Nonlinear distortion in mm-wave SiGe HBTs: modeling and measurements

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Outline

- Motivation
- Compact modeling approaches, requirements for mm-wave frequencies
- Standard compact models for SiGe HBTs, location of nonlinear effects
- Investigation method of distortion effects in SiGe HBTs
- Harmonic distortion: core model verification vs. intrinsic (1D) and internal (2D) transistors, analysis of distortion
- HICUM L2 verification on DC and RF characteristics of measured advanced SiGe HBTs
- HICUM L2 verification on harmonic distortion (FoM) on two tone load pull of SiGe HBTs
- Analysis of external parasitic compact model elements on harmonic distortion.
- Summary

Motivation

Benefits:

- SiGe based HBTs have proven to be among the fastest transistors on the market today.
- Recent SiGe HBT technology offers f_T/f_{max} = 300/500 GHz and enables mm wave circuits for various applications:
  - optical communications with 100 Gbit/s
  - 77 to 150 GHz collision radar applications
  - LNA at 260 GHz for receivers, Heterodyne receivers for operation at THz frequencies
  - cryogenic applications

Issues:

=>All those applications require physics based accurate models capable to capture nonlinearities at high frequency.

Fundamental compact modeling approaches

Goal: cover large variety of applications & circuit optimization (bias, T, f)

Criteria	Behavioral, X-par.	Physics-based
accuracy	high (within narrow ranges)	moderate to high over wide range
numerical stability	compromised outside fitting ranges	high (for standard models)
fabricated devices	need every possible layout used in circuits on test chip	only few devices (6 HF trs, 6 test structures)
measurement effort	moderate to high	moderate to low
par. extraction effort	moderate (single device), very high for library, imposs. at high f	moderate (single device) very low for library
geometry scaling	inconsistent (typically)	consistent
predictive capability	none	moderate to high
statistical modeling	none (very high effort)	good to excellent

⇒ *Physics-based* model (cuts design cycle & supports process dev.)

Compact HBT modeling at (sub-)mm-wave frequencies

Circuit design related requirements:

- design at the physical device and process technology limit
  => meeting specs is very challenging
- large variety of applications (implemented in BiCMOS SoCs)
  => need careful individual and sophisticated optimization (by e.g. device sizing)
- accurate models up to very high frequencies incl. subharmonics (i.e. distortion)

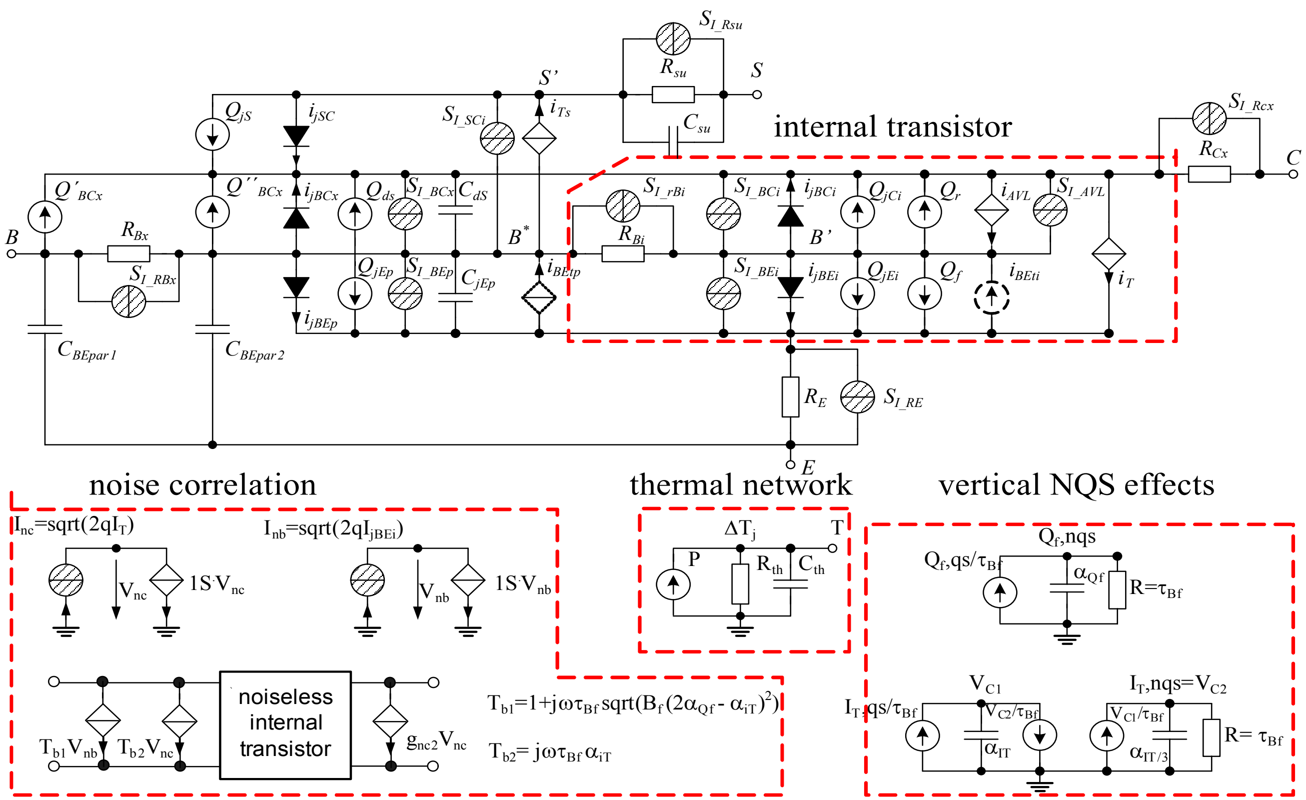
⇒ consequences for compact modeling (e.g. for foundries)

- **physics-based** => enables:
  - geometry scaling (i.e. contact configuration & emitter size)
  - extension into non-measurable operation (bias, frequency, temperature) ranges with reasonable accuracy
  - predictive and statistical design
- **geometry** scalable models => enables circuit optimization
- **large-signal** capability => enables accurate small-signal and distortion modeling

⇒ "good modeling" pays for itself if it saves *just one design iteration*!!

Existing *standard* large-signal BJT and HBT models

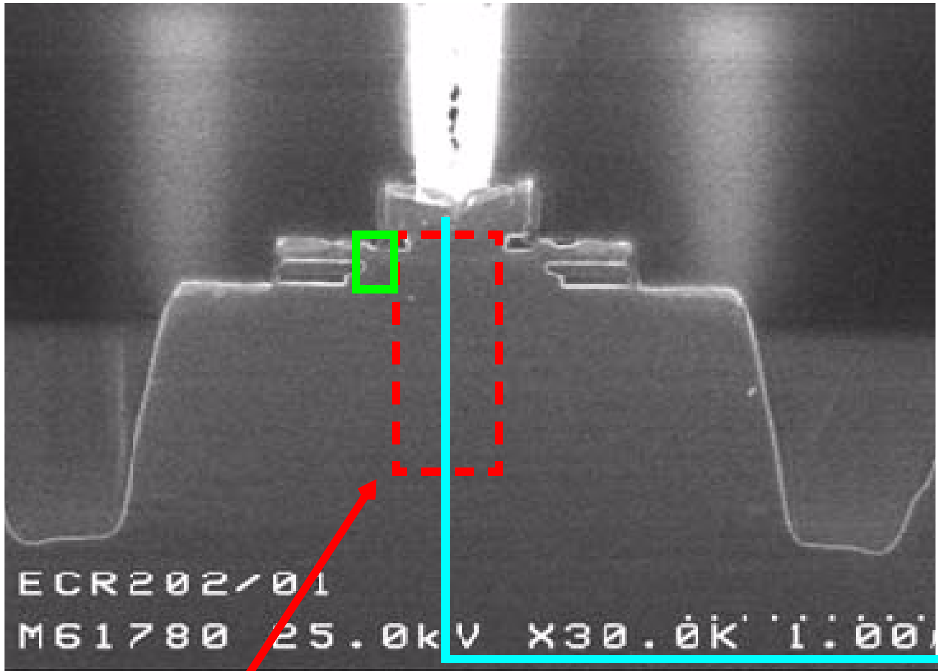
- SPICE Gummel-Poon model
  - addresses effects present in "70ies" ***BJT*** technologies, no HBT effects.
- HICUM/L2, MEXTRAM, VBIC
  - include some or all SiGe HBT related effects. HICUM includes mm-wave technology related effects in SiGeC HBTs (s. DOTFIVE).



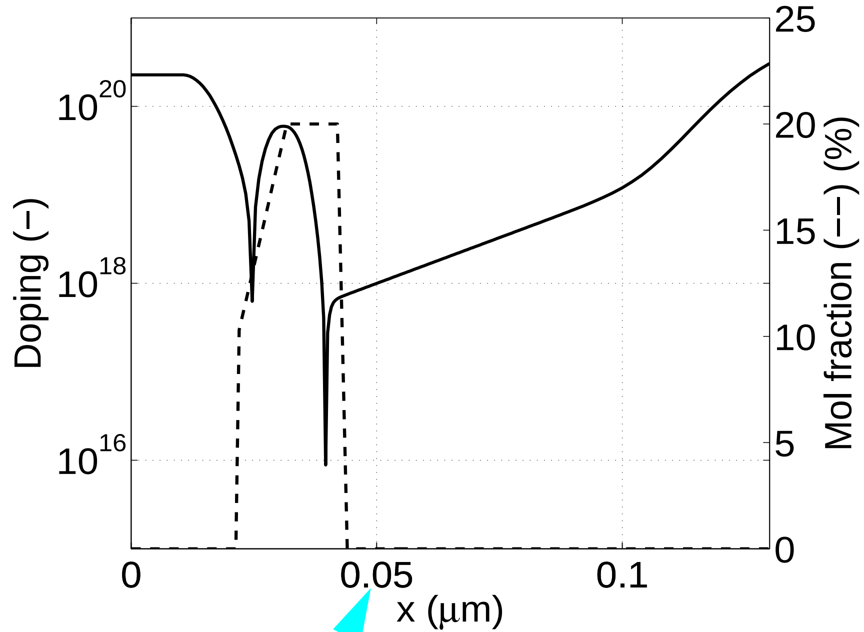
Where are the *nonlinear* effects in HBTs?

- $I_C \sim \exp(V_{BE}/V_T)$; $Q_{mobile} \sim I_C^{\gamma}$ $(\gamma \geq 1)$; $I_{aval} \sim I_C \exp(V_{CB}/V_B)$; $Q_{depl} \sim (1-V_j/V_D)^{-z}$ ...

schematic cross-section



typical profile



1D (or *intrinsic*) transistor (here: $f_{T,peak}$ = 250 GHz)

internal transistor (includes internal base resistance)

$\Rightarrow$ device nonlinearity is mostly defined by *intrinsic* transistor

Goals of this presentation

- consider *intrinsic* model based on 1D device simulation (as reference)
  start with single tone signal at fundamental frequencies of 1Hz, (10, 50, 200) GHz
  => verify compact model distortion behavior up to subharmonics of several peak f_T
  (i.e. far above measurable frequencies!!)

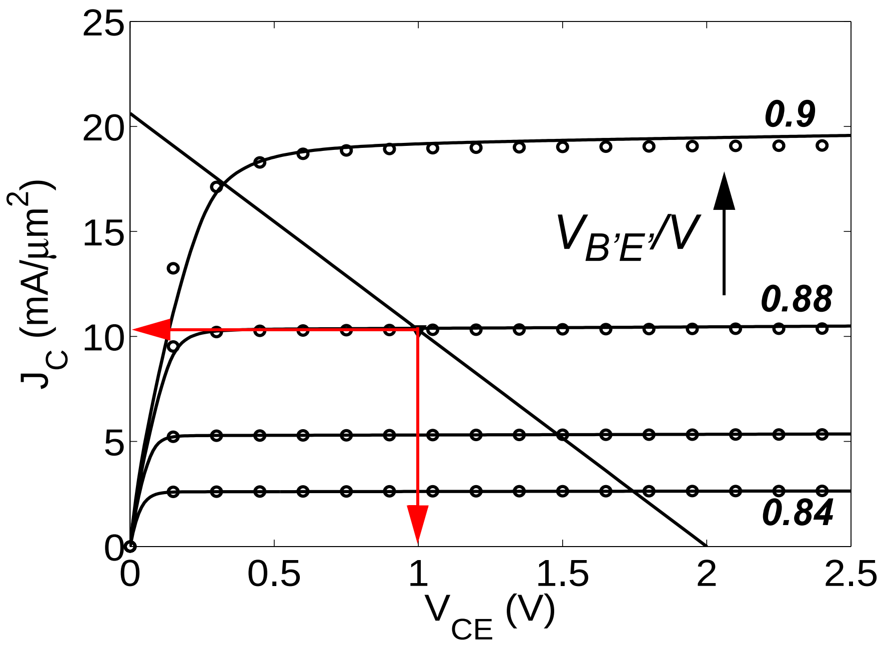
- extension to *internal* transistor (with 2D device simulation as reference)
  => impact of nonlinear internal base resistance

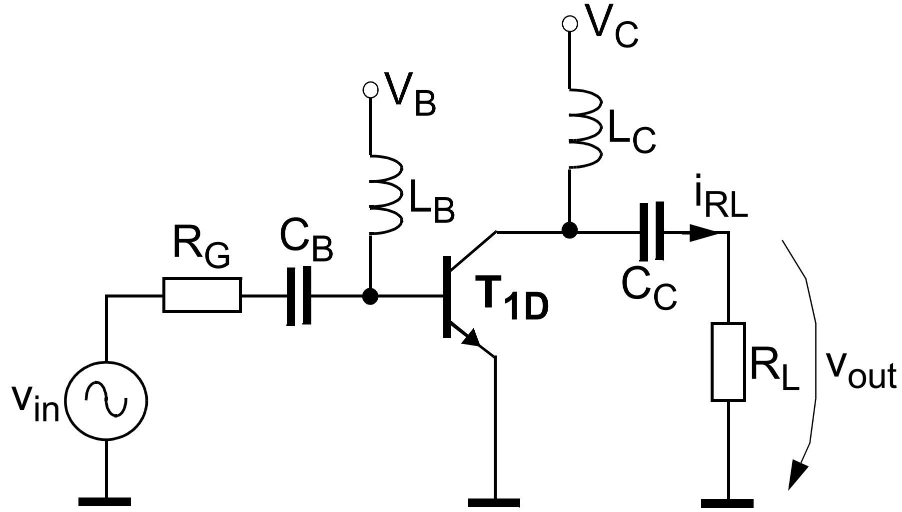
- extension to *complete (3D)* transistor structure and experimental characteristics
  => impact of external regions.

