EUROPEAN MICROWAVE WEEK 2015

SIX DAYS • THREE CONFERENCES • ONE EXHIBITION

PALAIS DES CONGRÈS, PARIS, FRANCE
SEPTEMBER 6 - 11, 2015

EuMW 2015
FREEDOM THROUGH MICROWAVES

Exhibition Opening Hours:
- Tuesday 8th September: 9.30 – 18.00
- Wednesday 9th September: 9:30 – 17.30
- Thursday 10th September: 9:30 – 16.30

Impact of physical effects and compact modeling on mm-wave circuit performance

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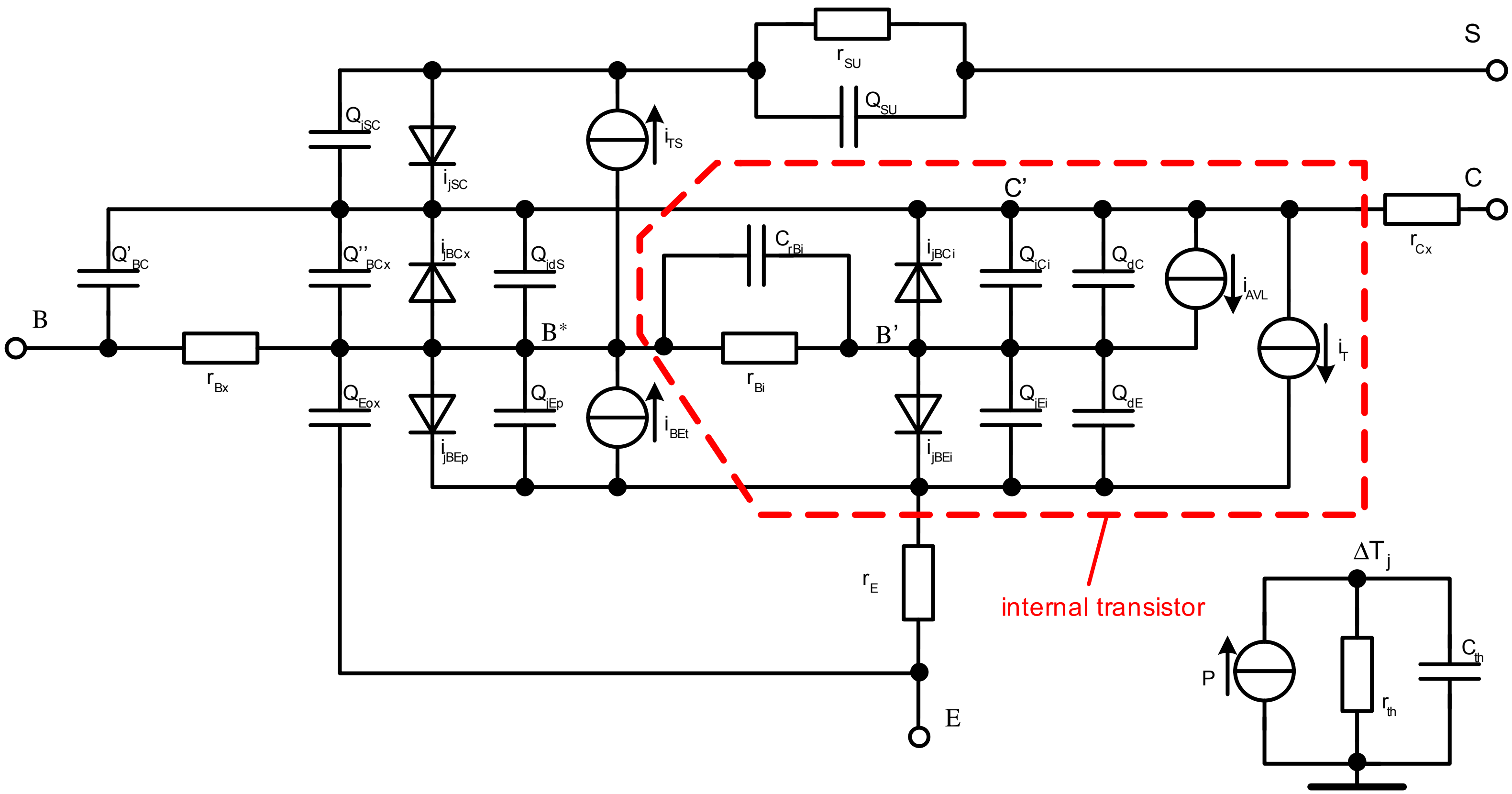
WS12: EuMIC - *SiGe for mm-Wave and THz*

Goals of the workshop

- Understanding of the basic concepts of HICUM/L2
  - core components and equations
  - equivalent circuit
  - transfer current
  - minority charges
- Impact of physical effects on circuit performance
  - focus on a few important effects
  - application example 1 - PA (numerical device simulation)
  - application example 2 - PA (realistic design)

HICUM/L2

- Physics-based compact model for bipolar transistors
  - including HBT related features
  - supported by CMC
  - available in all commercial circuit simulators



Transfer current - GICCR

- 1D transport equation of electrons => npn transistor
  - similar derivation of hole current of pnp transistor

$$J_n = q\mu_n\left[V_T\frac{dn}{dx} + nE\right] = q\mu_n\frac{d\varphi_n}{dx}$$

(φ_n => quasifermi-potential of electrons)

- rewritten for transfer current

$$I_T = \frac{qA_E V_T \overline{\mu_{nr} n_{ir}^2}}{\int h(x)p(x)dx}\left[\exp\left(\frac{V_{B'E'}}{V_T}\right) - \exp\left(\frac{V_{B'C'}}{V_T}\right)\right]$$

=> weighted hole charge

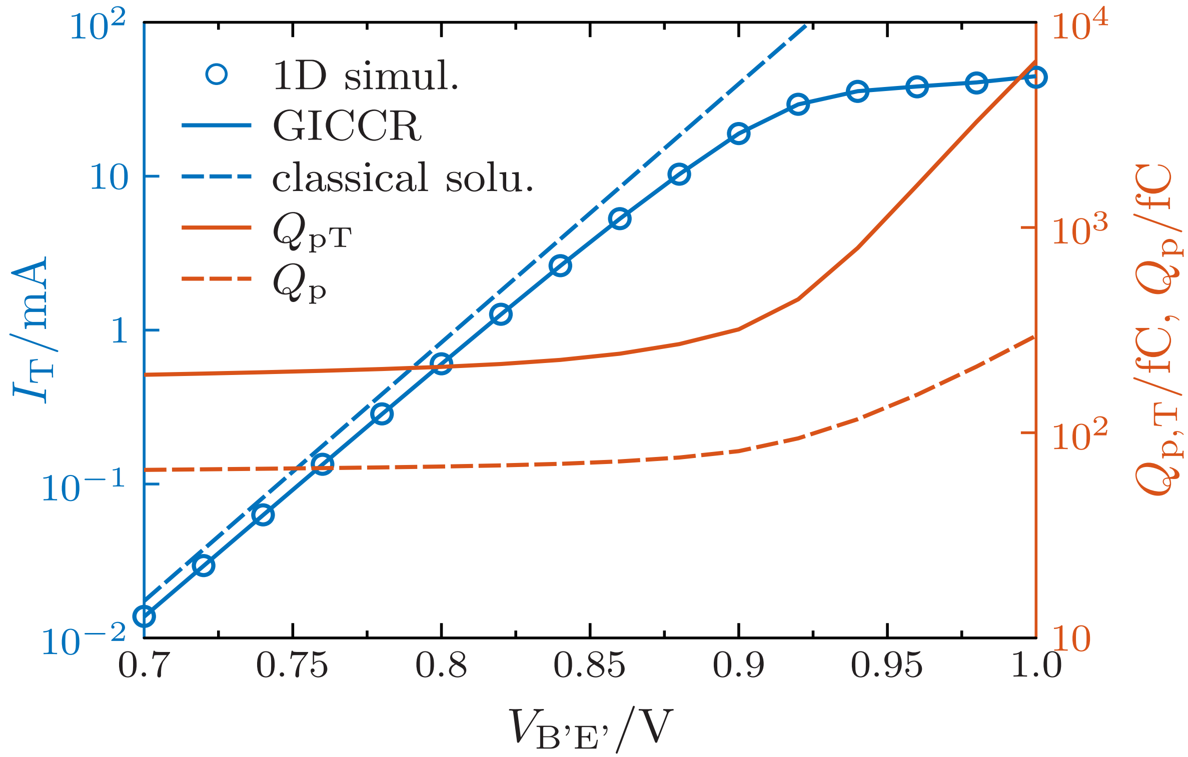
$$Q_{p,T} = q\int h(x)p(x)dx = q\int\frac{\overline{\mu_{nr} n_{ir}^2}}{\mu_n(x)n_i^2(x)}p(x)dx$$

Weighted Hole Charge

- Calculation of the transfer current by using charges

$$Q_{p,T} = Q_{p0} + h_{jEi}Q_{jEi} + h_{jCi}Q_{jCi} + h_{f0}i_{Tf}\tau_{f0} + h_{fE}Q_{Ef} + Q_{Bf} + h_{fC}Q_{pC}$$

