Capacitance modelling of a transistor for RF Power Amplifiers in 5G applications.

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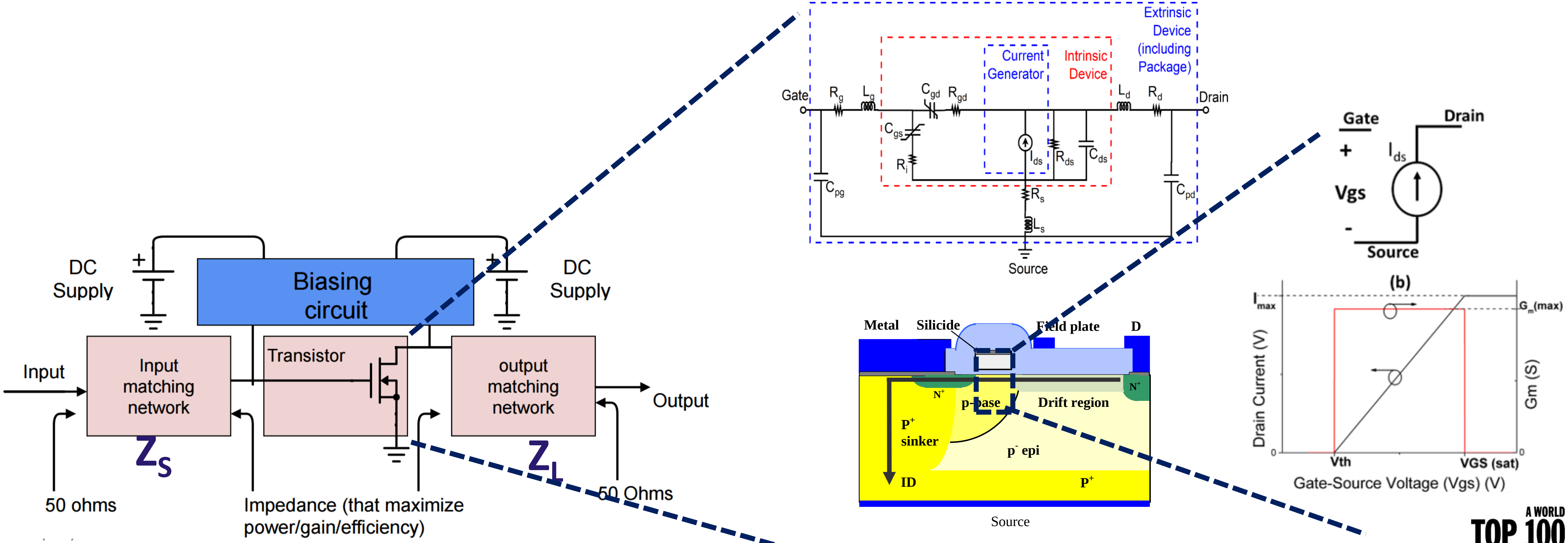
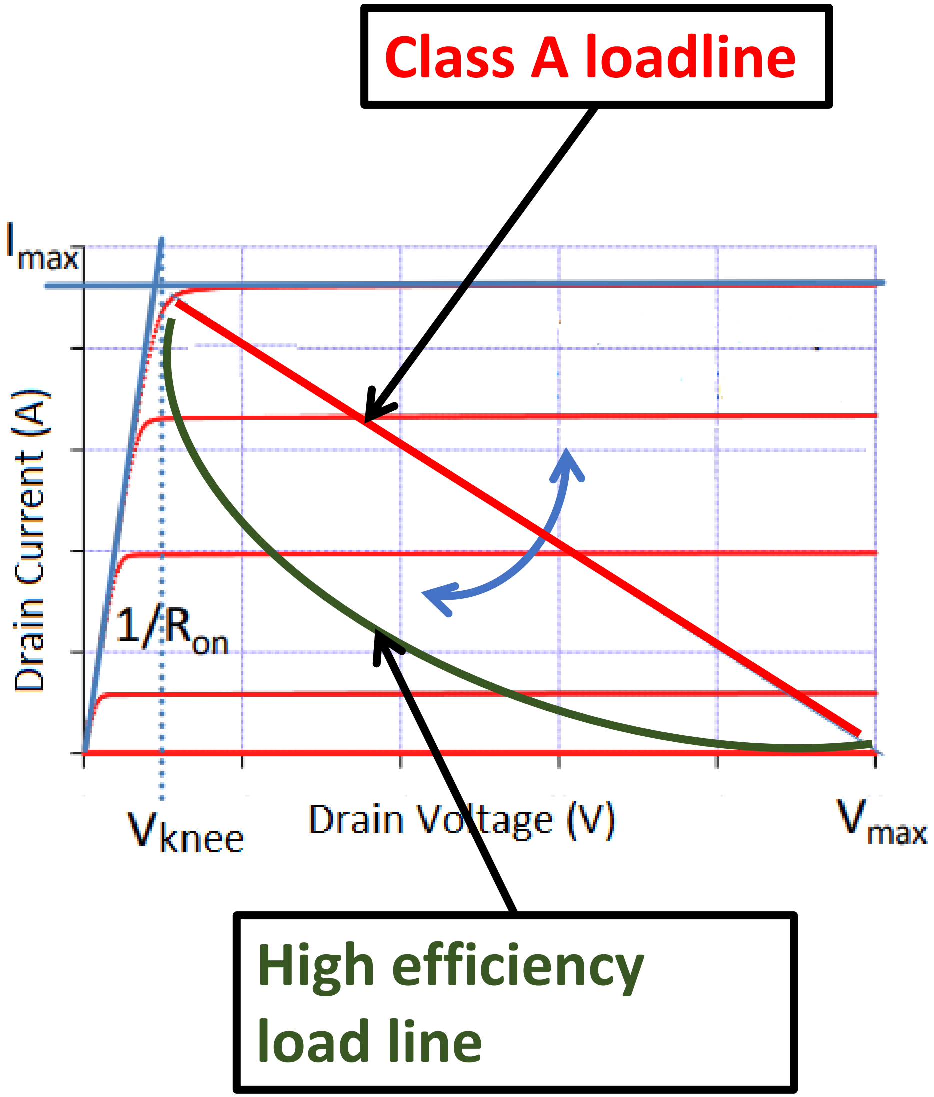
The RFPA design process

- Identifying the optimal source (Z_S) and load (Z_L) impedances at fundamental and harmonic frequencies
- Requires an accurate model of the transistor, consisting of the intrinsic device corresponding to the gated channel, (~linear current generator) and extrinsic parameters



Silicon LDMOS

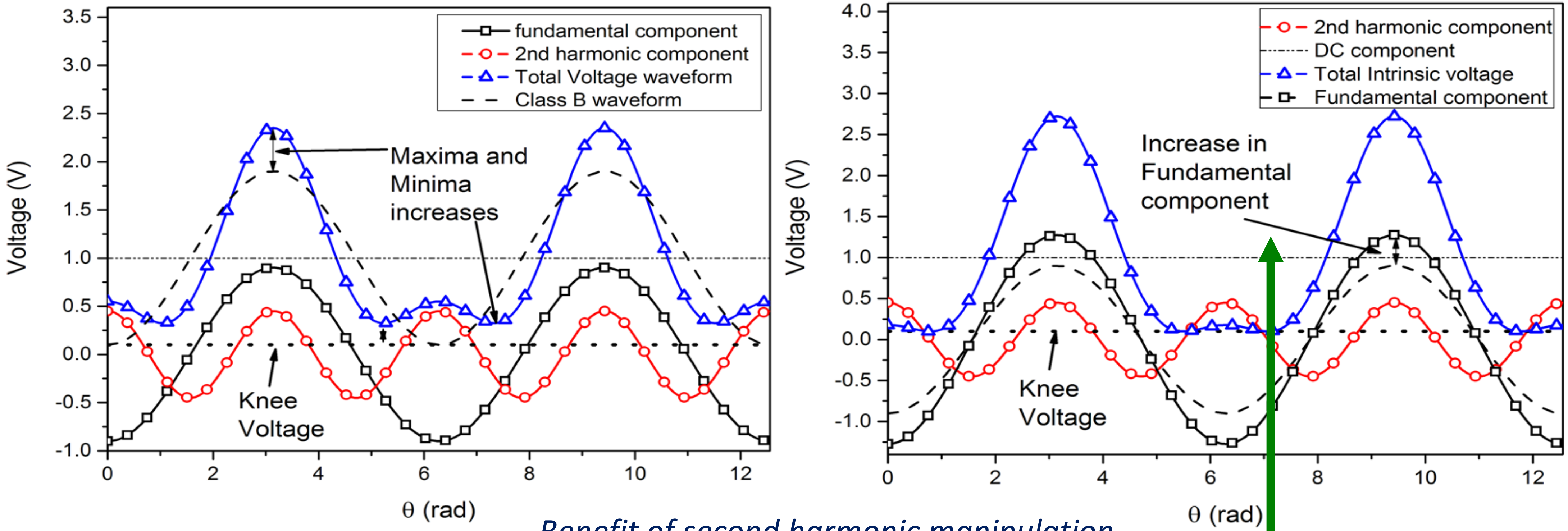
Motivation



- High efficiency and linear amplifier are required to meet the stringent requirements of fifth generation mobile networks.
  - High efficiency modes such as continuum modes that rely on the harmonic manipulation
- The accuracy of circuit design relies heavily on the accuracy of the transistor model
  - requires accurate modelling of capacitances especially in the knee region.
  - for accurate distortion simulation up to N^{th}-order requires models that have I-V and Q-V curves accurate up to Nth-order derivatives.
  - component-wise information about the dominant distortion sources helps to employ suppression techniques.

High efficiency modes

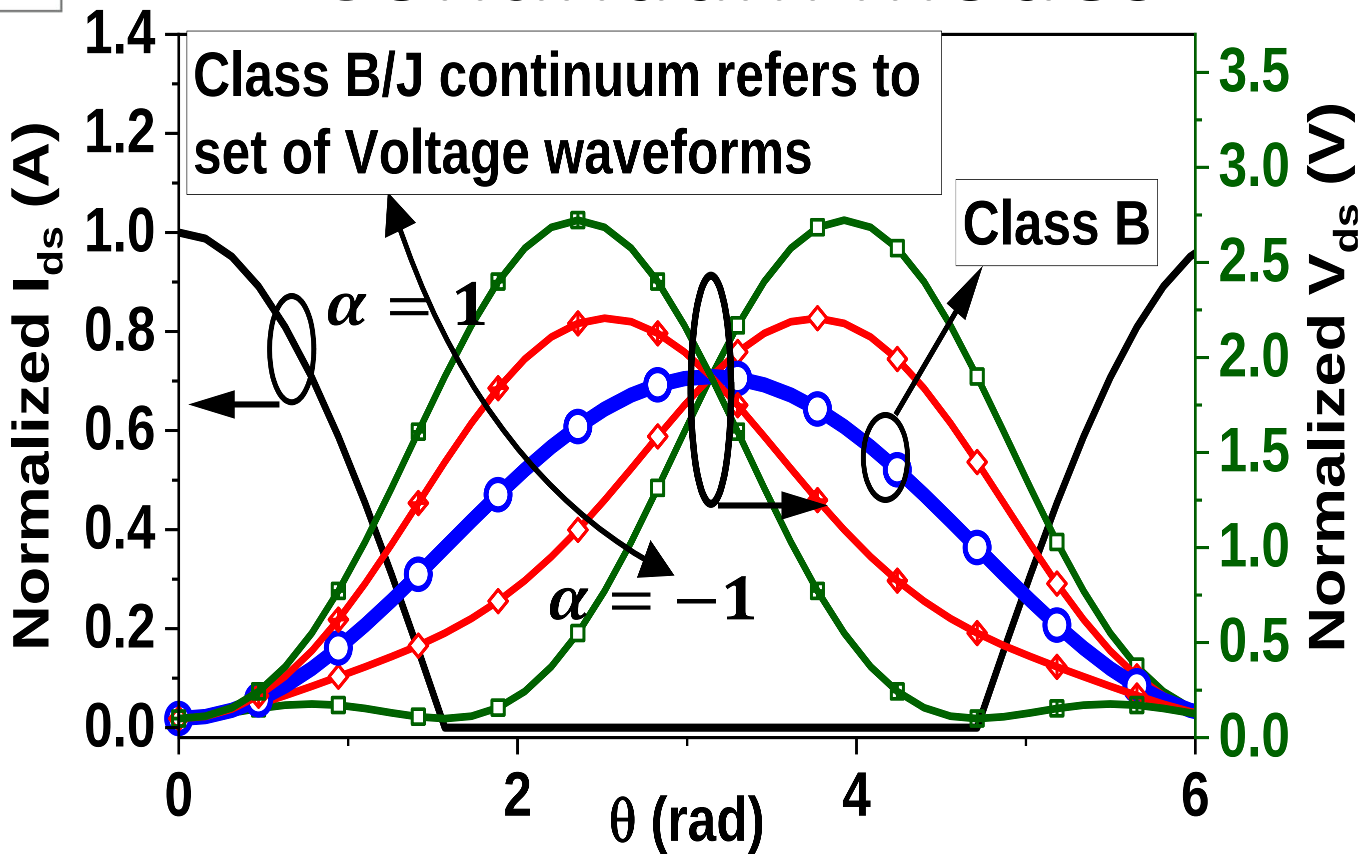
Principle of harmonic manipulation



Benefit of second harmonic manipulation

- The magnitude of the fundamental component increases by addition of the second harmonic component with an *appropriate* phase to the fundamental.
- This increase in voltage is often referred as “voltage gain” (δ_v).