Investigation method of distortion effects in SiGe HBTs

Start with 1D transistor => use 1D device simulation as reference

- define suitable DC bias point => simple amplifier circuit (R_G = 50 Ω, R_L = 97 Ω)





- T_{1D}: use either 1D numerical transistor or compact model (HICUM)
  => same numerical "environment" for compact model and reference

⇒ run mixed-mode device simulator with single-tone input signal

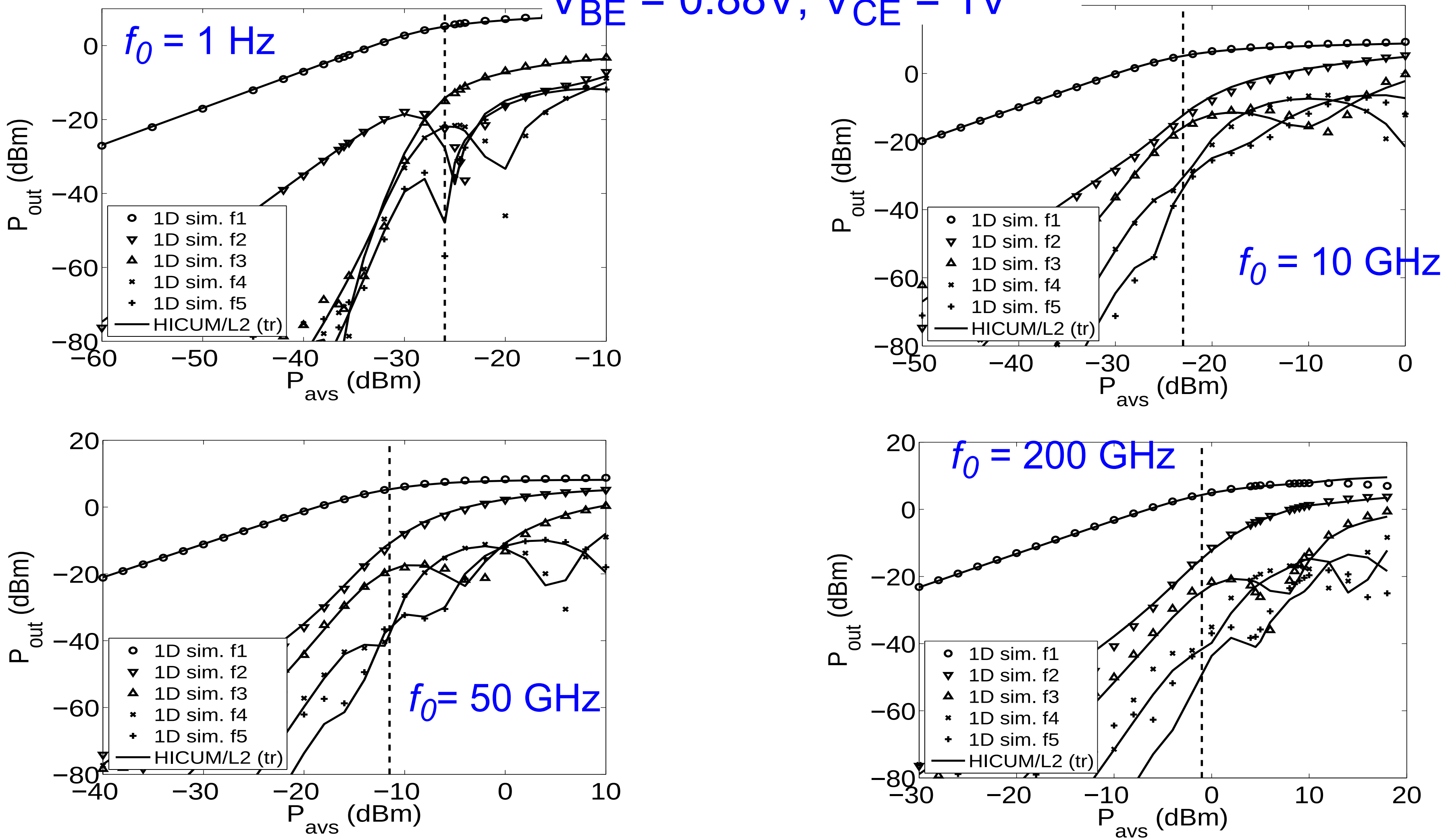
Model evaluation and verification procedure

... time domain transient simulation is employed

- input voltage amplitude from small-signal (1 mV) to large-signal is varied (200 mV)
  => input power P_{in} = [-40, 0] dBm (= [0.1μW, 1mW])
- fundamental frequencies f_0 of input signal are selected:
  - f_0 = 1 Hz (no capacitive effects, guaranteed quasi-static (qs) operation)
  - f_0 = 10 GHz (some capacitive effects, qs operation)
  - f_0 = 50 GHz (5th harmonic close to $f_{T,peak}$, capac. effects, some non-qs operation)
  - f_0 = 200 GHz (close to $f_{T,peak}$, 5th harmonic = 1THz, significant non-qs effects)
- to ensure stead-state at least 100 periods were simulated
- for each simulation: time domain waveform of last periods for node voltages, branch currents and charges were recorded
- Fourier transformation of waveforms of desired variables was applied
  => frequency components (=> harmonic distortion) of variables and FoMs
- *single-tone* and resulting harmonic distortion (HD) was considered
  => reveals fundamental model limitations
- evolution of FoMs {$P_{out}(P_{in})$, $P_{1dB}(J_C)$, $OIP_3(J_C)$} with f_0 is analyzed

1D: Harmonic distortion: P_{out} vs. P_{in}

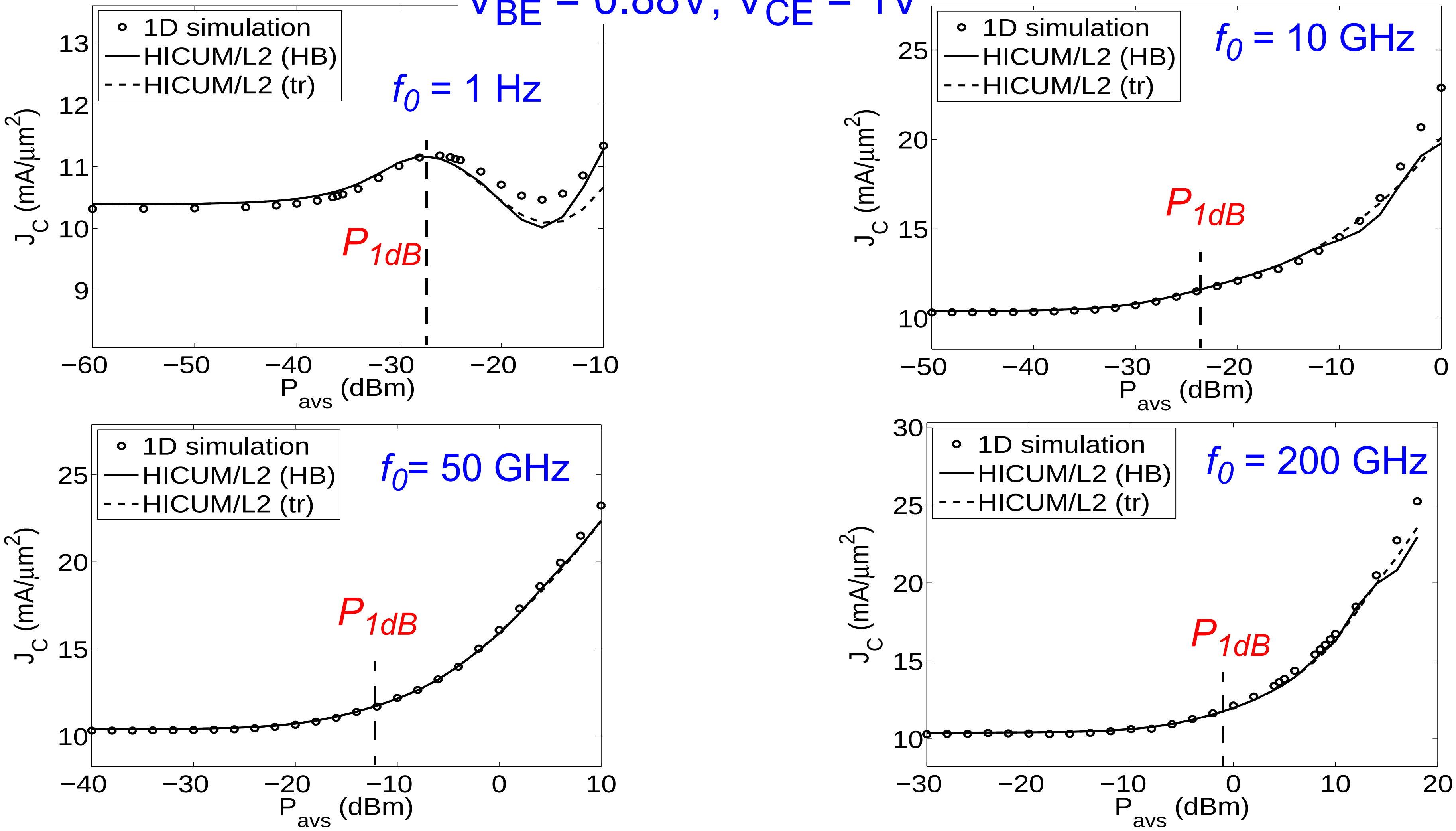
V_{BE} = 0.88V, V_{CE} = 1V



⇒ very good agreement up to $f_0 = f_{T,peak}/5$

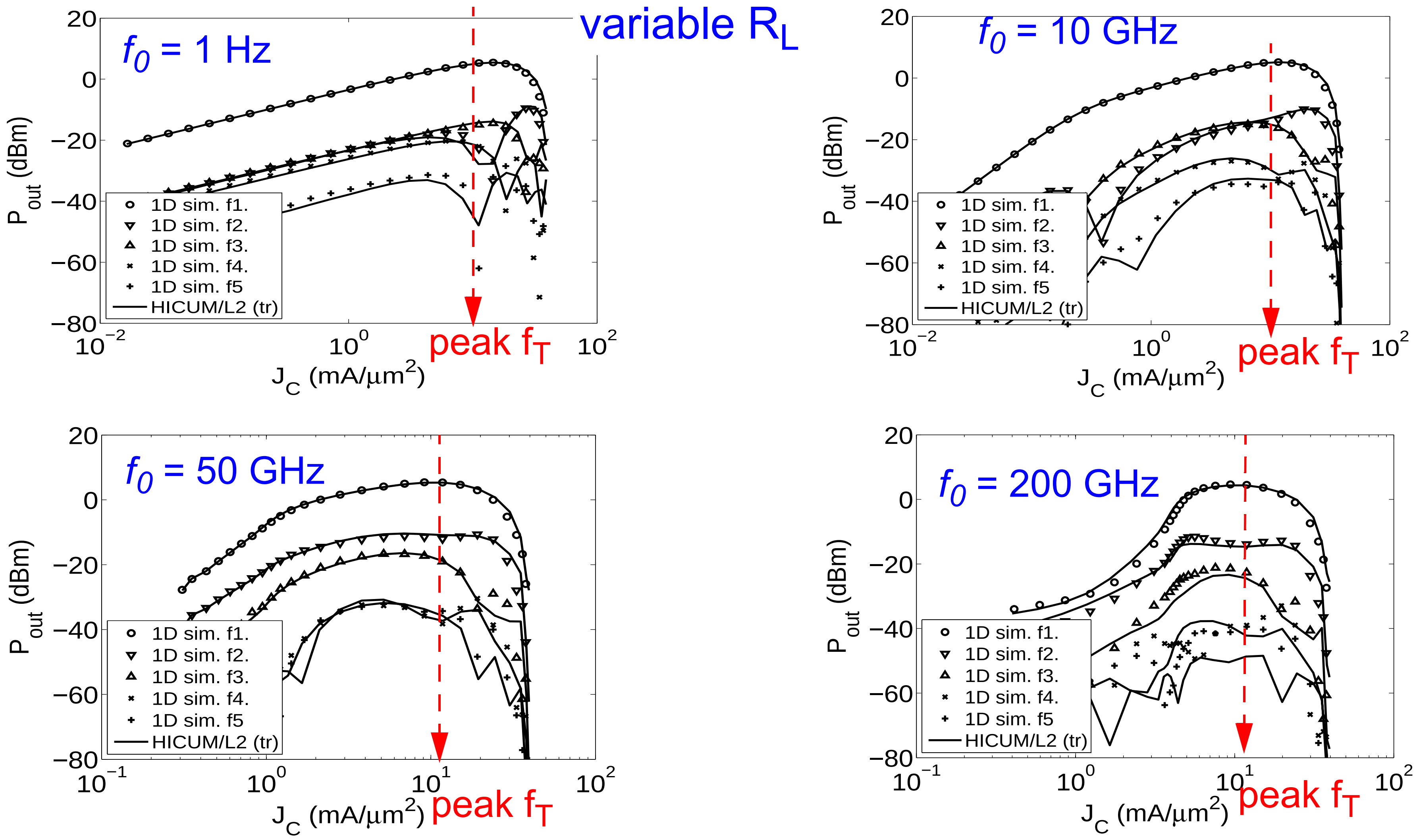
1D: Harmonic distortion: bias point shift vs. P_{in}

