Power Amplifier Classes Based upon Harmonic Approximation and Lumped-element Loading Networks

(Invited Paper)

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UCSD Power Amplifier Symposium

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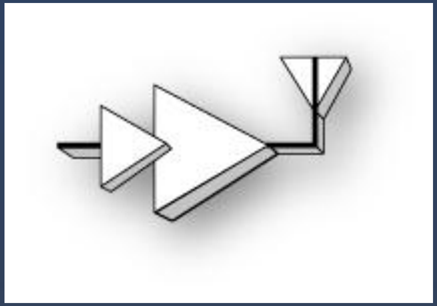
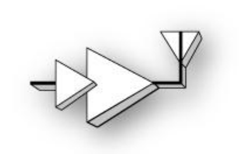


SKYWORKS

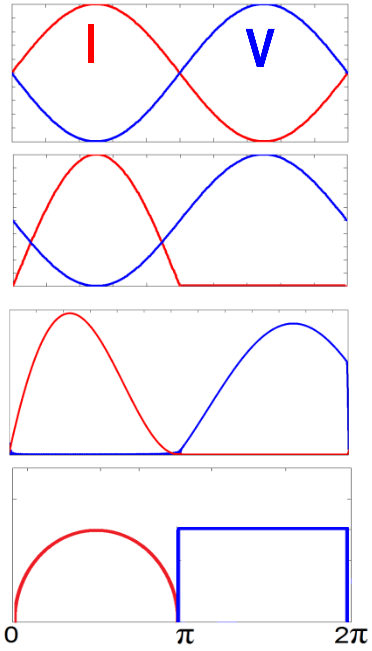


Outline

- Class-A, AB, B, C, D, E and F Power Amplifiers
- True-transient Operation
- Harmonic Approximation
- Loading Network Topologies for Compact PAs
- Load-Pull Contours and Load Modulation
- Summary