Continuum modes



- Maximum of Voltage shifted to the left or right (Class J/J*)
  - All these waveform result in efficiency 78.5 % (same as Class B)
- Result in an increase in design space

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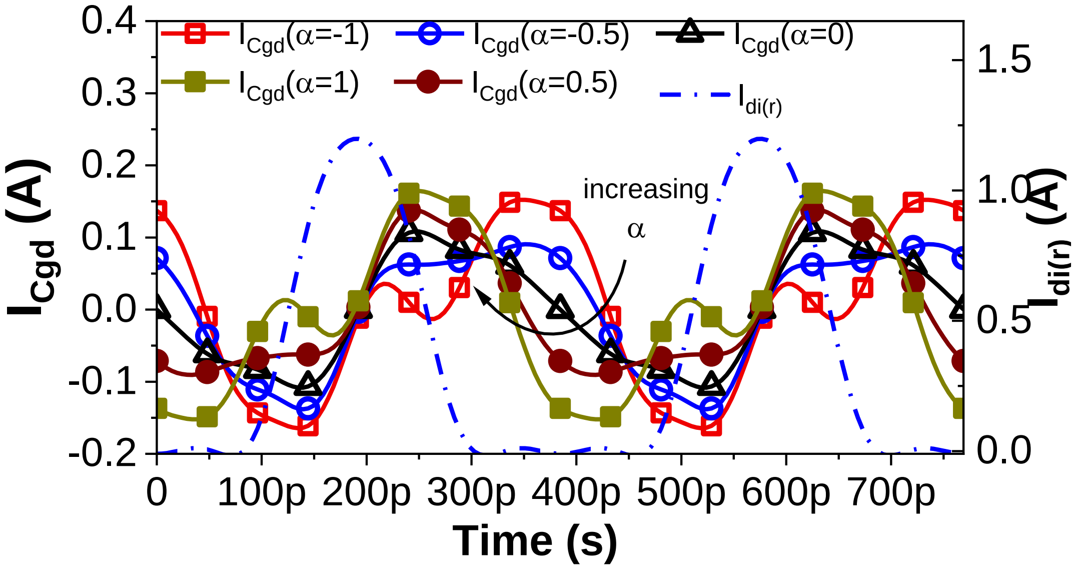
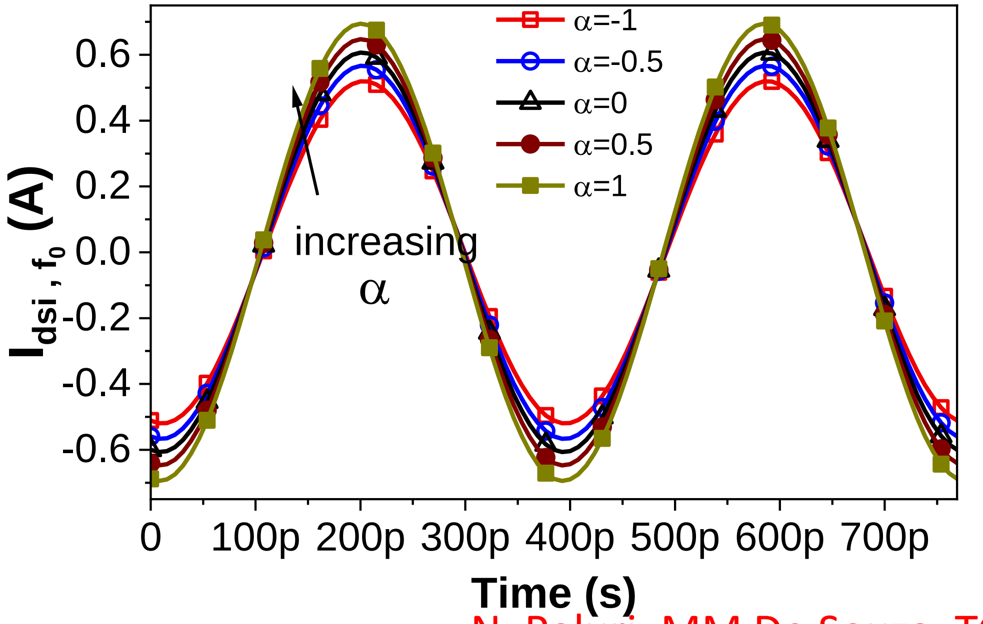
[1] S. C. Cripps et.al., IEEE MWCL., vol. 19, no. 10, pp. 665–667, 2009.

Impact of the Non-linear Caps on continuum modes



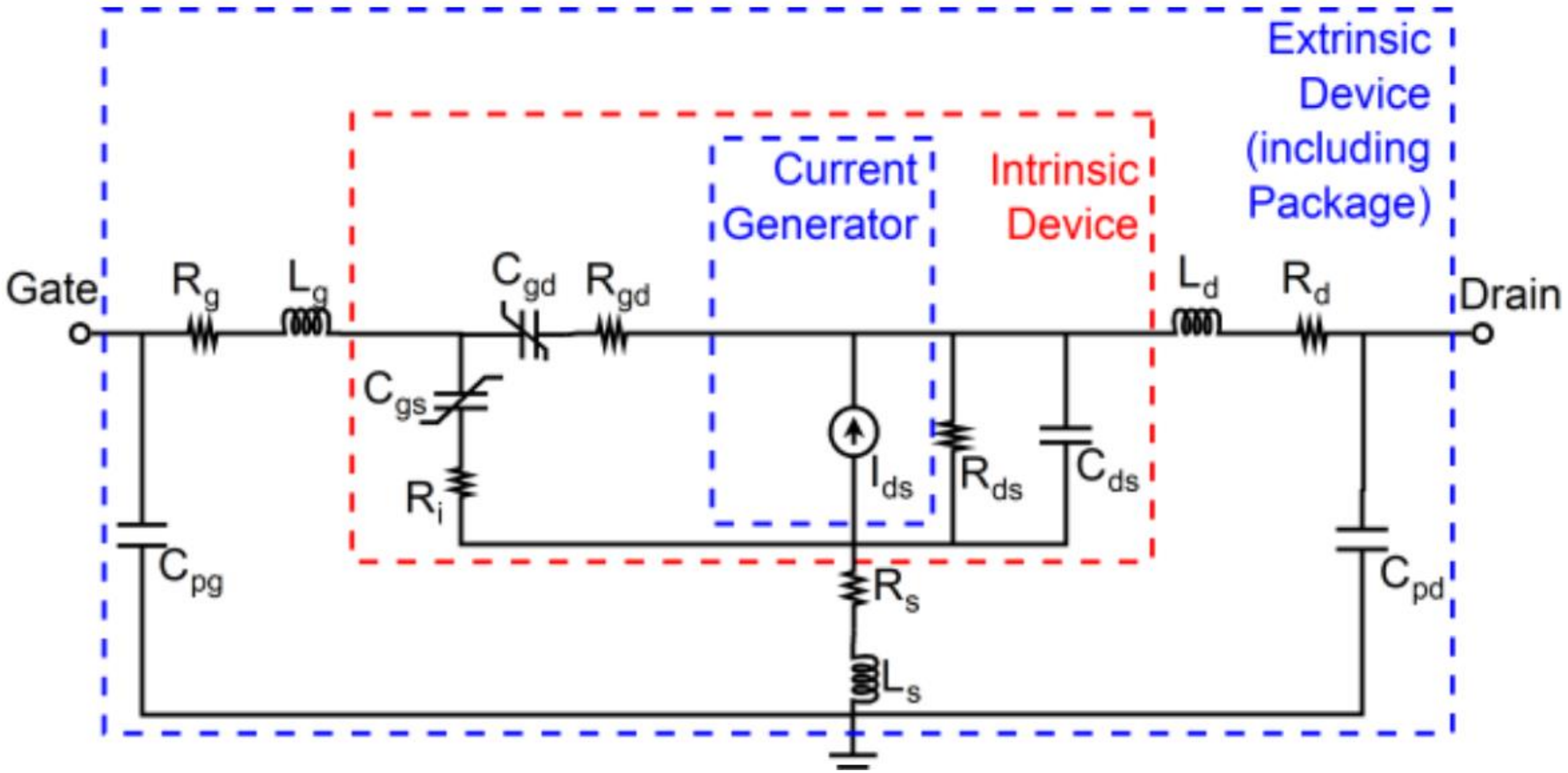


- Due to the variation of the phase of voltage in continuum mode, the phase of the current through Cgd changes.
  - Phase of Icgd varies relative the current from current generator (gm).
  - For some cases of α (such as -1) , Icgd is out of phase with the current from current generator.
- This phase variation of Icgd result in an improvement/reduction fundamental component of the current.
  - Improves efficiency and P1dB over class B for some subset of α

N. Poluri, MM De Souza, TCAS II, vol. 65, Issue 9, 2018

Small Signal model

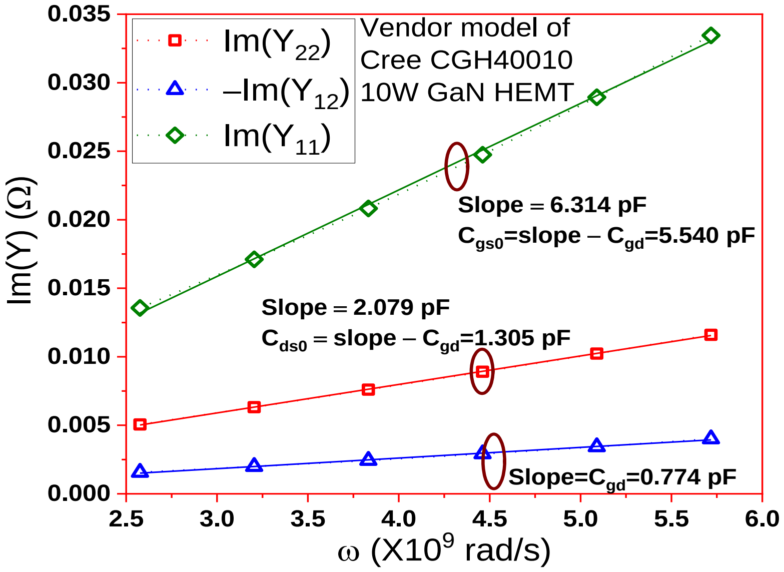
Equivalent circuit model

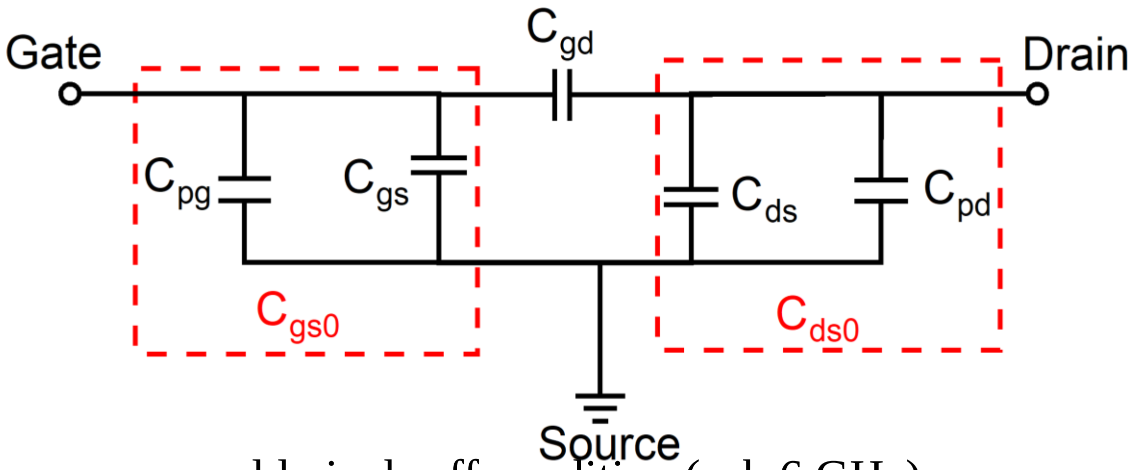


- Extrinsic parasitics are extracted from cold-forward (V_{ds}=0 V, V_{gs}≈0) and cold reverse conditions (V_{ds}=0 V, V_{gs}<V_{th})
- Intrinsic parameters are extracted for each bias point

