RF Power Amplifier Design Considerations for Amateur Radio

CUARS
Clwb Radio Amatur Prifysgol Caerdydd
Cardiff University Amateur Radio Society

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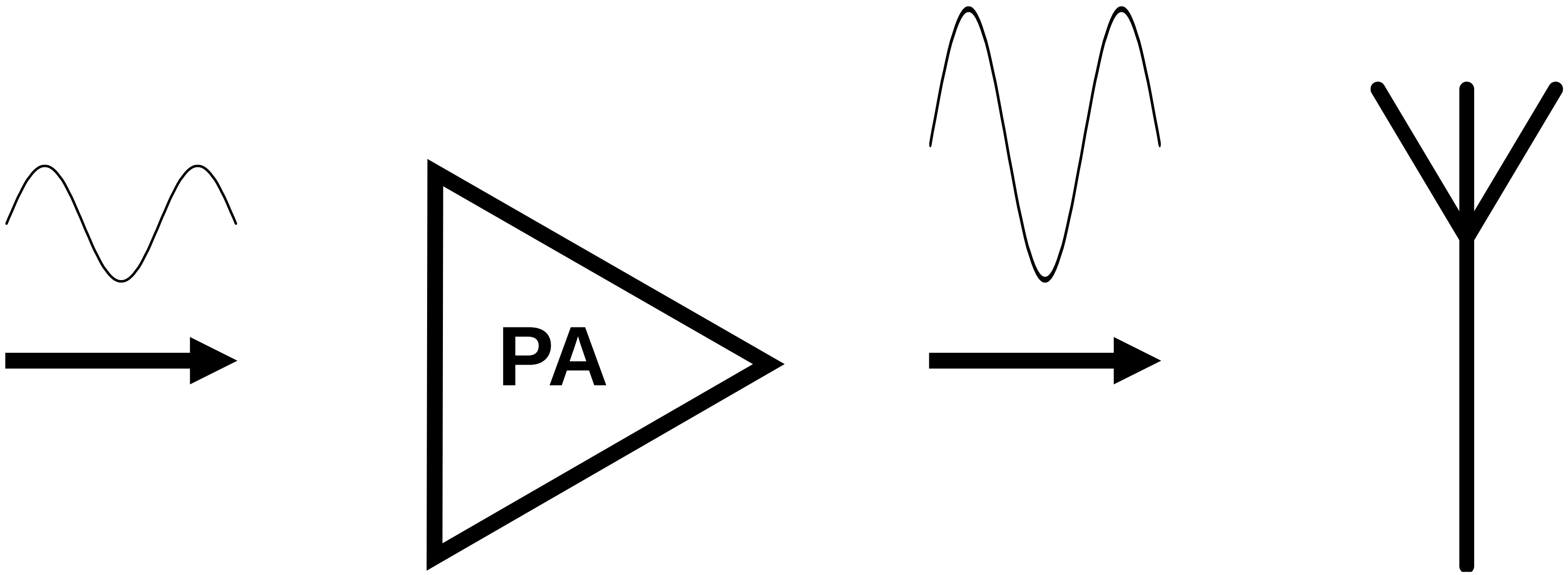
Introduction

Why are RF power amplifiers (PAs) important for amateur radio?



Generate the transmitted power used in transmission –

Cannot operate without them!

Commercial CAD Tools

Most popular industry electronic design automation (EDA) tools:

- Keysight Advanced Design System (ADS)
- AWR Microwave Office (MWO)

Very powerful tools BUT they are also very expensive, particularly for an individual user

Free CAD Tools

Looked for software that was free (and ideally open-source):

- What tools are needed for useful PA design software?
- What is currently available?
- What can they do?
- How does it compare against commercial software?

Talk Aim(s)

Demonstrate some PA design fundamentals using free CAD tools

Will upload files to Cardiff ARS website: *https://www.cardiffars.org.uk/*

Begin building a learning toolkit similar to those on industry CAD packages to gain greater understanding – But available to all!

Software Used

- *Quite Universal Circuit Simulator (Qucs)* – Circuit simulator
  Several forks…

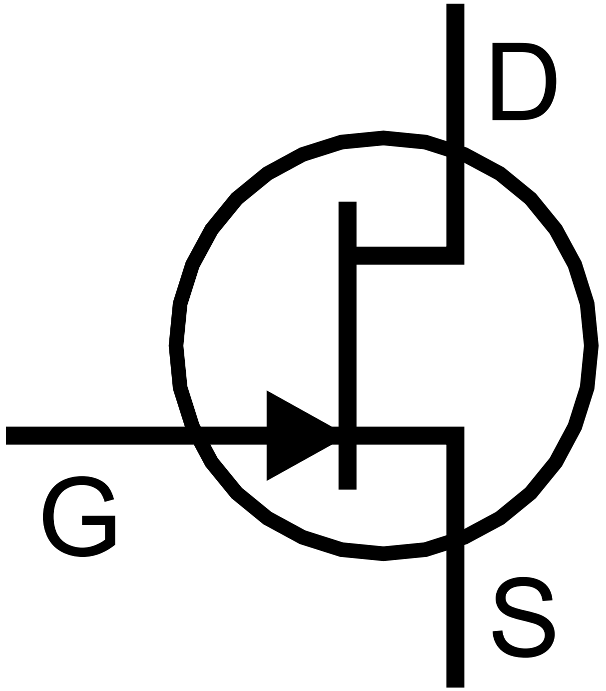
Qucs	Open Source	Linux, MacOS and Windows
Qucs-S	Open Source	Linux and Windows
QucsStudio	Closed Source 😬	Windows only 😬