Ideal Power Amplifier Theory

Voltage sources and switches



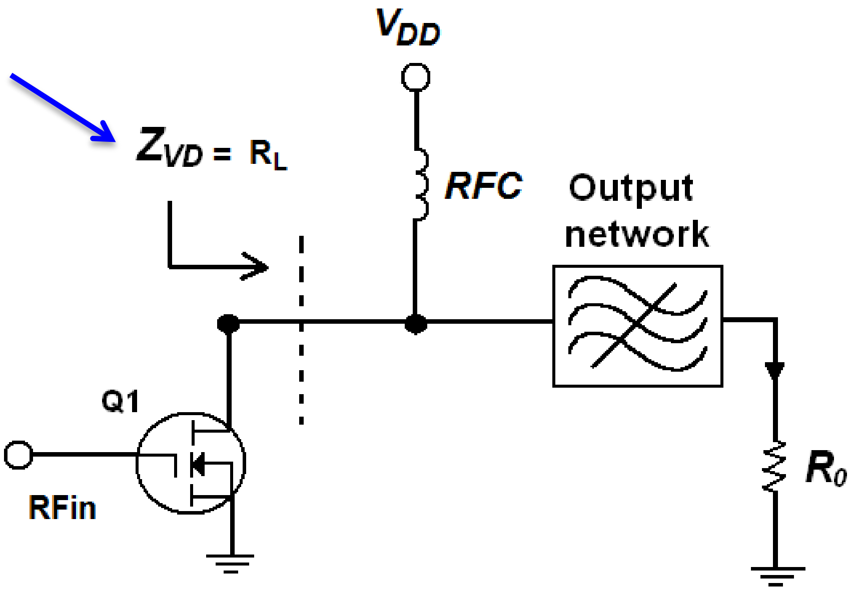
Class-A

Class-B
Even harmonics

Class-E
All harmonics

Class-F
All harmonics

Generic Power Amplifier
True-transient operation



Ideal Device

Power Amplifiers Practical Issues

Non-ideal voltage sources nor perfect switches

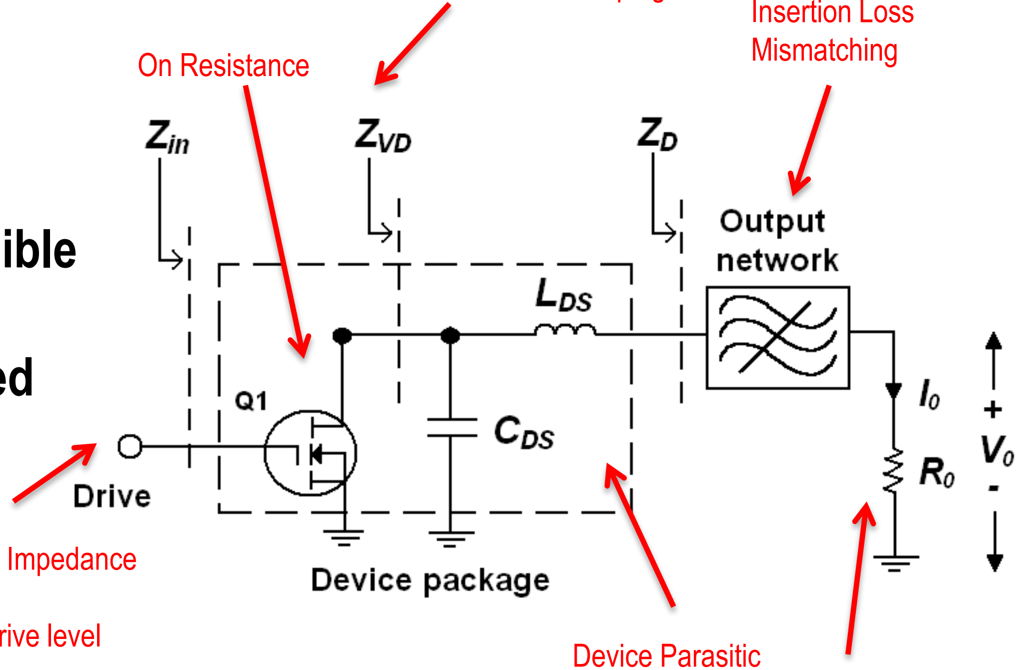
Amplifier major practical issues:

At high frequency

Device package and technology

True-transient Operation is not possible

Harmonic Approximation can be used



Intrinsic Drain Impedance
And Waveform Shaping

Insertion Loss
Mismatching

On Resistance

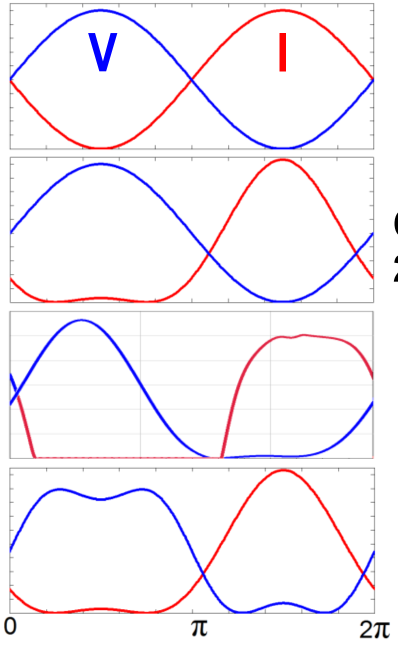
Input Impedance
and
RF drive level

Device Parasitic

Non Perfect Load Impedance
Operation over VSWR

Ideal Power Amplifier Theory with Parasitics

Non-Ideal voltage sources and switches



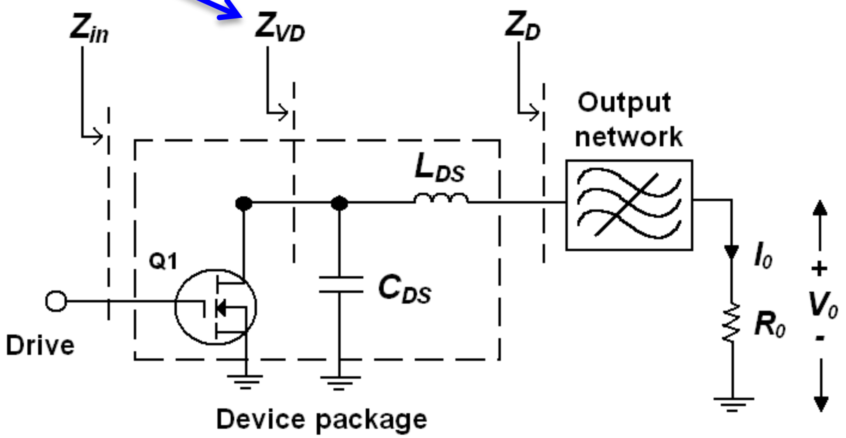
Class-A

Class-B_2
2nd harmonic

Class-E_2
2nd harmonic

Class-$F_{2,3}$
2nd and 3rd harm

Power Amplifier with Parasitics
Harmonic approximation



Waveform Coefficients for PA Design

Efficiency vs. number of harmonics

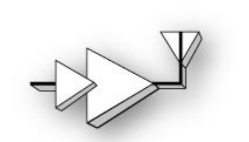
Efficiency upon combination of harmonics (in %)

HARM	1	3	5	Infinite
1	A 50	57.74	60.33	63.7
2	70.71	$F_{2,3}$ 81.65	85.32	90.03
4	74.97	86.56	90.45	95.45
Infinite	B 78.5	90.69	94.77	D, E 100

F. H. Raab, "Maximum efficiency and output of class-F power amplifiers," IEEE Trans. Microwave Theory Tech., vol. 49, no. 6, pp. 1162 - 1166, June 2001.

Amplifier Design by Waveform Factors

Coefficient values upon number of harmonics



$$Po = \frac{\left(\gamma_V \cdot V_{eff}\right)^2}{2R_L}$$

$$I_{DC} = \frac{\gamma_V \cdot V_{DD}}{\gamma_I R_L}$$

$$P_{DC} = V_{DD} I_{DC}$$

HARM	γ_V	γ_I
1	1	1
2	-------	1.4142
3	1.1547	-------
4	-------	1.0824
5	1.05146	------
Infinite	1.273	1.571

$$Efficiency = \frac{P_o}{P_{DC}} = \frac{\gamma_V \gamma_I \, {V_{eff}}^2}{2{V_{DD}}^2}$$

F. H. Raab, "Maximum efficiency and output of class-F power amplifiers," IEEE Trans. Microwave Theory Tech., vol. 49, no. 6, pp. 1162 - 1166, June 2001.