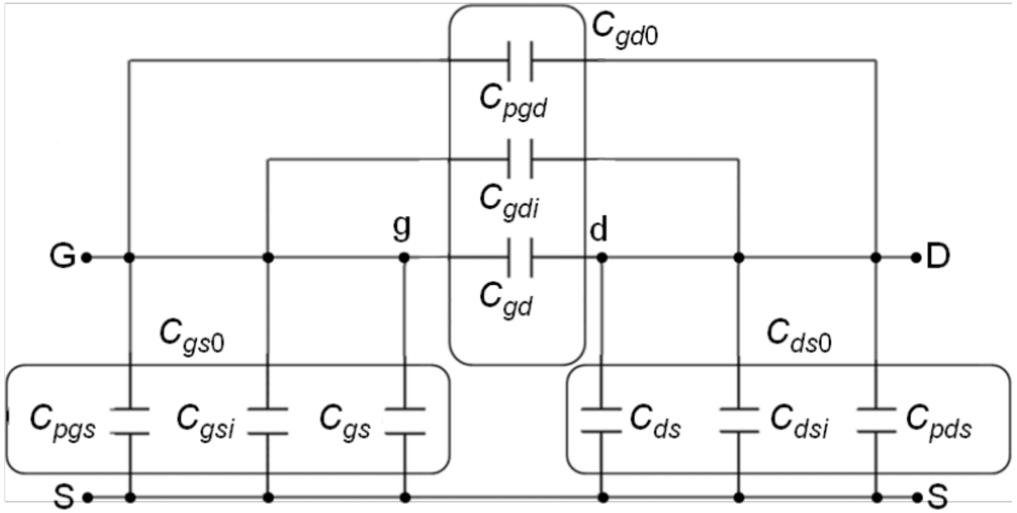
Extraction of extrinsic capacitances

- C_{gd} and branch capacitors (C_{gs0} and C_{ds0})
  - can be extracted from the slope of the Y parameters of the device with frequency, ω.
- Need more relations to separate pad from intrinsic caps (Cgs and Cds).
  - Equivalent circuits for frequency >6 GHz have more capacitances.





cold pinch-off condition (sub 6 GHz)



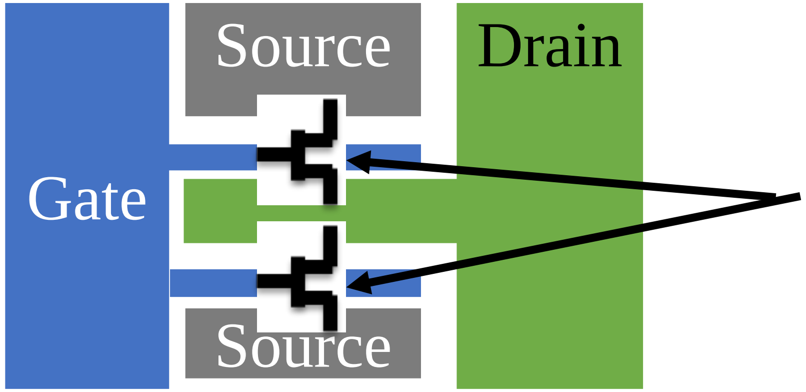
cold pinch-off condition (> 6 GHz, upto 40 GHz) [1]

[1] J. A. Z. Flores, PhD thesis, University of Kassel, Germany, 2012

Extraction of pad capacitances

If the device structure is known

- 3-D electromagnetic (EM) simulations of the metallization layer [1].



- Establish relationships between the extrinsic and/or intrinsic capacitances by
  - Theoretical modelling of the capacitance (C) by assuming $C \propto pad\ area$. [2]

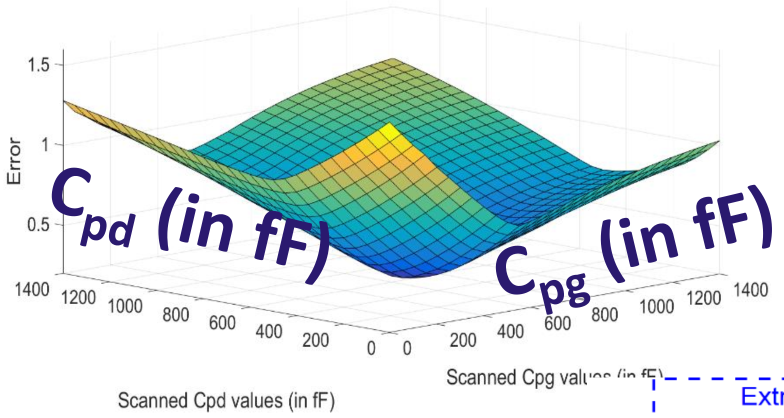
If device structure is unknown

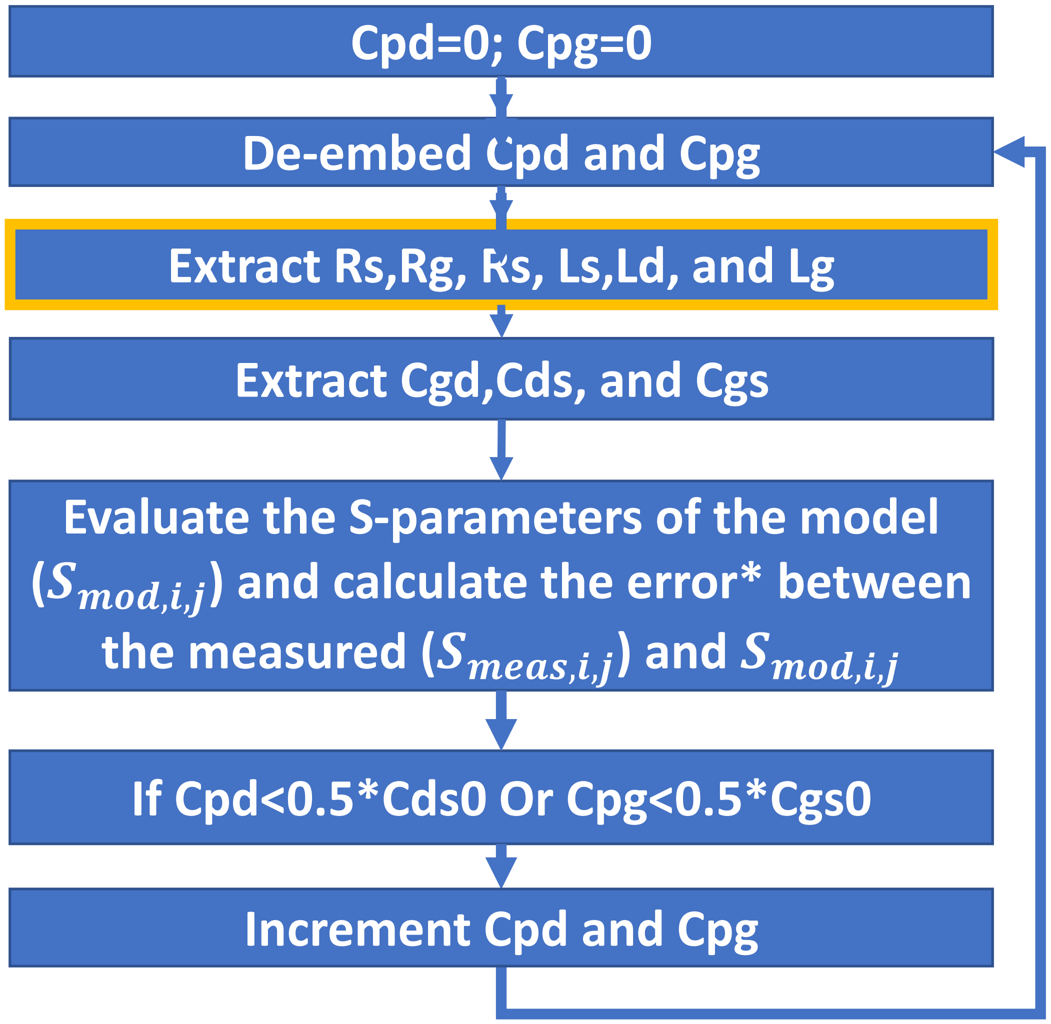
- Optimization to minimize the modelling error
  - Guess values of pad capacitances [3] or
  - The ratio of pad/device capacitances can be optimized (referred as Technology-related Empirical Capacitance Ratios (TECR) [2])

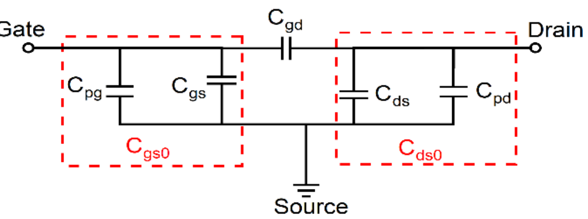
[1] Davide Resca et. Al. IEEE MTT, vol. 58, no. 4, 2010 [2] J. A. Z. Flores, PhD thesis, University of Kassel, Germany, 2012 [3] F. Lin and G. Kompa, IEEE MTT, vol. 42, no. 7, 1994

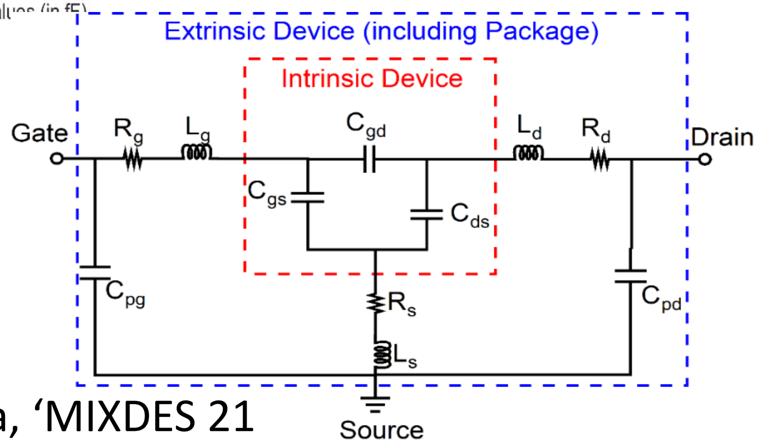
Modified TECR algorithm

- Simplified version of TECR algorithm for extraction of C_{pd} and C_{pg} whereas the Original version includes additional parasitics C_{pgi}, C_{pdi}, C_{pgd}, and C_{gdi}









*error is defined as (E)=

$$\sum_{i,j}^{2,2}\sum_f \left|S_{meas,i,j,f} - S_{mod,i,j,f}\right|^2$$

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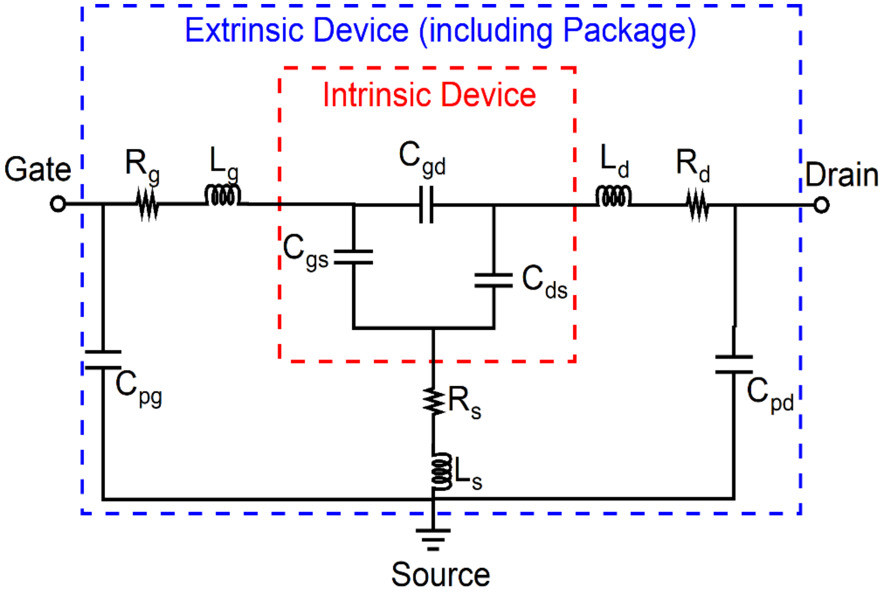
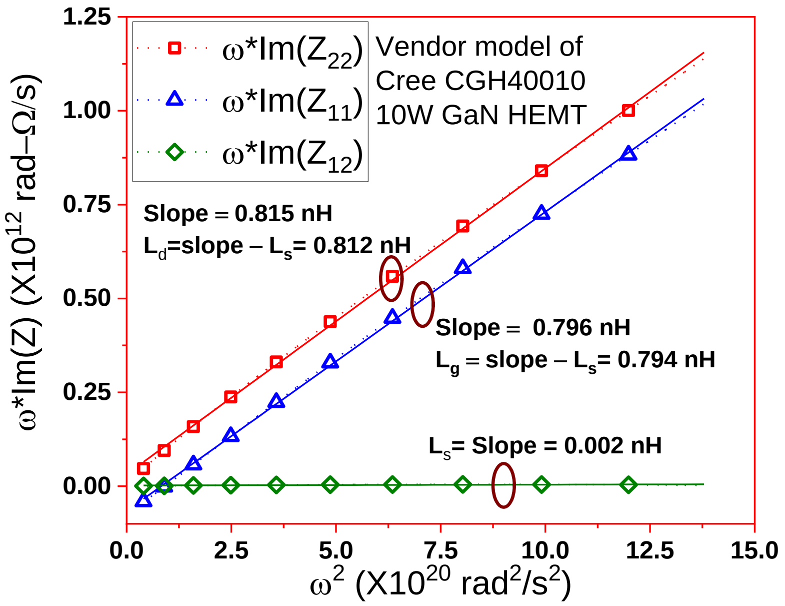
[1] Original version of TECR algorithm is proposed in J. A. Z. Flores, PhD thesis, University of Kassel, Germany, 2012 [2] N. Poluri et. Al., MIXDES, 2021