$V_{BE} = 0.88V$, $V_{CE} = 1V$



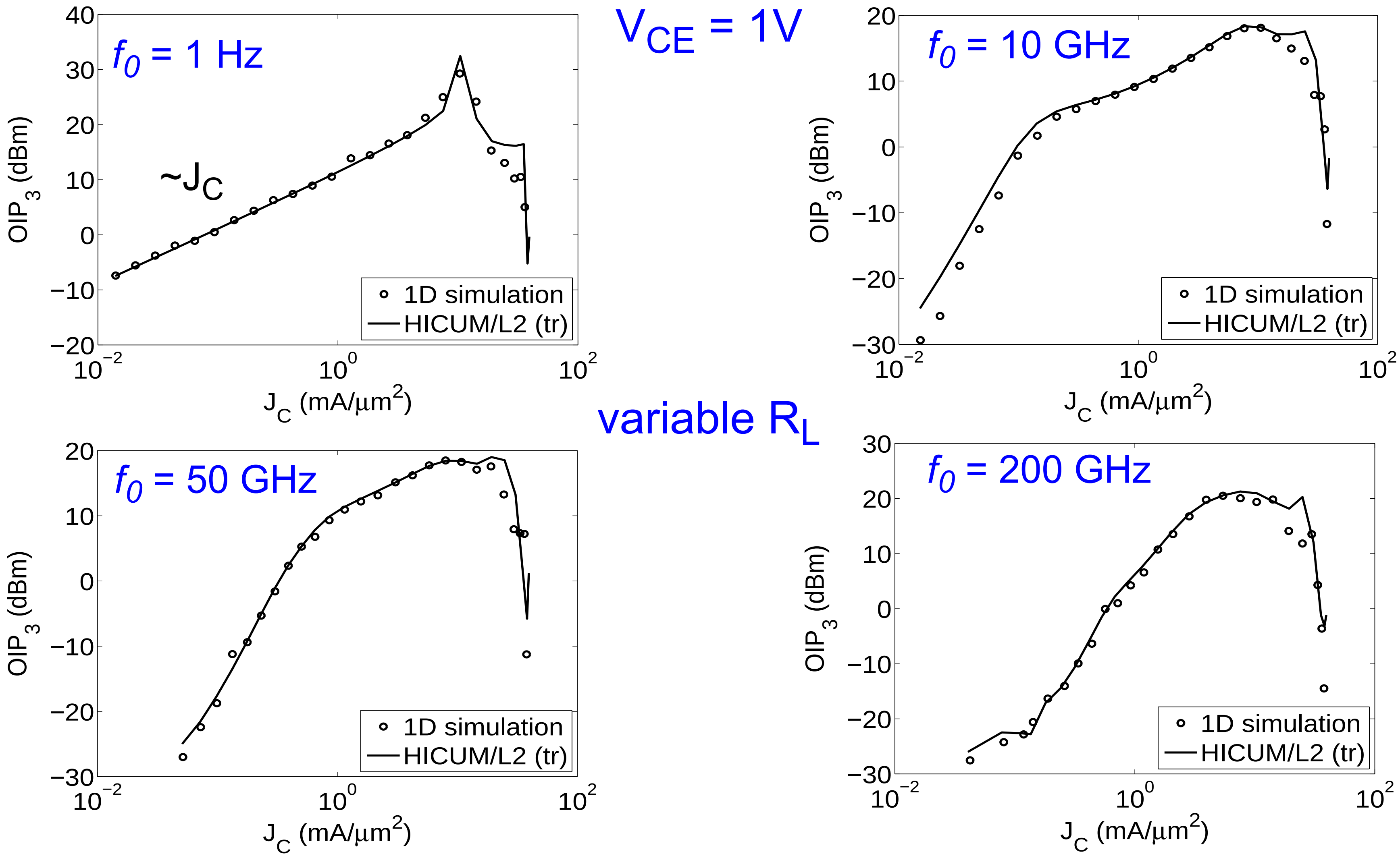
⇒ excellent agreement (also for harmonics) even beyond P_{1dB}

1D: Harmonic distortion: P_{out} vs. J_C at P_{1dB}



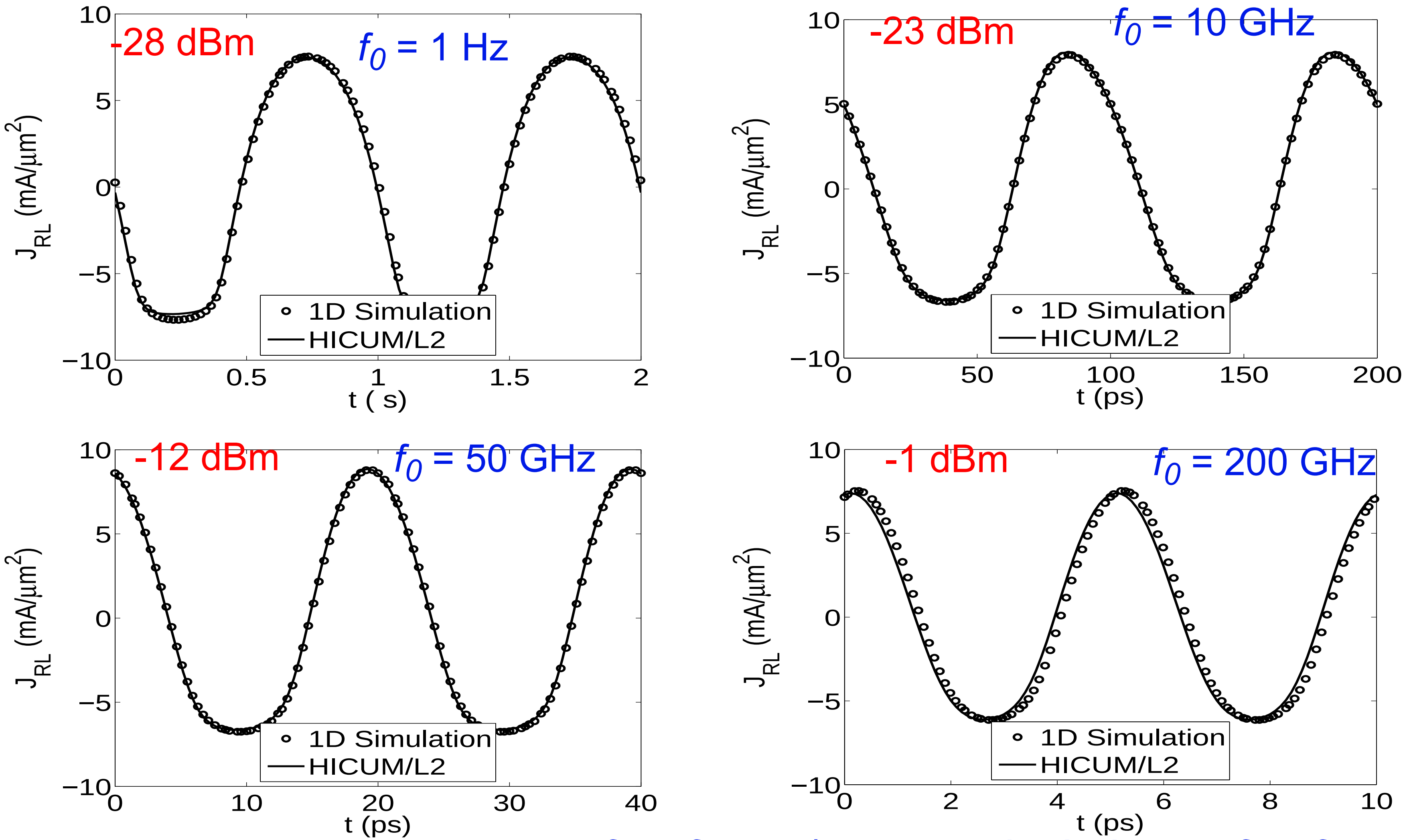
⇒ very good agreement up to $f_0 = f_{T,peak}/5$, some Δ at $f_0 \to f_{T,peak}$ & high J_C

1D: Harmonic distortion: OIP_3 vs. J_C



⇒ model tracks trend very well, some deviation beyond $J_C(f_{T,peak})$

1D: Time domain results at P_{1dB}: $V_{B'E'} = 0.88V$



⇒ excellent agreement up to $f_0 = f_{T,peak}/5$, some deviation at $f_0 \rightarrow f_{T,peak}$

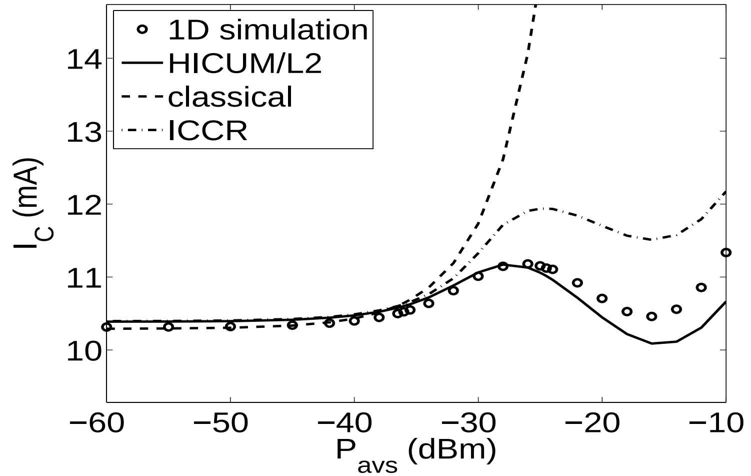
1D: Analysis of distortion effects

Impact of i_T and g_m modeling on bias point shift

- classical approximation

$$i_T = I_S \exp\left(\frac{v_{B'E'}}{m_C V_T}\right)$$

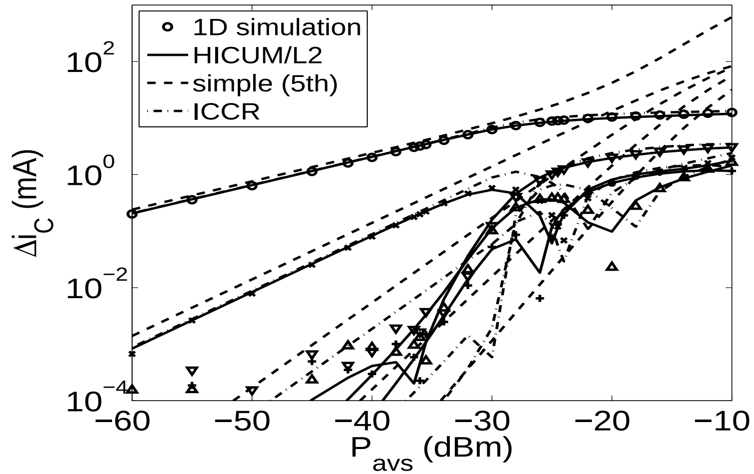
=> no compression due to missing impact of mobile charge



- simplified GICCR approximation (ICCR)

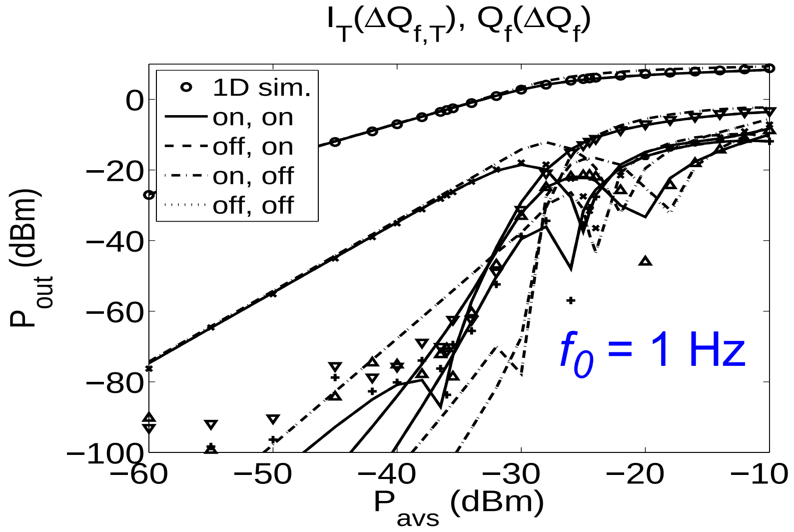
$$i_T = c_{10}\frac{\exp(v_{B'E'}/V_T) - \exp(v_{B'C'}/V_T)}{Q_{p0} + Q_{j,T} + h_{f0}\tau_{f0}i_T}$$

=> deviations, but correct trend



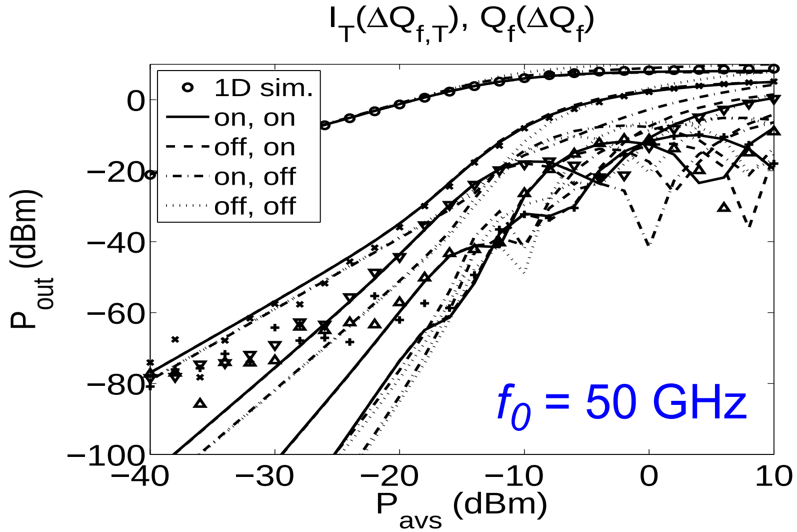
$\Rightarrow$ simple form of GICCR can already explain trends

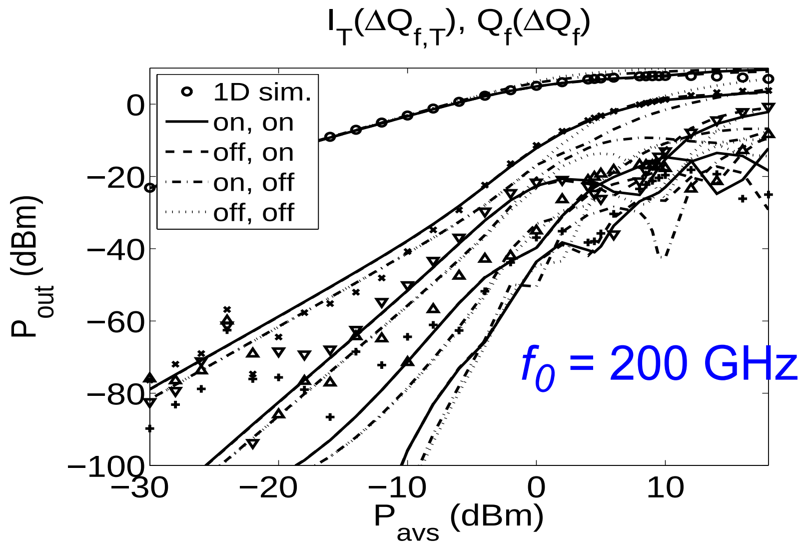
1D: Impact of high-current effects: P_{out} vs. P_{in}