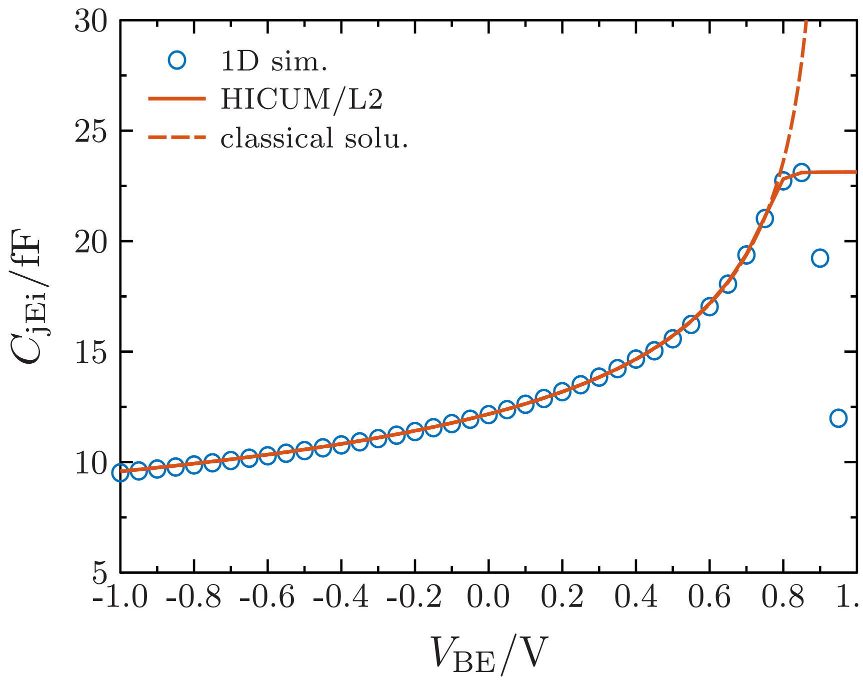
=> separately measured quantities

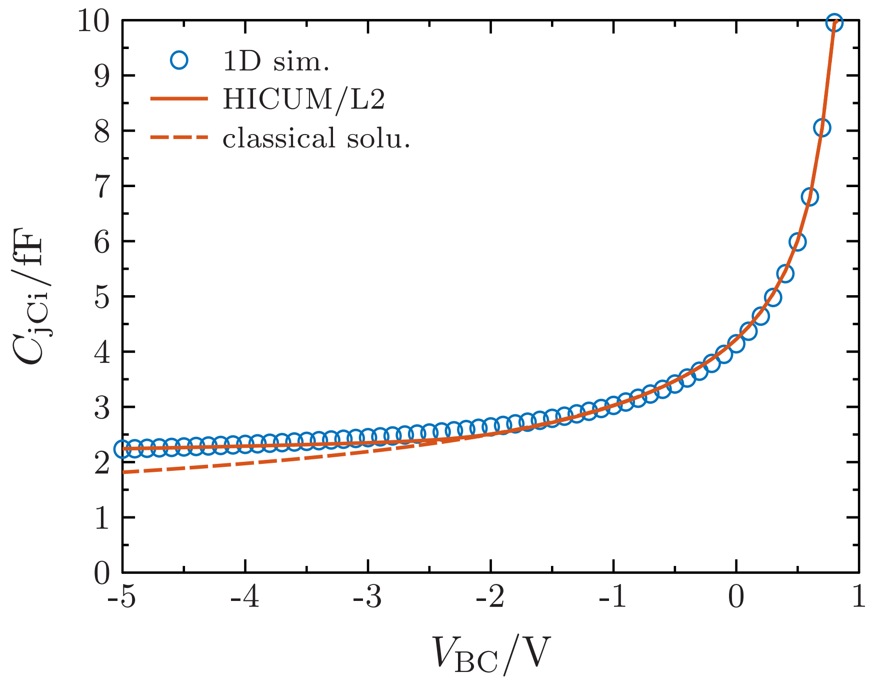


Charge Modeling

Depletion charges

- Two different models available
  - variable limit of maximum capacitance value => $C_{jE(i,p)}$
  - punch-through effect => $C_{jC(i,x)}$, C_{jS}





Charge Modeling

Mobile charges

- Low and high current component

$$\tau_f = \tau_{f0} + \Delta\tau_f$$

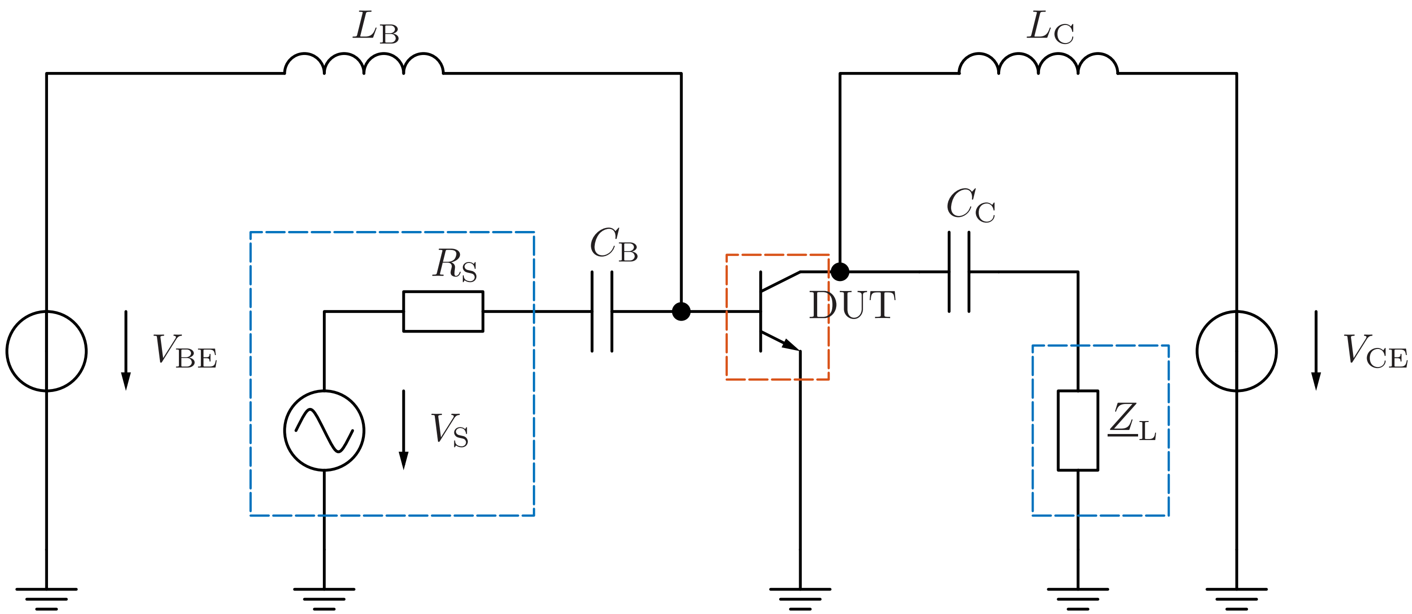
- Low current component including:
  - base width modulation => decrease of τ_f with V_{CB}
  - finite carrier velocity in BC-SCR => increase of τ_f with V_{CB}
- High current component including:
  - weak transit time increase at medium current densities => $f_{T,peak}$
  - strong charge increase due to Kirk-effect and BC-barrier term
- Version 2.30 released in 2011, actual version 2.33
  - version 2.34 to be released in 2015

HICUM/L2 Version 2.3x

- Main changes
  - bandgap effects on transfer current
  - improved knee-current modeling (by physics-based weight factors)
  - improved temperature models of the transfer current
  - BC-barrier term
  - temperature dependent thermal resistance

Application Example 1 - PA

- Simple PA circuit with power source and load impedance

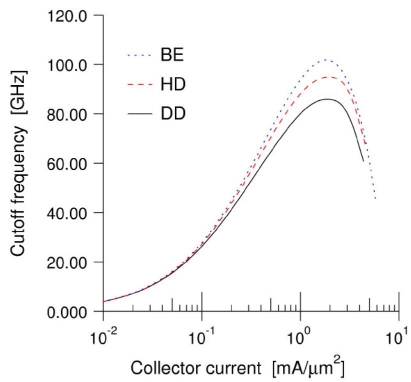


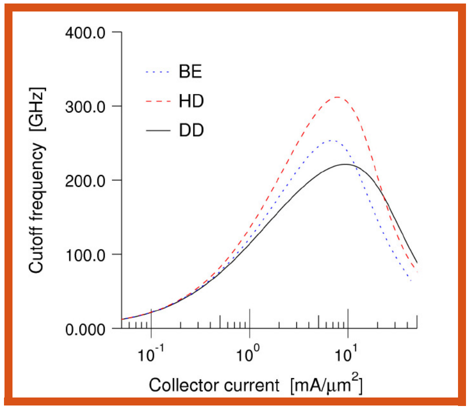
transistor DUT simulated as

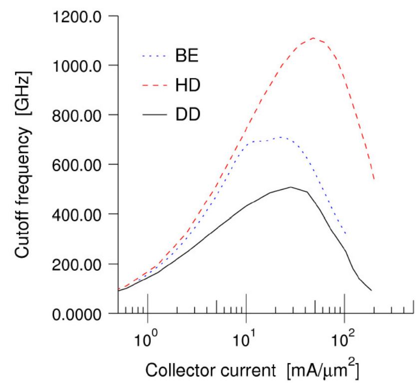
numerical 1D device
compact model HICUM/L2