  Can pick and choose tools from each fork

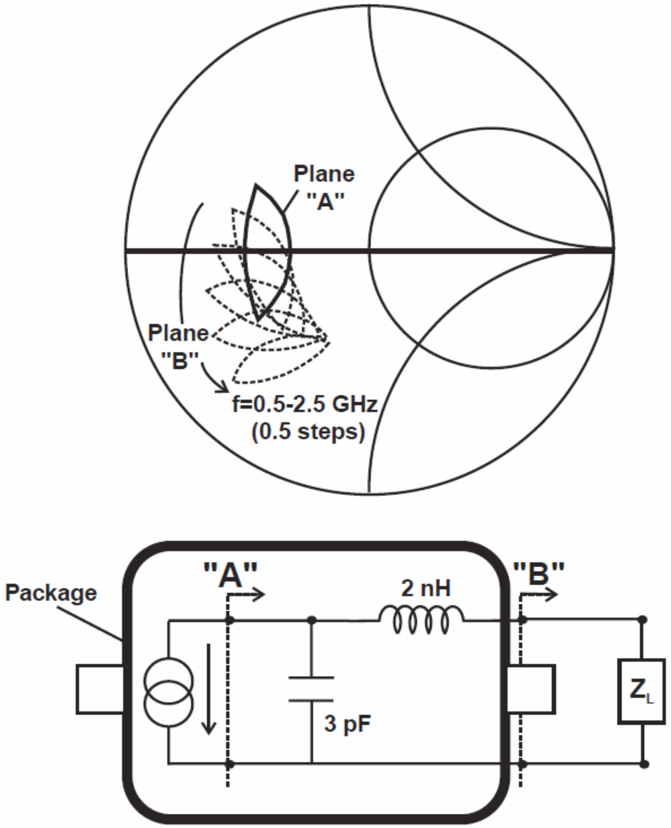
- *SimSmith* – Smith chart tool

- *GNU Octave* – Free alternative to MATLAB

FET Transistor

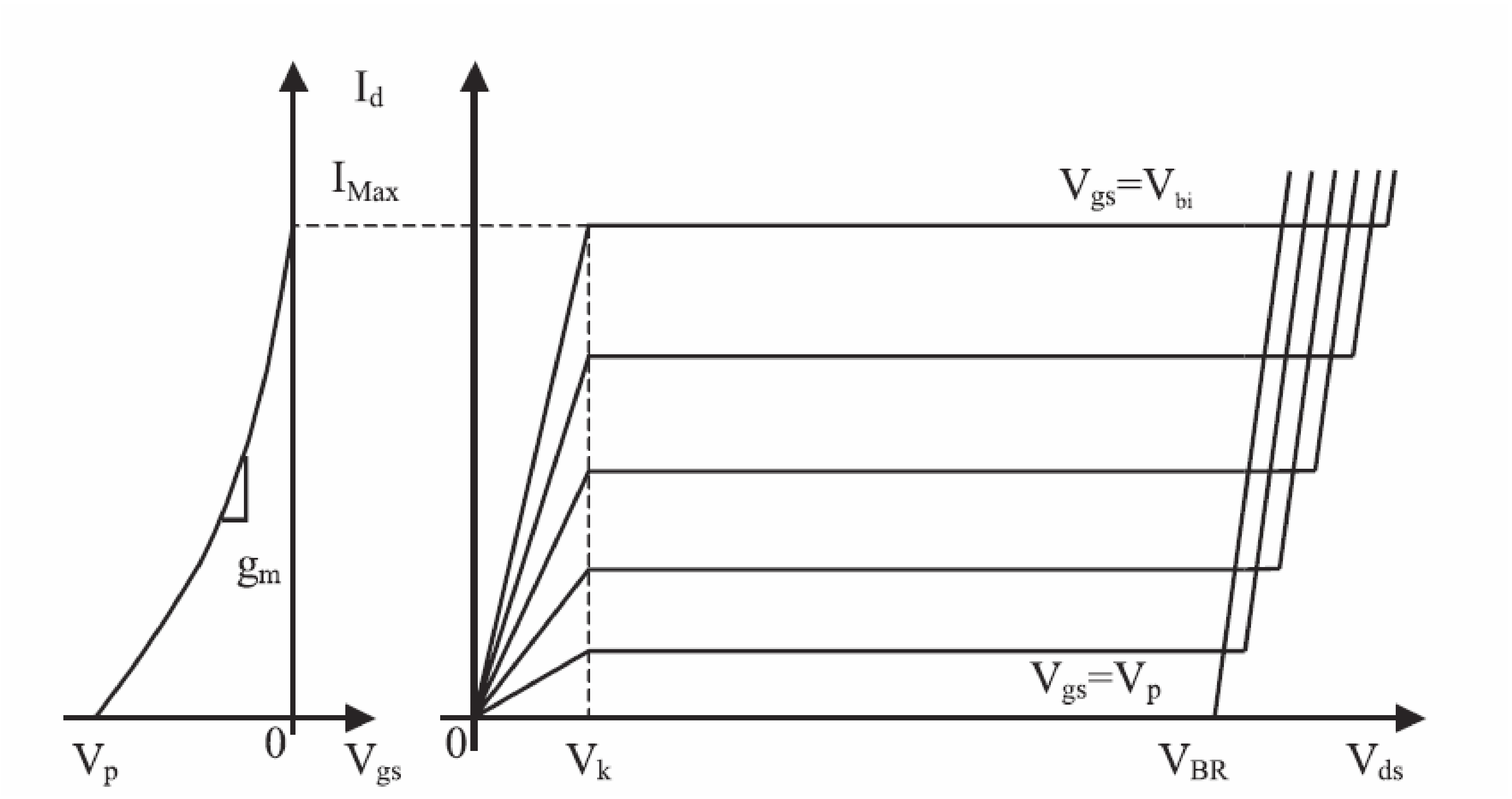


Current Generator Plane



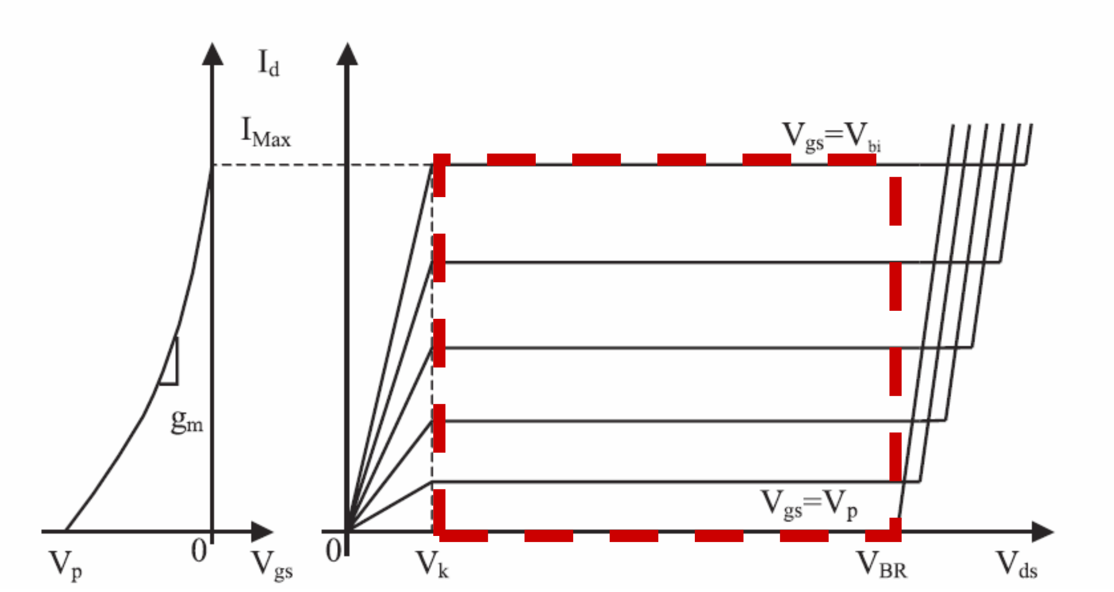
Cripps, S., 2006. *RF Power Amplifiers for Wireless Communications*. 2nd Ed. Artech House Inc., p. 30.

DC-IV Characteristic



Colantonio, P, Giannini, F. and Limiti, E., 2009. *High Efficiency RF and Microwave Solid State Power Amplifiers*. John Wiley & Sons Inc., p58.

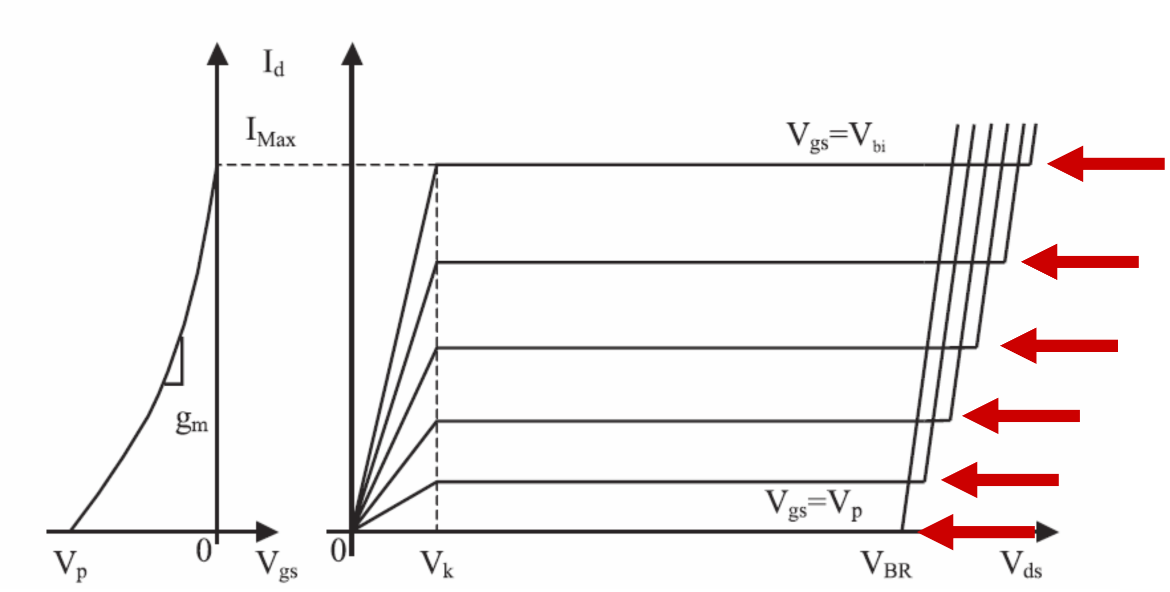
DC-IV Characteristic



Apply a DC voltage to the drain-source (V_{DS}): The current will rapidly rise to a value at which it will remain for any further increase in drain voltage – *The saturation region*

Colantonio, P, Giannini, F. and Limiti, E., 2009. *High Efficiency RF and Microwave Solid State Power Amplifiers*. John Wiley & Sons Inc., p58.