V_{BE} = 0.88V, V_{CE} = 1V

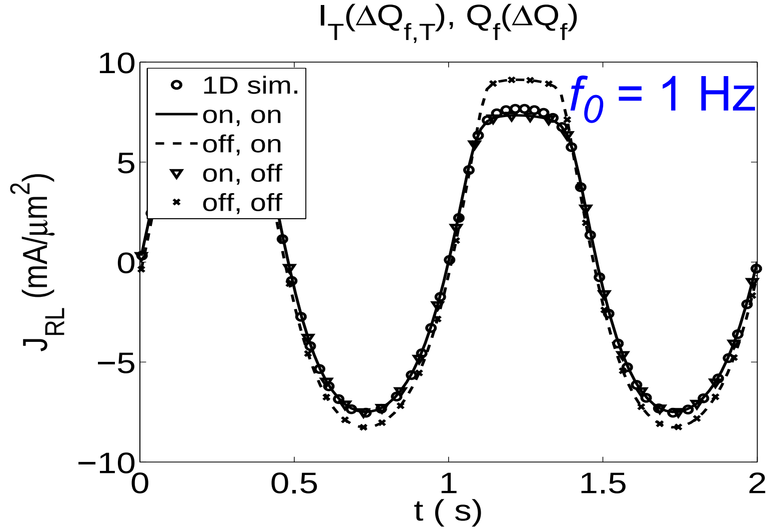
- high-current effect related model parameters turned on/off separately for charge (ΔQ_f) and transfer current ($\Delta Q_{f,T}$)
- low f: deviations from $\Delta Q_{f,T}$ at f_2 and P_{1dB}
- high f: deviations from ΔQ_f at f_3 and P_{1dB}





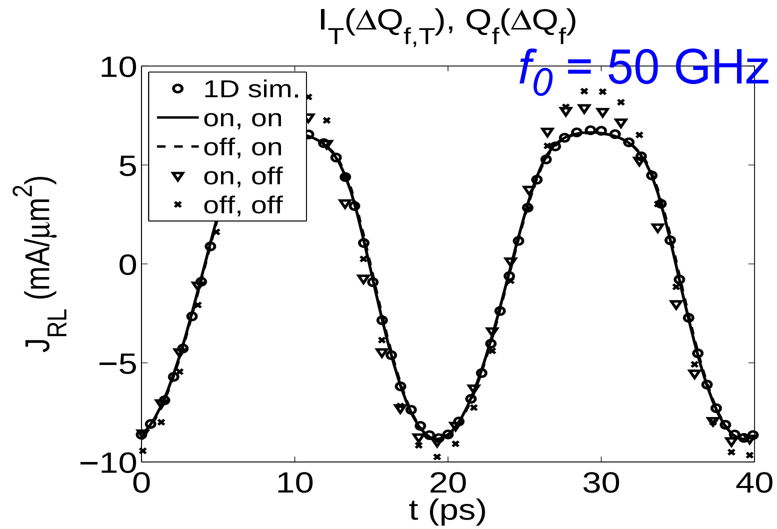
⇒ high-current effects should be considered

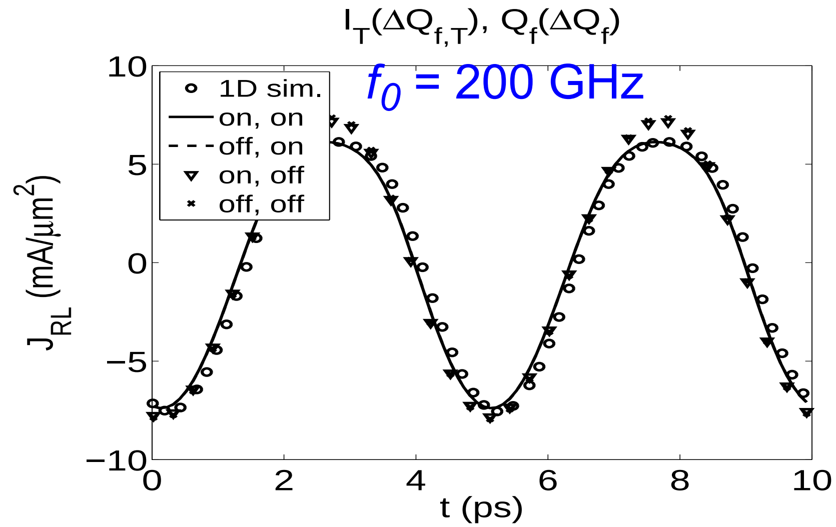
1D: Impact of high-current effects: time domain at P_{1dB}



V_{BE} = 0.88V, V_{CE} = 1V

- high-current effect related model parameters turned off/on separately for charge (ΔQ_f) and transfer current ($\Delta Q_{f,T}$)
- low f: amplitude deviations from $\Delta Q_{f,T}$
- high f: only small deviations from ΔQ_f

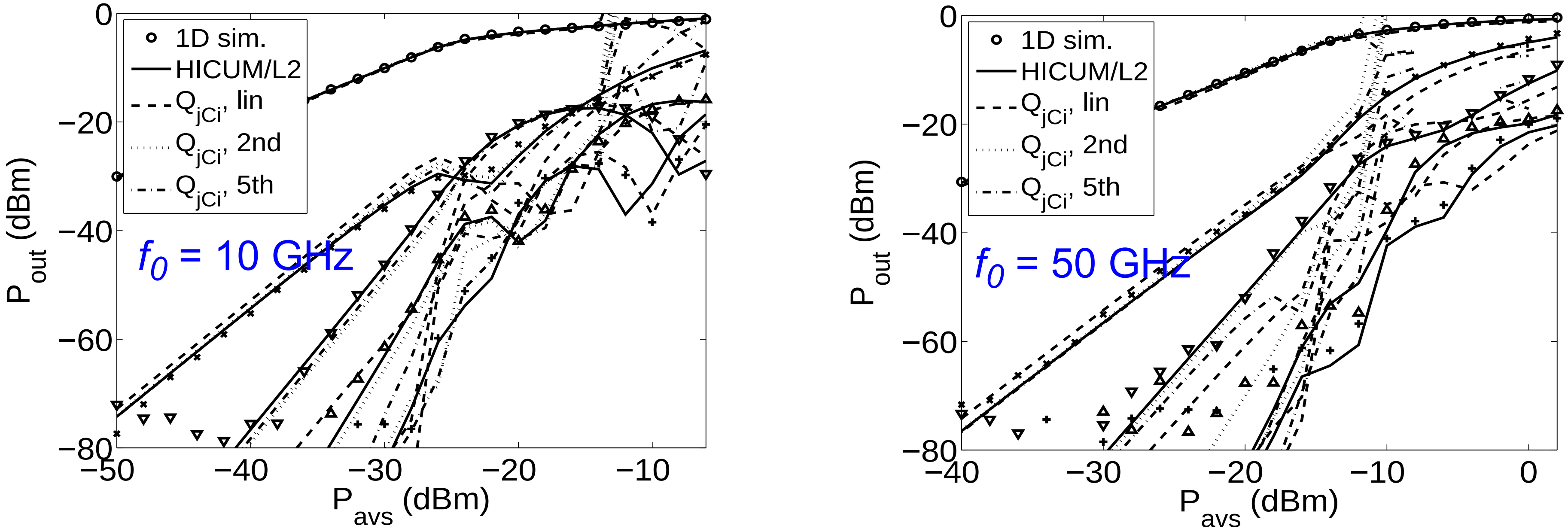




⇒ high-current effect impact mainly on amplitude, less on phase

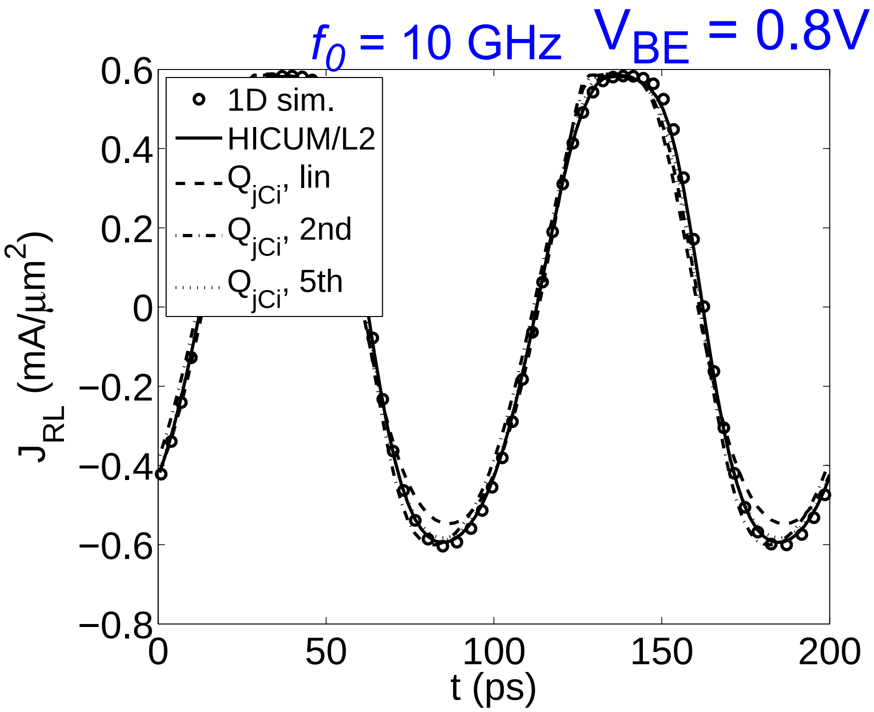
1D: Impact of BC depletion capacitance: P_{out} vs. P_{in}

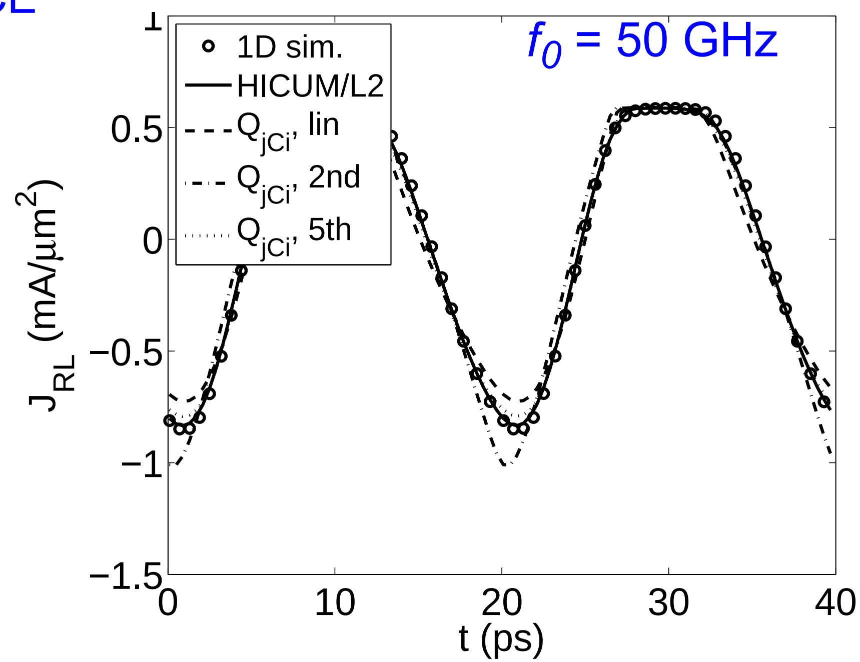
V_{BE} = 0.8V, V_{CE} = 1V



- $Q_{jCi}(V_{B'C'})$ approximated by 5th-order polynomial over relevant voltage range => consider only linear or 2nd-order approximation for charge term (keep using complete analytical term in GICCR to keep bias current unaffected)
- linear Q_{jCi} (i.e. C_{jCi}=const): visible impact from f_3 on & already at low power level 2nd-order polynomial: visible impact from f_4 on & at low power level

Impact of BC depletion capac.: time domain results at P_{1dB}



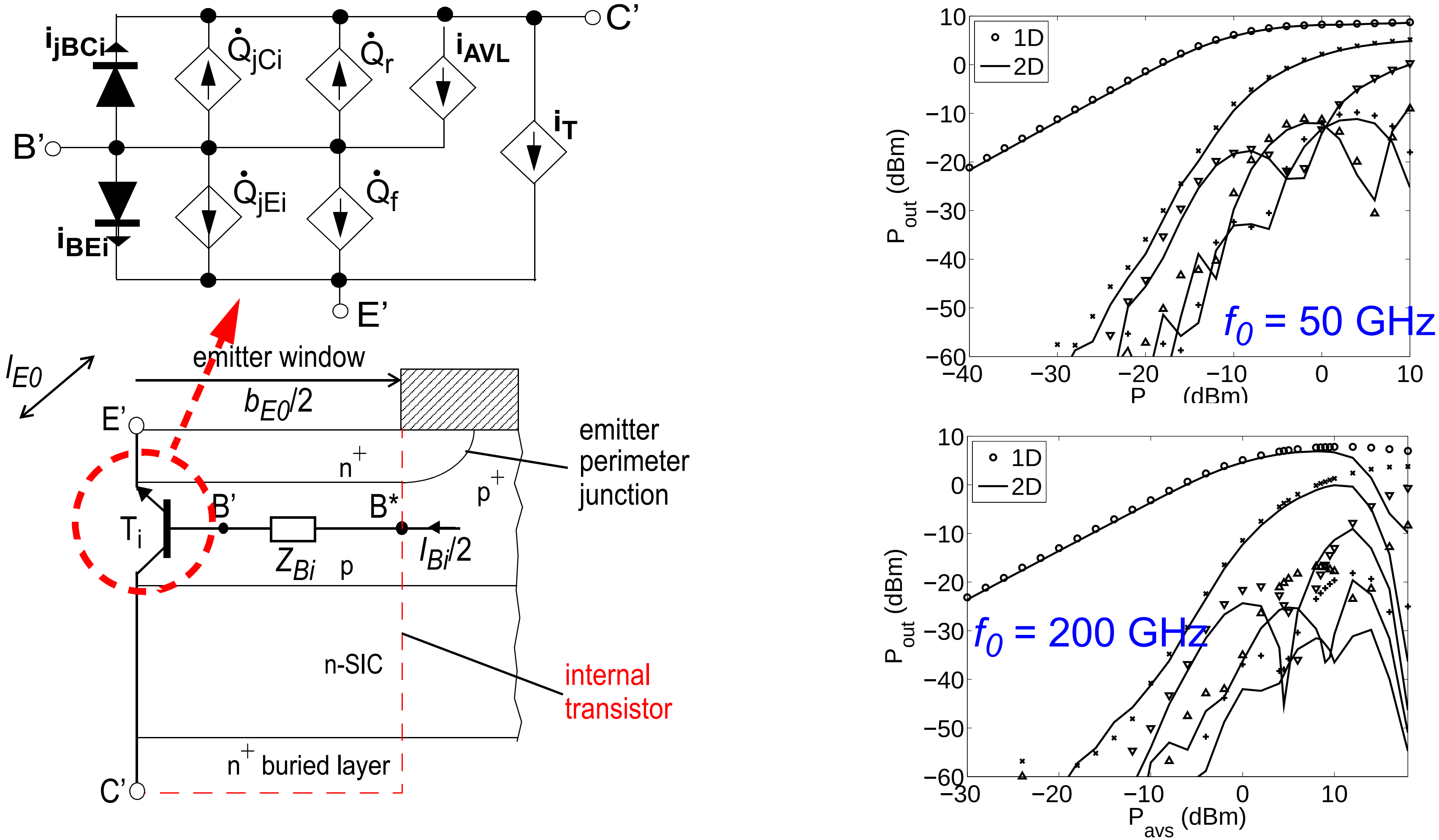


- low f: mostly amplitude and some shape deviation for linear Q_{jCi}
- high f:
  - amplitude and shape deviation increase, also incorrect phase
  - 2nd-order approximation of Q_{jCi} is worse than first-order approximation

