (2/3)

HICUM comparison: v2.1(Weil) vs v2.3 (adj. network)

Small-signal frequency-domain simulation: Y21





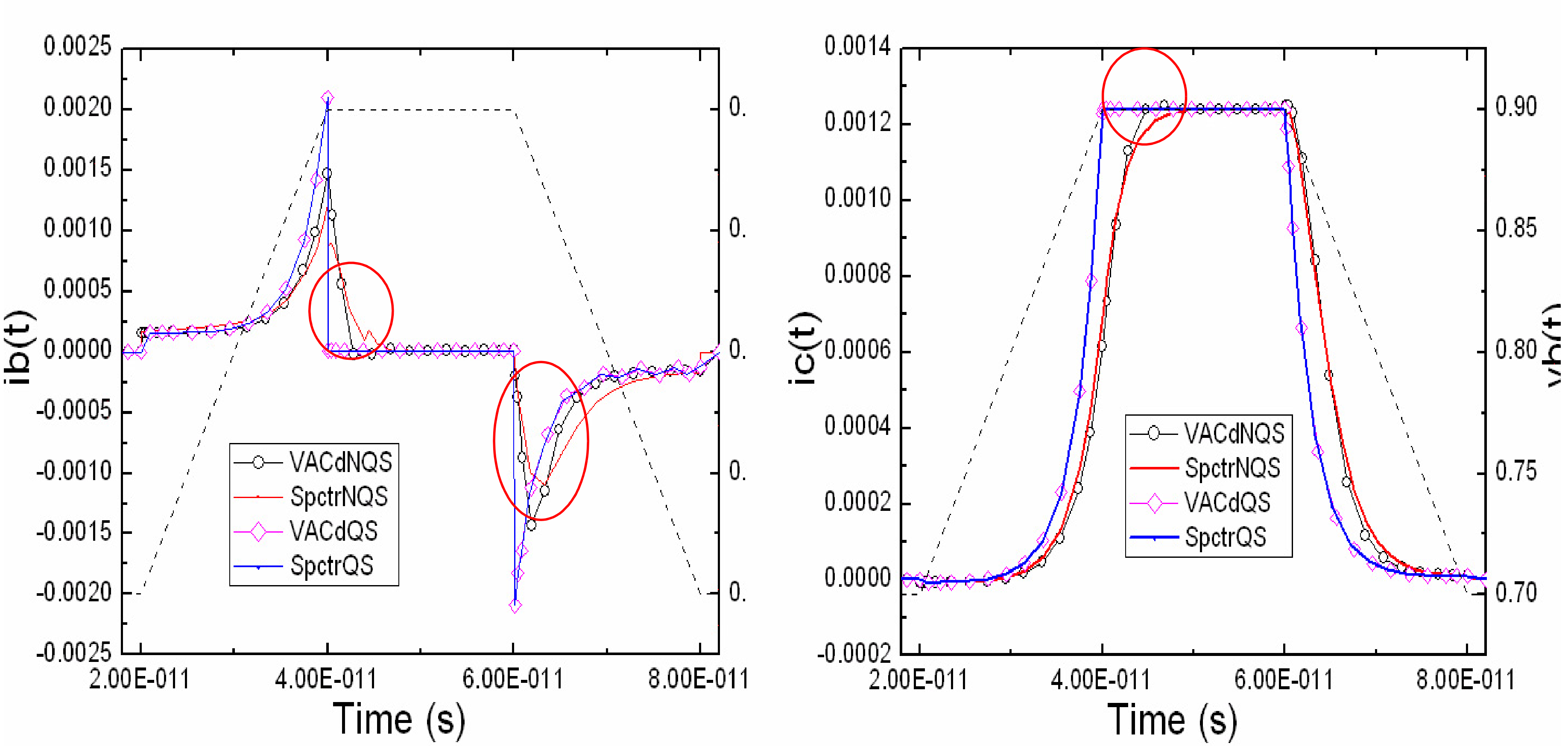
=> excellent agreement

=> "undesired derivative problem" seems to be solved

Results of VA NQS effect implementation (3/3)

HICUM comparison: v2.1(Weil) vs v2.3 (adj. network)

Large-signal transient simulation (first results)



=> Agreement for QS (reference), but some deviations for NQS case

Conclusions

Weil's approach and Bessel polynomial ...

- excellent approximations for device theory and circuit applications
- consistent representation in time and frequency domain
  - Note: inverse transformation including bias dependence of τ would lead to incorrect results in time domain

=> **bias dependent delay/phase**:

LCR-like adjunct network with bias ***dependent*** "C" elements is not a suitable approach for realizing device theory and modeling goals

Solutions:

- modified adjunct network appears to generate correct AC results
  - need to do more testing of TR analysis to understand deviations (mostly in base current)
- VA construct for automating implementation of Weil's approach

=> model remains compatible with older versions