Class-A and AB PAs

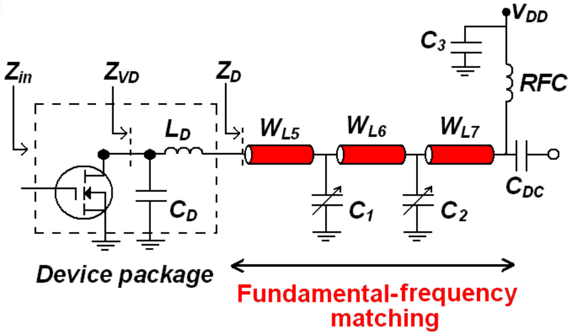
Transmission-lines and Lumped Elements

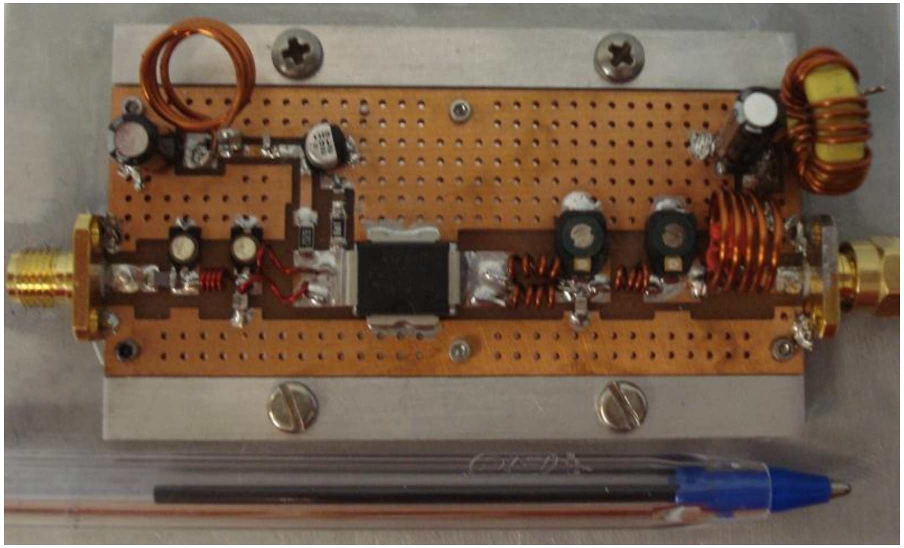
Class-A or AB η = 50 to 60 %

$Z_{VD} = R_L$

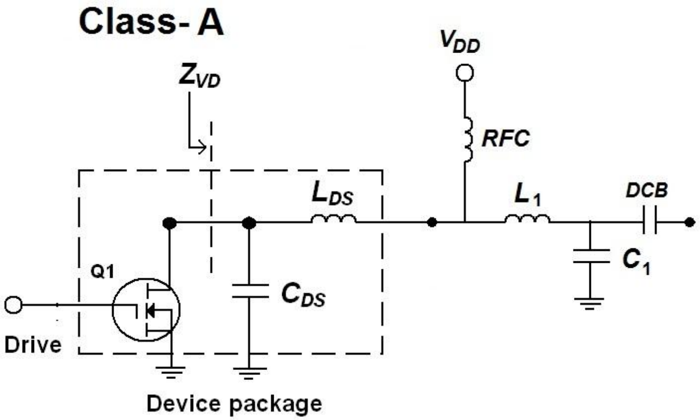
$$\gamma_V = 1$$
$$\gamma_I = 1$$

It doesn't require harmonic component neither in drain voltage nor in drain current waveforms