Numerical 1D Transistor

- Drift-Diffusion simulation for profile with f_T=250 GHz

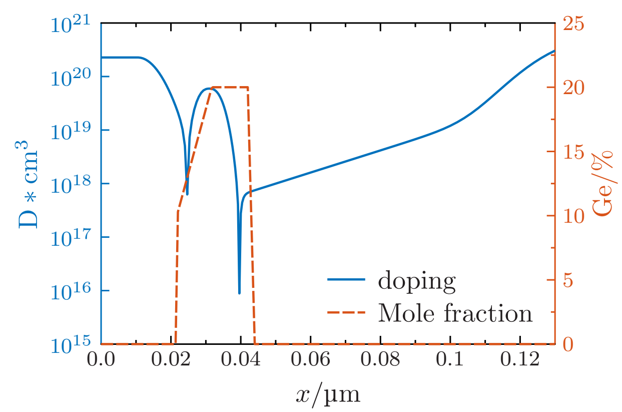






=> limits of DD model

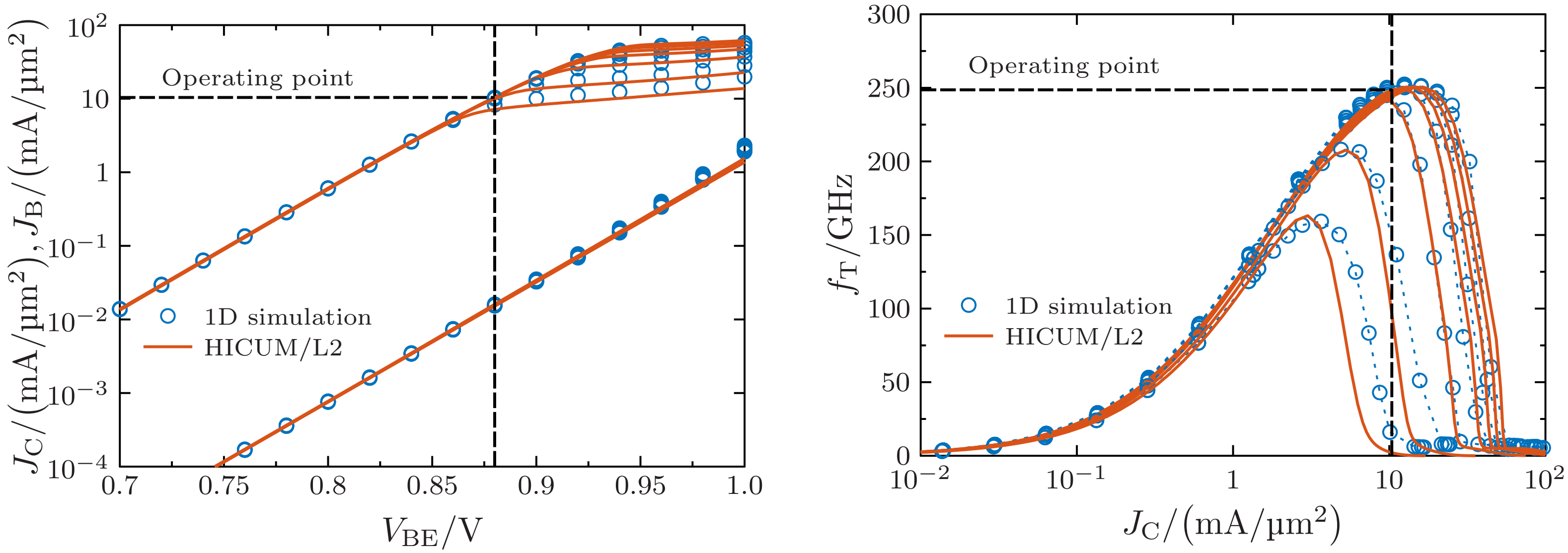
length of internal transistor:	130 nm
base width:	15 nm
internal collector width:	70 nm
maximum base doping:	$6*10^{19}$ cm^{-3}
J_C @ $f_{T,peak}$:	10 mA/µm^2
B_{VCE0} @ V_{BE}=0.7 V:	1.5 V



[S.-M. Hong, C. Jungemann, "Electron transport in extremely scaled SiGe HBTs," BCTM 2009, S. 67-74.]

HICUM/L2 Model

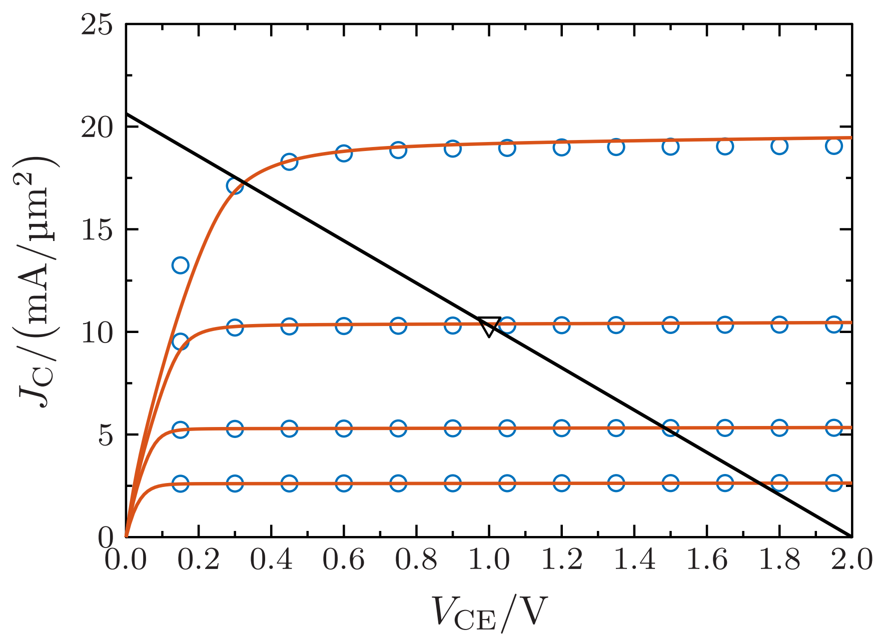
- Usage of latest available version
  - extraction based on standard characteristics (DC, small signal AC)



  - extraction of all parameter corresponding to 1D transistor

Power Amplifier

- Operating point close to f_T => strong impact of high current effects



  - 1D transistor used with A_E=1 µm^2 => Load resistance: RS=100 Ω

    close to 50 Ω => realistic environment

- Focus on harmonic distortion

Simulation

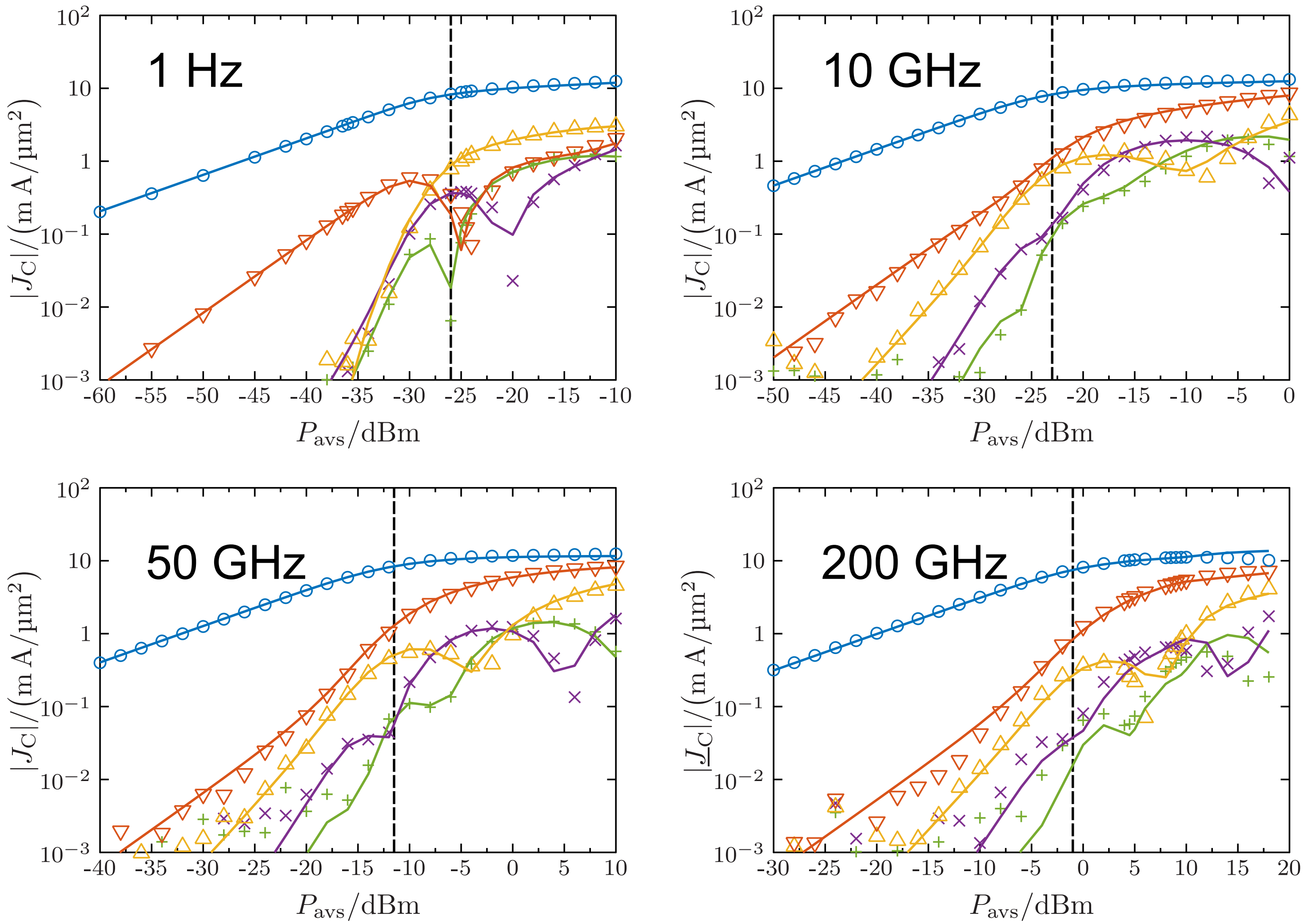
- for numerical 1D simulations, only transient simulation possible
- transformation into frequency domain

- Fundamental frequencies
  - 1 Hz: no impact of dynamic currents => verification of static current
  - 10 GHz: quasi-static behavior => verification of charges
  - 50 GHz: 5th harmonic at peak f_T => starting influence of NQS effects
  - 200 GHz: close to peak f_T => 5th harmonic at 1 THz

- Focus on output power in frequency domain

Output Current

Frequency domain results



Nonlinear Modeling

- Accurate non-linear large-signal modeling with HICUM/L2
  - up to very high frequencies far beyond $f_{T,peak}$

=> Which physical effects are significant?

- Discussed here:

High-current effects

  - compression at high input power

=> saturation

=> transfer current modeling

  - high-current effects in charges due to strong increase of carriers

=> impact on I_C (via $Q_{p,T}$)

=> impact on Q_f

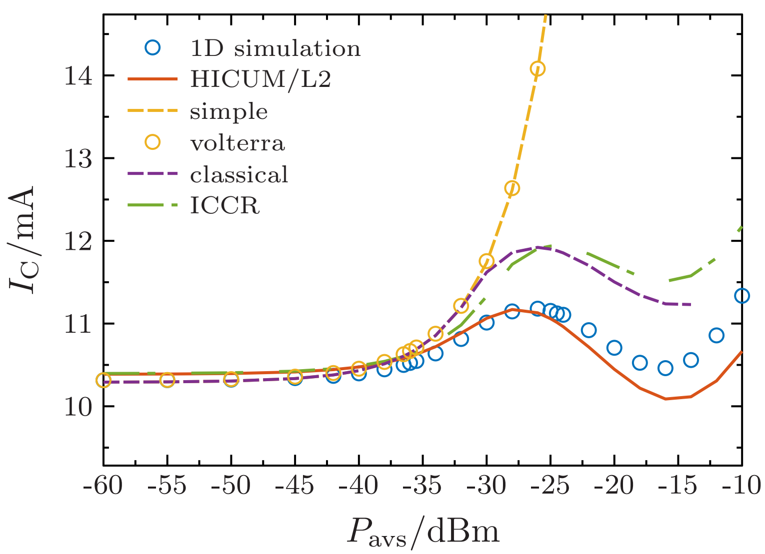
Compression (1 Hz)