DC-IV Characteristic



That saturated value is controlled by the DC voltage applied to the gate (V_{GS})

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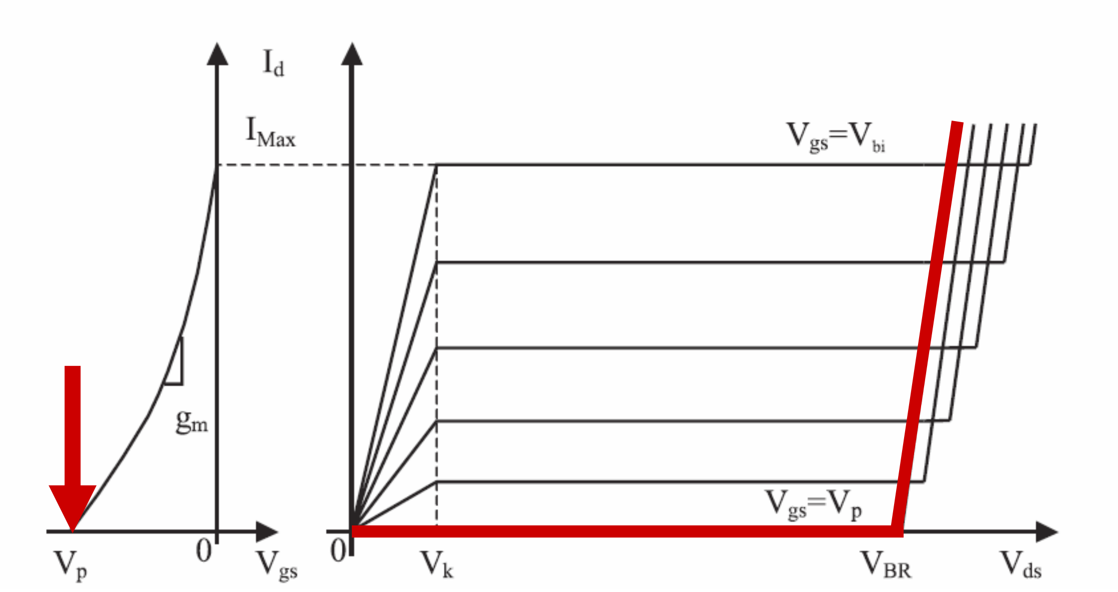
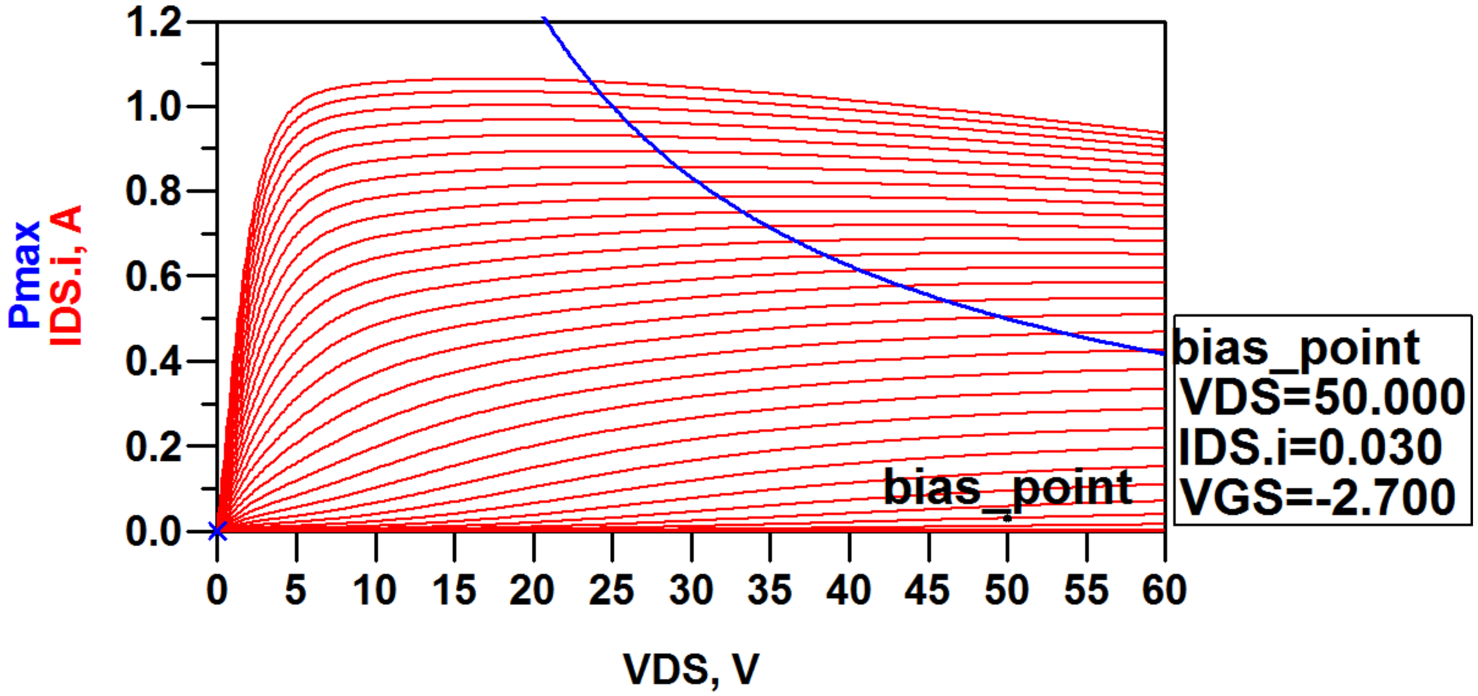
DC-IV Characteristic



As you reduce the voltage on the gate there will come a point where there is (simply) no more current being drawn – The 'pinch-off' (or cut-off) voltage, V_p

Colantonio, P, Giannini, F. and Limiti, E., 2009. *High Efficiency RF and Microwave Solid State Power Amplifiers*. John Wiley & Sons Inc., p58.

