On the experimental determination of fmax

A. Pawlak, M. Schröter
CEDIC, University of Technology Dresden, Germany
andreas.pawlak@tu-dresden.de

Bipolar Arbeitskreis 2016, Infineon, Neubiberg

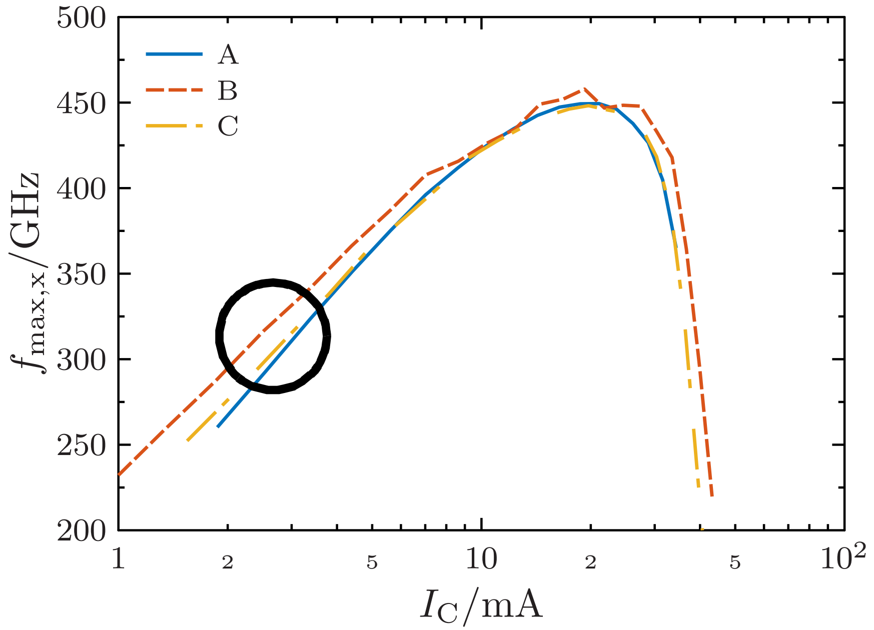
Overview

- Introduction
- Determination of fmax
- Measurements of Y12
- Deembedding structures
- Comparison versus frequency
- Modeling point of view
- Comments on the calibration
- Conclusion

Introduction

measurements of f_{max}

- Three measurement sites
  - same transistor on same wafer (although on different dies)
  - non-deembedded data



Determination of f_{max}

- Calculation based on Masons Unilateral Power Gain

$$U = \frac{\left|\underline{Y}_{21} - \underline{Y}_{12}\right|^2}{4(\Re\{\underline{Y}_{11}\}\Re\{\underline{Y}_{22}\} - \Re\{\underline{Y}_{12}\}\Re\{\underline{Y}_{21}\})}$$

$$f_{\max} = f\sqrt{U}$$

- Useful estimations

$$\Re\{\underline{Y}_{12}\}\Re\{\underline{Y}_{21}\} \gg \Re\{\underline{Y}_{11}\}\Re\{\underline{Y}_{22}\}$$

$$\Re\{\underline{Y}_{21}\} \gg \Re\{\underline{Y}_{12}\} \quad \text{and} \quad \Im\{\underline{Y}_{21}\} \approx \Im\{\underline{Y}_{12}\}$$

$$f_{\max} \approx \frac{f}{2}\sqrt{-\frac{\Re\{\underline{Y}_{21}\}}{\Re\{\underline{Y}_{12}\}}}$$

Measurements of Y_{12}

real part of small-signal parameters

$$f_{\max} \approx \frac{f}{2}\sqrt{-\frac{\Re\{\underline{Y}_{21}\}}{\Re\{\underline{Y}_{12}\}}}$$

- $f_{\max}$ almost "only" depends on the real parts of $\underline{Y}_{12}$ and $\underline{Y}_{21}$

$$\Re\{\underline{Y}\} = |\underline{Y}|\cos(\angle\underline{Y})$$

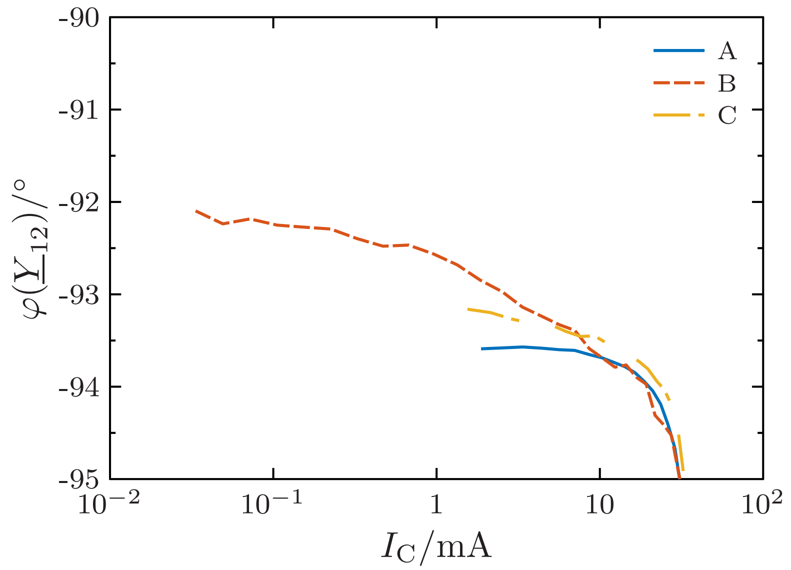
=> phase close to n*π: weak dependence on phase ($\underline{Y}_{21}$)