ST LDMOS FET PD57070



Efficiency: 35% in Class-A Output power: 70 Watts Frequency band: 290-390 MHz

Class-B PA implementation

Transmission-lines and Lumped Elements

Class-B$_2$ η = 70.71%

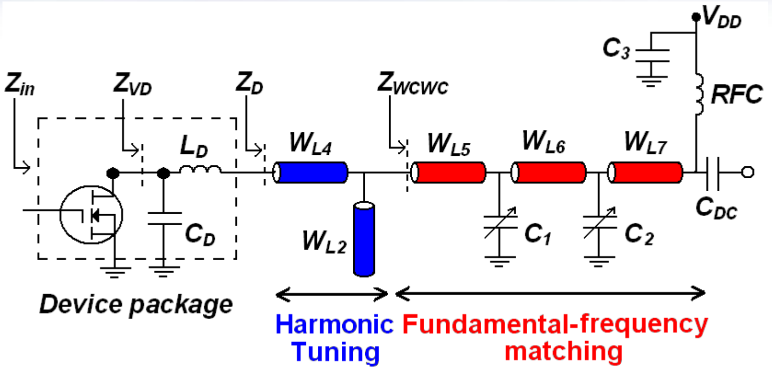
Z_{VD} = R_L at f_0

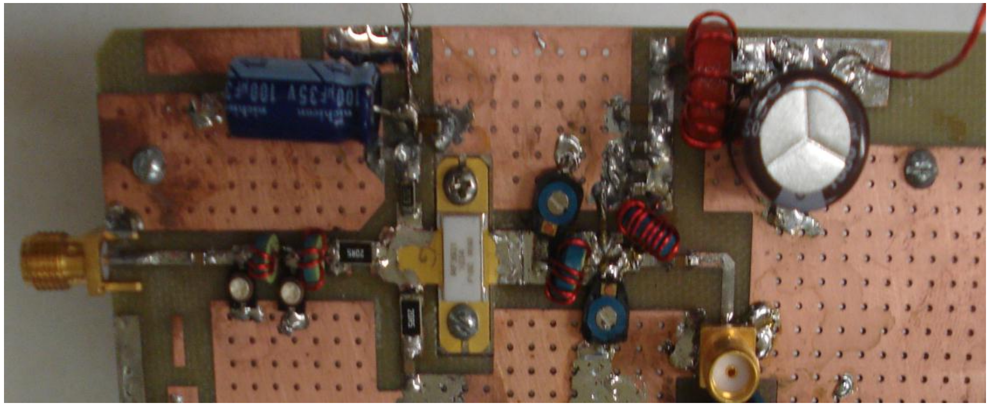
= 0 at $2f_0$

$$\gamma_V = 1$$

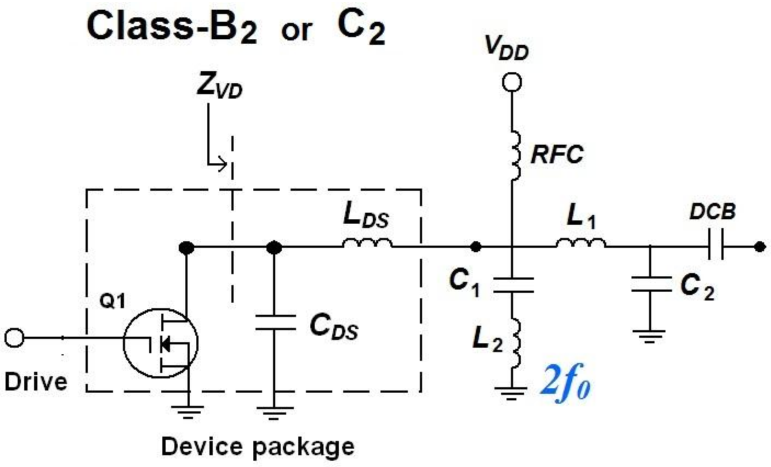
$$\gamma_I = 1.4142$$

It requires harmonic component in drain current waveforms





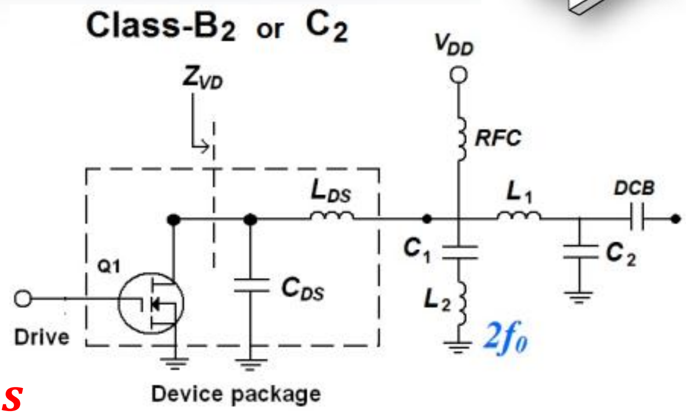
GaN FET RF3931



Efficiency: 65%; Output power: 5 Watts; Frequency 144-MHz

Class-C and D

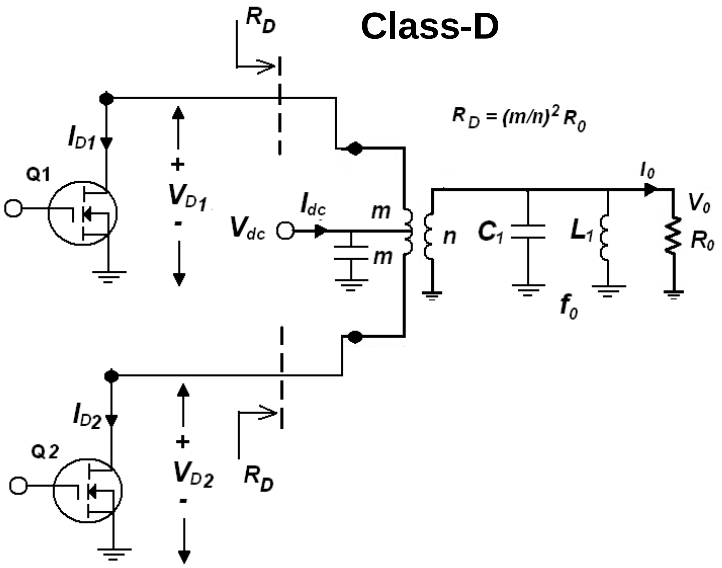
Transmission-lines and Lumped Elements



Class-C can be regarded as a reduce conduction angle class-B with a large number of harmonic currents added at VD.

$Z_{VD} = R_L$ at f_0
$= 0$ at $2f_0$
$\eta = 78.5\ \%$

$$\gamma_V = 1$$
$$\gamma_I = 1.571 \; all\ harmonics$$



Class D is a push–pull class-F PA

-the two active devices provide each other with paths for the even harmonics.

Therefore, class-D PA is related to class-$F_{2,3}$ as explain later.