DC-IV Characteristic



DC-IV Characteristic for Qorvo QPD1010 10W GaN Device

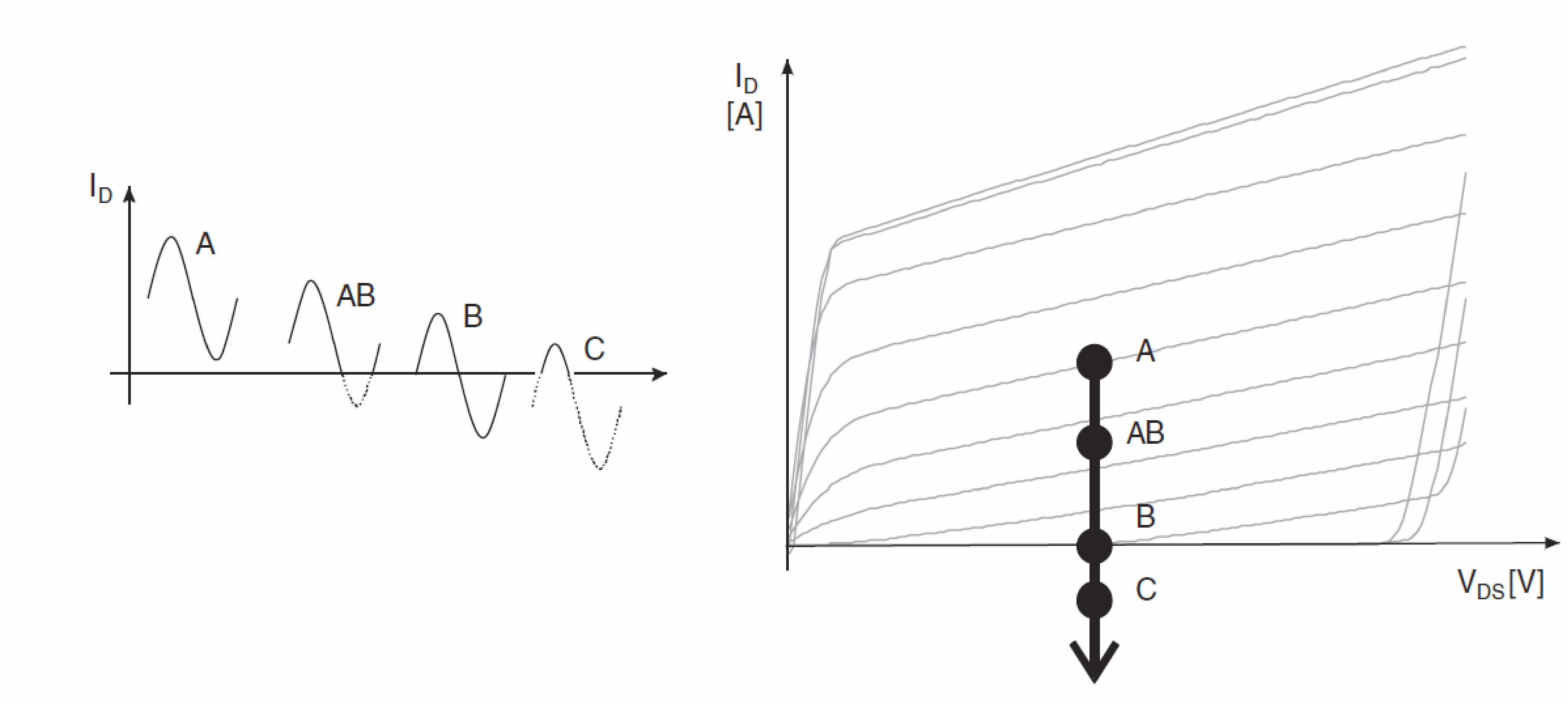
Load Line

- To create an output voltage a resistor is needed to complete the circuit: R_{opt} :

$$R_{OPT} = \frac{V_{RF}}{I_{RF}} = \frac{V_{DC}}{I_{MAX}/2}$$

- This will allow us to extract the maximum power from a given transistor

Biasing: ‘Classic’ Amplifier Classes



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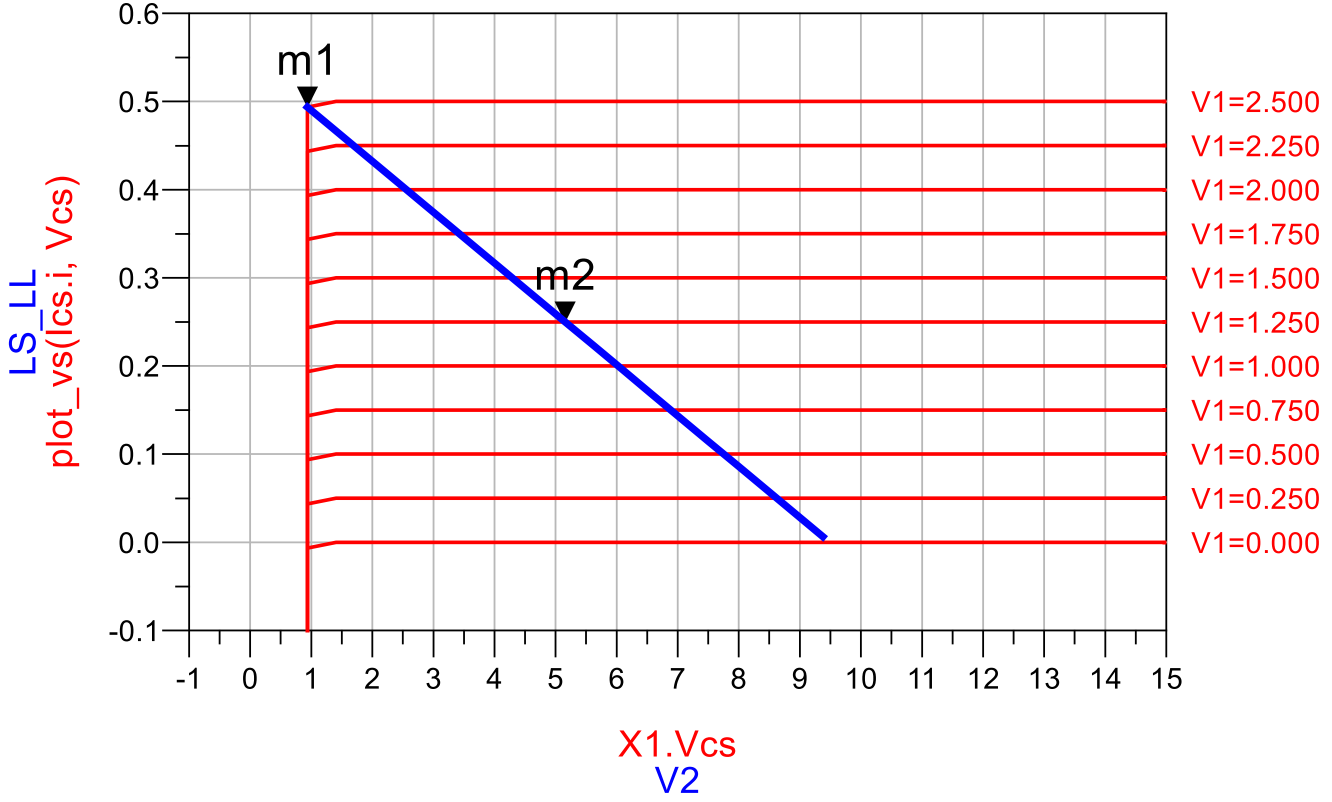
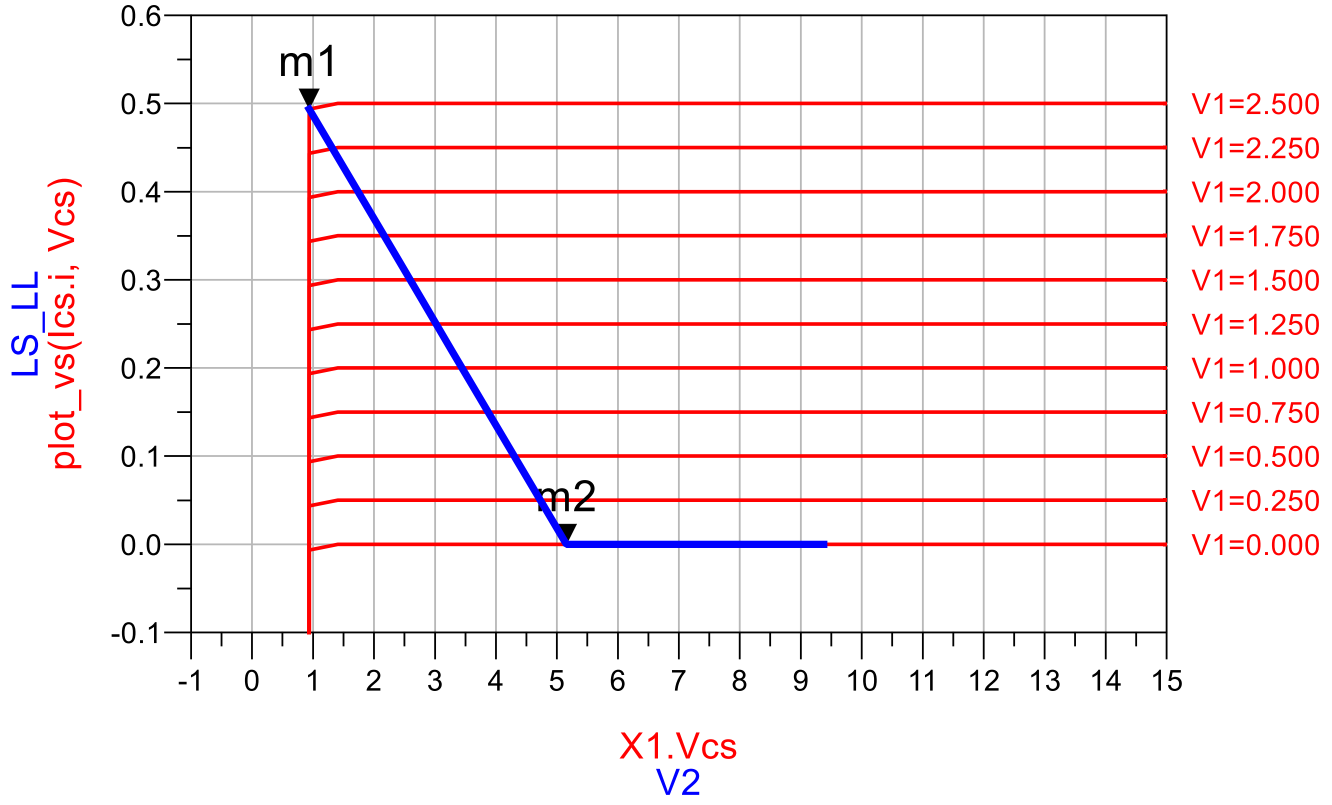
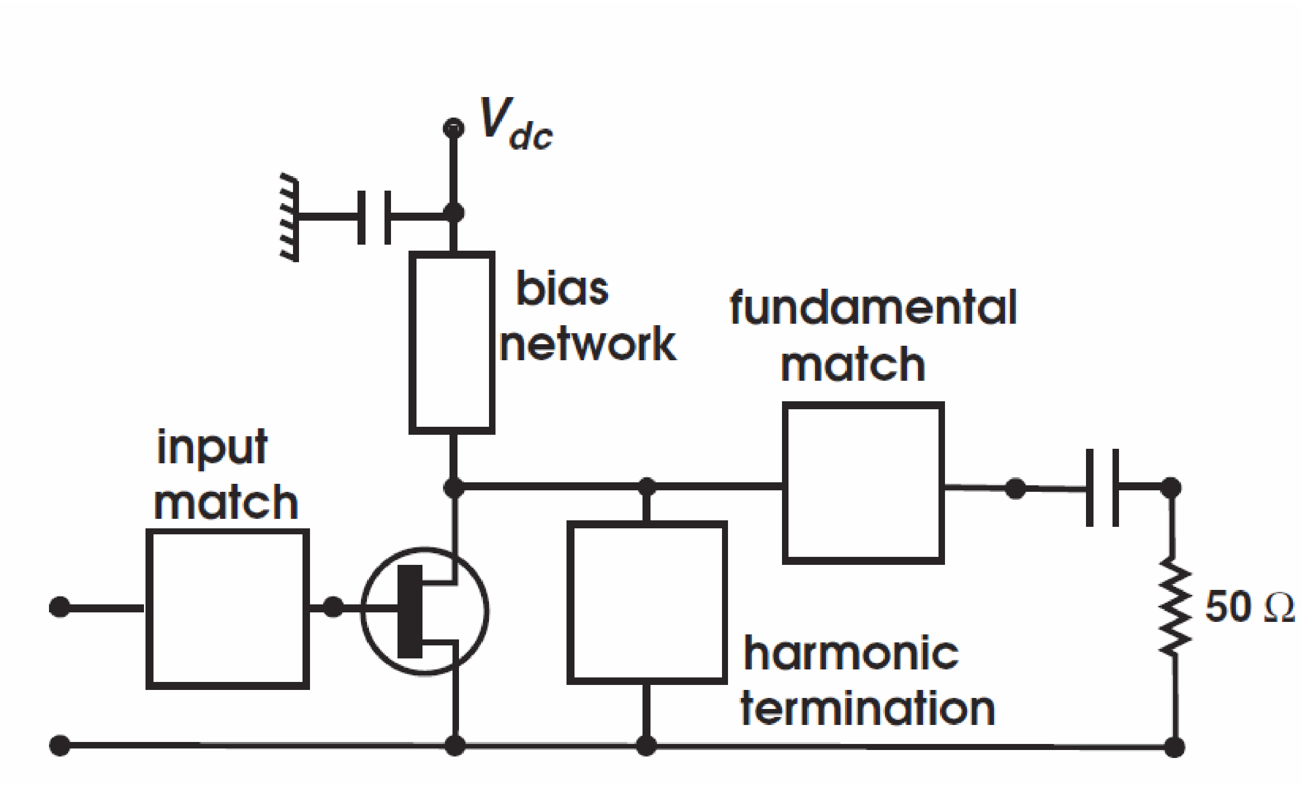