⇒ need to have accurate $Q_{jCi}(V_{B'C'})$, do not need $Q_{jCi}(J_C)$

2D: Impact of nonlinear internal base resistance

$V_{BE} = 0.88V$, $V_{CE} = 1V$



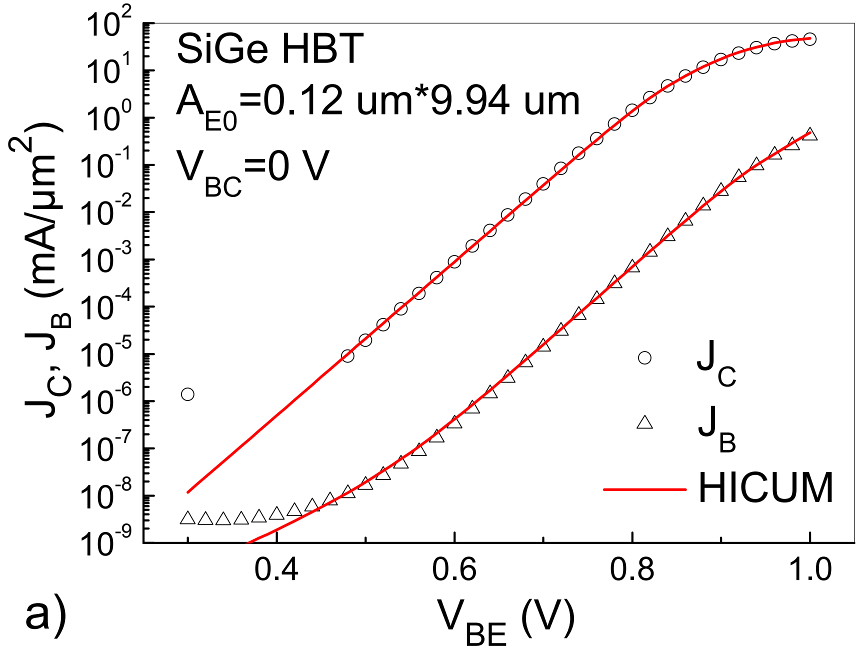
⇒ significant impact of R_{Bi} on higher order distortion at high frequencies

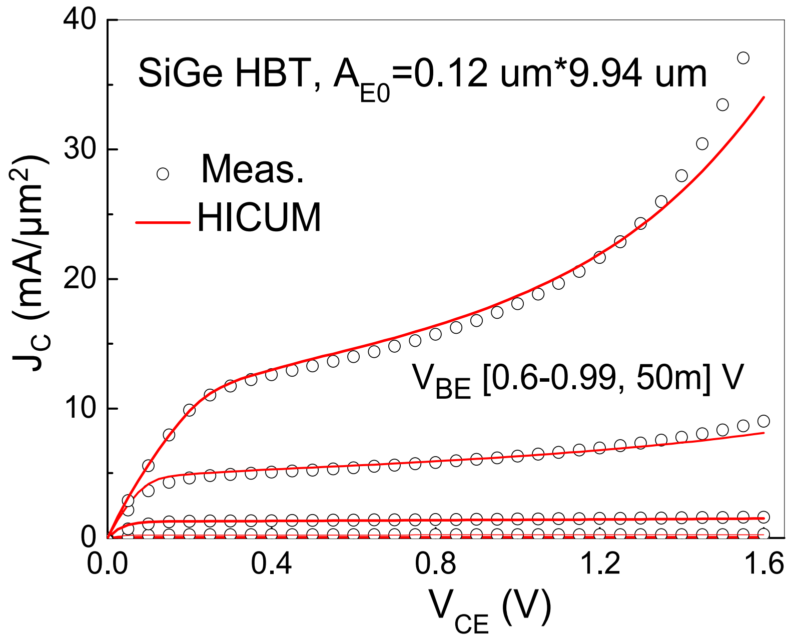
Measured devices

SiGe HBTs:

- IHP, Frankfurt/Oder, f_T = 300 GHz, f_{max} = 500 GHz, A_{E0} = 8* 0.12 μm*0.96 μm
- ST Microelectronics, f_T = 320 GHz, f_{max} = 370 GHz, A_{E0} = 0.12 μm*9.94 μm

3D: model verification: IV characteristics

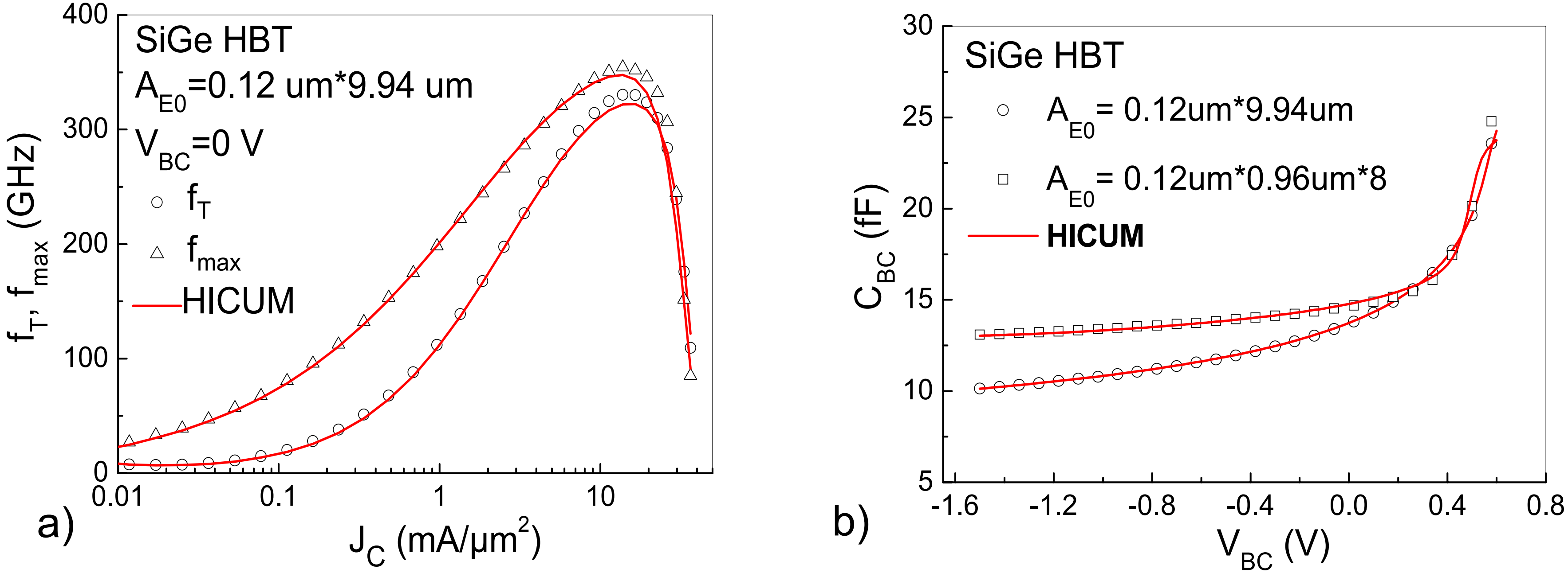




a) Forward Gummel plot with V_{BC}=0 V. => High collector current linearity and current gain β =3000.
b) Output characteristic with a V_{BE} drive.

=> HICUM is in a perfect agreement.

3D: model verification: f_T, f_{max}, C_{BC}



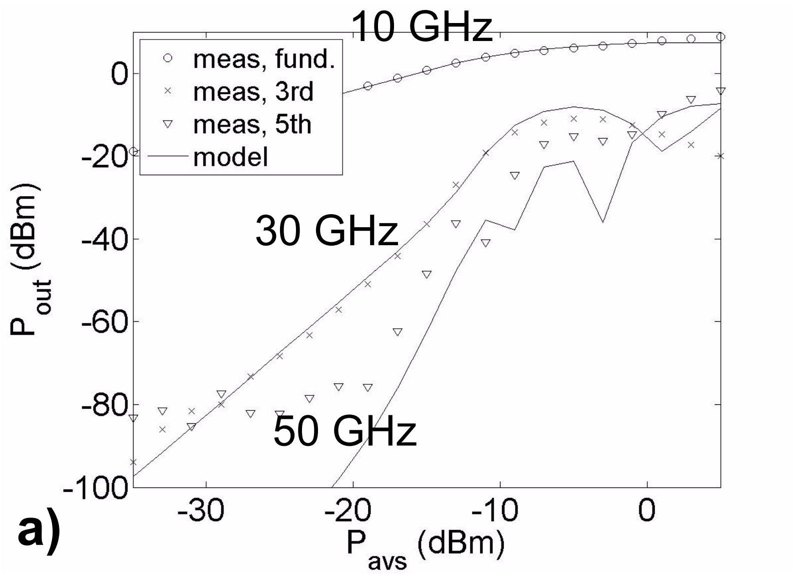
- => good agreement in a whole bias range.
- => weakly nonlinear depletion capacitance behavior.

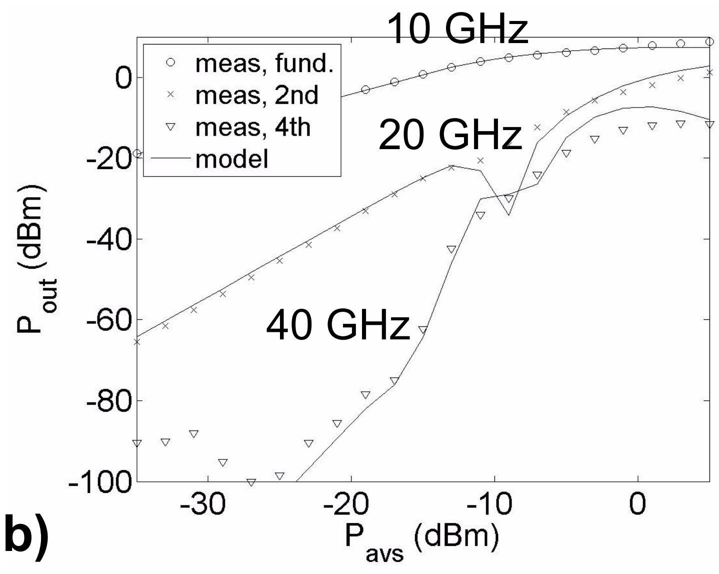
=> HICUM is in good agreement.

-

500 GHz SiGe HBT, harmonic distortion: P_{out} (P_{avs})

Fundamental frequency of 10 GHz, five harmonics were measured.

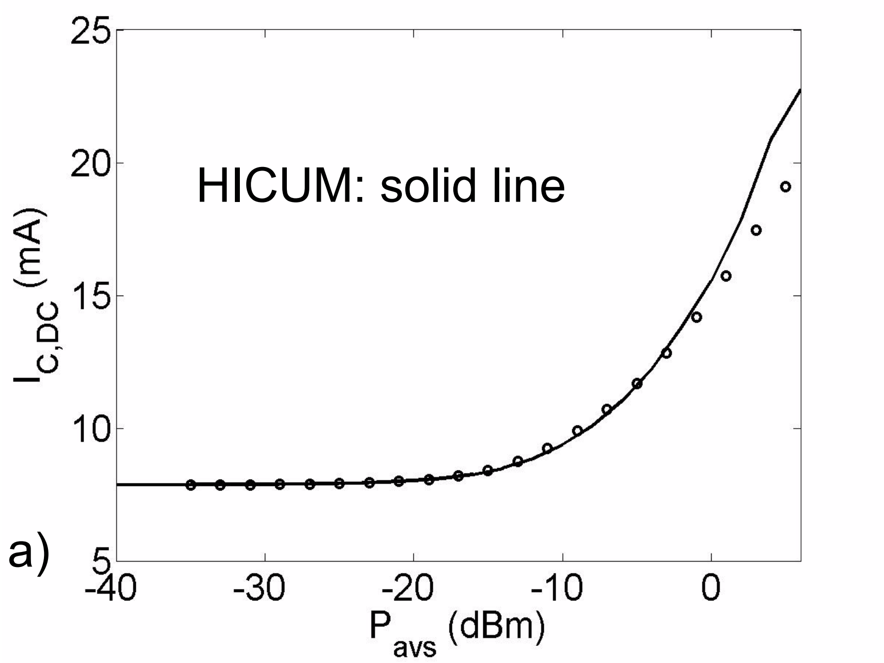


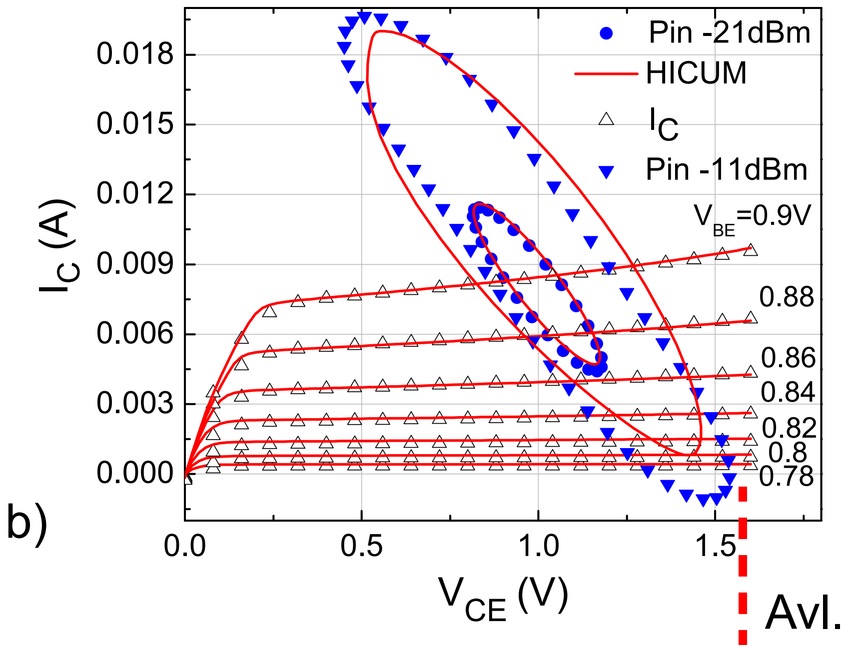


- SiGe HBT A_{E0} = 8* 0.12 µm*0.96 µm, V_{CE} = 1 V, V_{BE} = 0.9 V.
- The 5th harmonic is on the limit of network analyzer frequency, 50 GHz.
- From the linearized capacitance simulations it was found a negligible impact of base/ collector junction capacitance C_{BC} on nonlinearity.
- HICUM is in a good agreement.