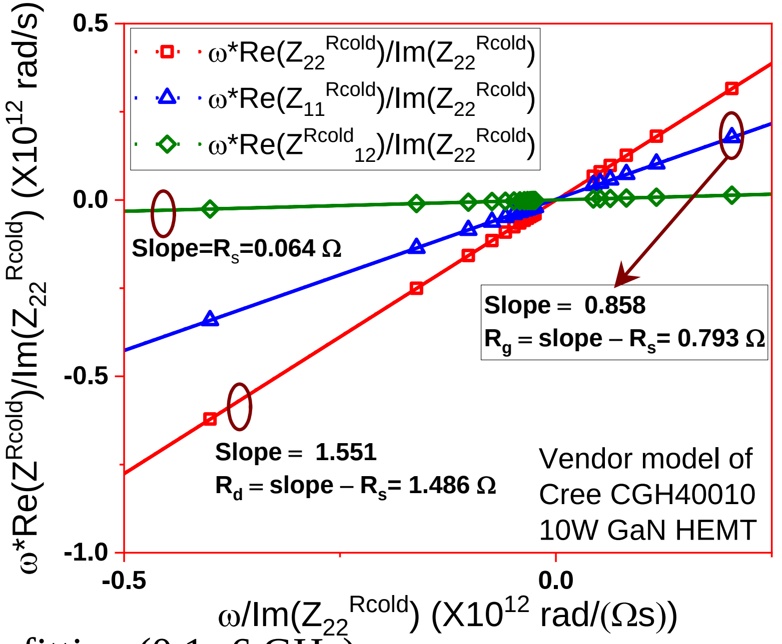
Extraction of Extrinsic parameters

- Extrinsic resistances and inductances are extracted from cold forward condition (Vgs>Vth and Vds=0) [1].



cold forward condition (< 6 GHz).



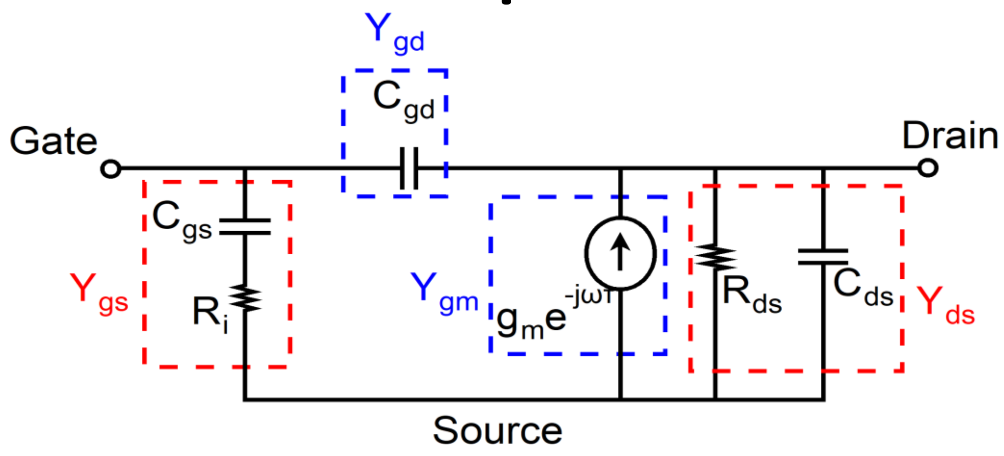


Frequency range used for fitting (0.1- 6 GHz).

[1] J. A. Z. Flores, PhD thesis, University of Kassel, Germany, 2012

Extraction of Intrinsic parameters

- De-embed extrinsic parameters.
- Related to Y parameters
- Analytical expressions are easier to program compared to curve fitting.



Analytical expression [2]

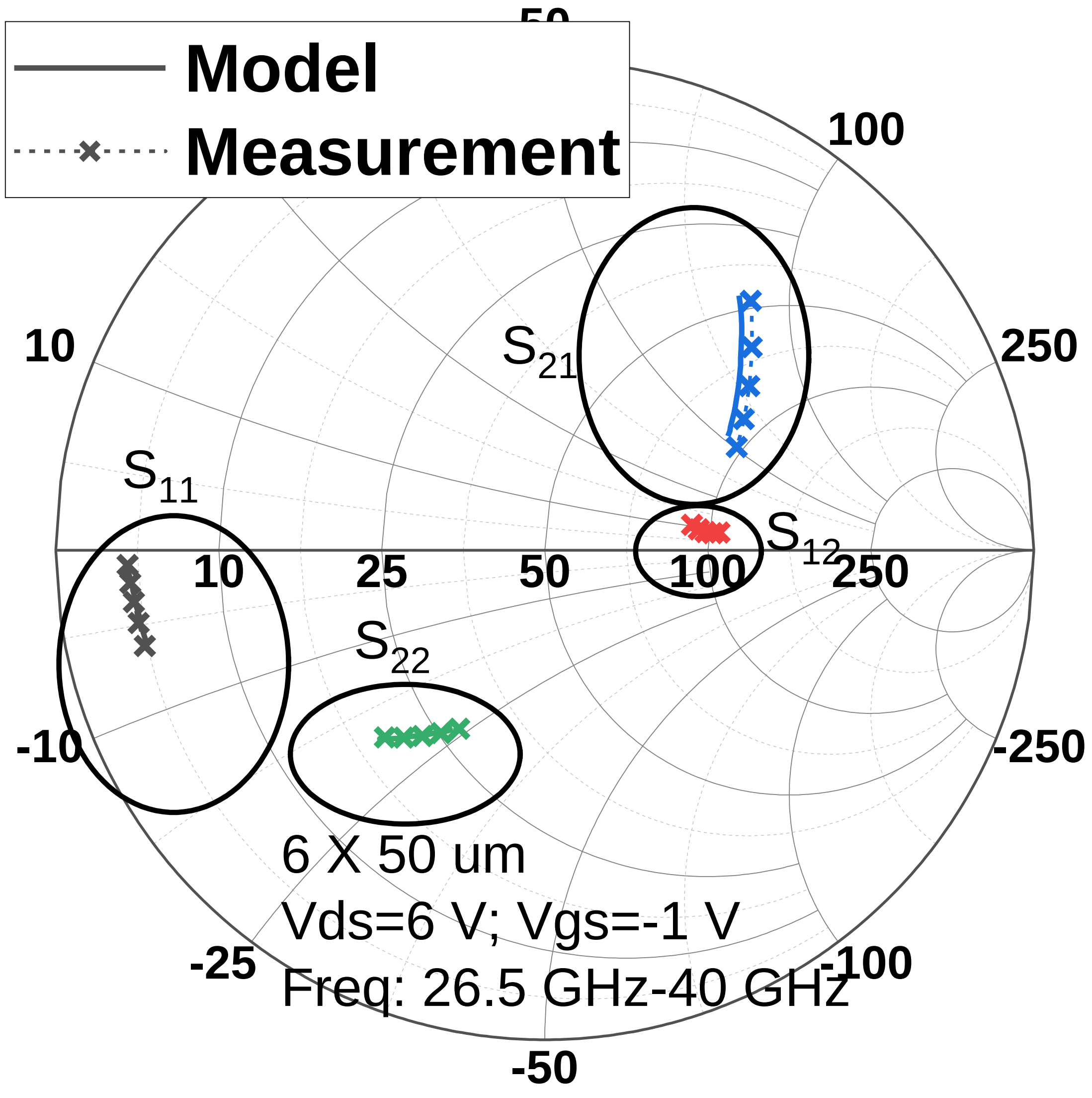
- $C_{gs} = \frac{\frac{1}{2\pi}\sum_k \left(|Y_{gs}(f_k)|/f_k\right)^2}{\sum_k Im\left(Y_{gs}(f_k)\right)/f_k}$
- $C_{ds} = \frac{1}{2\pi}\frac{\sum_k Im(Y_{ds}(f_k))}{\sum_k f_k}$
- $C_{gd} = \frac{1}{2\pi}\frac{\sum_k \left(|Y_{gd}(f_k)|/f_k\right)^2}{\sum_k Im\left(Y_{gd}(f_k)\right)/f_k}$

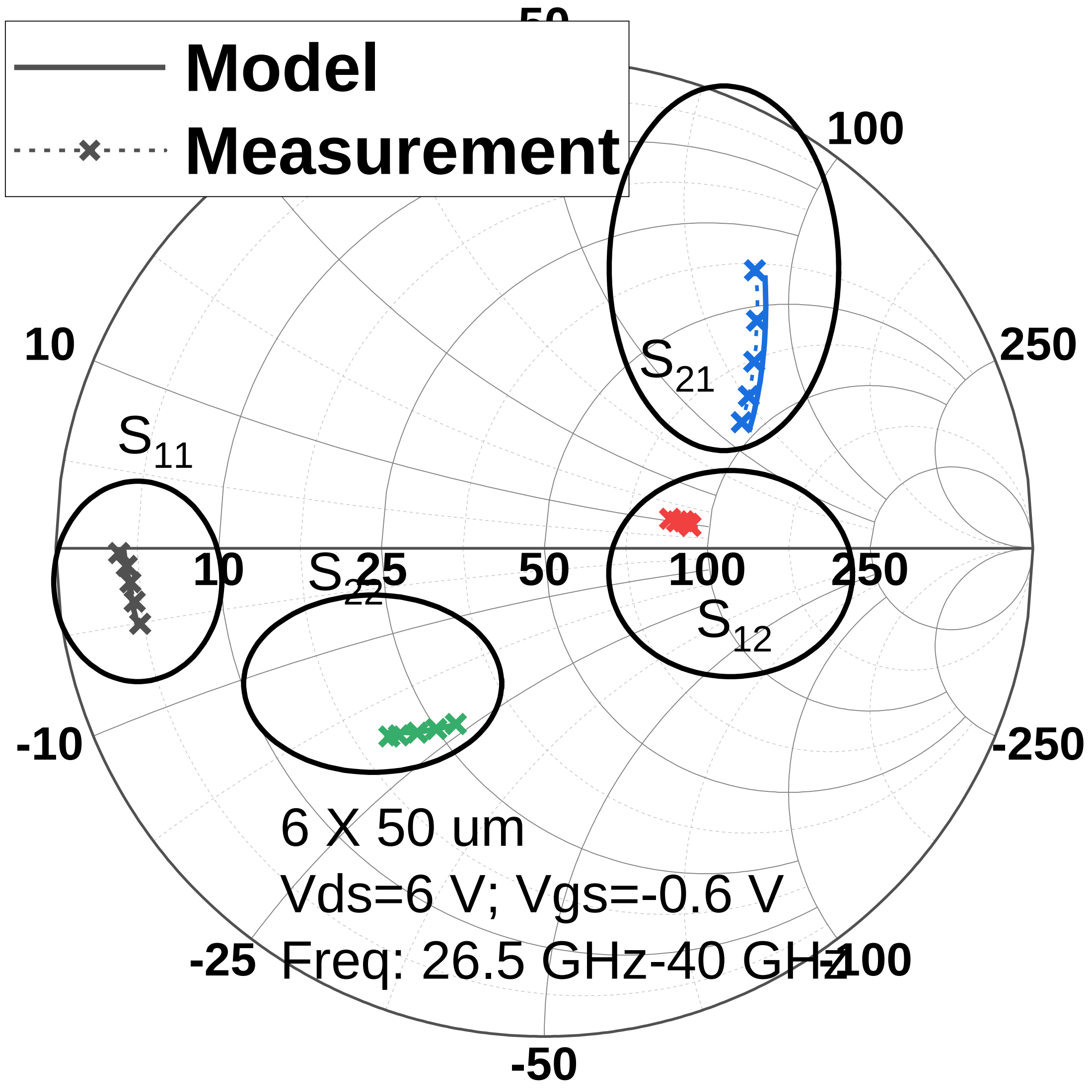
Relations for Curve/data fitting [1]

- $\omega^2 C_{gd} = \omega|Y_{gd}|^2/Im(Y_{gd});$
- $\omega^2 C_{gs} = \omega|Y_{gs}|^2/Im(Y_{gs});$
- $\omega \mathrm{C_{ds}} = Im(Y_{ds})$