Biasing: 'Classic' Amplifier Classes



Generalised PA Architecture – Class AB



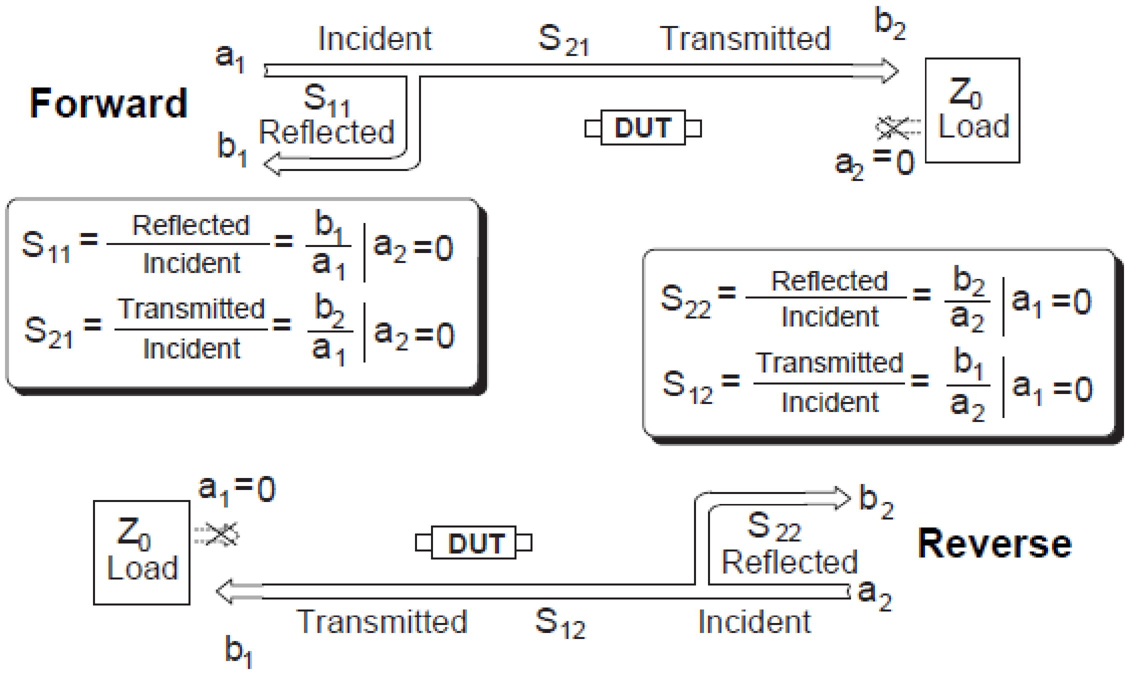
Cripps, S., 2012. Amplifier Classes, A to S. In: Walker, J. ed, 2012. *Handbook of RF and Microwave Power Amplifiers*. 1st ed. Cambridge: Cambridge University Press, Ch. 4, Fig. 4.9.

Simulation Controllers

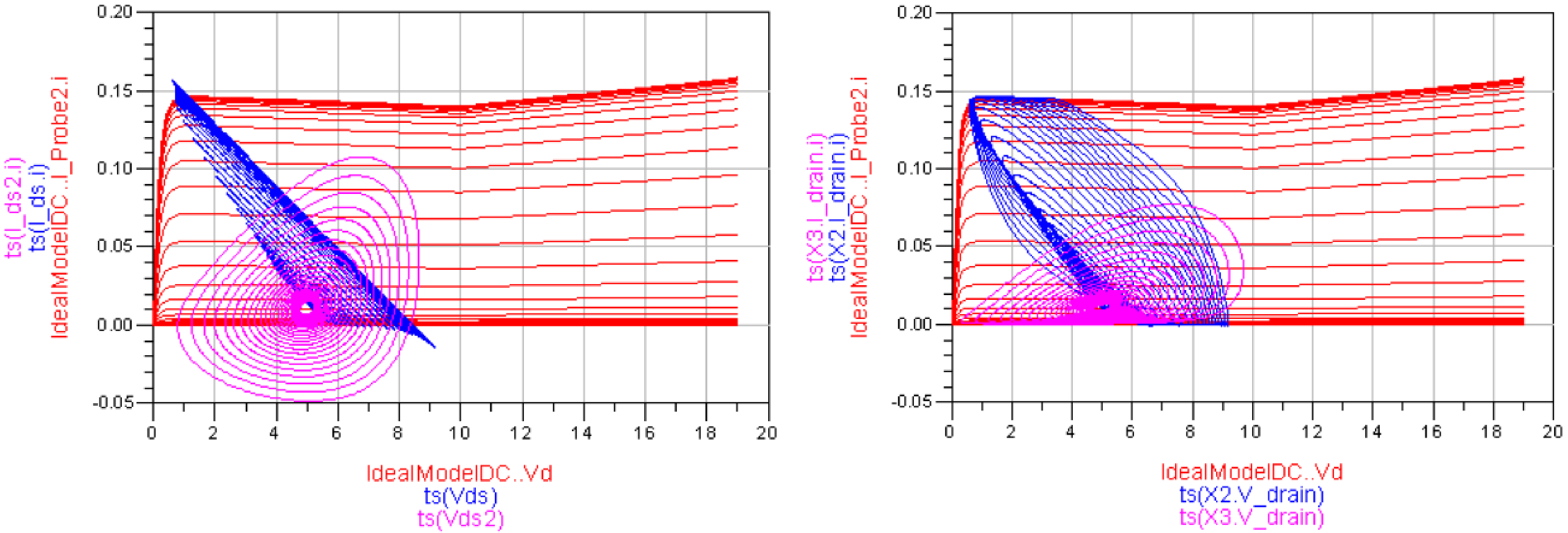
- The type of simulation controllers is important – They dictate what circuit analysis you can do
- For QucsStudio:
  - DC – Fundamental
  - AC – Linear (small-signal)
  - Transient – Solves a set of differential equations that express time dependence of I's and V's of circuit
  - **S-Parameter**
  - **Harmonic Balance**
  - Parameter Sweeps (used with other controllers)
  - *Missing Envelope Simulation - Fast and complete analysis of complex signals such as digitally modulated RF signals, has advantages for some applications*
- QucsStudio can only run one controller at a time