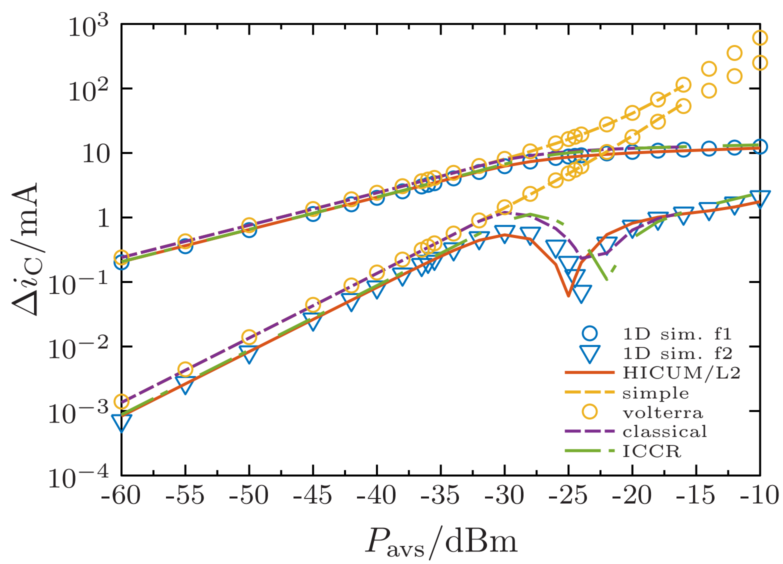
- Transfer current modeled by:

simple equation: $I_T = I_S \exp\left(\frac{V_{BE}}{V_T}\right)$ (no saturation, no BC current)

classical equation: $I_T = I_S\left[\exp\left(\frac{V_{BE}}{V_T}\right) - \exp\left(\frac{V_{BC}}{V_T}\right)\right]$ (saturation, const. I_S)

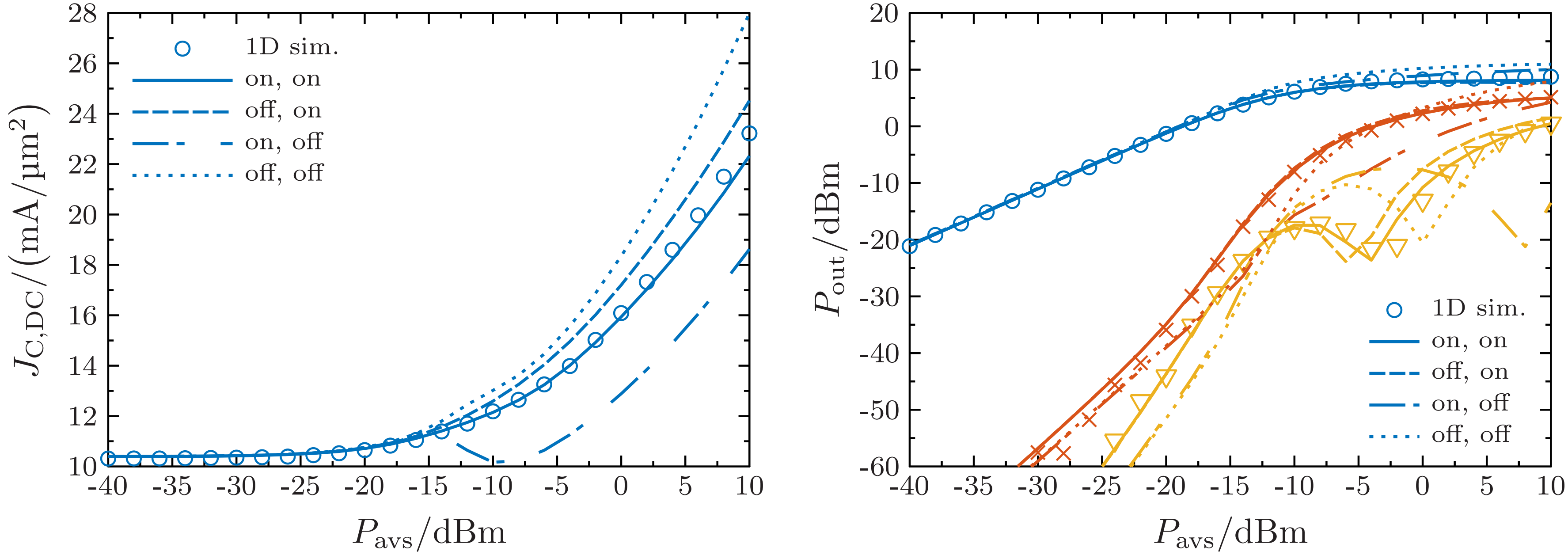
ICCR: $Q_{p,T} = Q_{p0} + Q_{j,T} + h_{f0} i_{Tf} \tau_{f0}$ (no high-current effects on I_T)





High-Current Effects (50 GHz)

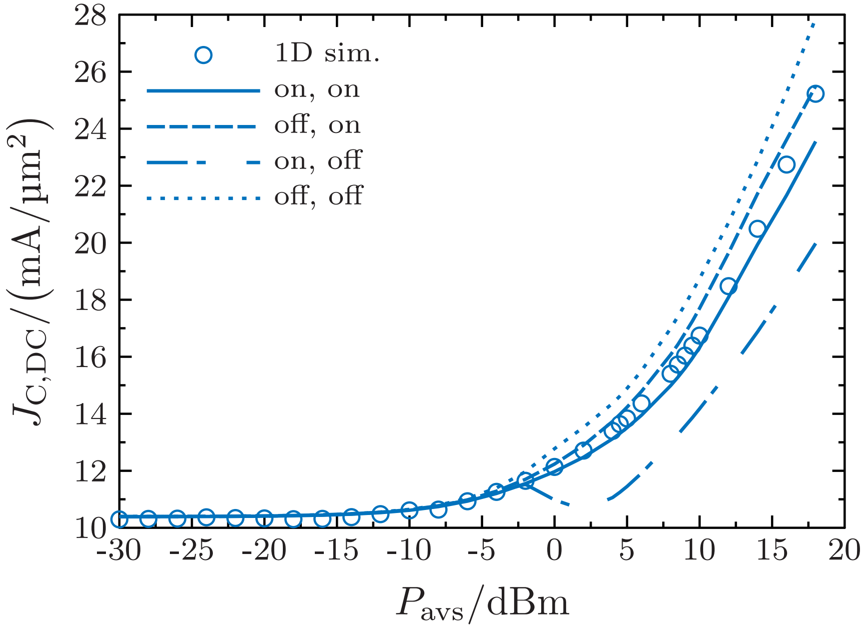
- Legend here: high current effects in $Q_{p,T}$ => I_C, Q_p

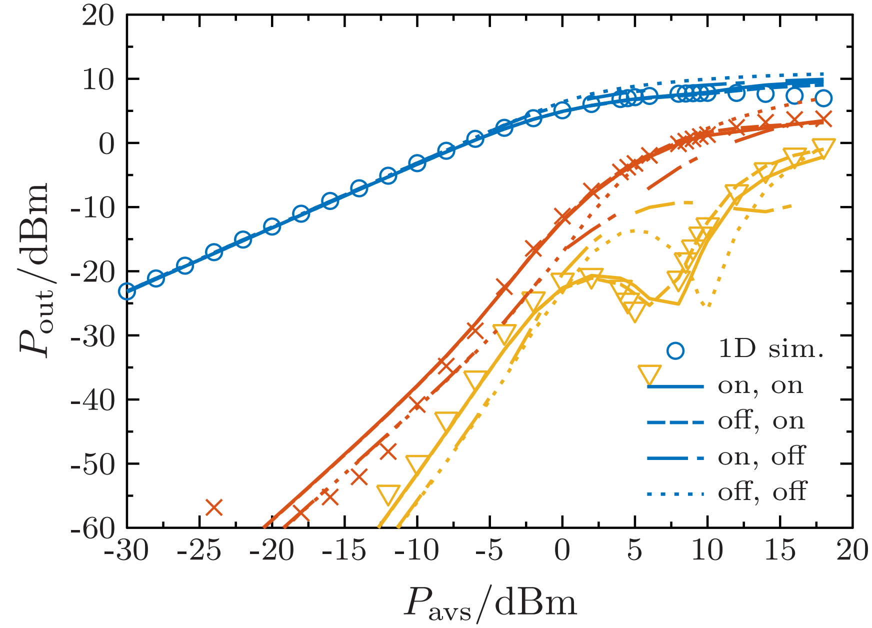


=> accurate charge modeling required

High-Current Effects (200 GHz)