$\eta = 81.65\ \%$

$$\gamma_V = 1.1547$$
$$\gamma_I = 1.4142$$

Class-E

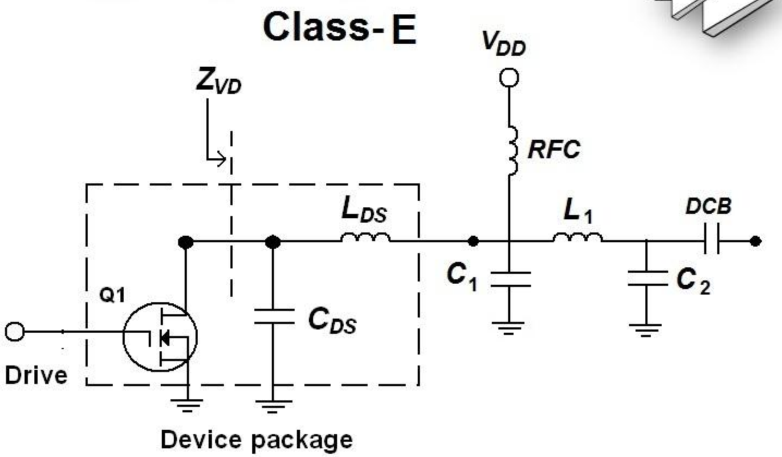
True-Transient Suboptimum Operation

Class-E_{10} $\eta = 100\%$

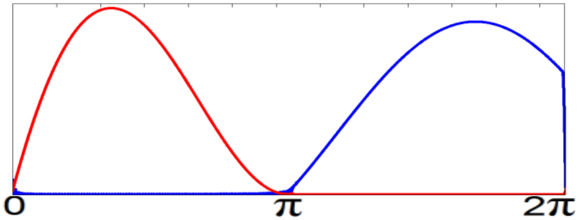
$Z_{VD} = R_L + jX_L$ at f_0

$= -j5.4466 \cdot R_0/n$ at nf_0

Harmonic impedances are not just short circuits.

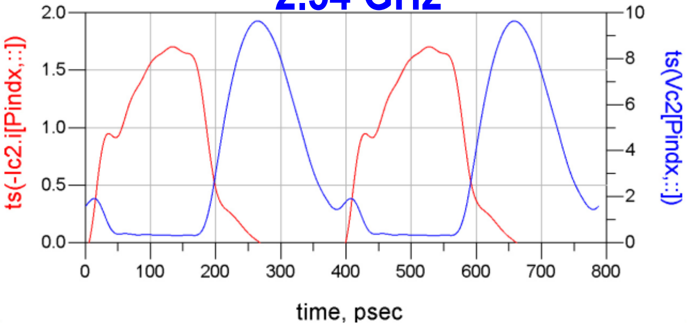


Ideal true-transient waveforms →



Generally mistuned at high-frequencies
It is a good approximation if we have access to the intrinsic drain →

2.54 GHz



Class-E Amplifier Reactances

Impedances for ideal Class-E

Specific Drain Impedances Z_{VD}

$V_{DD} = 15\ V$

$Pout = 11.5\text{-}W$

Freq.	Ideal Class-E R_0=10-Ohms
f_0	15.26+j11.064
$2f_0$	-j27.23
$3f_0$	-j18.15
$4f_0$	-j13.61
$5f_0$	-j10.89
$6f_0$	-j9.03
$7f_0$	-j7.78
$8f_0$	-j6.77
$9f_0$	-j6.05
$10f_0$	-j5.42

$Z_{VD} = (1.526+j1.106)\cdot R_0$

$B_S=0.1836/R_0$
$X_S=1.15\cdot R_0$

$X_n = -j5.4466\cdot R_0/n$

Class-E$_2$

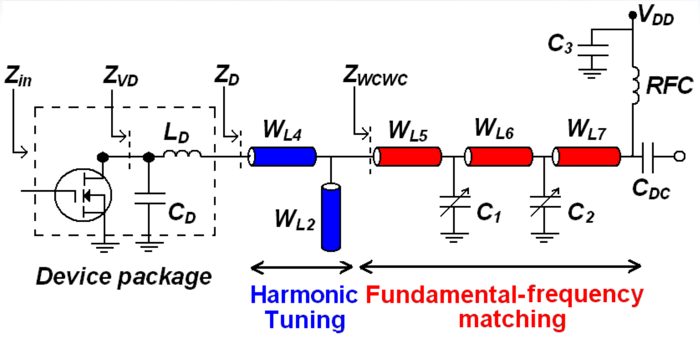
Second harmonic Approximation to Class-E Operation