S-Parameters

- Widely used by industry and amateurs alike
- Ratio measurements, not absolute measurements
- LINEAR



S-Parameters



- (Pink) Reverse measurement, (Blue) Forward measurement
- (Left) Extrinsic, (Right) Intrinsic

S. Woodington, *Behavioural Model Analysis of Active Harmonic Load-Pull Measurements*, Doctoral thesis submitted to Cardiff University. 2012

Smith Chart Tool

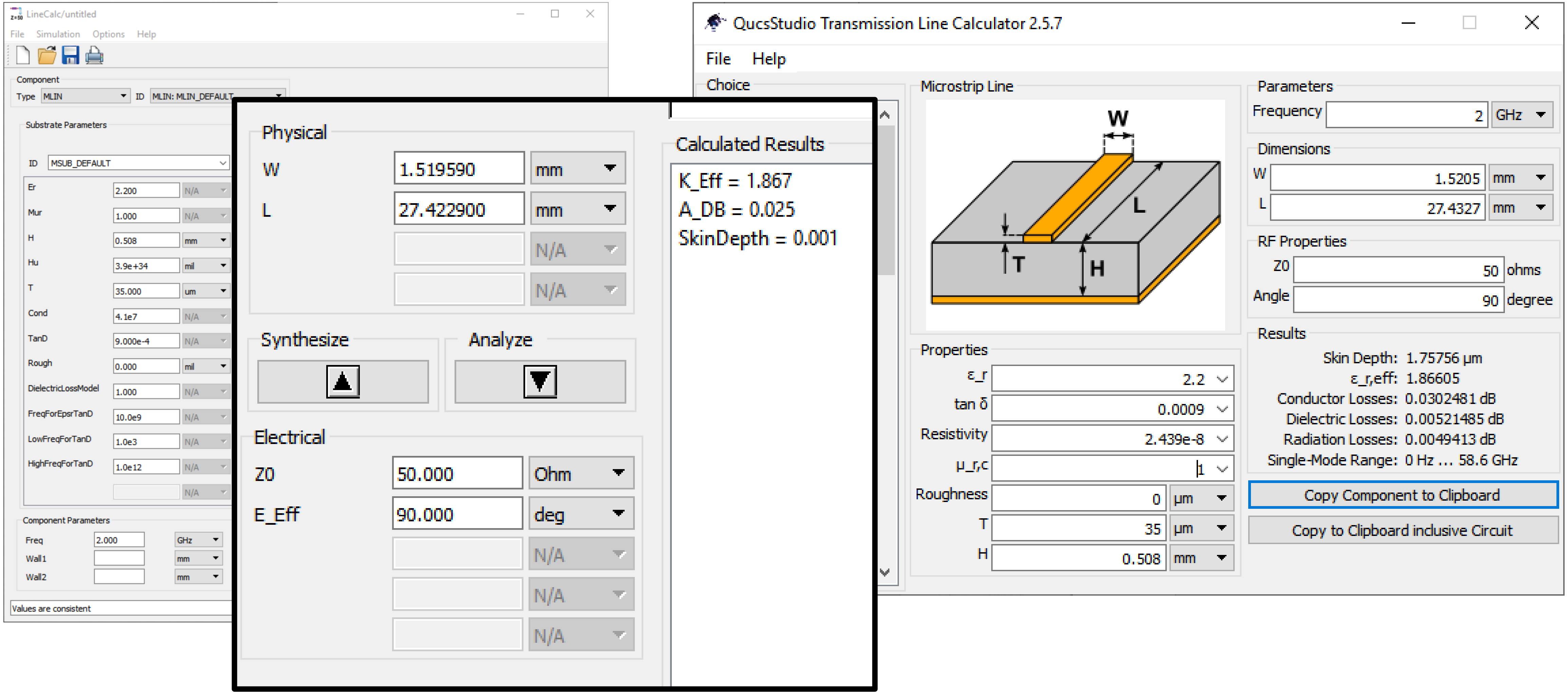
- Automated Smith chart tool greatly reduces speed of designing matching networks
- SimSmith is a free tool for this purpose
- Available at: http://www.w0qe.com/SimSmith.html

TLine Calculator Comparison

- Compared QucsStudios Transmission Line Calculator to ADS LineCalc
- Used a Rogers RT/Duroid 5880 to calculate a microstrip line:
  - 2GHz
  - Er = 2.20
  - TanD = 0.0009
  - Substrate Thickness = 0.508mm
  - Conductor Thickness = 35um

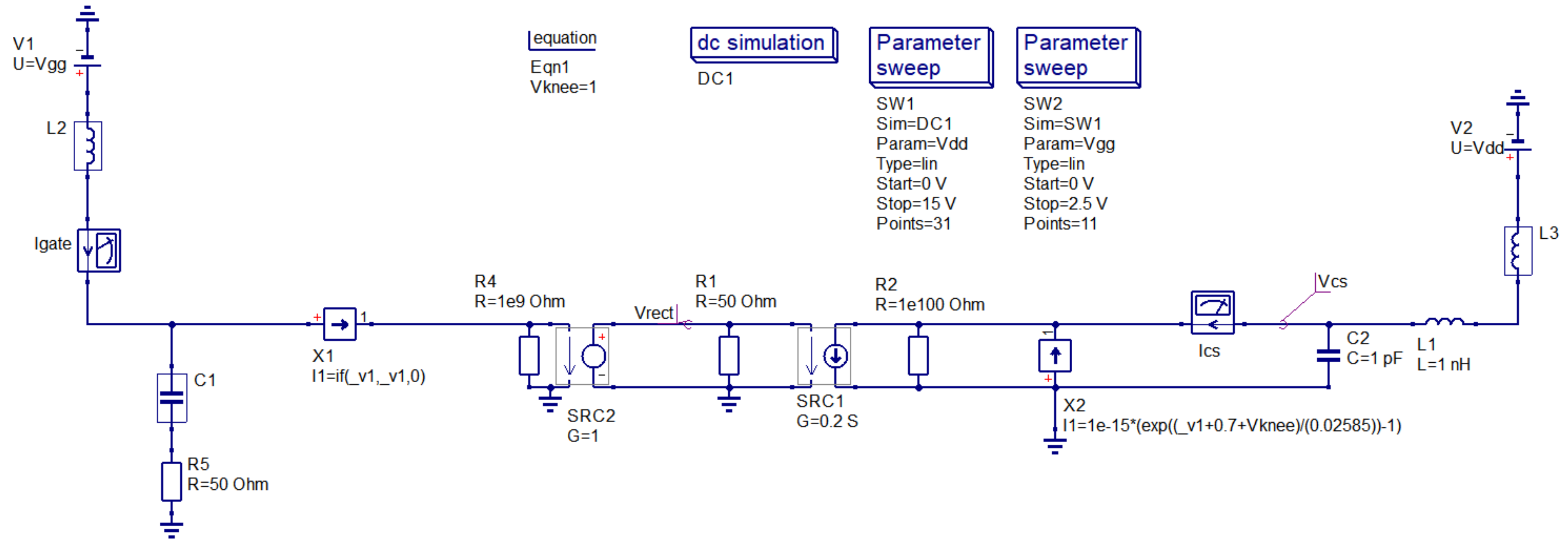
https://www.rogerscorp.com/documents/606/acs/RT-duroid-5870-5880-Data-Sheet.pdf