- Second and third harmonic above $f_{T,peak}$





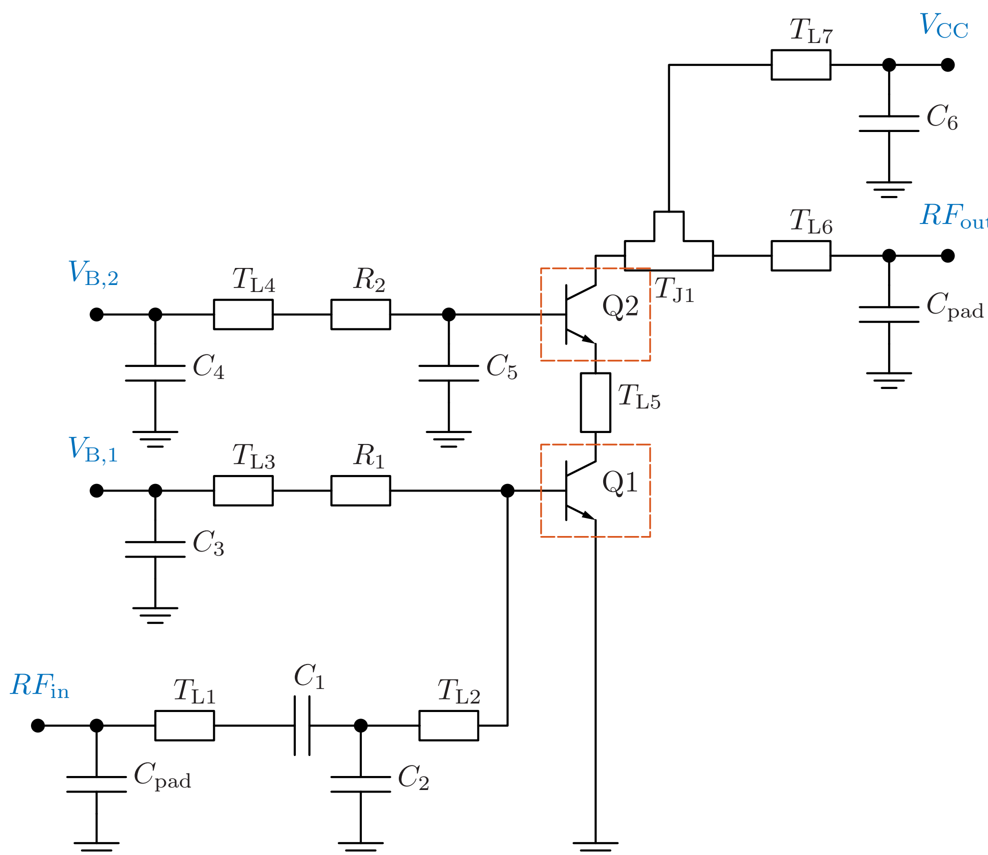
=> similar results to 50 GHz

even more emphasize on the charge due to high frequencies

Application Example 2 – 2-stacked PA

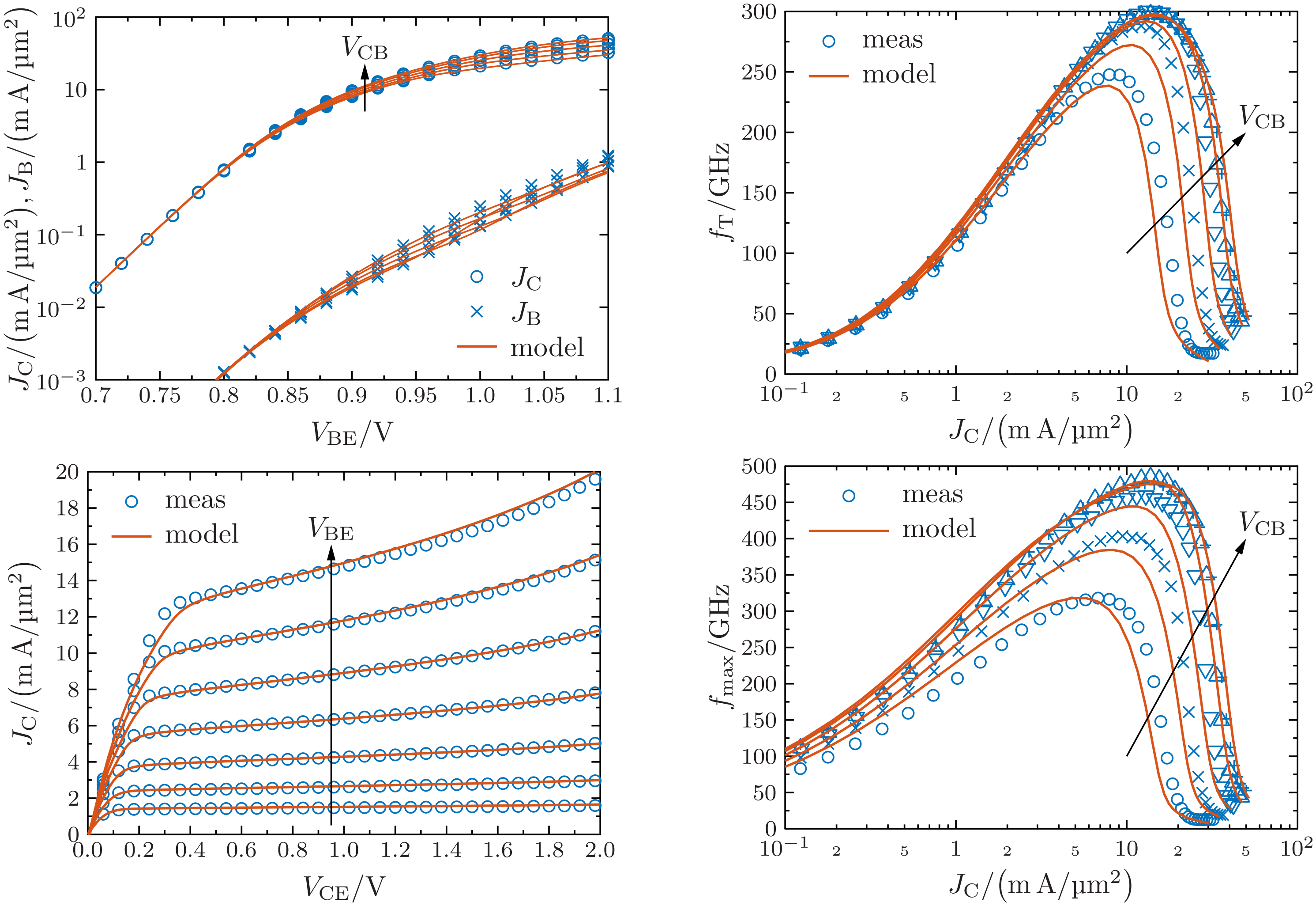
- Circuit designed in IHPs SG13G2 technology
  - transistors with $f_{T,peak}$=300 GHz and $f_{max,peak}$=500 GHz
  - cascode connection to increase available voltage swing
  - transistors biased at
    V_{BE}=0.91 V
    V_{CE}=1.1 V

    => close to $f_{T,peak}$
  - operating frequency: 94 GHz



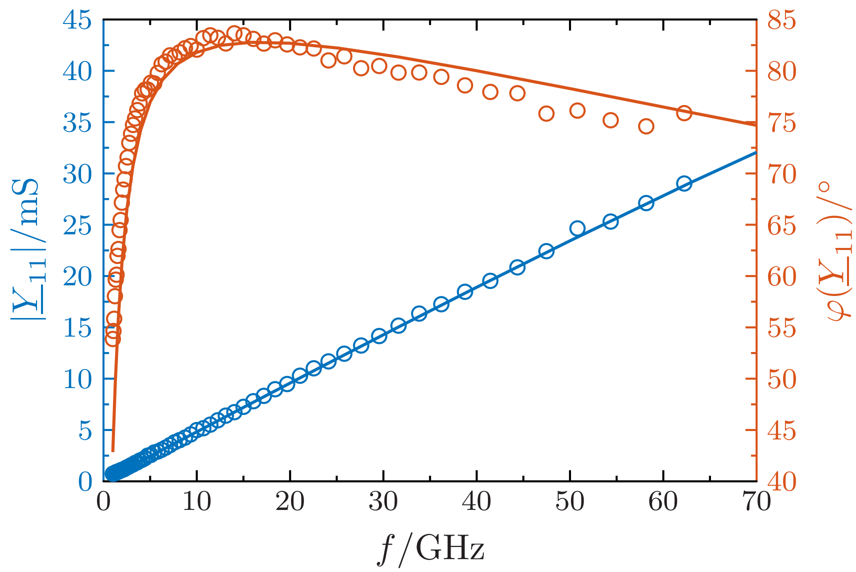
Experimental results - transistor

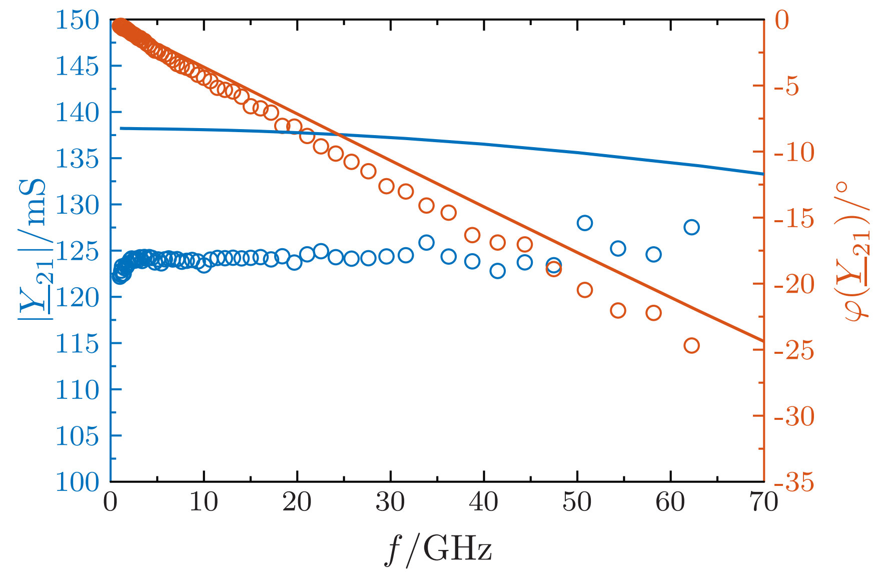
Linear modeling (selected results)