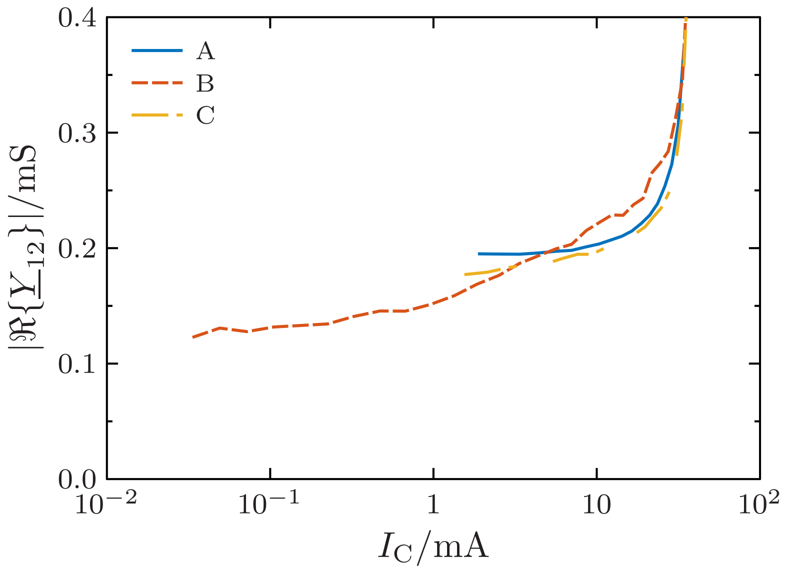
=> phase close to (2n+1)/2*π: strong dependence on phase ($\underline{Y}_{12}$)

Measurements of the phase

$$\Re\{\,\underline{Y}_{12}\,\} = \left|\underline{Y}_{12}\right|\cos(\angle\underline{Y}_{12})$$

- Different bias dependence of the measured phases





directly visible in the real part of $\underline{Y}_{12}$ and thus f_max
almost flat for A, increasing for B and C

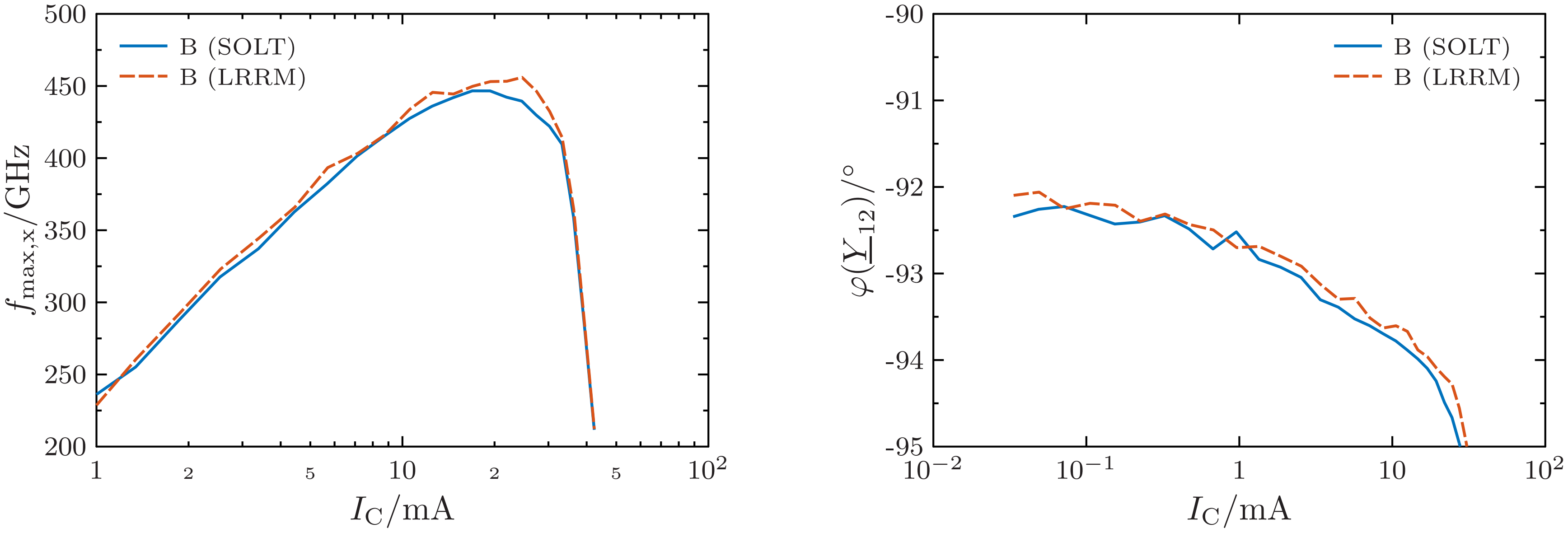
Possible causes of deviations

- Measurement setup
  - Probes
  - Cables
  - Bias-Tees
  - VNA (model and settings)
- Calibration
  - Routine
  - Results