LineCalc Tool



QucsStudio – Ideal Transistor

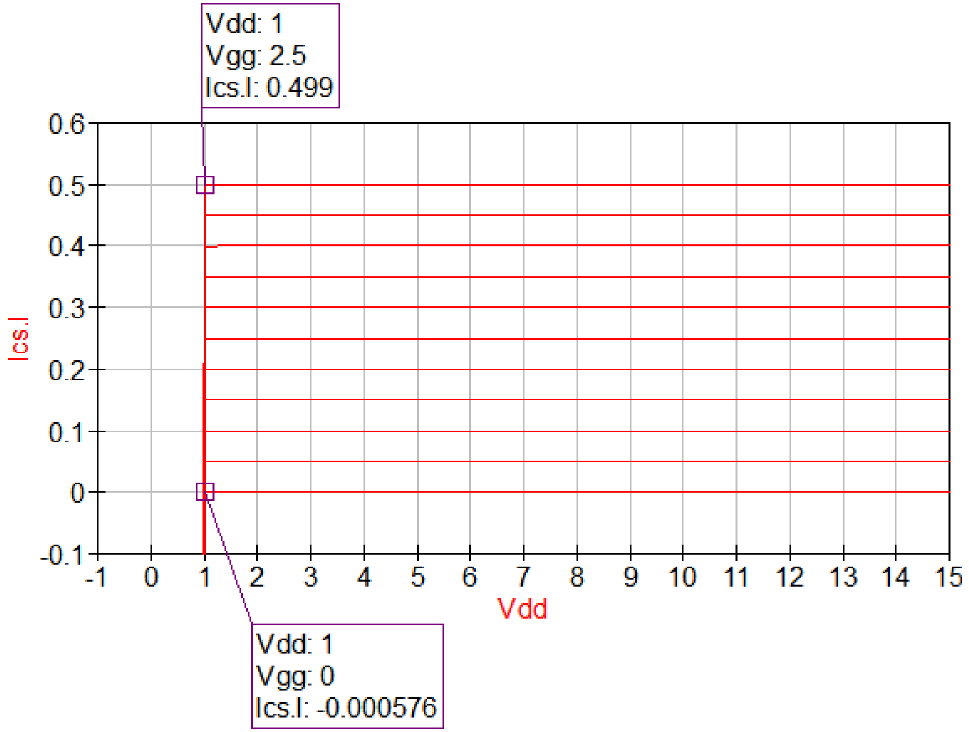
- DC-IV simulation of ideal transistor (can specify Vknee and gain)



Idea came from Keysight Technologies YouTube video 'How to Design an RF Power Amplifier: Class A, AB and B' (https://www.youtube.com/watch?v=GhPqPVlDRPY) – Worth watching!

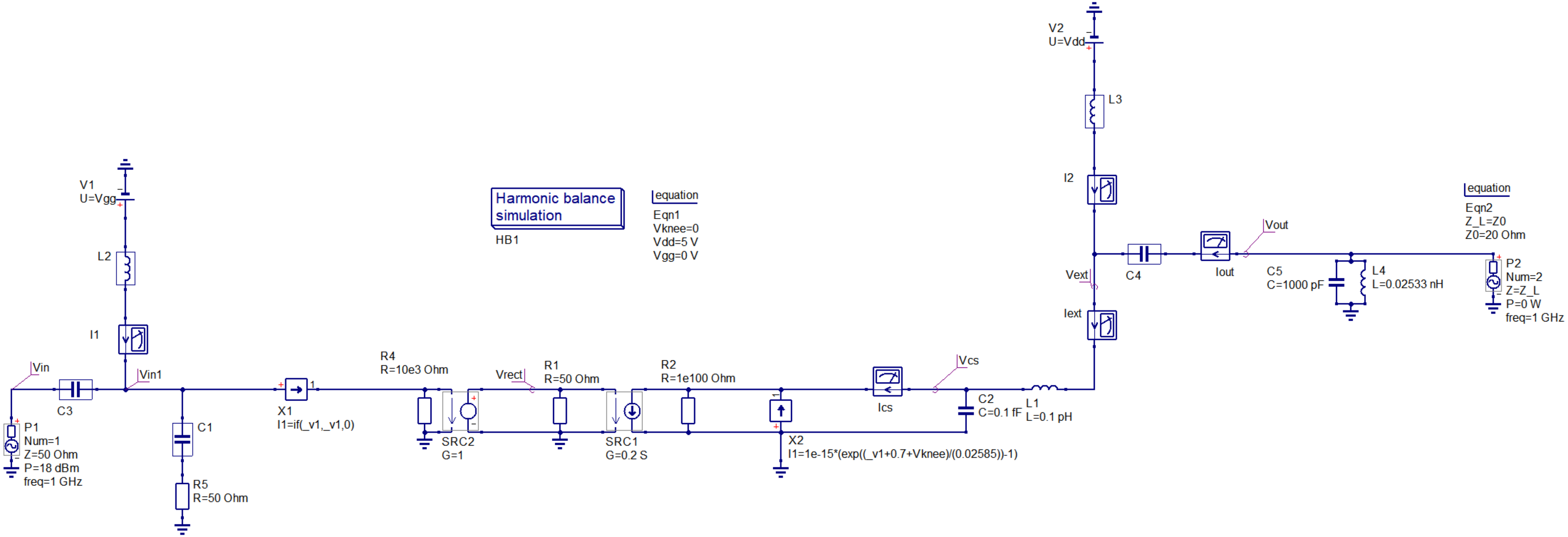
QucsStudio – DC-IV Plot

- Vknee = 1V and Imax = 0.5A
- Plotted using QucsStudio's inbuilt data display tool



QucsStudio – Class B Amplifier

- Ideal 'Class B' waveforms produced by biasing the transistor appropriately (specify Vgg as shown)



QucsStudio – Octave Script

- Harmonic Balance simulation performed for ideal Class B amplifier shown in previous slide
- Problem: Frequency-domain data produced, want to plot the ideal waveforms (convert results to time-domain)
- One solution: Octave scripts can be integrated into QucsStudio (and other Qucs branches)! Write script to perform Inverse-Fast Fourier Transforms (IFFTs) on I and V data and plot it
- **Octave integration gives complete control over data manipulation and display**