[1] J. Lu, et. Al. *Solid. State. Electron.*, vol. 52, no. 1, pp. 115–120, 2008
[2] F. Lin and G. Kompa, IEEE MTT, vol. 42, no. 7, 1994

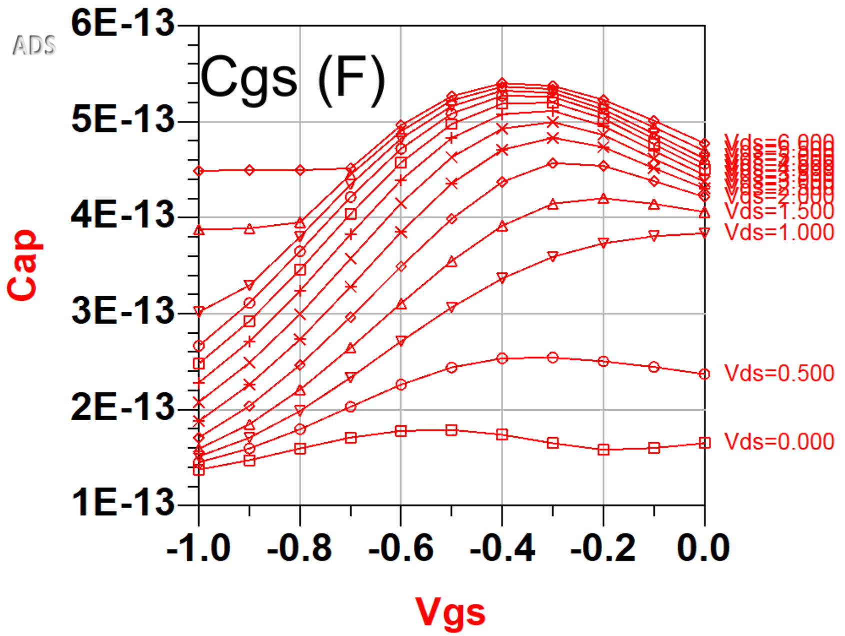
Comparison of S-parameters (small signal model)

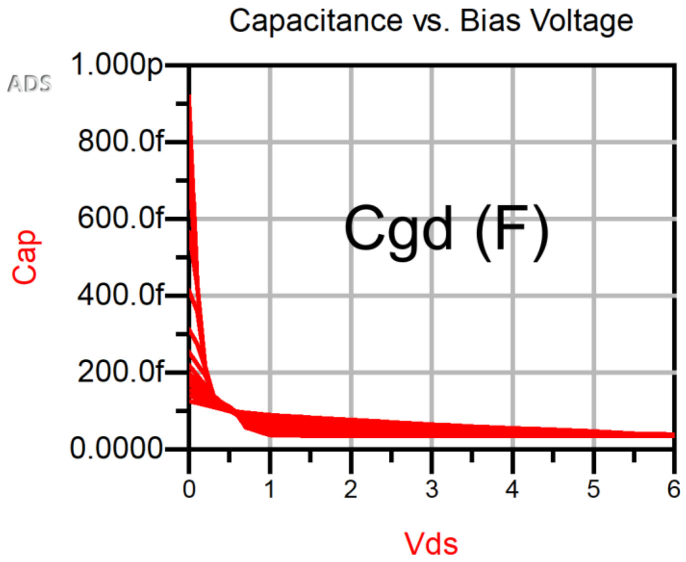


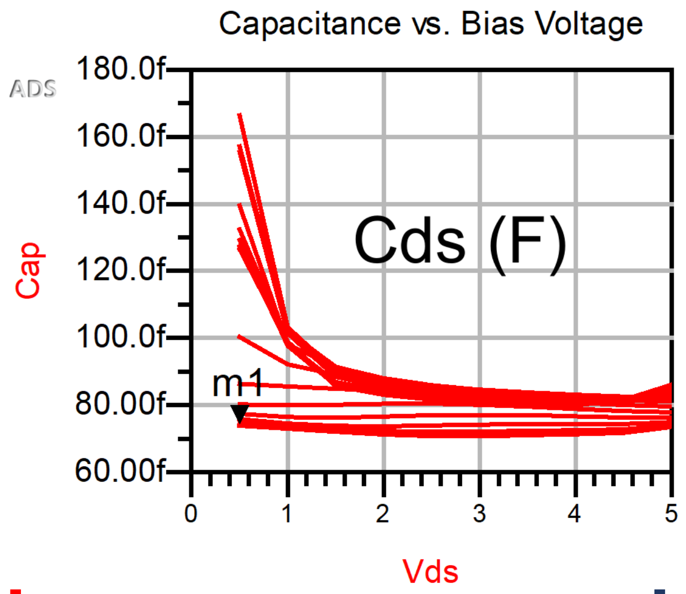


Large signal model

Mapping voltages from the extrinsic to the intrinsic plane

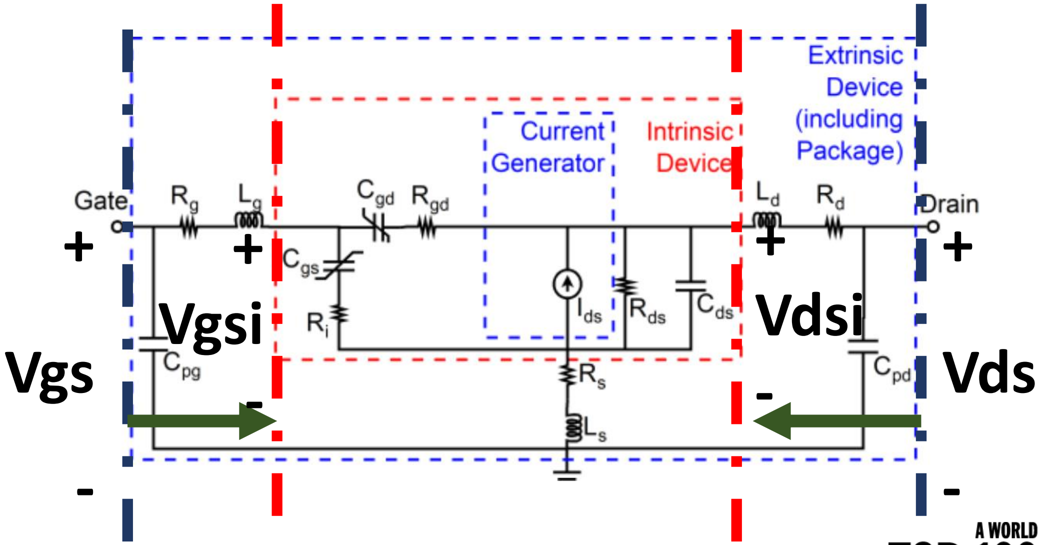




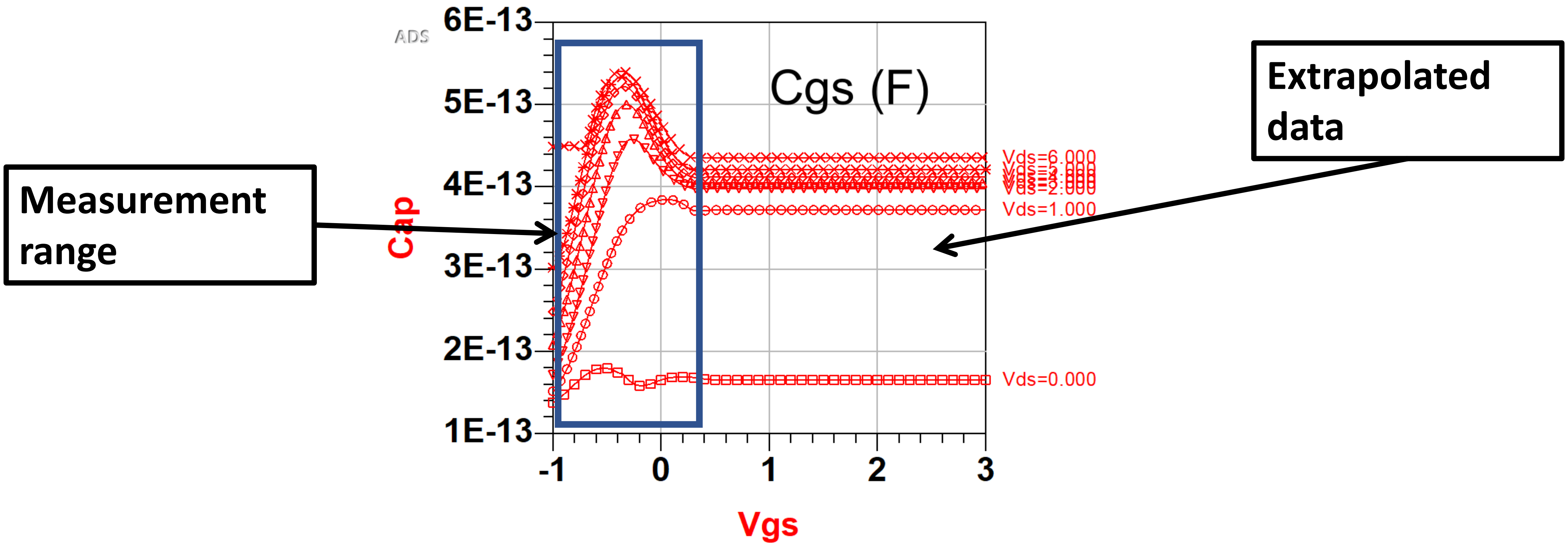


- Intrinsic capacitances obtained from extraction are a function of extrinsic voltages (V_{gs} and V_{ds}).
- Intrinsic parasitics are "re-gridded" to intrinsic gate (V_{gsi}) and drain (V_{dsi}) voltages.

$$V_{dsi} = V_{ds} - (R_d + R_s)I_{ds} - R_s I_{gs}$$
$$V_{gsi} = V_{gs} - \left(R_g + R_s\right)I_{gs} - R_s I_{ds}$$



Extrapolation beyond measurement range



- Device cannot be measured for all the gate and drain voltages because device might get damaged due to
    - device oscillations
    - thermal impact.

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Cgd and Cgs modelling [1]

Division by charge

$$Q_g = Q_{gs} + Q_{gd}$$

- The reactive gate current (I_g) as

$$I_g = I_s + I_d$$

$$I_s = C_{gs}\frac{dV_{gsi}}{dt} + \frac{\partial Q_{gs}}{\partial V_{gdi}}\frac{dV_{gdi}}{dt}$$

$$I_d = \frac{\partial Q_{gd}}{\partial V_{gsi}}\frac{dV_{gsi}}{dt} + C_{gd}\frac{dV_{gdi}}{dt}$$

Where, $\frac{\partial Q_{gd}}{\partial V_{gs}}$ and $\frac{\partial Q_{gs}}{\partial V_{gd}}$ denote trans-capacitances

- **The following is easy to implement in HB simulation**

$$I_s = \frac{Q_{gs}(V_{gs} + dV_{gs}, V_{ds} + dV_{ds}) - Q_{gs}(V_{gs}, V_{ds})}{dt}$$

- **Difficult to determine trans-caps.**
- **Could result in charge non-conservation→ periodic excitation that conserves Q_g could result in non periodic Q_{gs} and Q_{gd}.**