Comparison of calibrations

SOLT vs. LRRM

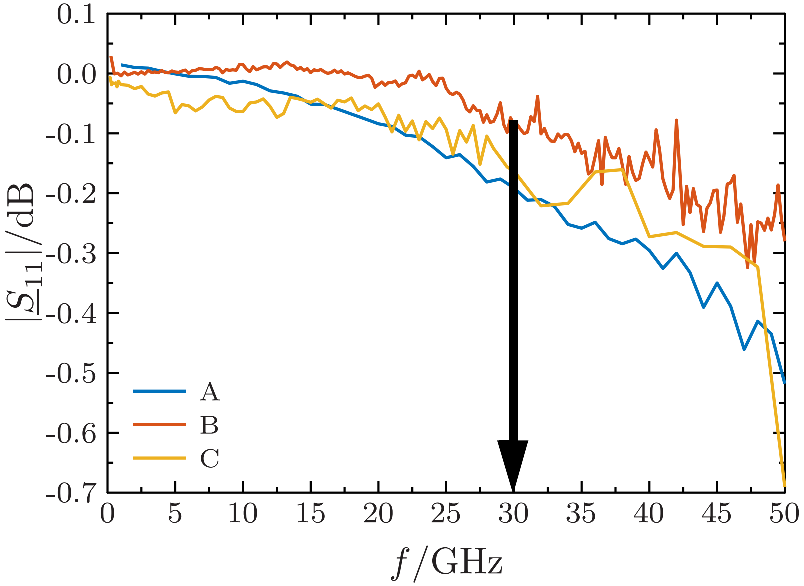
- LRRM less dependent on models for calibration standards



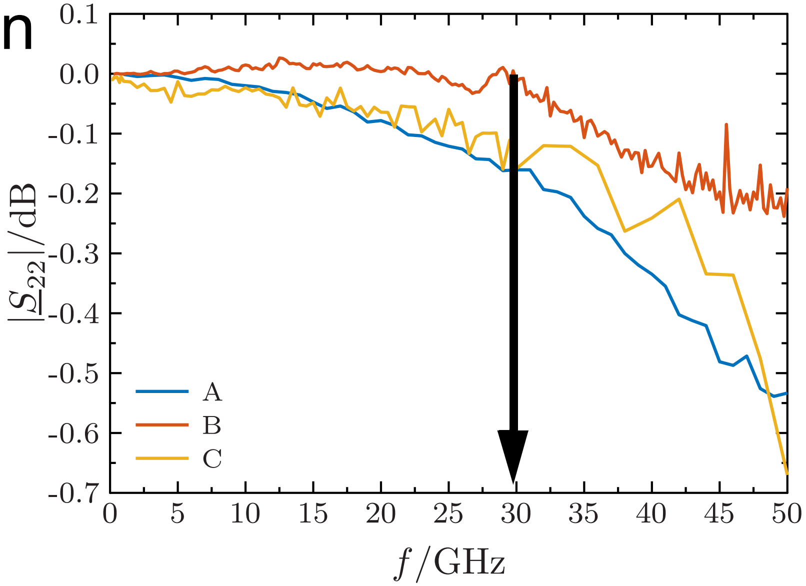
very similar results obtained for both methods

Deembedding structures

- "Simple" passive structures (open and short)
  - less sensitive to variations on the wafer
- Useful to compare calibrations