Experimental results - transistor

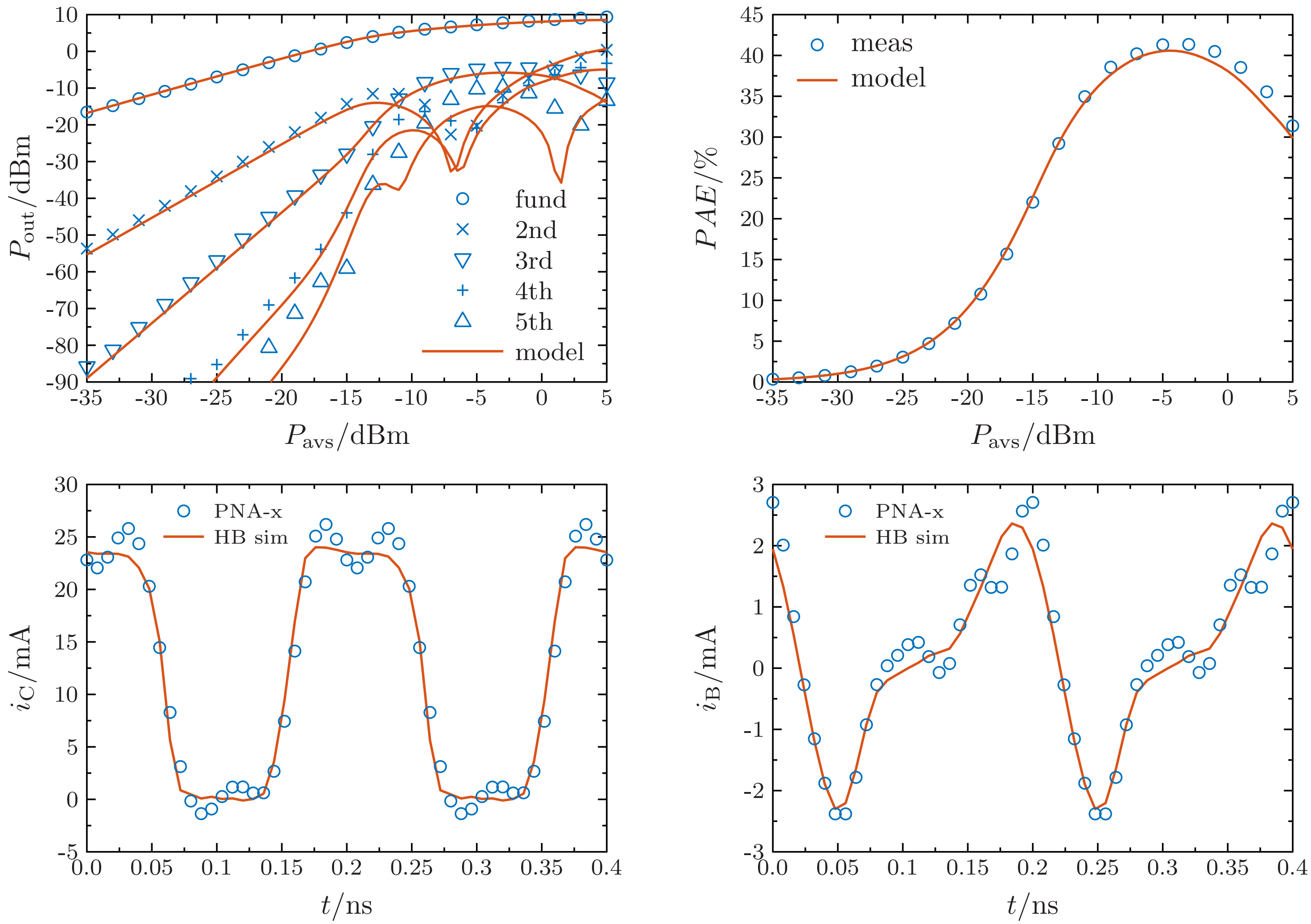
Small-signal (V_{BE}=0.9 V, V_{CB}=0.3 V)





Experimental results - transistor

Large-signal (V_{BE}=0.875 V, V_{CE}=1 V, f_0=5 GHz, P_{avs}=-5 dBm)



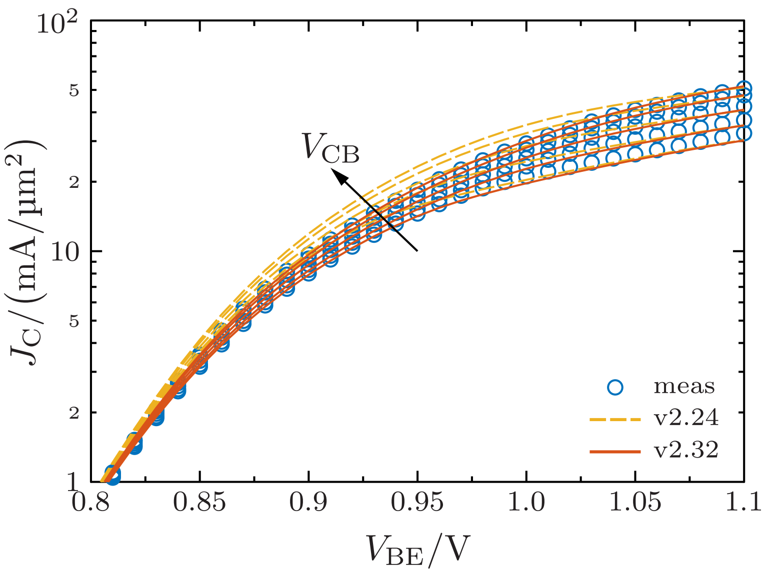
HICUM/L2 Version 2.2x version 2.3x

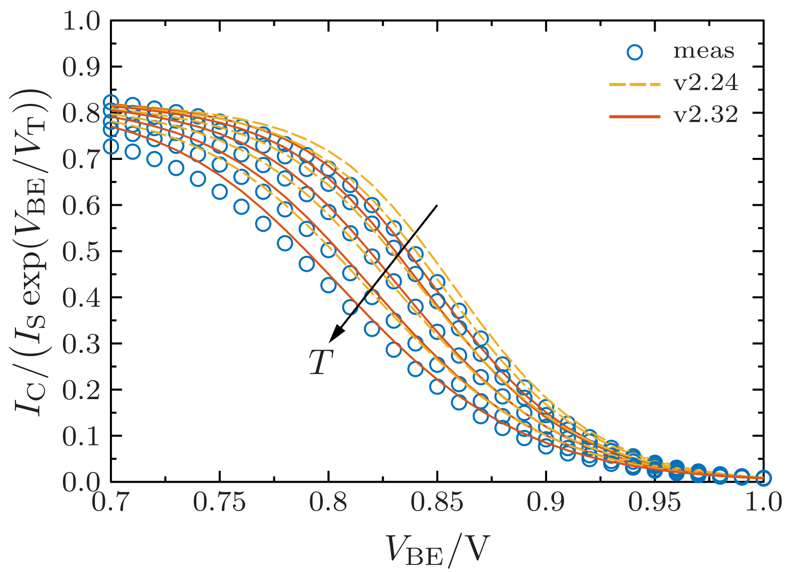
- Improved modeling of the transfer current
  - weight factor h_{f0} for medium injection => knee-current modeling

$$Q_{p,T} = Q_{p0} + h_{jEi}Q_{jEi} + h_{jCi}Q_{jCi} + h_{f0}i_{Tf}\tau_{f0} + h_{fE}Q_{Ef} + Q_{Bf} + h_{fC}Q_{pC}$$

  - temperature dependent weight factors => correct impact of self-heating

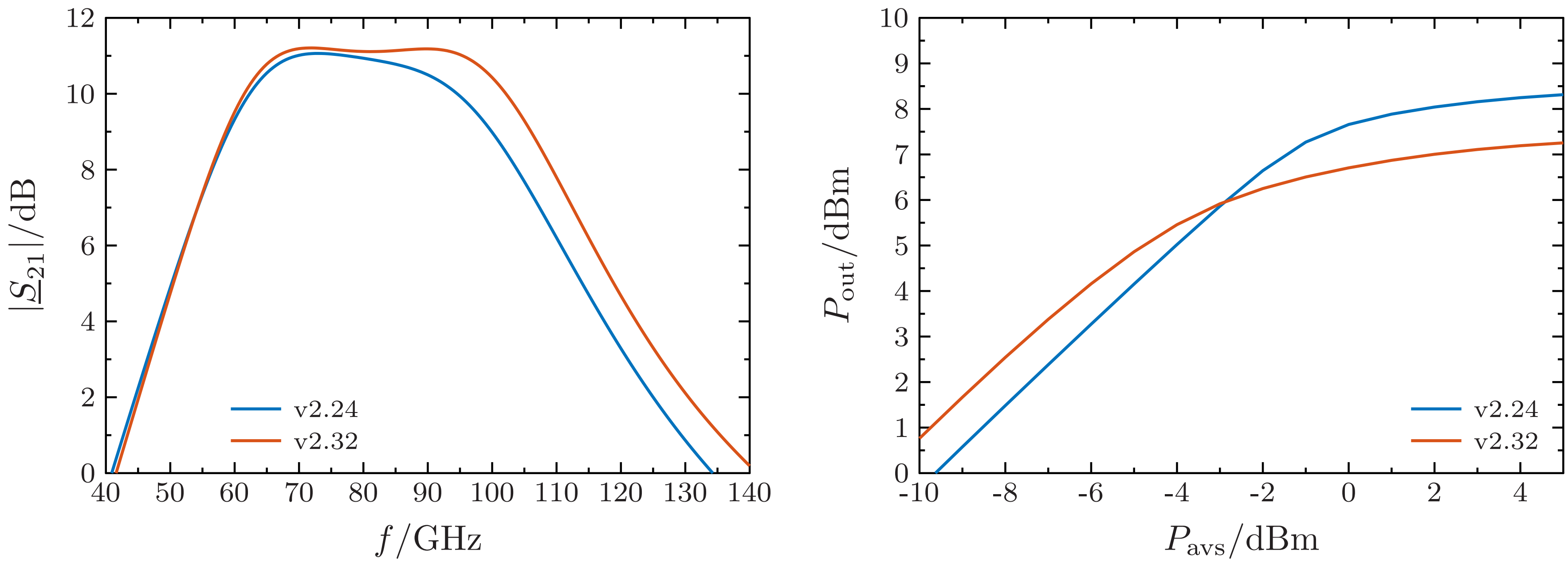
$$h(T) = h(T_0)\exp\left(\frac{V_{gB} - V_g}{V_T}\right)$$