500 GHz SiGe HBT, HD: I_C (P_{avs}), load circles

Fundamental frequency 10 GHz

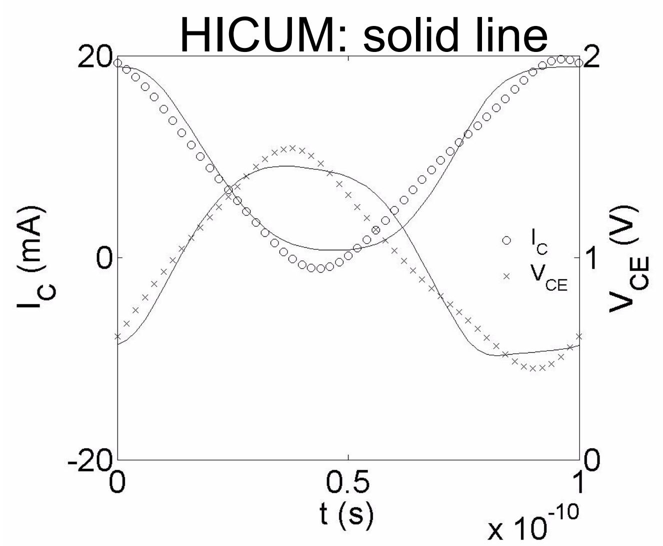




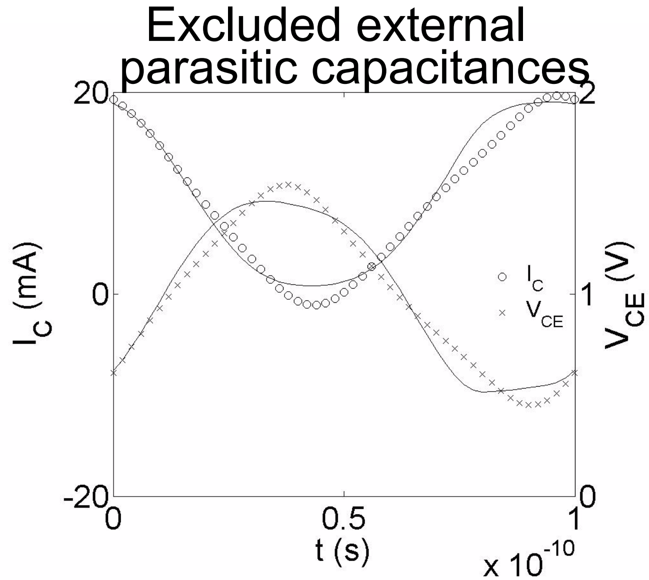
- SiGe HBT A_{E0} = 8* 0.12 μm*0.96 μm, V_{CE} = 1 V, V_{BE} = 0.9 V.
- Deviation from quiescent collector current with input power is due to self-biasing.
- At high input power non quiescent bias can may trigger impact ionization (V_{CE}>1.6 V) and pronounced selfheating => increase of HD.

500 GHz SiGe HBT, HD: Impact of external capacitances

Time domain, excitation with 10 GHz and -21 dBm CW power.



a)

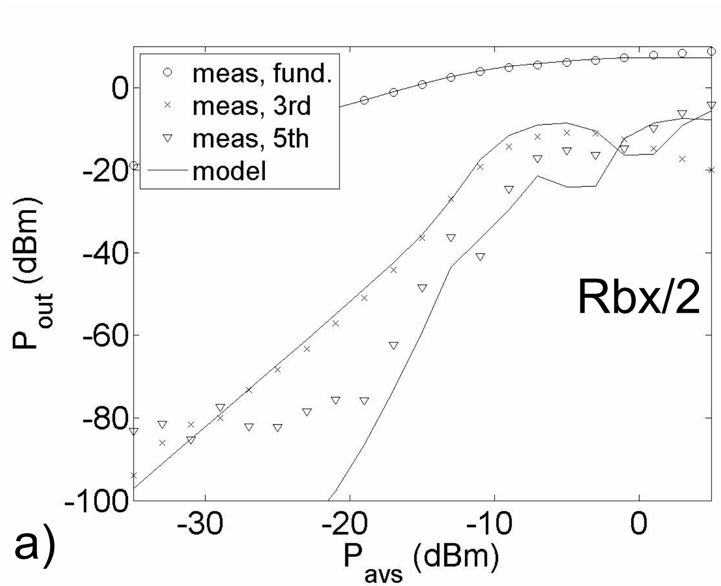


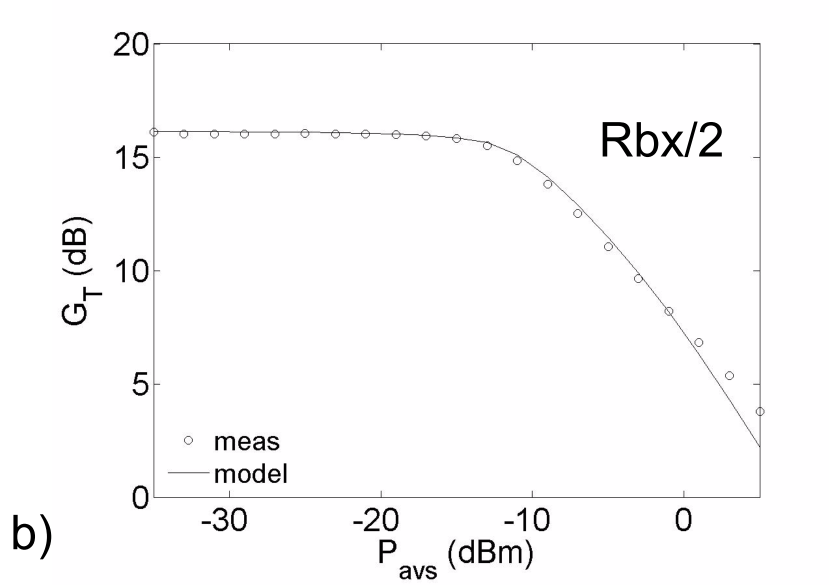
b)

- SiGe HBT: A_{E0} = 8* 0.12 µm*0.96 µm, V_{CE} = 1 V, V_{BE} = 0.9 V.
- Exclusion of the external parasitic base/emitter and base/collector capacitances only slightly impacts the dynamic collector current.
- At higher frequencies an impact may be more evident.

500 GHz SiGe HBT, HD: Impact of external base resistance

A_{E0} = 8* 0.12 µm*0.96 µm, V_{CE} = 1 V, V_{BE} = 0.9 V, excitation with 10 GHz.

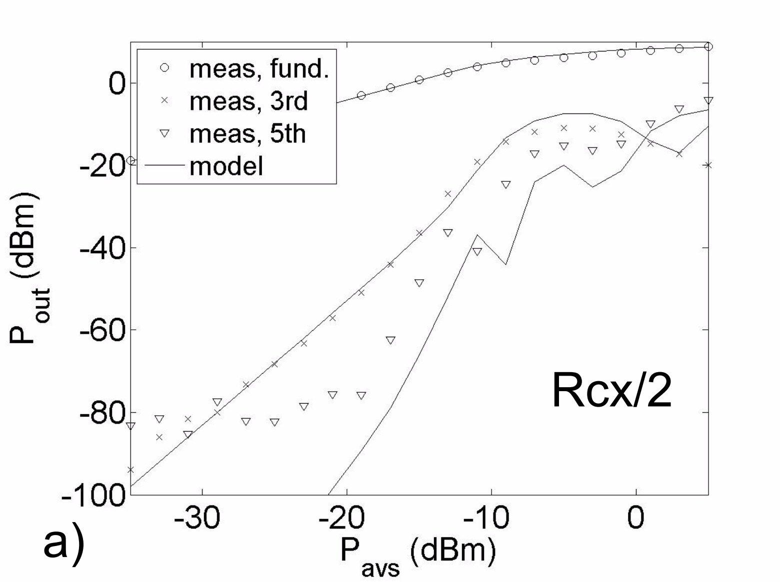


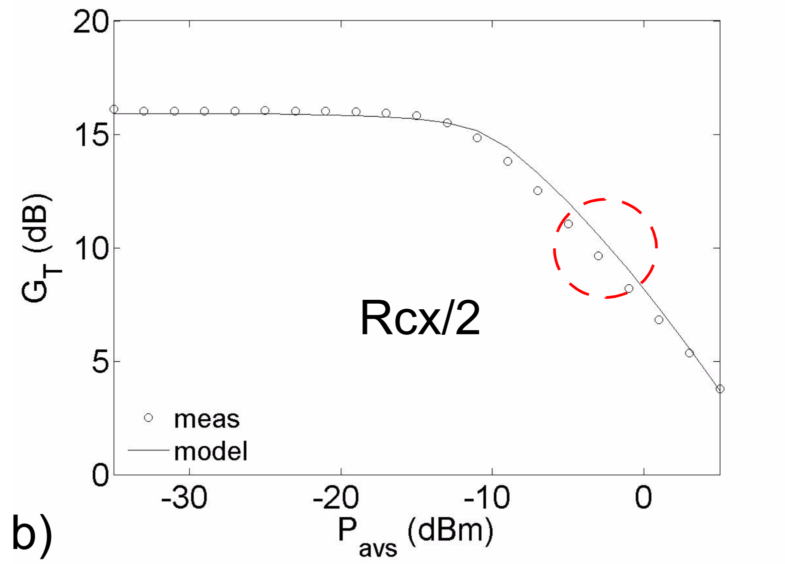


- Reduced external base resistance from 11 Ω to 5.5 Ω increase f_{max} value. Standard IV and RF characteristics are preserved.
- No impact on HD since external parasitic resistance is constant with bias.

500 GHz SiGe HBT, HD: Impact of external collector resistance

A_{E0} = 8* 0.12 µm*0.96 µm, V_{CE} = 1 V, V_{BE} = 0.9 V, excitation with 10 GHz.





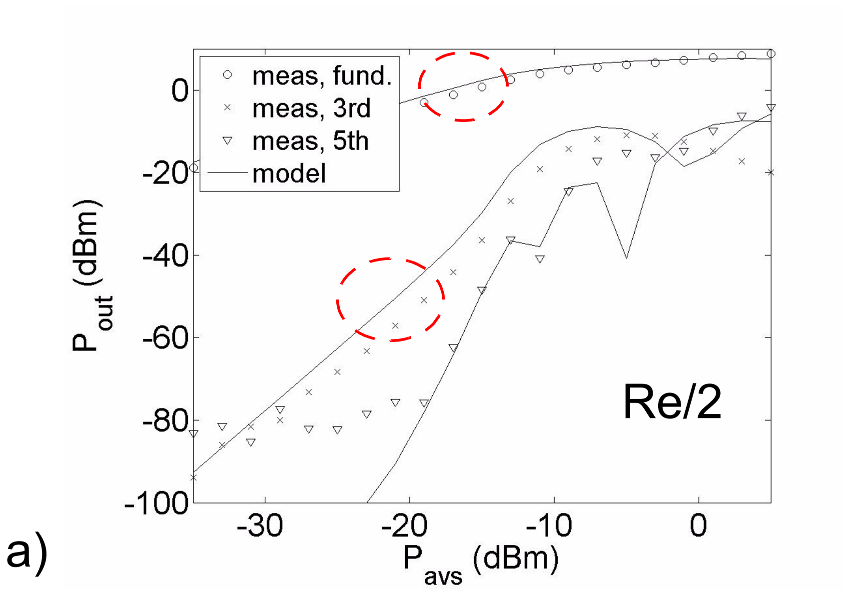
- Reduced external collector resistance from 10 Ω to 5 Ω.

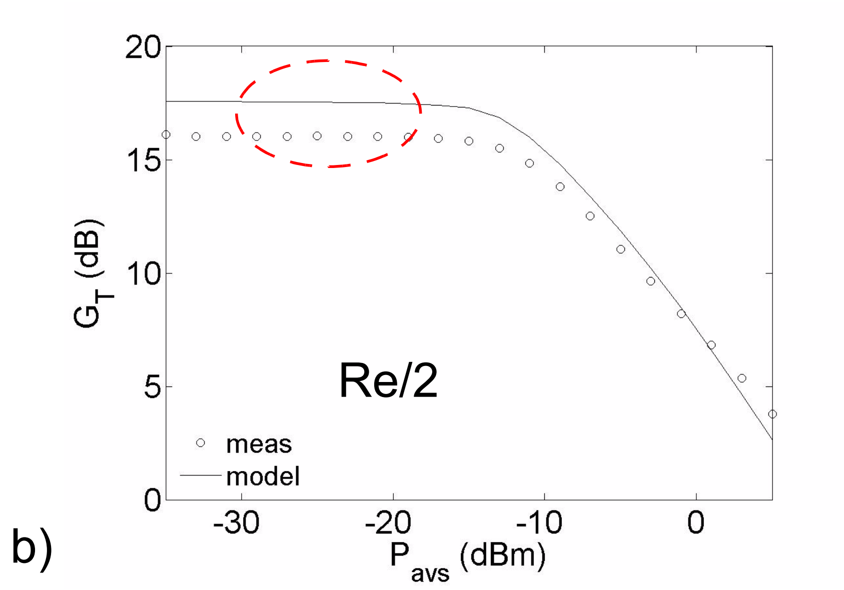
=>increase f_{max} and f_T values, improves IV and RF performance.