Open

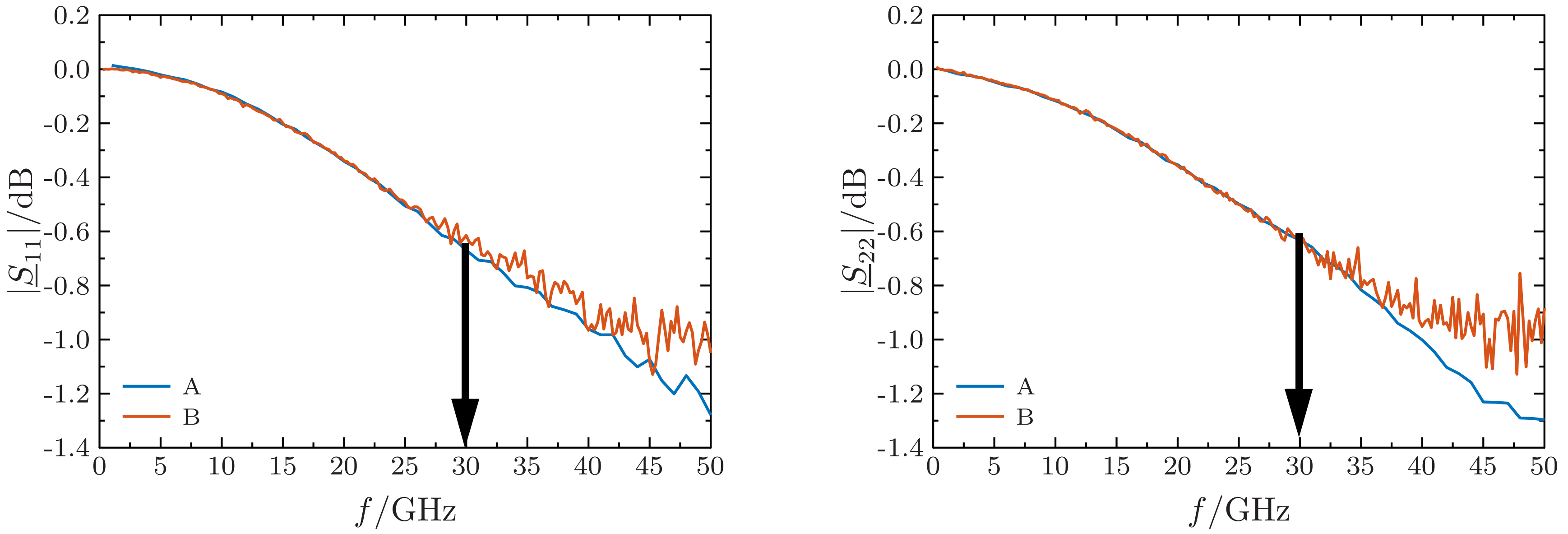


visible deviations in the reflection coefficients

Passive transistor

- Comparison of HBT at $V_{BE} = V_{BC} = 0$ V

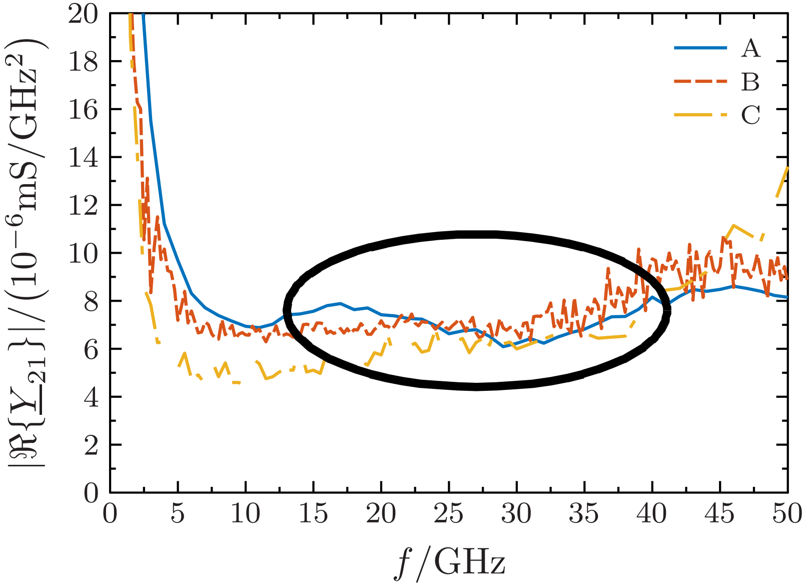
similar characteristics as for the open



deviations at large frequencies

Comparison versus frequency

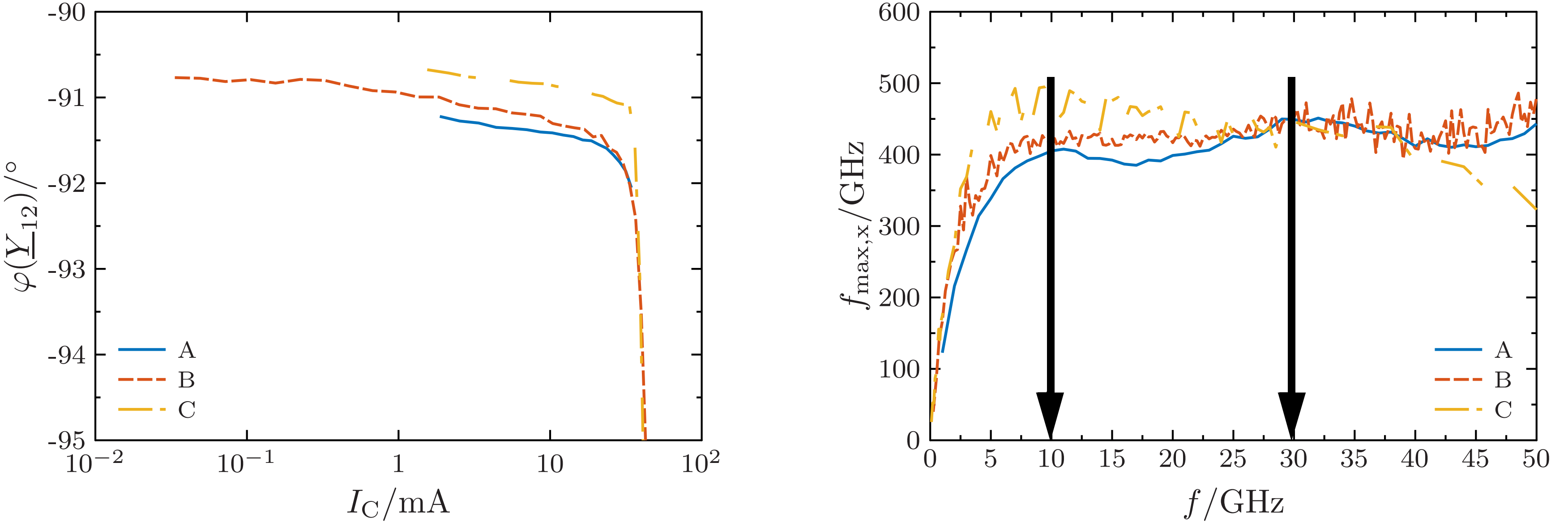
- Different frequency dependence of the S-parameter
- What does the frequency dependence of $\underline{Y}_{12}$ look like?