HICUM/L2 Version 2.2x version 2.3x

Small-signal and large-signal results

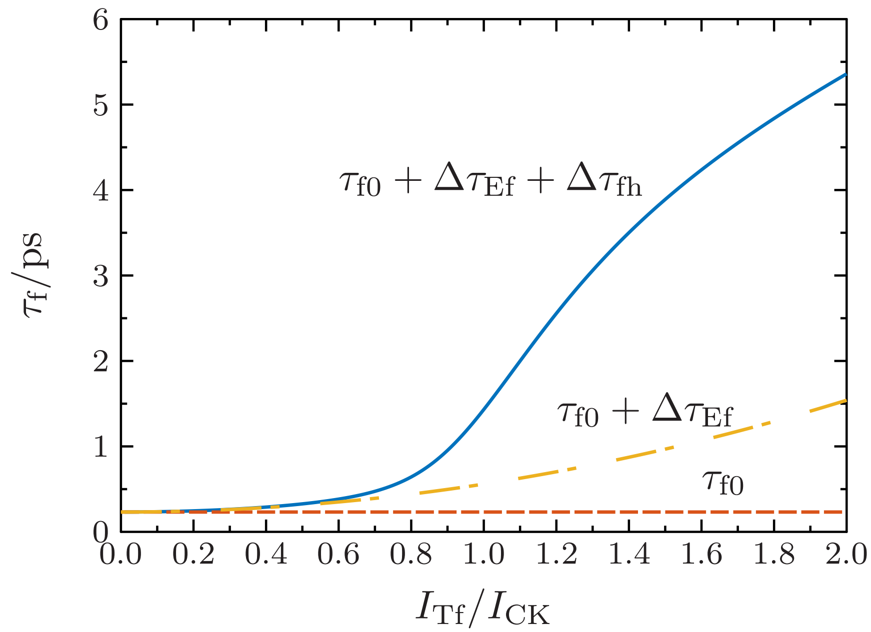


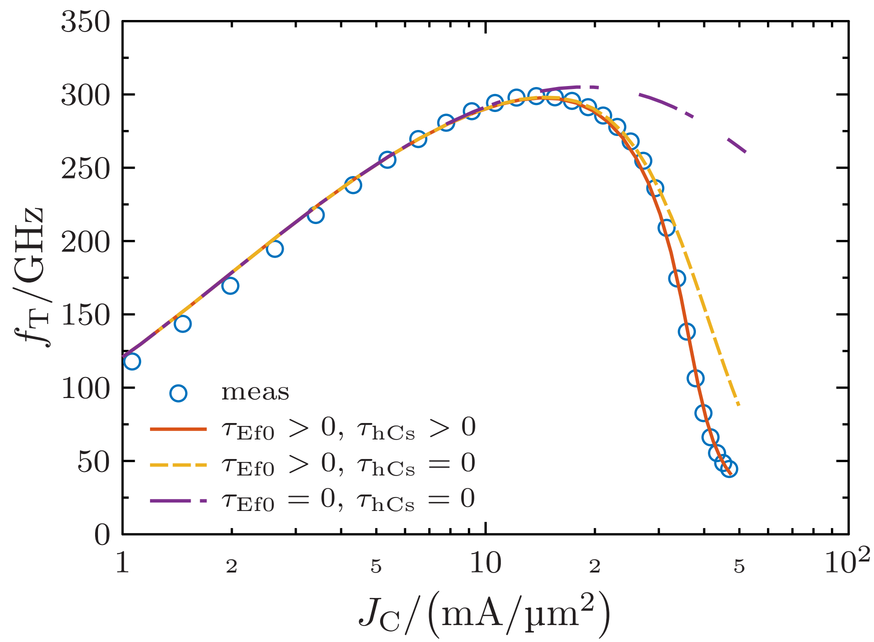
=> reduction of power at target frequency
significant differences in compression behavior

High-Current Transit Time

$$\tau_f = \tau_{f0} + \Delta\tau_{Ef} + \Delta\tau_{fh}$$

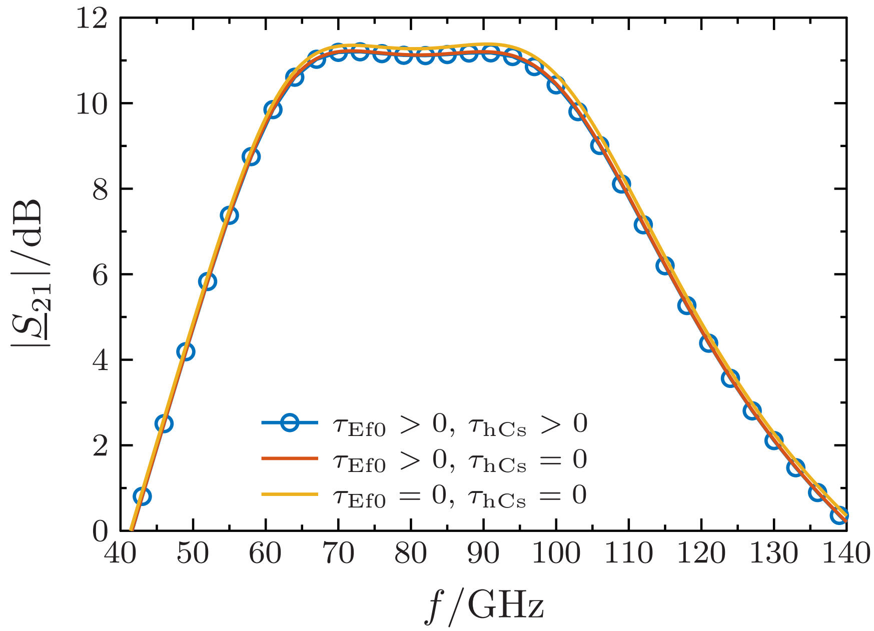
- τ_{f0} => medium injection
- $\Delta\tau_{ef}$ => before onset of high current effects
- $\Delta\tau_{fh}$ => high current effects

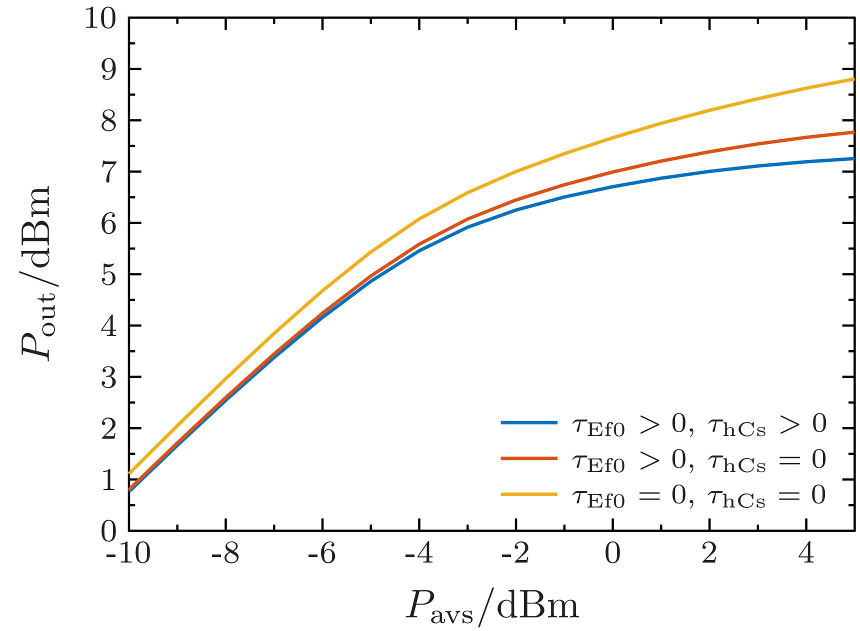




High-Current Transit Time

Small-signal and large-signal results

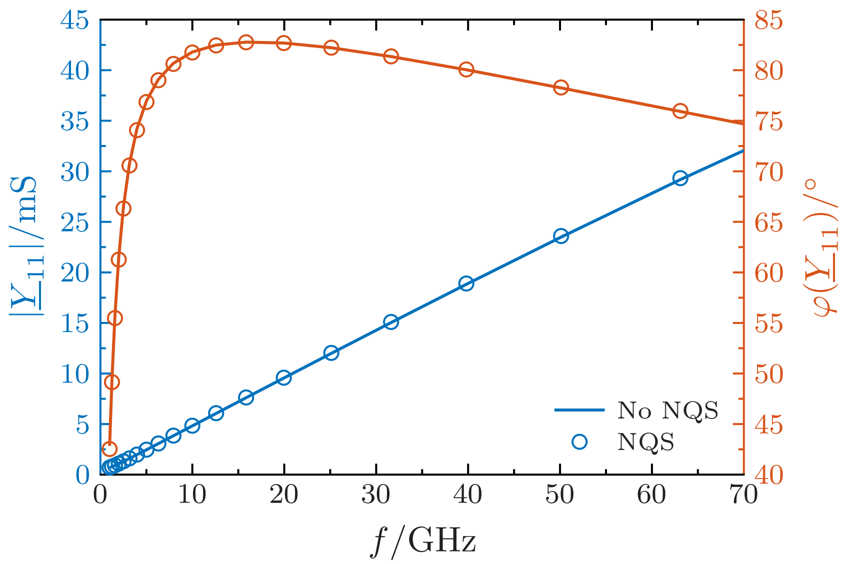


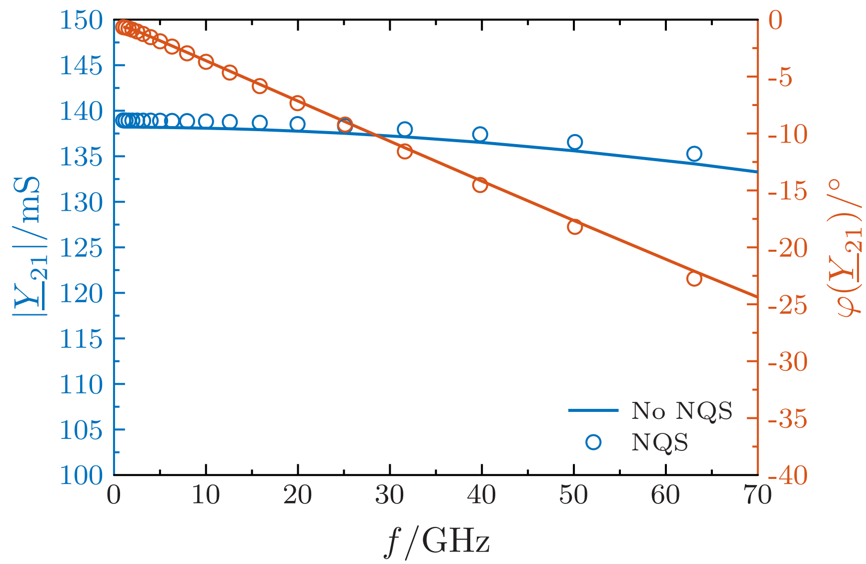


=> less influence of small signal results
(due to operating point)
different modeling of the compression

NQS Effects

- Delay in input charge and output current
  - in HICUM: modeled by adjacent networks
  - first order delay for Q_f
  - second order delay for I_{Tf}