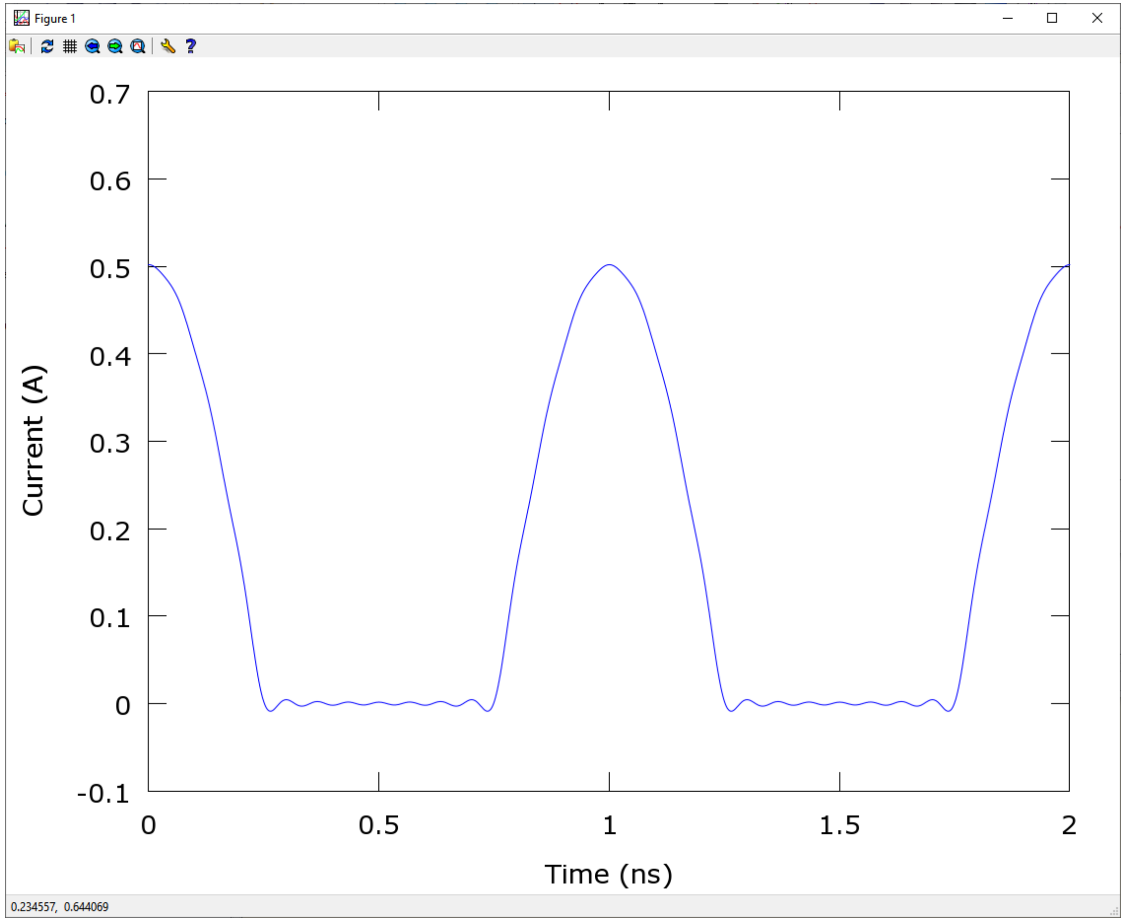
QucsStudio – Octave Script

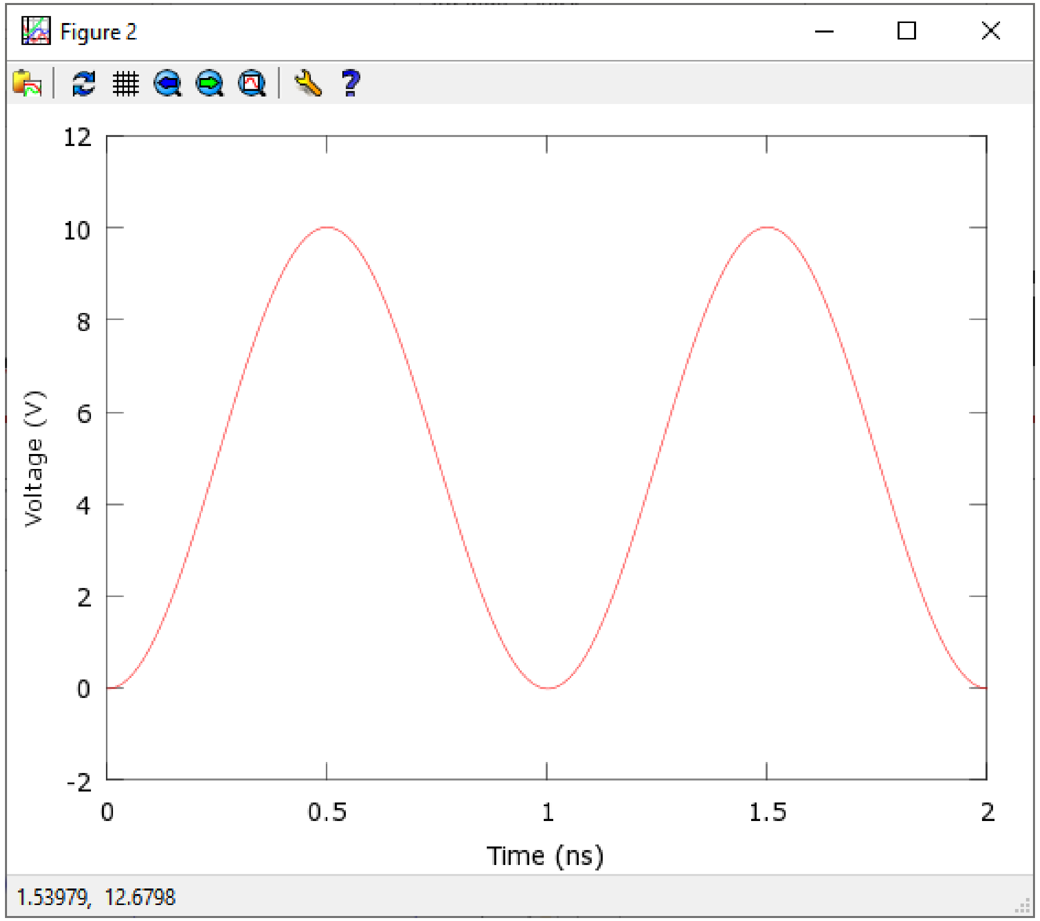
- Write script in Octave then set data display in QucsStudio to use the resulting .m file

CUARS_Talk_3.m

```
# Post-processing script for circuit simulation file "CUARS_Talk_3.sch"
# Plots the current and voltage waveforms at the current generator plane

freq = loadQucsVariable("CUARS_talk_3.dat", "hbfrequency");
Ics = loadQucsVariable("CUARS_talk_3.dat", "Ics.Ib");
Vcs = loadQucsVariable("CUARS_talk_3.dat", "Vcs.Vb");

padding_size = 2^10;

time = 1/freq(2);
time = time * (1e9); # Convert to ns

# ---- Calculate and plot Ics waveform ----
# FFT coefficients w/o zero padding, with negative freq values
wave_Ics_fl = [Ics(1) rot90(Ics((2:end))/2) rot90(conj(Ics((end:-1:2)))/2)];
wave_Ics_fl = [Ics(1) rot90(Ics((2:end))/2) zeros(1,(padding_size - length(wave_Ics_fl))) rot90(conj(Ics((end:-1:2)))/2)];

# FFT coefficients, w/ zero-centered zero padding, with negative freq values
# # of zeros is calculated to produce a power-of-two # of total values
# by subtracting the original length of testwave_v2_fl
wave_Ics_tl = ifft(wave_Ics_fl);
# Calculate and apply scaling to zero-padded iffts w/ respect to original ifft
wave_Ics_tl = padding_size * wave_Ics_tl;
# Double waveform (for clarity when plotting), comment out and change t to be linspace between 0 and 1 to have just one cycle
wave_Ics_tl = [wave_Ics_tl wave_Ics_tl];

# Plot waveform
t = linspace(0,2*time,length(wave_Ics_tl));
figure(1);
plot(t,wave_Ics_tl,'b');
xlabel('Time (ns)');
ylabel('Current (A)');

# ---- Calculate and plot Vcs waveform ----
# FFT coefficients w/o zero padding, with negative freq values
wave_Vcs_fl = [Vcs(1) rot90(Vcs((2:end))/2) rot90(conj(Vcs((end:-1:2)))/2)];
wave_Vcs_fl = [Vcs(1) rot90(Vcs((2:end))/2) zeros(1,(padding_size - length(wave_Vcs_fl))) rot90(conj(Vcs((end:-1:2)))/2)];

# FFT coefficients, w/ zero-centered zero padding, with negative freq values
# # of zeros is calculated to produce a power-of-two # of total values
# by subtracting the original length of testwave_v2_fl
wave_Vcs_tl = ifft(wave_Vcs_fl);
# Calculate and apply scaling to zero-padded iffts w/ respect to original ifft
wave_Vcs_tl = padding_size * wave_Vcs_tl;
# Double waveform (for clarity when plotting), comment out and change t to be linspace between 0 and 1 to have just one cycle
wave_Vcs_tl = [wave_Vcs_tl wave_Vcs_tl];
```

QucsStudio – Octave Script





QucsStudio – Octave Script

- These QucsStudio examples are definitely work-in-progress, they simply prove that there is a lot of untapped potential
- Should be possible to extend the Octave script to include a GUI (sliders ect) and plot the load-line, giving data display capabilities approaching commercial software equivalents
- ‘Under-the-hood’ there is more capability available in QucsStudio ect. than shown right now but it is not particularly easy to use (especially for beginners)
- **A reminder: The files will be available on our website (*https://www.cardiffars.org.uk/*) – Please contribute to improving this!**

Conclusions

- Free tools are available and can be useful
- Steeper learning curve, particularly if you have no prior experience
- Steadily being improved
- You can help right now through creating example workspaces for learning: **Share your knowledge!**

Conclusions

Questions?