valley for A exactly at reference extraction frequency

Comparison at small frequencies

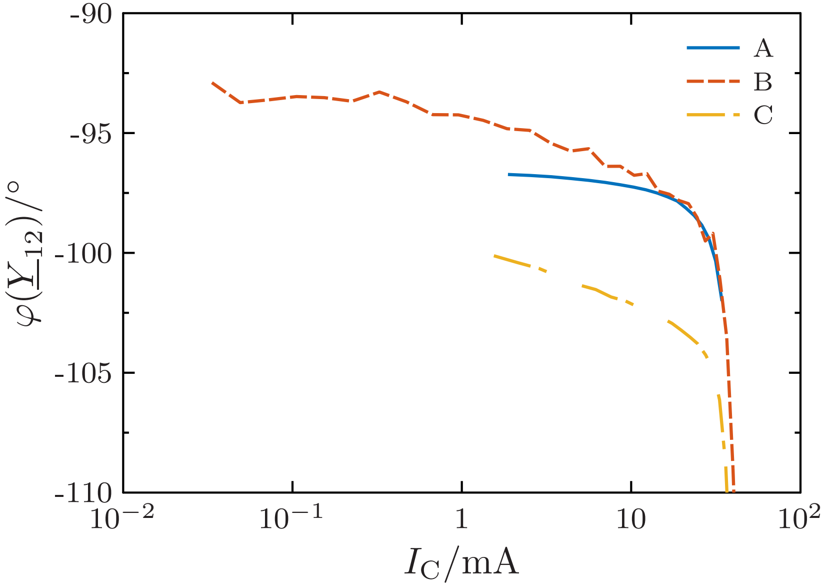
- Comparing results at 10 GHz
  - similar results for all transistors