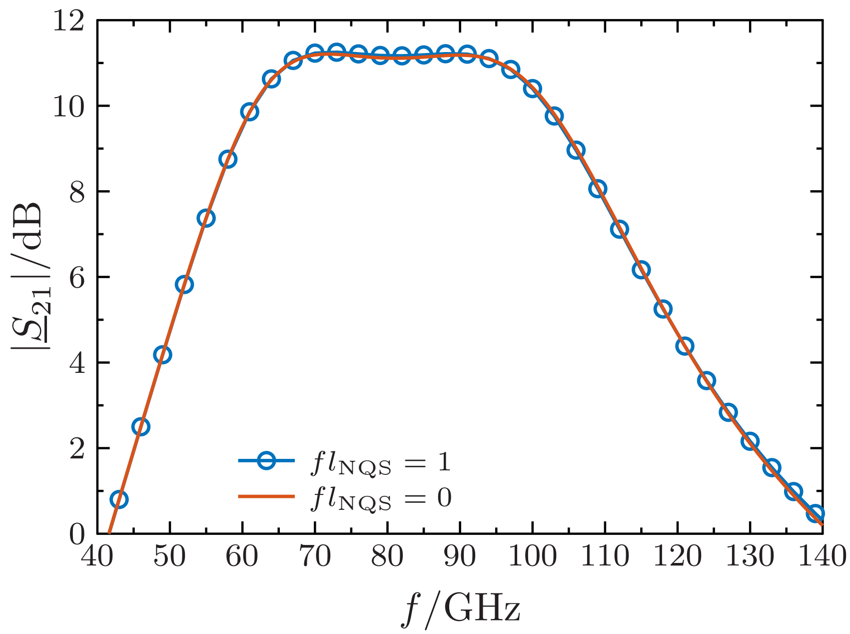


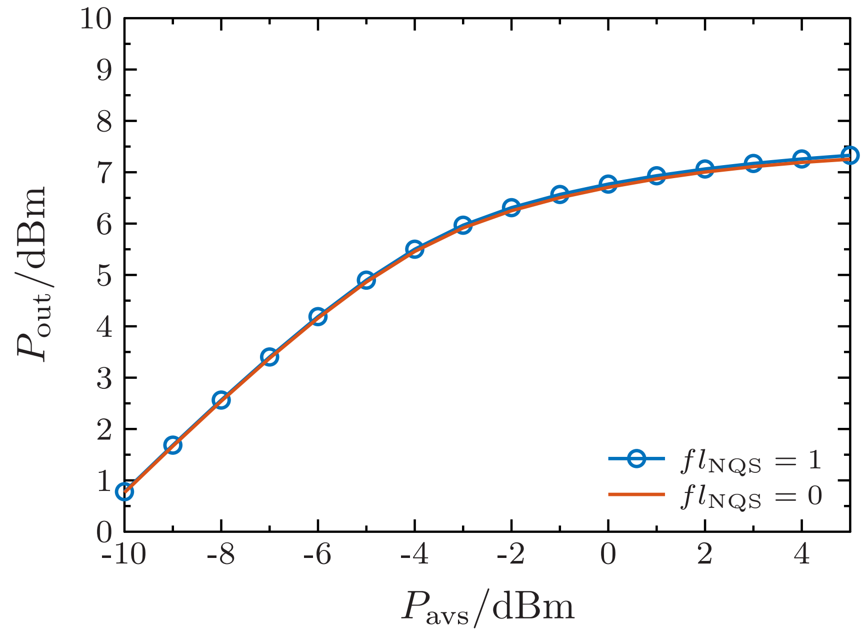


=> almost no impact for given transistor

NQS Effects

Small-signal and large-signal results



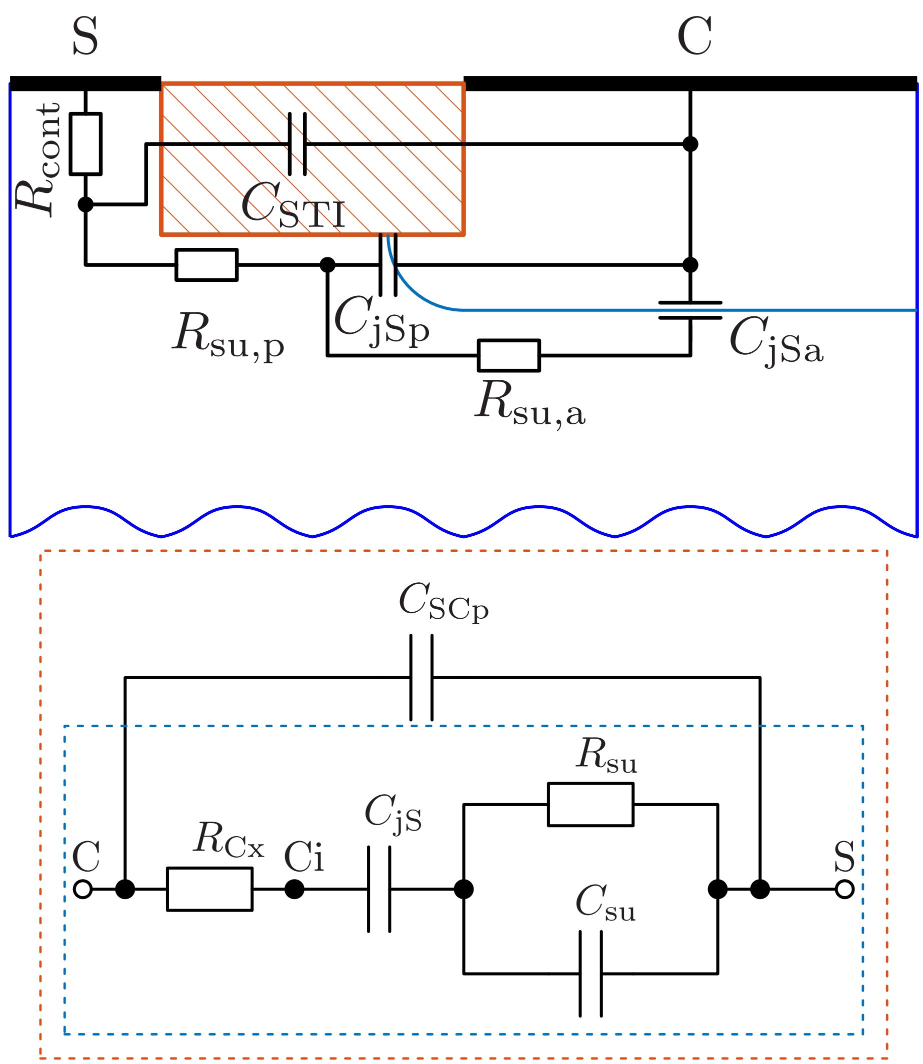


=> no visible impact

[cf. also:
C. Raya, B. Ardouin, "Model verification through benchmark circuits", 15th HICUM Workshop, Böblingen, 2015.]

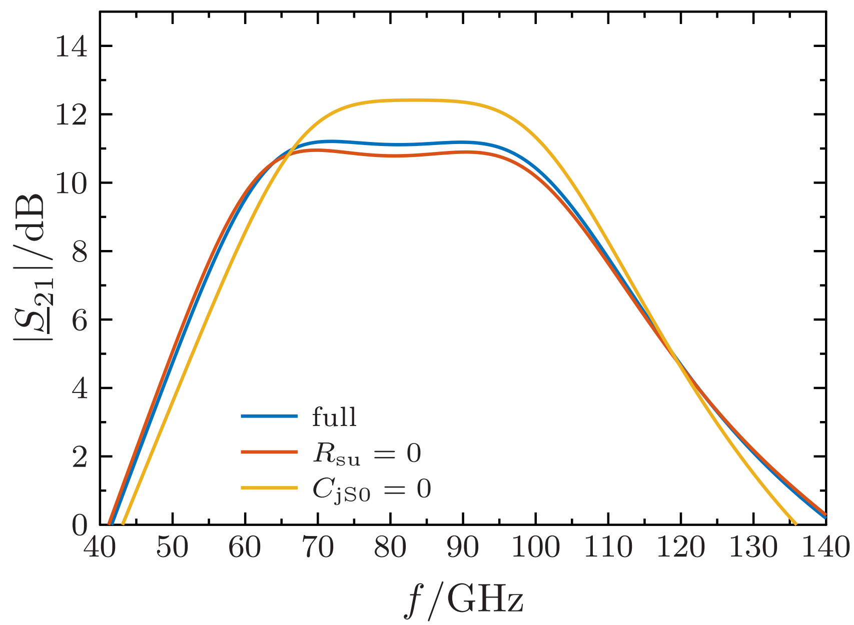
Substrate Effects

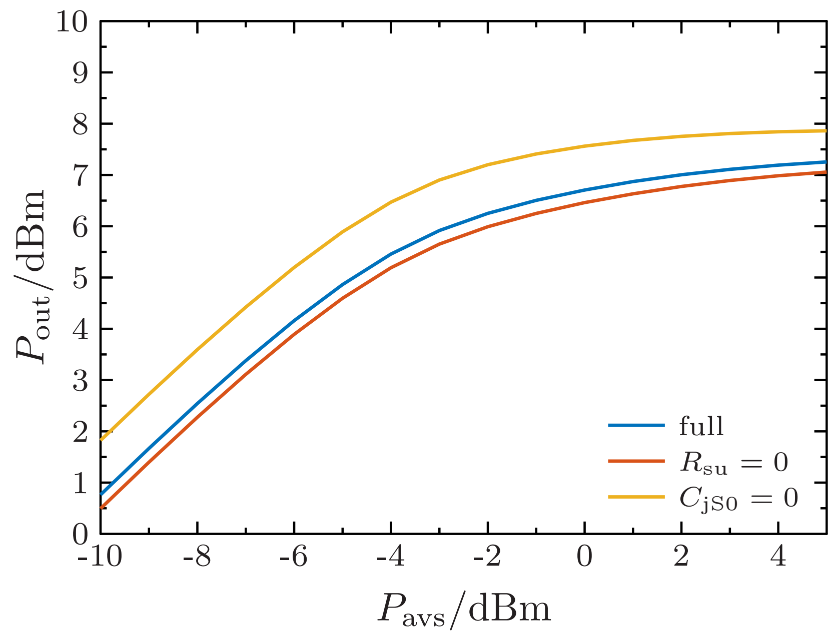
- Substrate capacitance due to pn-junction (SC) or trench oxide



Substrate Effects

Small-signal and large-signal results





=> strong influence of substrate capacitance due to impact on output conductance

=> substrate coupling required for actual correct value of substrate capacitance at given frequency

Summary

- Accurate nonlinear large-signal modeling capabilities of HICUM/L2
  - highlight of the important model features
  - high-current effects on charges and transfer current
  - new model version
  - substrate coupling effects
  - parameter extracted on standard DC and small-signal data sufficient for accurate large-signal modeling
- Impact on two circuits were shown
  - numerical simulations are required to overcome limitations by equipment
  - excellent agreement with respect to numerical results
  - experimental results for 2-stacked PA not yet available