- negligible impact on HD.

500 GHz SiGe HBT, HD: Impact of emitter resistance

A_{E0} = 8* 0.12 µm*0.96 µm, V_{CE} = 1 V, V_{BE} = 0.9 V, excitation with 10 GHz



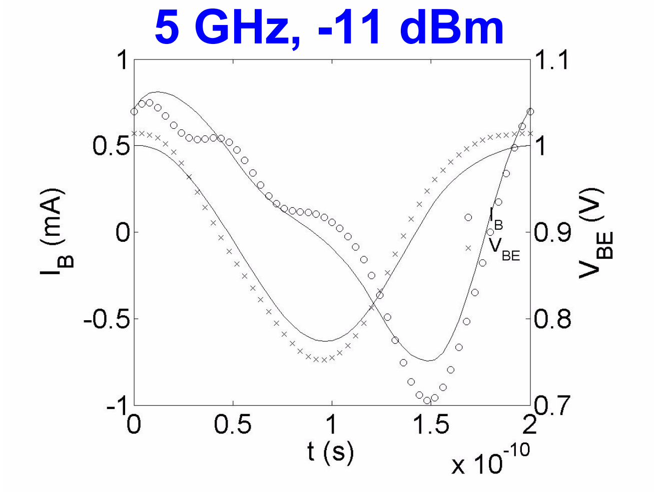


- Reduced external emitter resistance from 2.9 to 1.45 Ω.

=> slight increase f_T, f_{max}.
=> decrease of J_C at peak f_T, f_{max}.
=> base and collector current increase at high V_{BE}.
=>HD increase, G_T increase due to lower negative feedback, ie. lower linearization by constant resistor.

500 GHz SiGe HBT, HD: modeling at high input power

Excitation with 5 and 10 GHz Pin -11 dBm and +1 dBm CW power.



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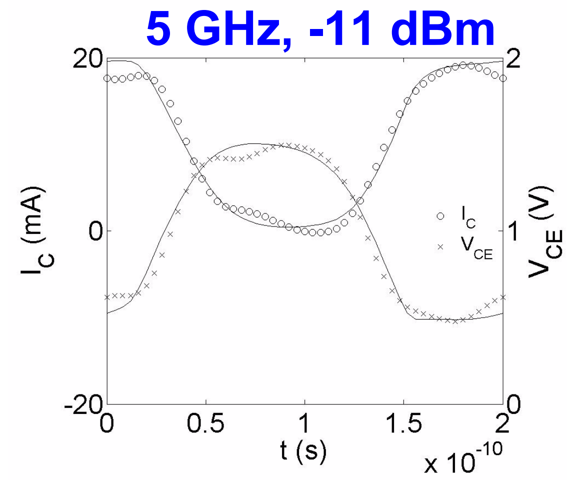

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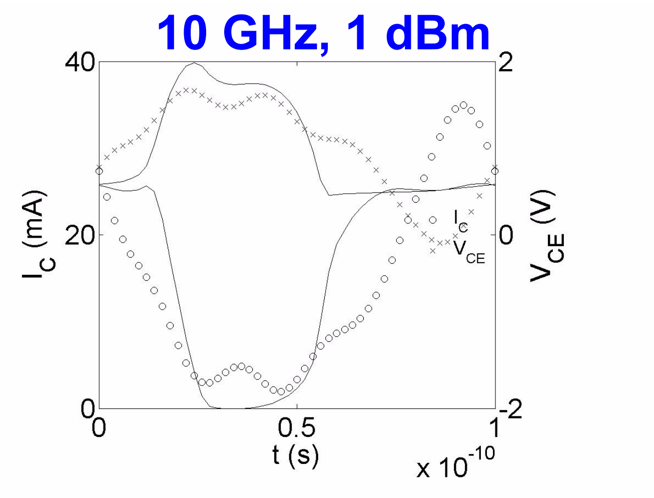

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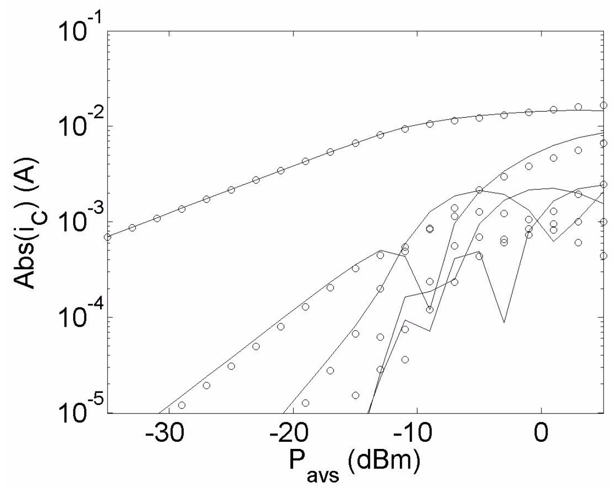
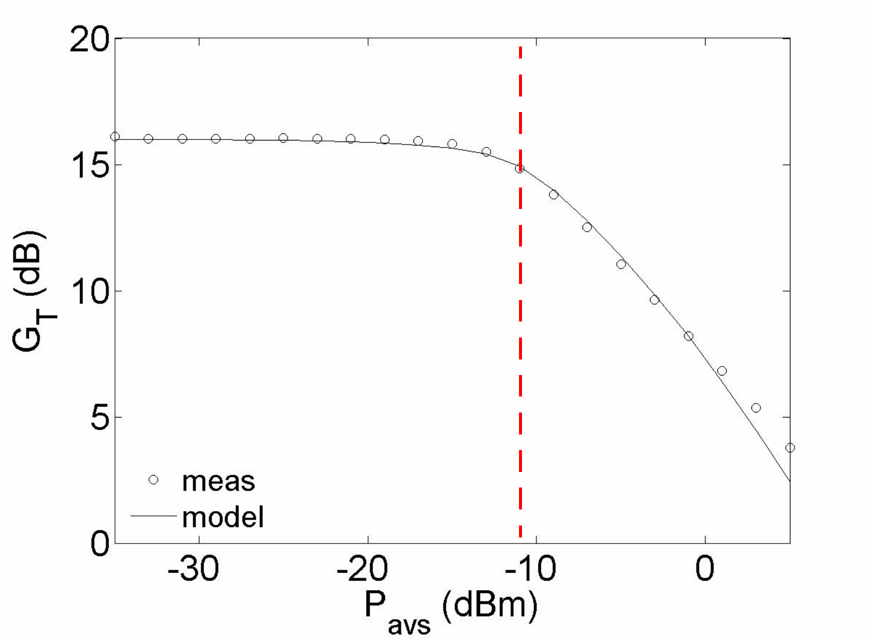
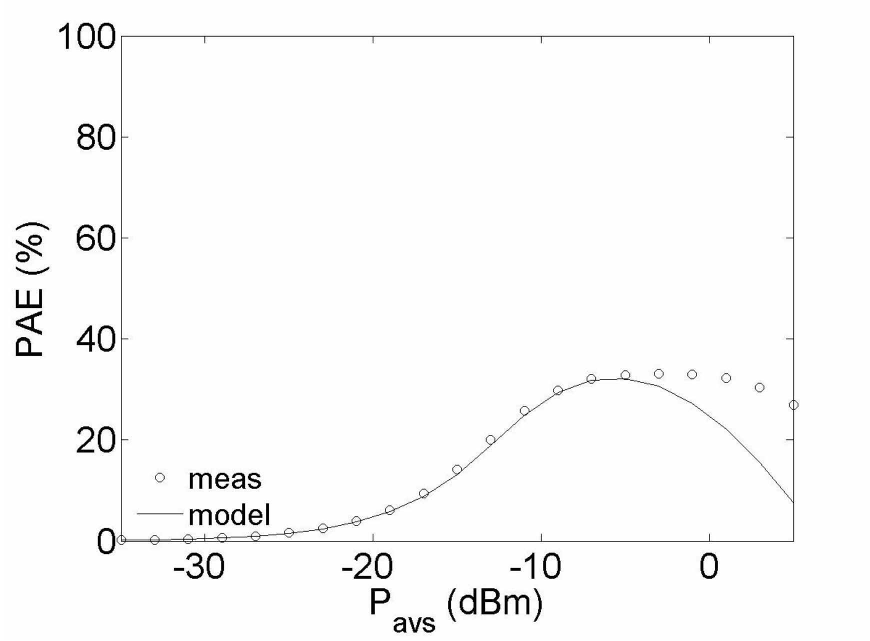


d)

500 GHz SiGe HBT, G_T and PAE%

A_{E0} = 8* 0.12 µm*0.96 µm, V_{CE} = 1 V, V_{BE} = 0.9 V, excitation with 10 GHz

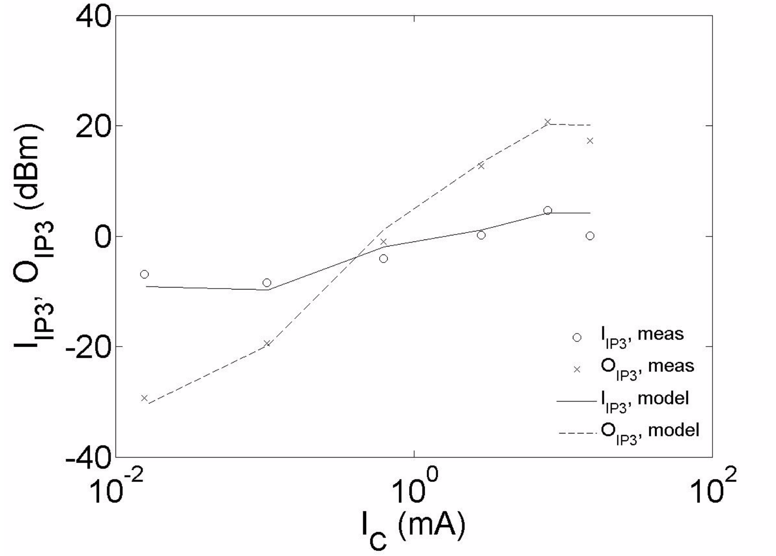




- Linear gain up to -11 dBm is observed.
- 35% of maximum power added efficiency at 10 GHz is achieved.

500 GHz SiGe HBT, IIP3, OIP3 versus I_C

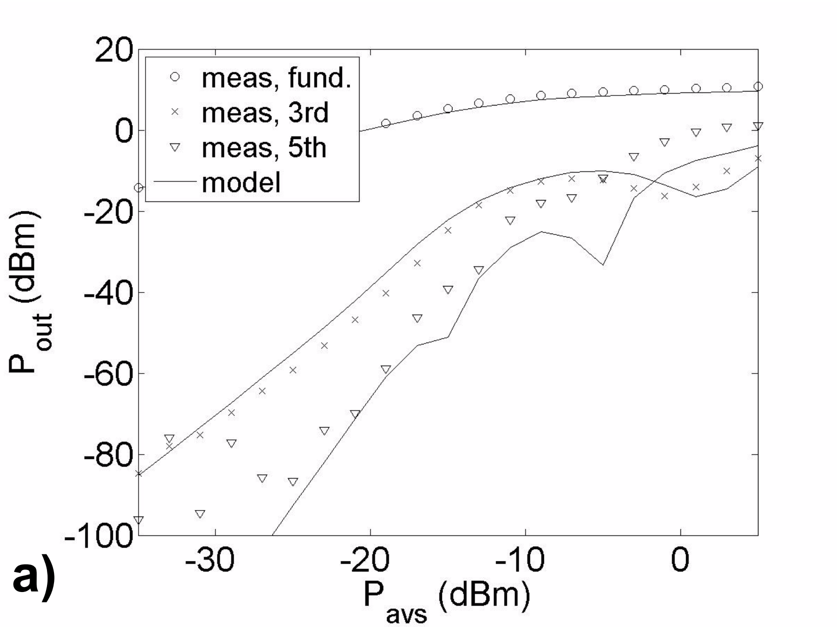
A_{E0} = 8* 0.12 µm*0.96 µm, V_{CE} = 1 V, V_{BE} = 0.9 V, excitation with 10 GHz



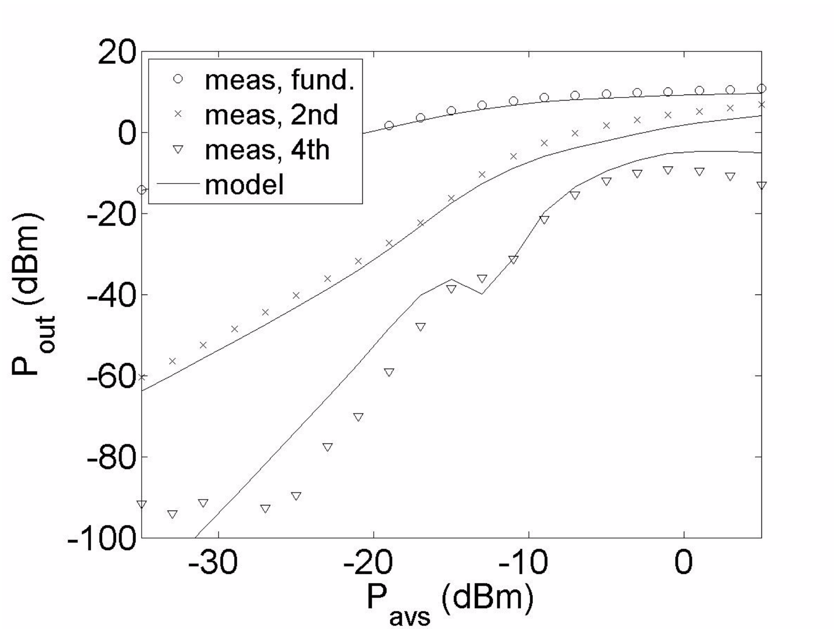
- Good agreement with HICUM of third order input IIP3 and output OIP3 interception points.