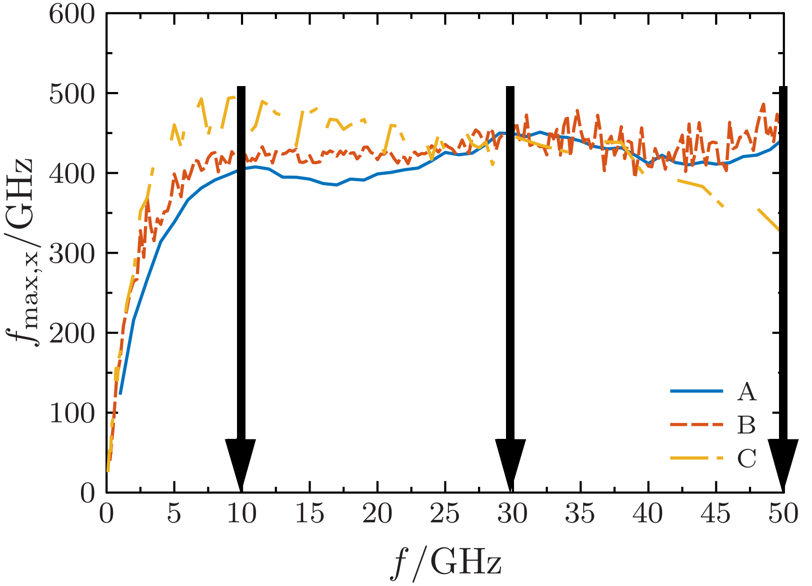


however, a small frequencies large differences in the peak f_{max}

Comparison at large frequencies

- Comparing results at 50 GHz
  - similar results for all transistors



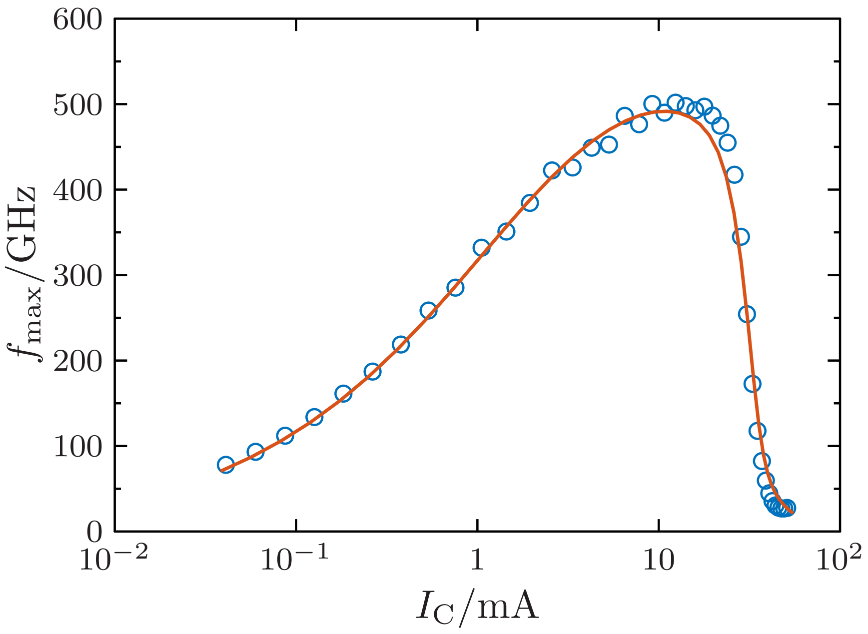


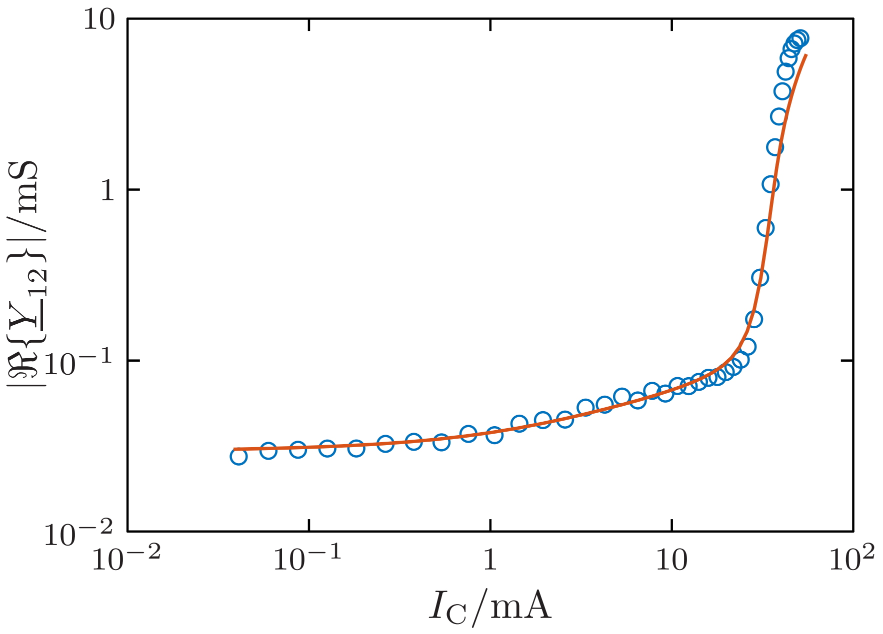
more reasonable bias dependence of A again
large differences of C to A and B (strongly reduced f_max)

Modeling point of view

What does the model predict and why?

- HICUM/L2 model





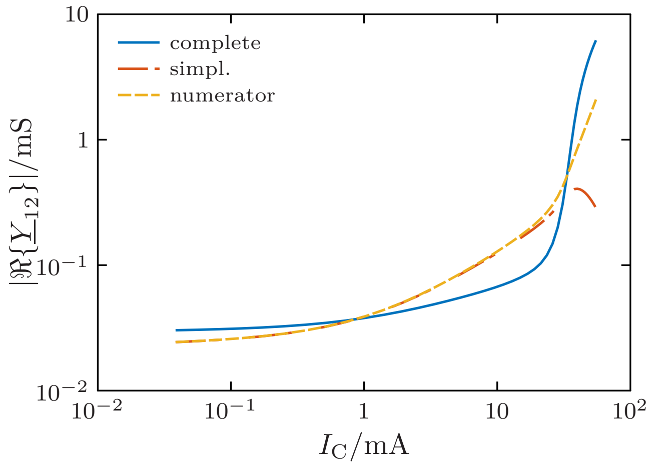
good agreement on both characteristics

Calculation of Y_{12}

- Simple assumptions

$$\underline{Y}_{12} = \frac{\underline{Y}_{12,\mathrm{i}}}{1 + R_{\mathrm{B}}\underline{Y}_{11,\mathrm{i}}}$$

$$\Re\{\underline{Y}_{12}\} \approx -\frac{R_{\mathrm{B}}\omega^2 C_{\mathrm{BC}}(C_{\mathrm{BE}} + C_{\mathrm{BC}})}{1 + R_{\mathrm{B}}^2\omega^2(C_{\mathrm{BE}} + C_{\mathrm{BC}})^2} \approx -R_{\mathrm{B}}\omega^2 C_{\mathrm{BC}}(C_{\mathrm{BE}} + C_{\mathrm{BC}})$$



Bias dependence

$$\Re\{\underline{Y}_{12}\} \approx -\frac{R_{\mathrm{B}}\omega^2 C_{\mathrm{BC}}(C_{\mathrm{BE}}+C_{\mathrm{BC}})}{1+R_{\mathrm{B}}^2\omega^2(C_{\mathrm{BE}}+C_{\mathrm{BC}})^2} \approx -R_{\mathrm{B}}\omega^2 C_{\mathrm{BC}}(C_{\mathrm{BE}}+C_{\mathrm{BC}})$$