Division by capacitance

- The reactive gate current (I_g) as

$$I_g = I_s + I_d$$

$$I_s = \frac{\partial Q_{gs}}{\partial t} = C_{gs}\frac{dV_{gs}}{dt}$$

$$I_d = \frac{\partial Q_{gd}}{\partial t} = C_{gd}\frac{dV_{gd}}{dt}$$

- For charge conservation $\frac{\partial C_{GS}}{\partial V_{GD}} = \frac{\partial C_{GD}}{\partial V_{GS}}$
- **Lack of trans capacitance simplifies modelling.**
- **Consistent with small signal model.**
- **Difficult to implement differential with only one variable in HB simulations**

$$I_s = \frac{Q_{gs}(V_{gs} + dV_{gs}, V_{ds}) - Q_{gs}(V_{gs}, V_{ds})}{dt}$$

[1] S. Maas, Nonlinear Microwave and RF circuits, Artech House 2003

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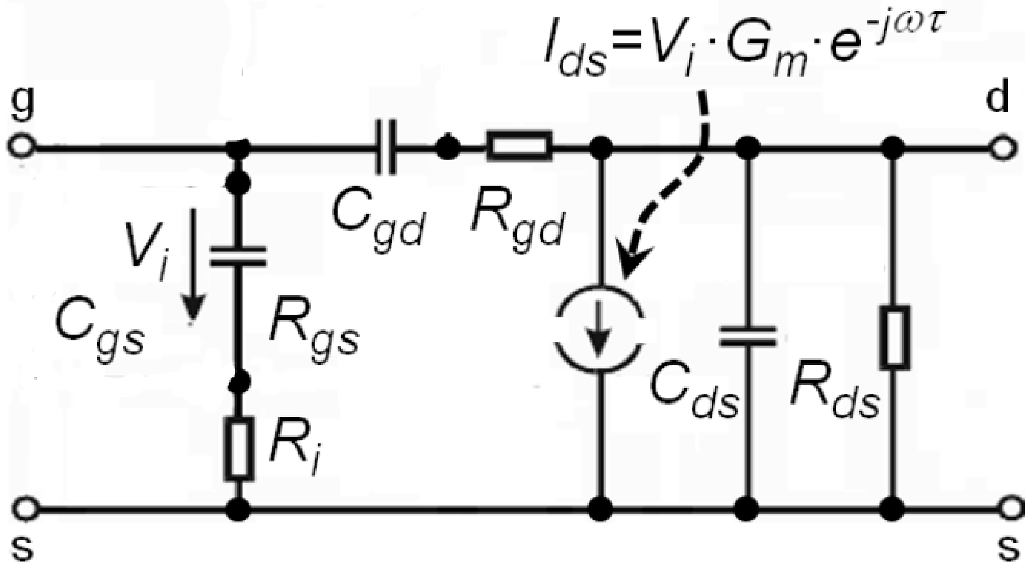
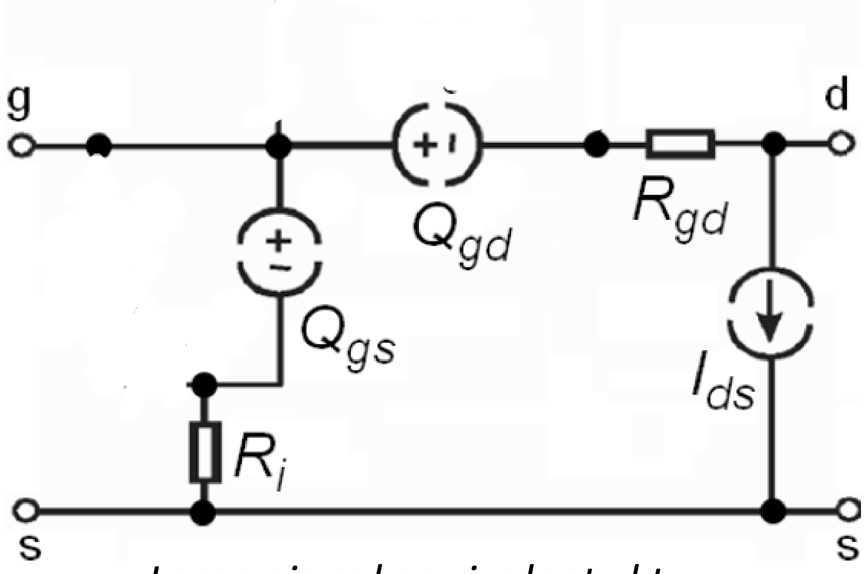
Table based intrinsic device modelling (division by charge)



Small signal equivalent ckt



Large signal equivalent ckt

- $\boldsymbol{I_{ds}}$, Q_{gs}, Q_{gd}, C_{gs}, C_{gd}, and C_{ds} are read directly from table

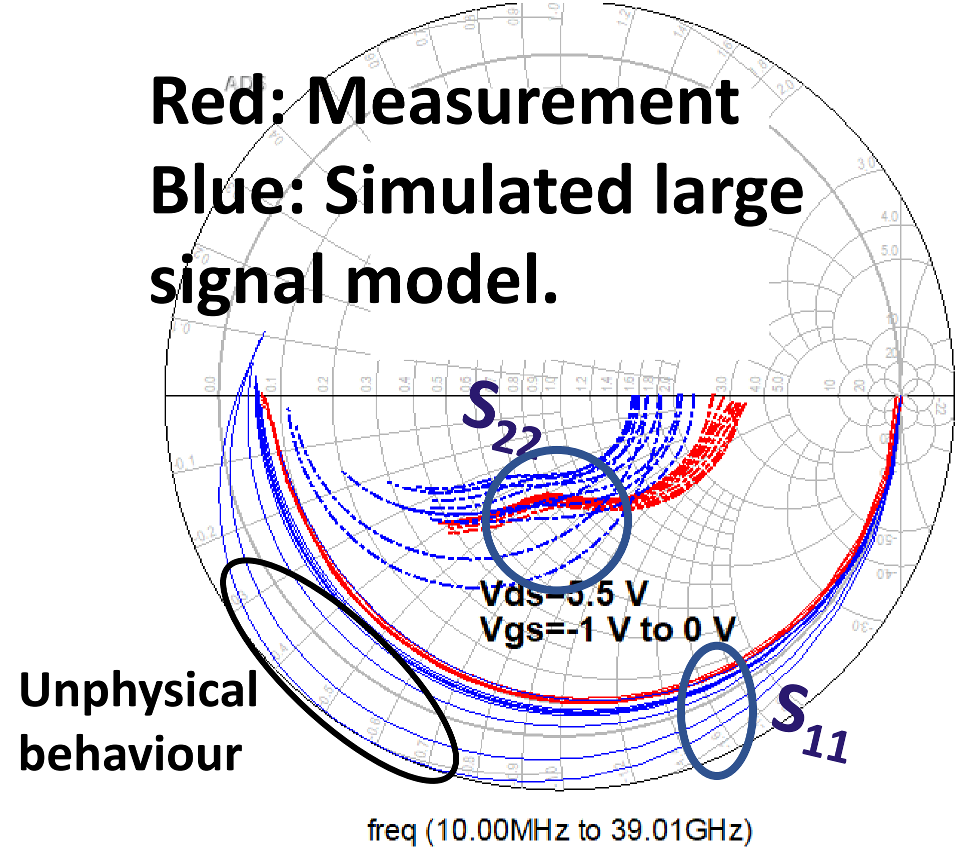
$$Q_{gs}(V_{gs},V_{ds}) = \int_{(V_{gs0},V_{ds0})}^{(V_{gs},V_{ds})} C_{gs} dV_{gs} + \int_{(V_{gs0},V_{ds0})}^{(V_{gs},V_{ds})} C_{ds} dV_{ds}$$

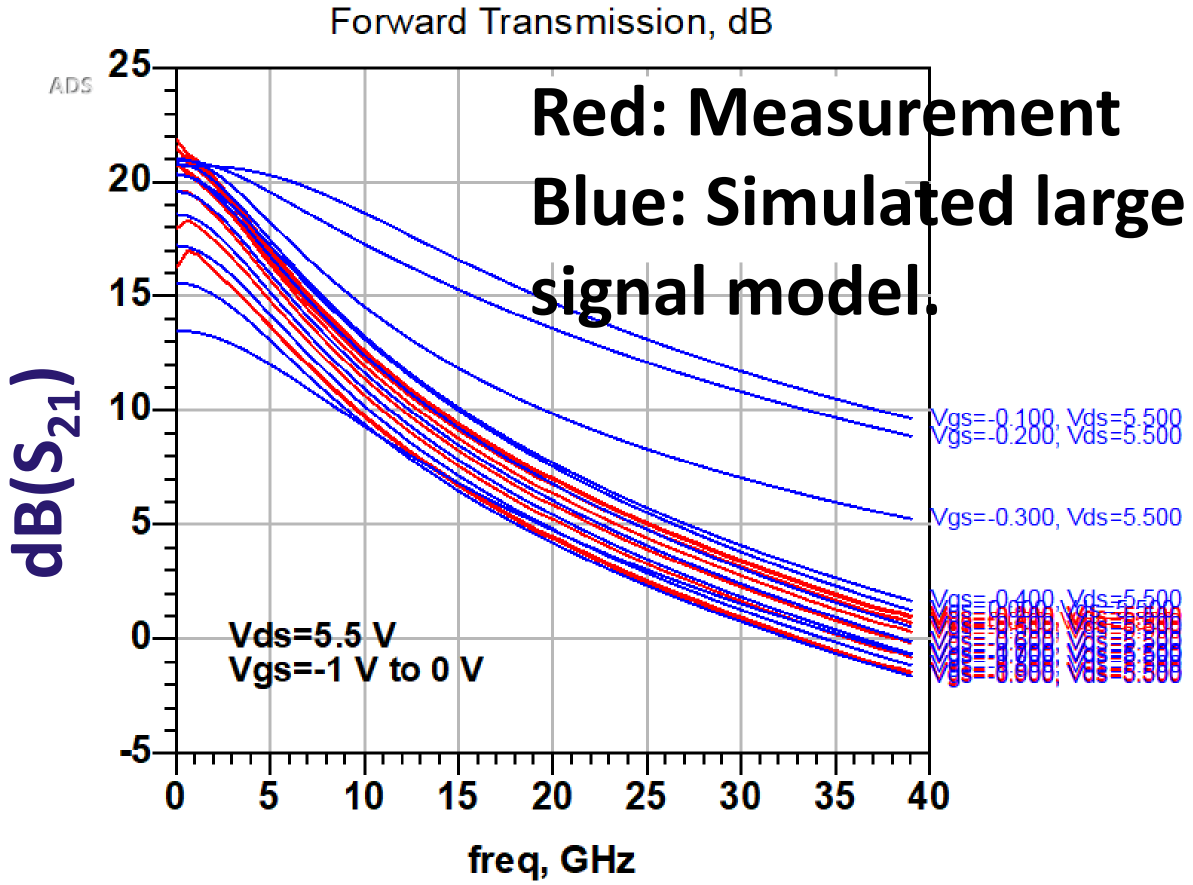
$$Q_{gd}(V_{gs},V_{ds}) = \int_{(V_{gs0},V_{ds0})}^{(V_{gs},V_{ds})} C_{gd} dV_{gs} + \int_{(V_{gs0},V_{ds0})}^{(V_{gs},V_{ds})} (-C_{gd} - C_{ds}) dV_{ds}$$