370 GHz SiGe HBT, HD: P_{out} (P_{avs})

Fundamental frequency 10 GHz



a)

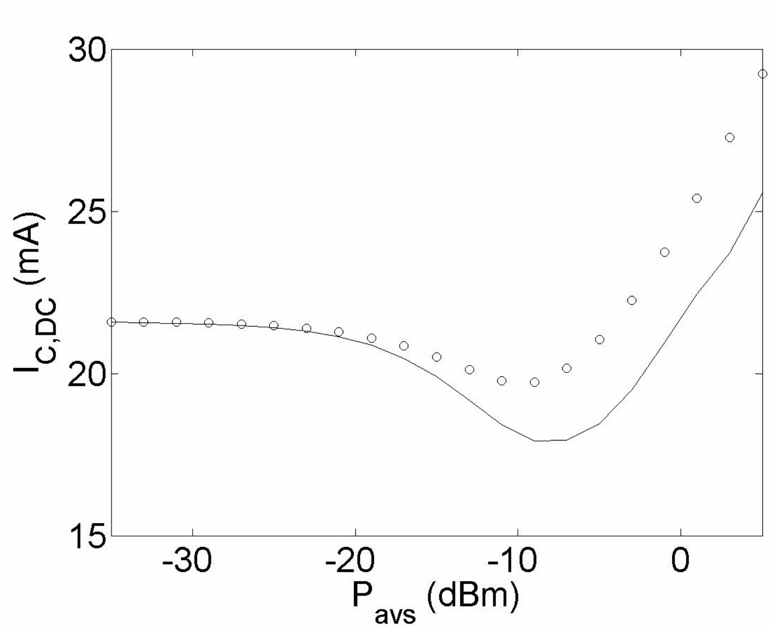


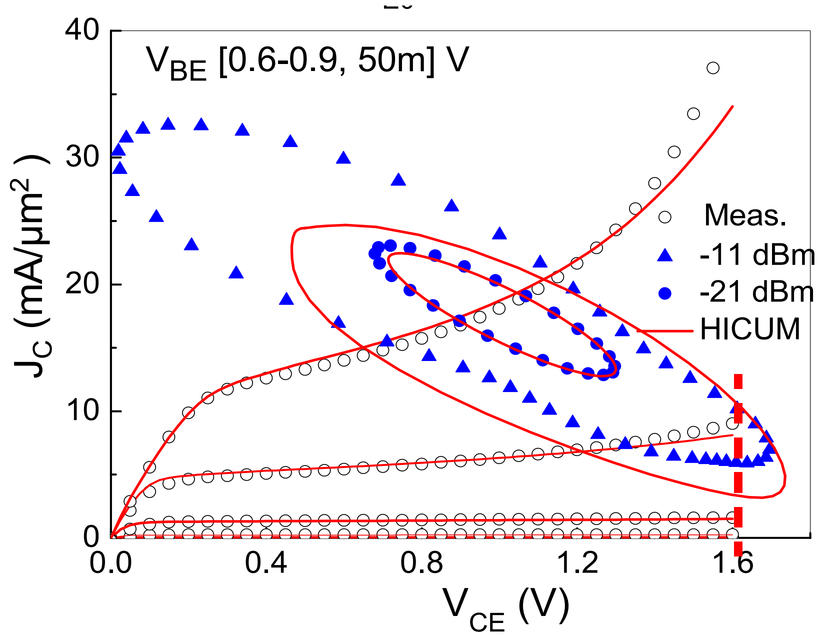
b)

- SiGe HBT A_{E0} = 0.12 µm*9.94 µm, V_{CE} = 1 V, V_{BE} = 0.9 V.
- HICUM is in fair agreement.

370 GHz f_{max} SiGe HBT, HD: $I_{C,DC}$ (P_{avs}), load circles

Fundamental freq. 10 GHz

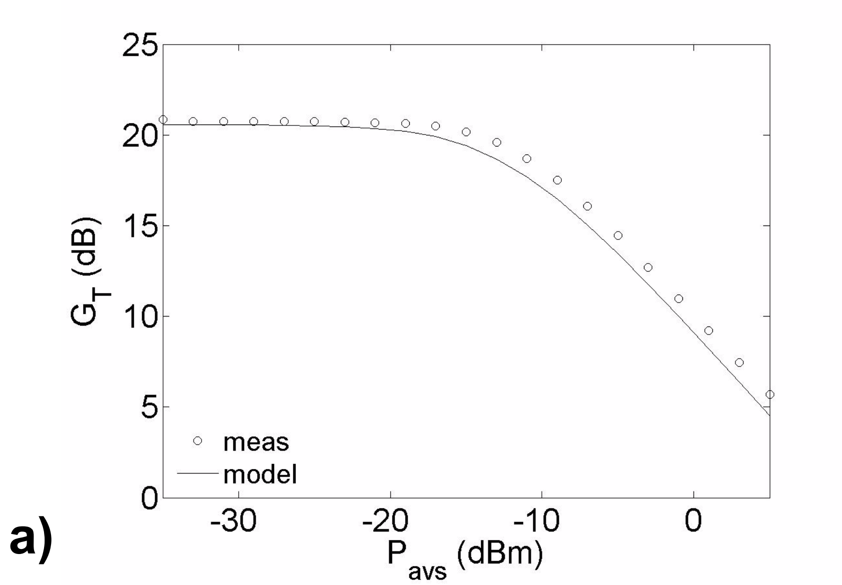


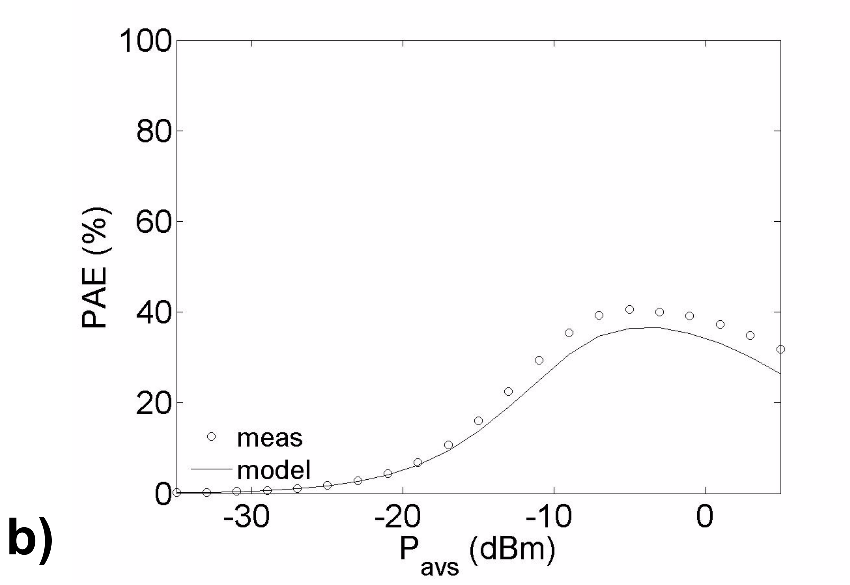


- SiGe HBT A_{E0} = 0.12 µm*9.94 µm, V_{CE} = 1 V, V_{BE} = 0.9 V.
- Collector current drops with input power with a following increase.
- Dynamic current circles at P_{in}= -11 dBm hit the region of impact ionization BV_{CE0} = 1.6V.
- HICUM is in fair agreement but not for the load circles.

370 GHz SiGe HBT, HD: G_T (P_{avs}), PAE%

Fundamental frequency 10 GHz

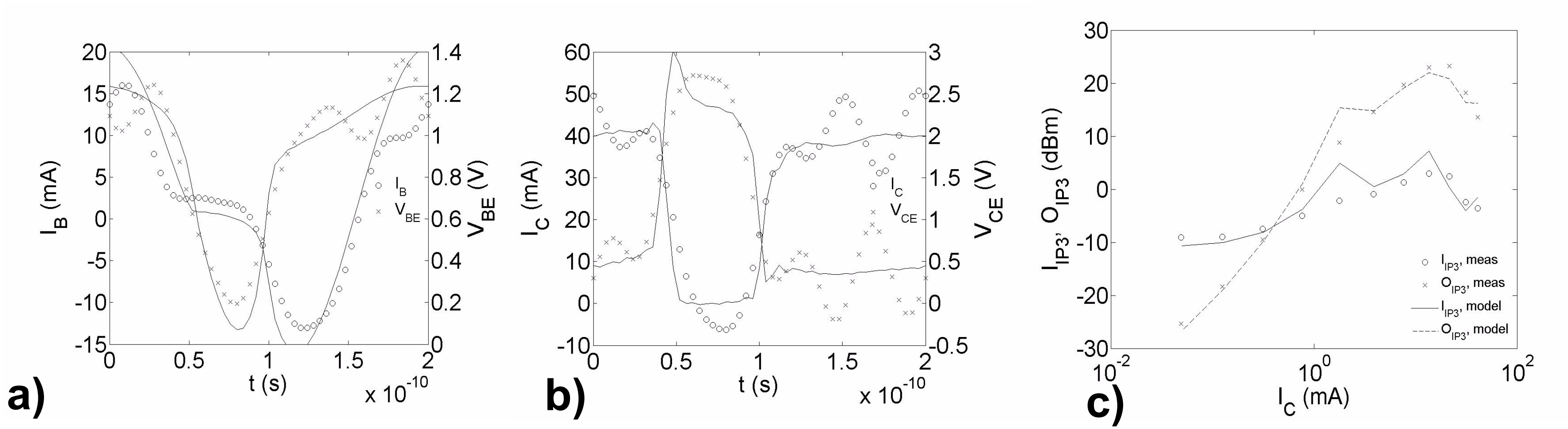




- SiGe HBT A_{E0} = 0.12 µm*9.94 µm, V_{CE} = 1 V, V_{BE} = 0.9 V.
- PAE reaches 40%.
- Good agreement with HICUM.

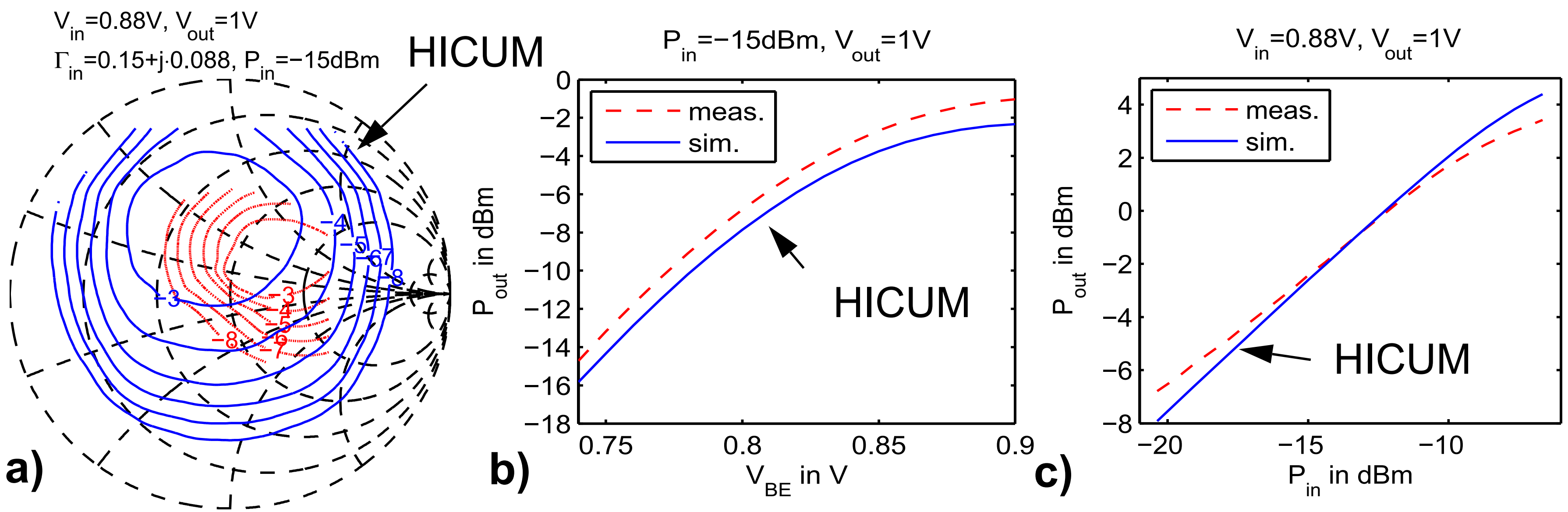
370 GHz SiGe HBT, HD: dynamic base and collector current and voltage waves and IIP3 and OIP3 versus bias.

SiGe HBT A_{E0} = 0.12 µm*9.94 µm, V_{CE} = 1 V, V_{BE} = 0.9 V.



- a) base dynamic current and voltage at 5 GHz and P_{in}= 5 dBm.
- b) collector dynamic current and voltage at 5 GHz and P_{in}= 5 dBm.
- IIP3 and OIP3 at 10 GHz.

SiGe HBT, measured load pull at 45 GHz



- SiGe HBT A_{E0} = 8* 0.12 μm*0.96 μm, V_{CE} = 1 V, V_{BE} = 0.88 V.

a) Simulated load isopower lines fairly matches the measured data at 45 GHz. Measurements were performed with Maury impedance automated tuner (MT984A) system ATS.

b) The power of the sum of harmonics versus V_{BE}. HICUM is solid line.

c) Output power versus input power.

Summary

HBT modeling approaches

- physics-based vs. behavioral v: ***clear advantages for physics-based models***
  => exclusively used in SiGe HBT design kits

Detailed comparison of core compact model formulation with 1D device simulation

- typical distortion characteristics over wide range of input power, bias, and frequency
  => - very good agreement up to at least P_{1dB}, $J_C(f_{T,\,peak})$, and $f_0 = f_{T,peak}/4$
  - still reasonable agreement at $f_0 = 0.8\ f_{T,\,peak}$ (with f_5 = 1THz !!)

Analysis of distortion in advanced SiGe HBTs

- impact of high-current effects, BC depletion capacitance, internal base resistance
  => identification of the contribution of transfer current and charge-storage nonlinearity

Detailed comparison of compact model with measurements (3D)

- Perfect agreement of DC, RF characteristics of high speed SiGe HBTs (f_T/ f_{max} = 320/370 GHz), SiGe HBTs (f_T/f_{max} = 300 /500 GHz).

- Nonlinear characteristics were measured on wafer with a 50 GHz PNA -X. Load pull single and two tone measurements were carried out with automated impedance tuner system from Maury.
- HICUM model agrees fairly well with measured nonlinear data up to measure 50 GHz.
- External parasitic bias independent capacitances for SiGe HBTs have negligible influence on the harmonics.

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