- For both, V_{CE} and V_{BC} const. measurements

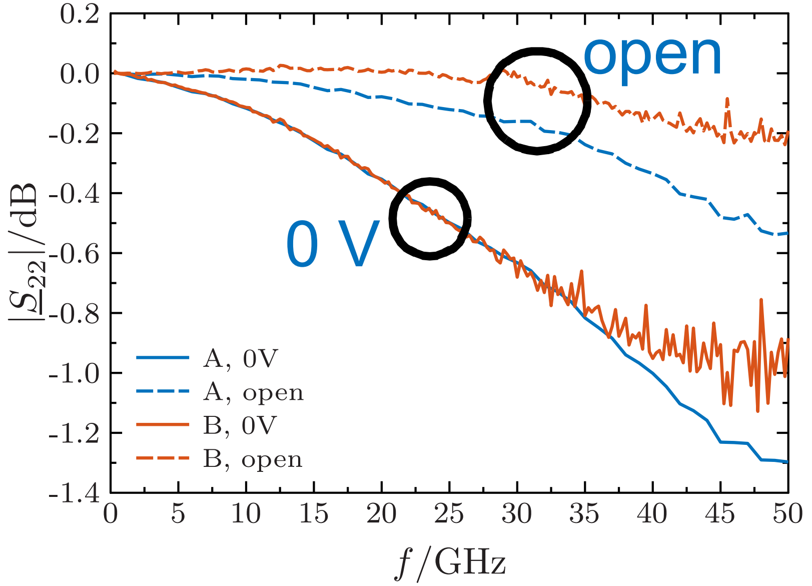
  => all capacitances increase with V_{BE}

- Base resistance decrease, but to a smaller extend
- Overall, $|\mathrm{Re}\{\underline{Y}_{12}\}|$ should increase as for *all* measurements at 10 GHz and 50 GHz and *some* at 30 GHz

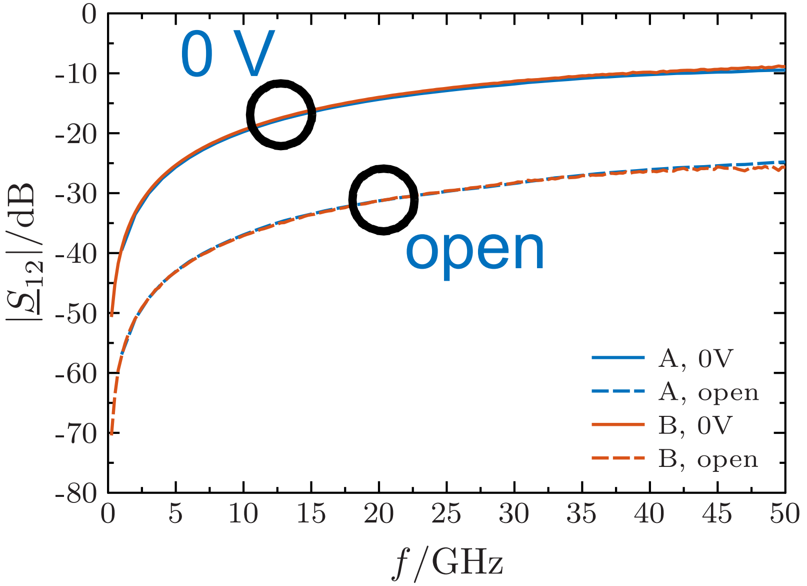
Comments on the calibration

some more discussions on measured S-parameters

- Comparison of HBT 0 V and open measurements


open

0 V

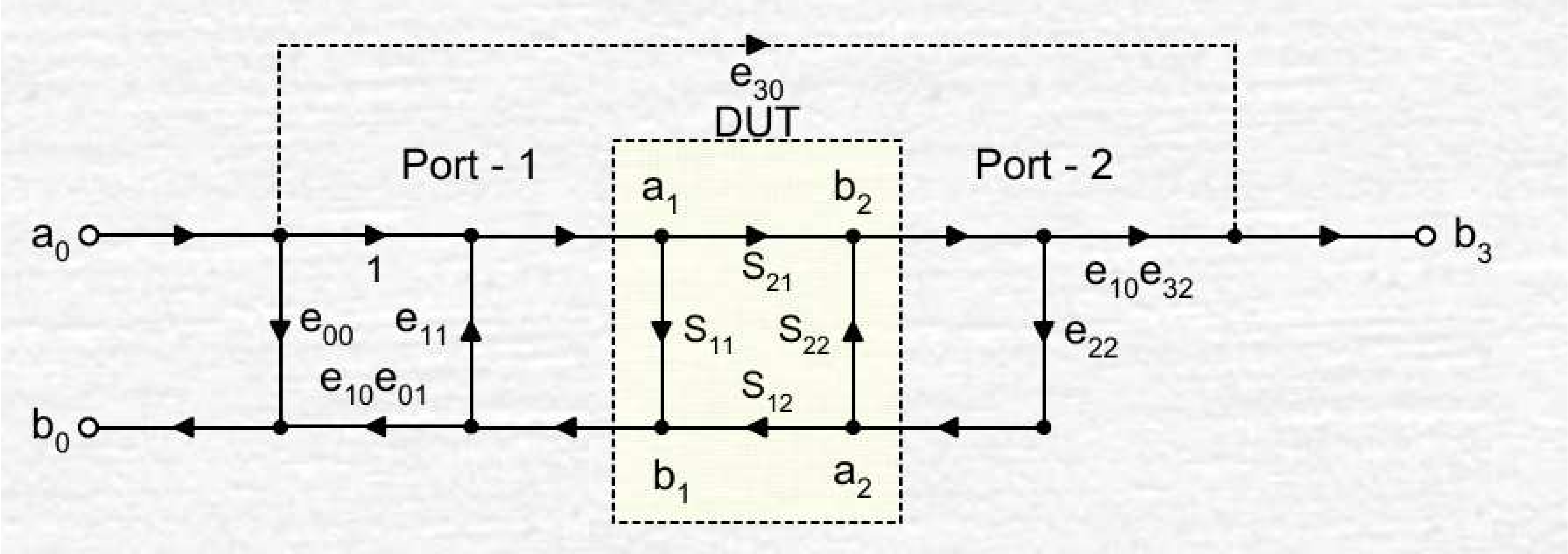

0 V

open

deviations at different frequencies

Calculations

- Most measurements are with SOLT calibration



[Doug Rytting, "Network Analyzer Error Models and Calibration Methods]