Approximately models the trans capacitance

Flores, PhD thesis,University of Kassel, Germany

Comparison of S-parameters with table based capacitor model

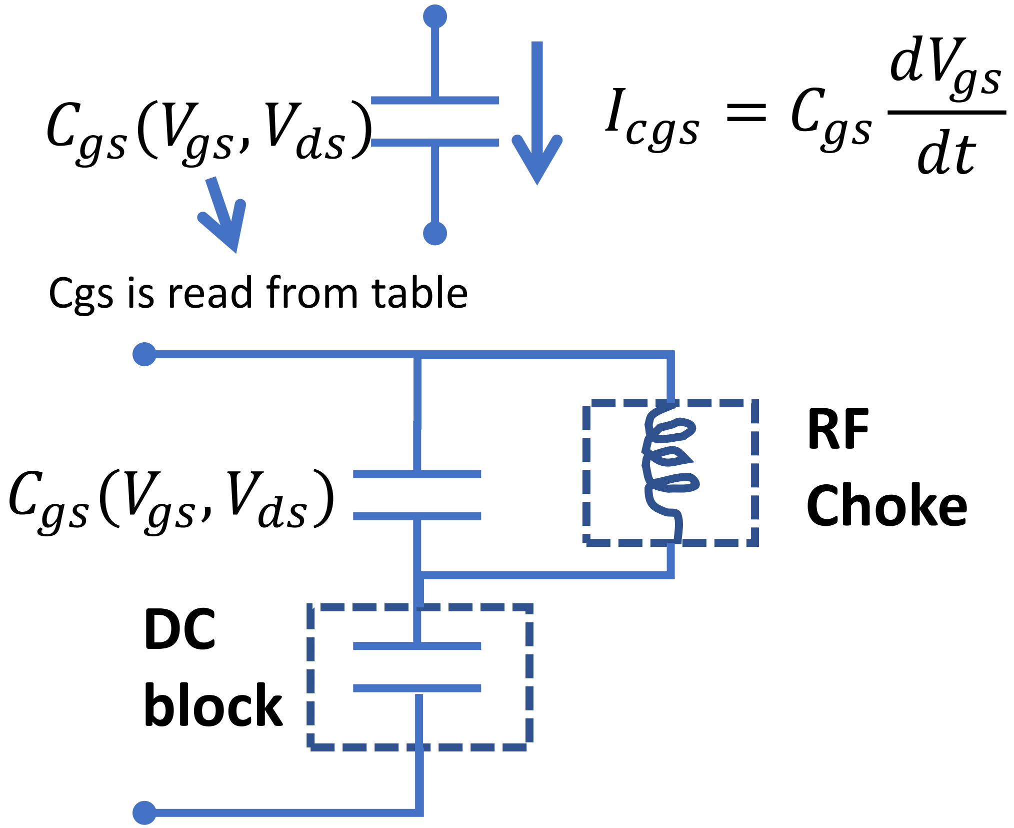


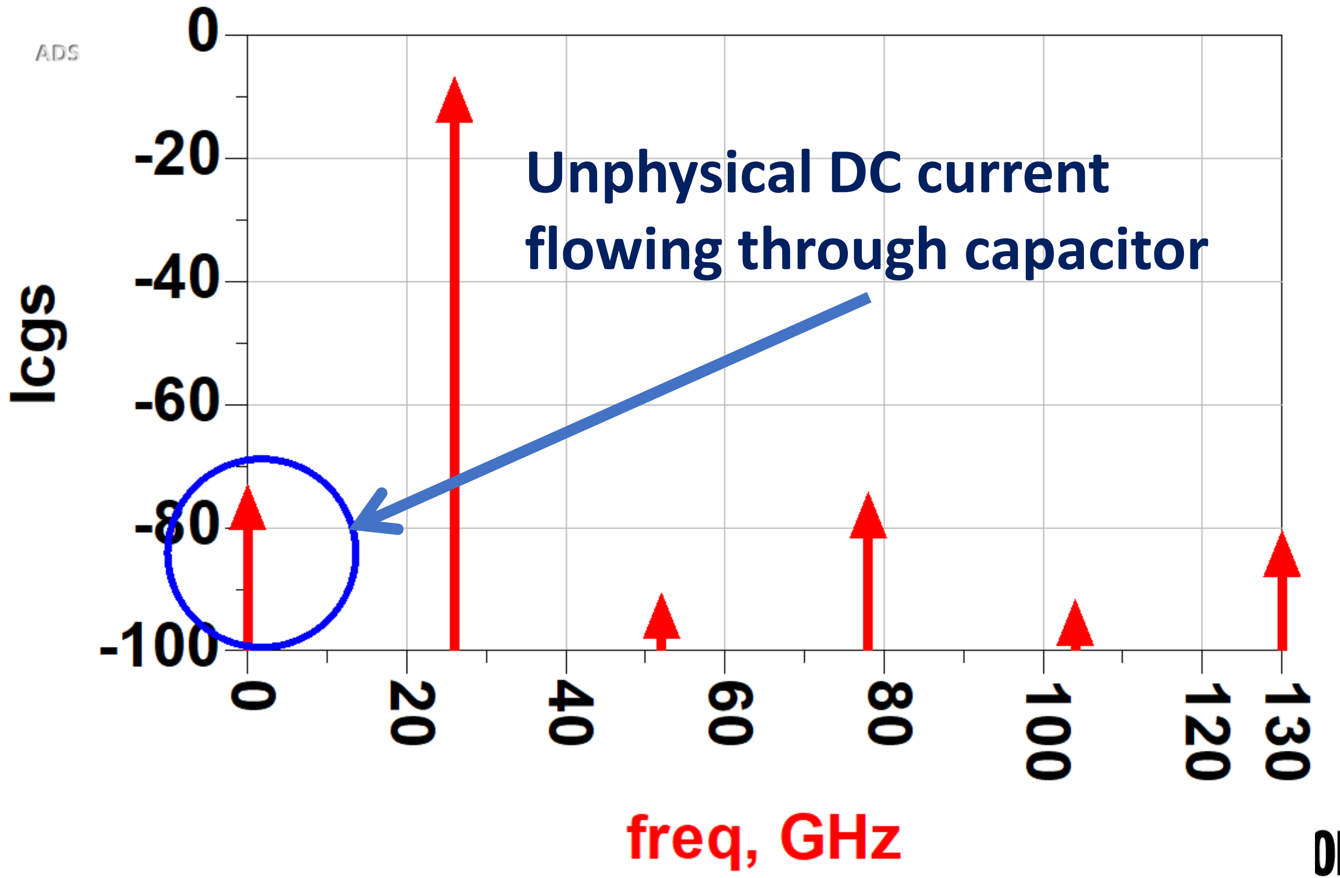


- Hard to debug as it is difficult to separate the impact of Qgs and Qgd
- We think the interpolating spline used to model the capacitor beyond its measured range causes oscillations between the data points, hence nonphysical fluctuations.

Division by capacitance (issue with Cdv/dt)

- Implementation of a capacitor as $C\left(\frac{dv}{dt}\right)$ results in unphysical DC current flowing through capacitor.
- A fix is to use a C block and RF choke to short the DC component→ results in inaccurate harmonic





Capacitance implementation in HB simulation

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- How to implement of the differential with one variable in HB simulation?

$$I_s = \frac{Q_{gs}(V_{gs} + dV_{gs}, V_{ds}) - Q_{gs}(V_{gs}, V_{ds})}{dt}$$

- Capacitor is modelled as a product of functions of gate and drain voltage

$$\mathrm{C_{gs}} \propto f(V_{gs})g(V_{ds})$$

- Charge is calculated by integrating with terminal voltage

$$Q_{gs} = g(V_{ds})\int f(V_{gs})dV_{gs} = g(V_{ds})Q_{pgs}(V_{gs})$$

- Capacitance is implemented as

$$I_s = g(V_{ds})\frac{dQ_{pgs}(V_{gs})}{\mathrm{dt}}$$

Multiply the dependence with remote voltage

Differentiate the terminal voltage dependence → simply multiply $Q_{pgs}(V_{gs})$ by j*2πf

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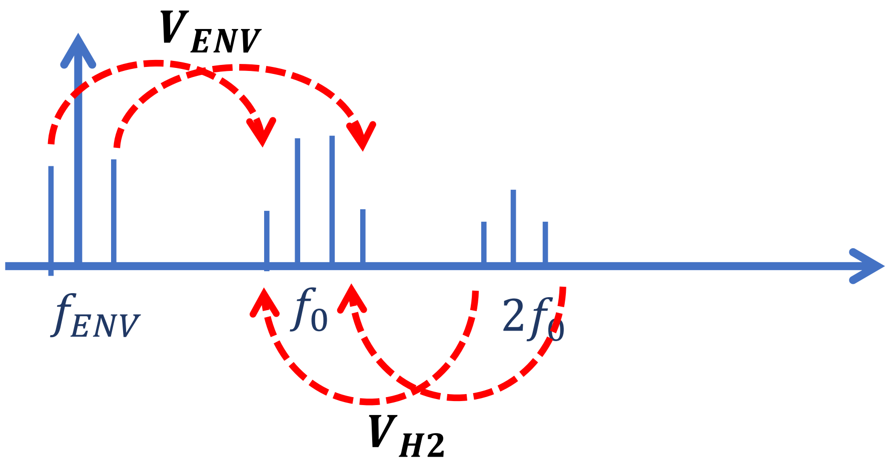
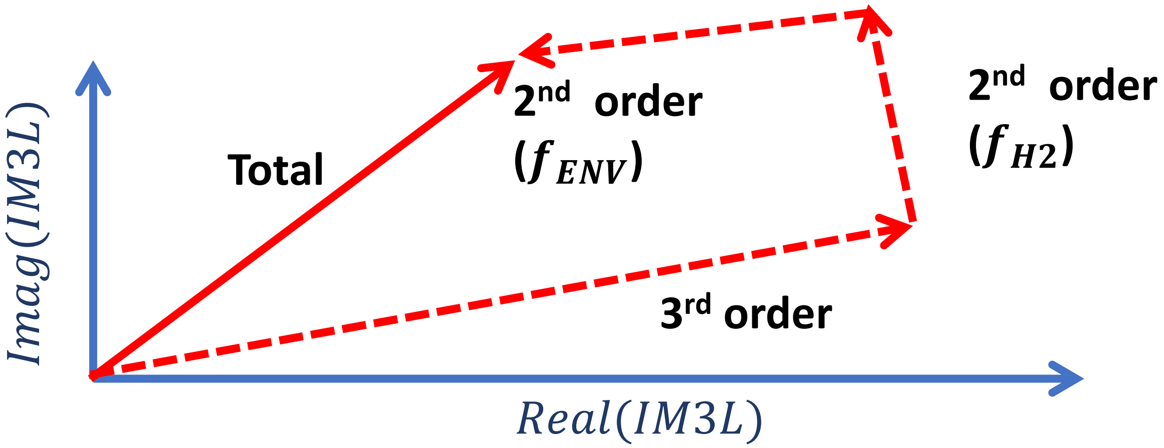
Conventional Polynomial model (division by Capacitance)

$$C_{gs} = C_{gs00} + C_{gs10}v_{gs} + C_{gs01}v_{ds} + C_{gs11}v_{gs}v_{ds} + \cdots$$
$$C_{gd} = C_{gd00} + C_{gd10}v_{gs} + C_{gd01}v_{ds} + C_{gd11}v_{gs}v_{ds} + \cdots$$

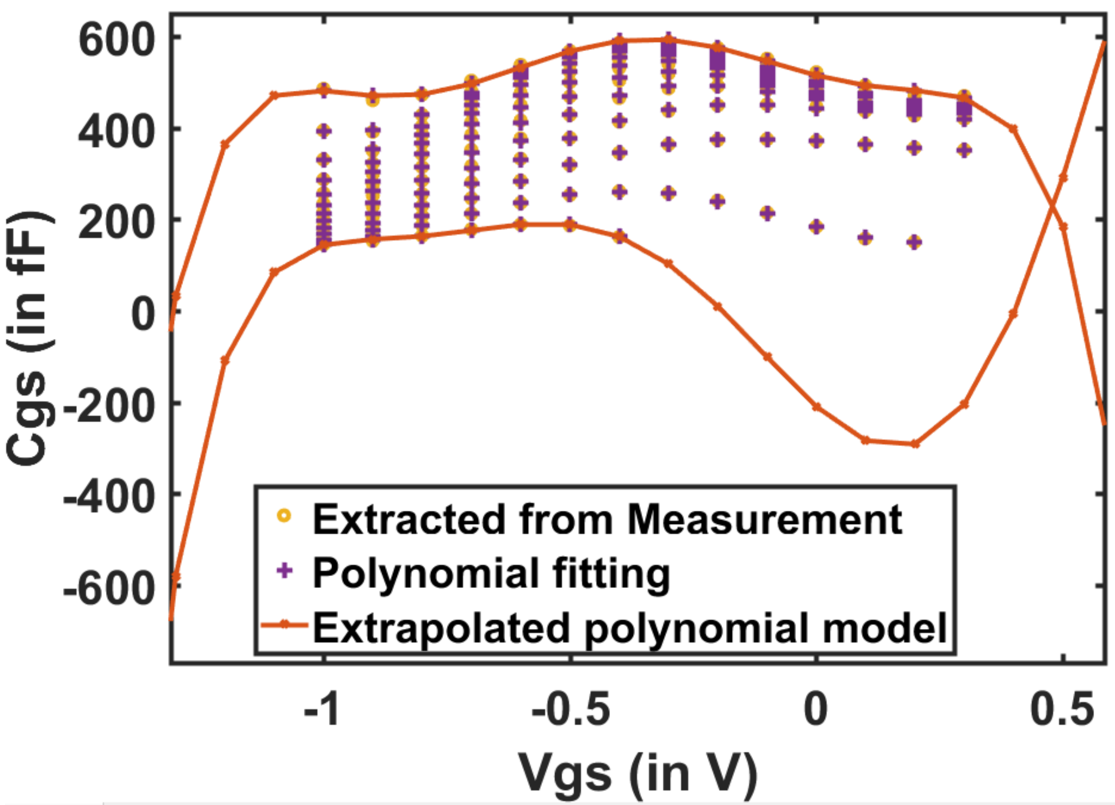
- Well-know numerical techniques are available and their derivatives are also devoid of discontinuities
- Suitable for Volterra analysis to understand multiple mixing mechanisms can also be recognized
  - which aids the design of harmonic terminal impedances.