$$S_{11M} = \frac{b_0}{a_0} = e_{00} + (e_{10}e_{01})\frac{S_{11} - e_{22}\Delta S}{1 - e_{11}S_{11} - e_{22}S_{22} + e_{11}e_{22}\Delta S}$$

Calculations

Open

- Very good isolations (< -30 dB)

$$\left|\underline{S}_{11}\underline{S}_{22}\right| \gg \left|\underline{S}_{12}\underline{S}_{21}\right|$$

$$S_{11\mathrm{M}} \approx e_{00} + \frac{(e_{10}e_{01})S_{11}}{1 - e_{11}S_{11}}$$

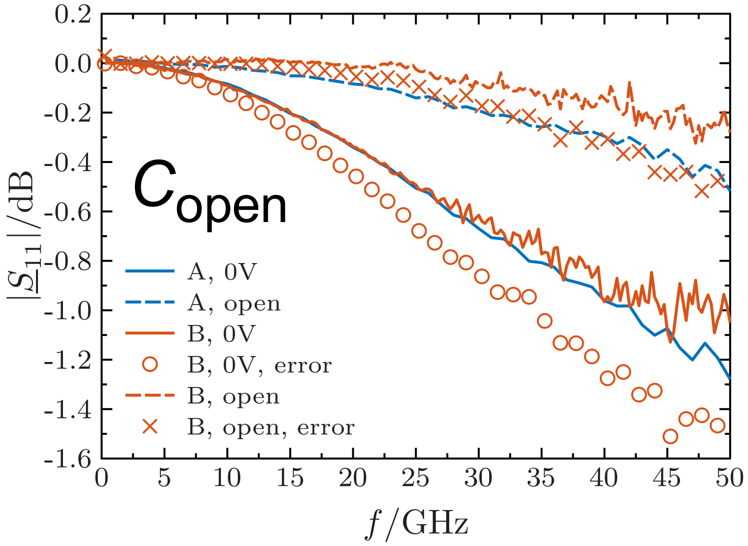
only one port SOL calibration to take into account for Open

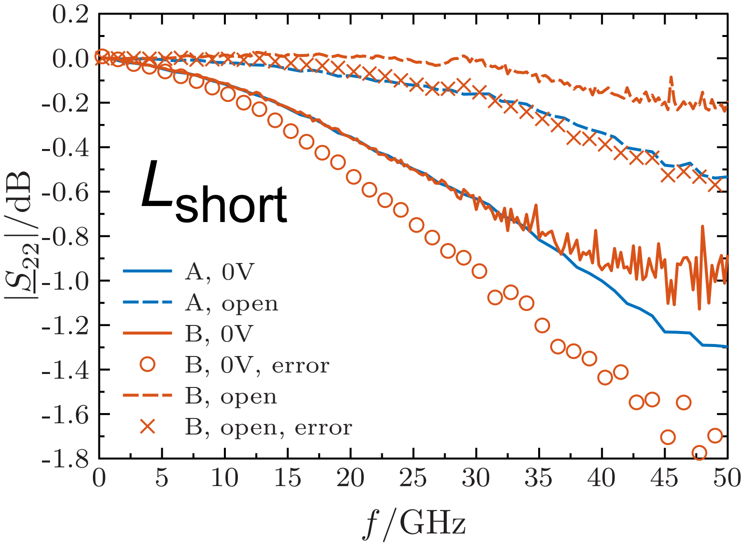
Impact of calibration standards

- Procedure (full SOLT)
  - Calculate raw S-parameters of calibration standards with deviations in the Rs, Ls and Cs with reference error terms
  - Calculate new *erroneous* error terms
  - Calculate raw S-parameters of open and 0 V measurements using reference error terms
  - Calculated new S-parameters using *erroneous* error terms
- Parameters
  - C of open
  - L of short
  - R and L of load

Results

- Load:
  - L has on small impact
  - R has large impact but also on $\underline{S}_{12}$ and $\underline{S}_{21}$
- Open and short
  - always impact on in the complete frequency range





Conclusion

- Difficulties to obtain consistent f_{max} for the same transistor at different measurement sites
- Can be tracked back to deviations in the phase of $\underline{Y}_{12}$
- Physical and non-physical behavior strongly frequency dependent
- No simple explanation possible with calibration errors

Acknowledgments

The authors would like to thank

- DFG: DFG SCHR695/7-1 and Highly Adaptive Energy-Efficient Computing (SFB 912)
- Bernd Heinemann, Holger Rücker, Gerhard Fischer and Christian Wipf from IHP
- Klaus Aufinger vom Infineon
- Paulius Sakalas from TUD
- Andrej Rumiantsev from MPI