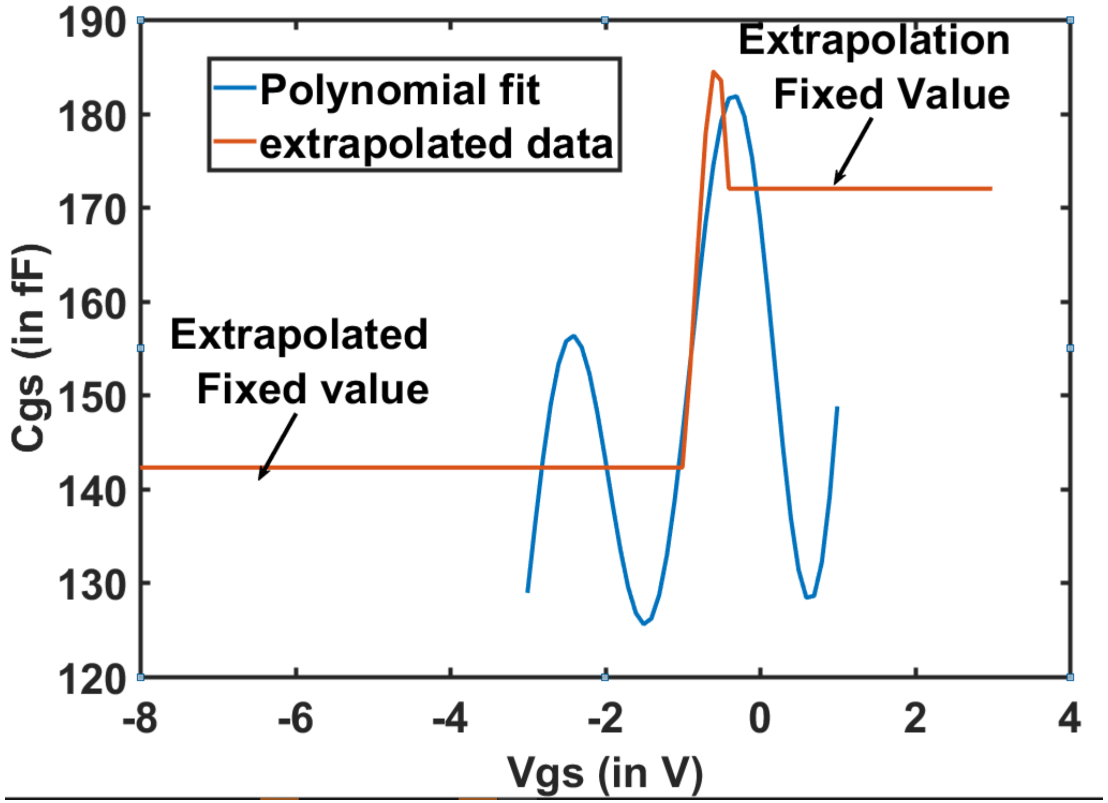




Conventional Polynomial model

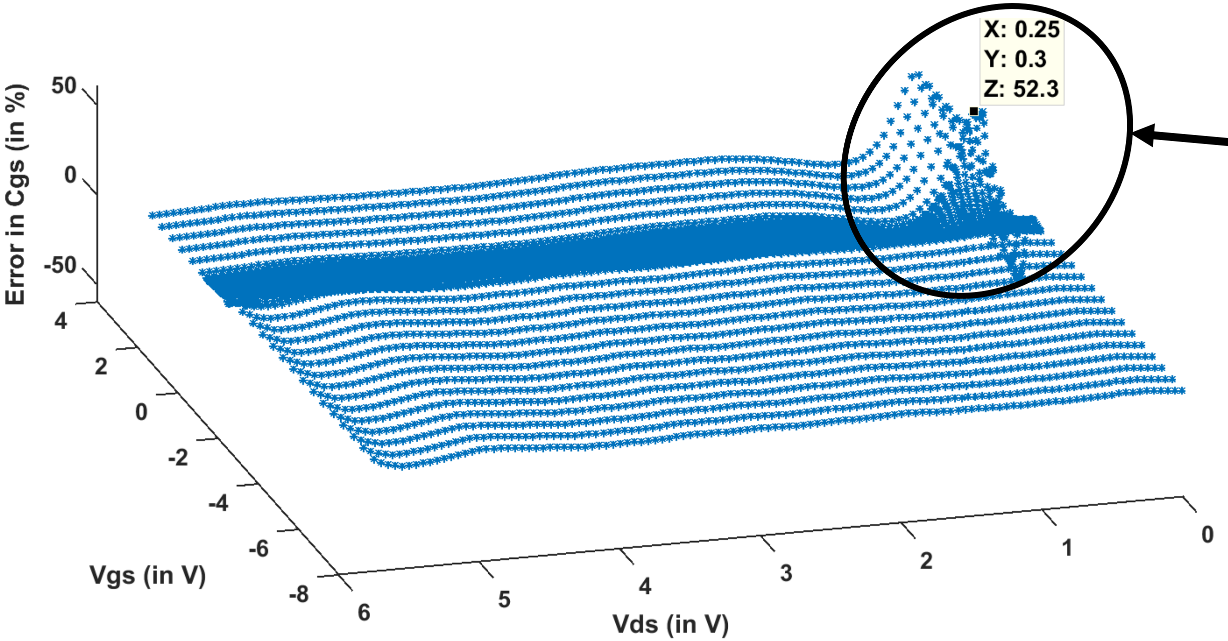
- Outside the range of data used to generate the polynomial can result in undesirable behaviour.
- Small variation in the measured data due to noise may result in large changes in the polynomial coefficients→ un-realisitic derivatives





UoS Capacitor Model (division by capacitance)

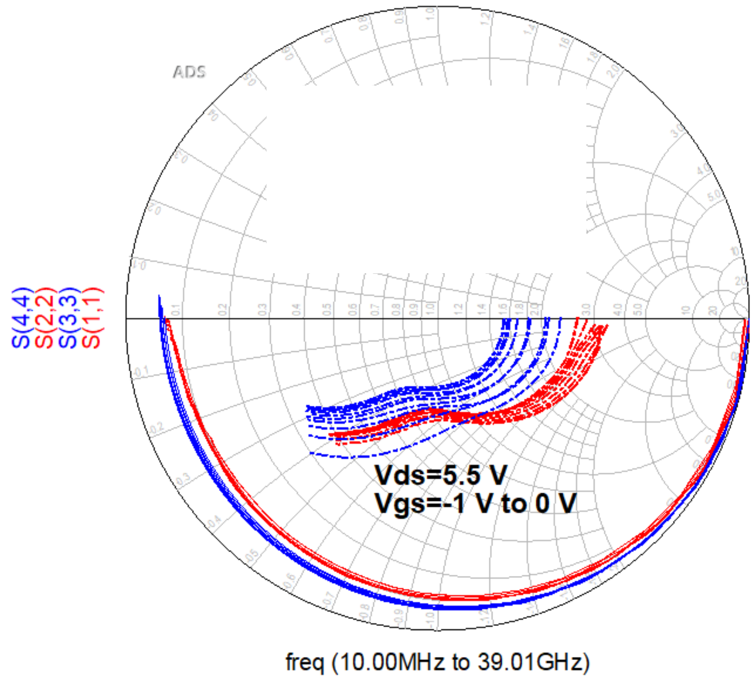
- Capacitances are expressed as $C_{gs}(V_{gs}, V_{ds}) = \sum_{n=0}^{N} f_{gs(n)}(V_{gs}) g_{(n)}(V_{ds})$ and $C_{gd}(V_{gs}, V_{gd}) = \sum_{\mathrm{n=0}}^{\mathrm{N}} -g_{\mathrm{gd(n)}}(\mathrm{V_{gs}})\, g_{(n)}(V_{gs} - V_{gd})$
  - In our implementation, $g_{(n)}(V_{ds}) = \begin{cases} (1 - V_{ds}/\mathrm{V_{dsq}})^{\mathrm{n}} & 0 < \mathrm{V_{ds}} < \mathrm{V_{dsq}} \\ 0 & \mathrm{V_{ds}} > \mathrm{V_{dsq}} \end{cases}$
  - $g_{(n)}(V_{ds})$ denoted the nth power of RF component of the V_{ds}.
- $f_{\mathrm{gs}(n)}(V_{gs})$ and $g_{\mathrm{gd(n)}}(\mathrm{V_{gs}})$ is obtained from the curve fitting tool in matlab and read from a table in ADS.

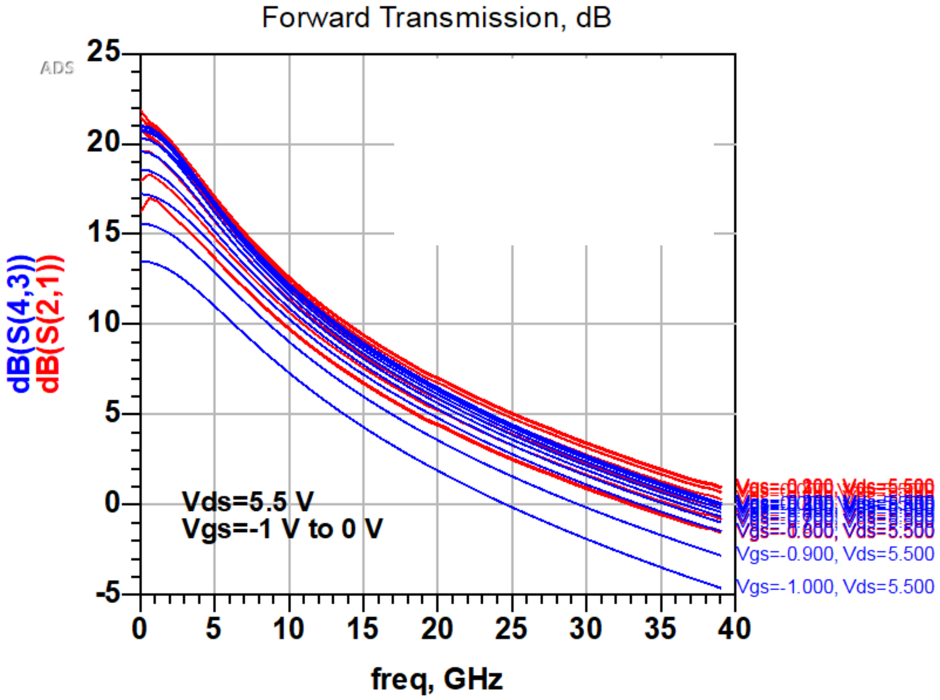


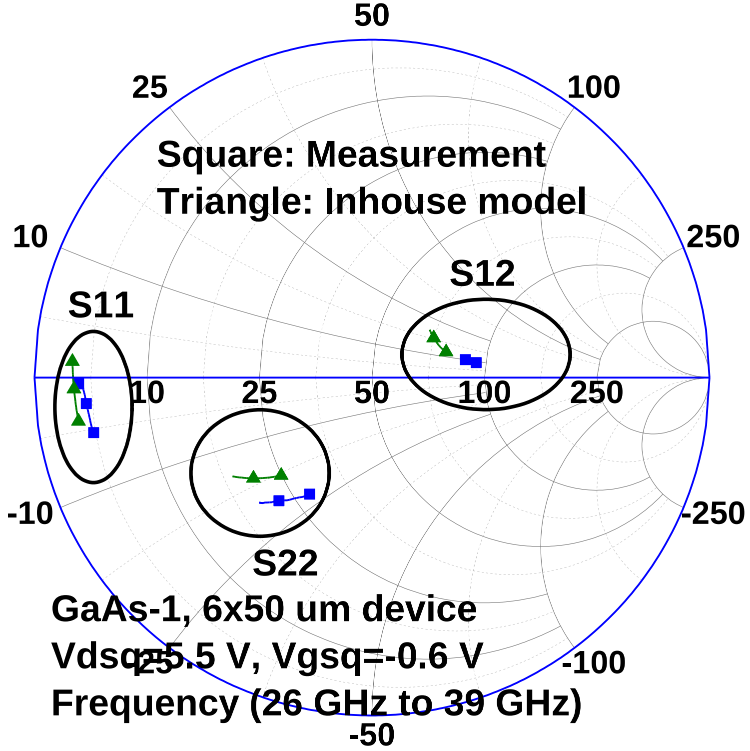
Except for these voltages, error is less than 2%

$f_{gs(n)}(V_{gs})$ is linearly extrapolated outside the measured data.

Accuracy of Large signal UoS Model

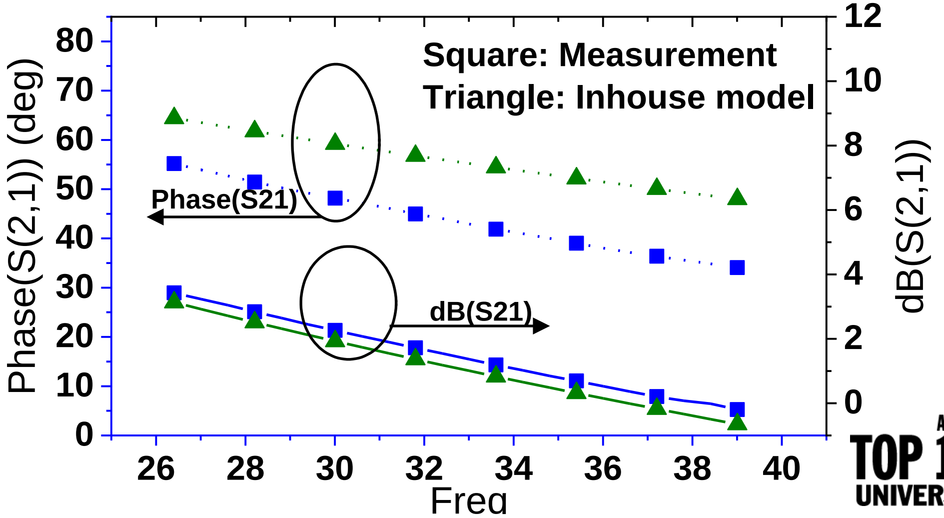






- Excellent match with S11 and S21 is obtained.

Vgsq=-0.6 V; Vdsq=6 V	Extracted model
$\Delta S_{11}(f_0)$	6.6 %
$\Delta S_{12}(f_0)$	2.2 %
$\Delta S_{21}(f_0)$	22.7 %
$\Delta S_{22}(f_0)$	15%



Summary

- Each of the modelling techniques have deficiencies:
  - **Table based Capacitor models**
    - **Easier to implement.**
    - **Accurately models within the measurement range.**
    - **However, interpolating spline can create oscillations between the data points and hence nonphysical fluctuation in the higher order derivatives.**
  - **Empirical model (The propose model)**
    - **Higher order derivatives are well defined.**
    - **Well defined beyond the measurement range.**
    - **Suitable for Volterra analysis.**
    - **less accurate than table based model.**

Thank you for your attention