Class-E$_2$ η = 70.71%

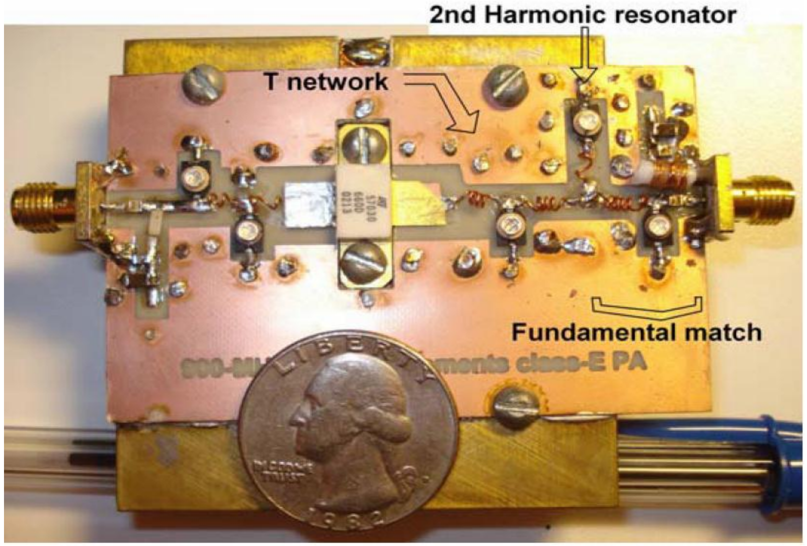
$Z_{VD} = R_L + jX_L$ at f_0

$= -jX_2$ at $2f_0$

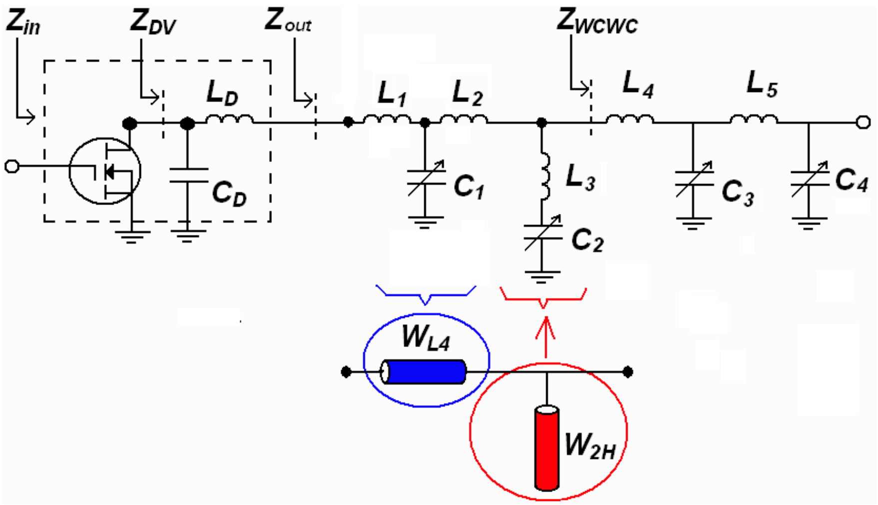
$$\gamma_V = 1.4142$$
$$\gamma_I = 1.4142$$



The 2nd harmonic in drain current waveform requires A GIVEN REACTANCE (not just a short)



ST LDMOS FET SD57030



Efficiency: 67%; Output power: 10 Watts; Frequency 900-MHz

Class-E_2

Second harmonic Approximation to Class-E Operation

Fundamental and Second harmonic Impedances

V_{DD} = 15 V

Pout = 11.5-W

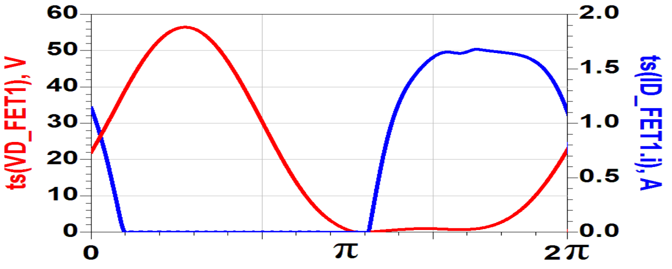
Freq.	Class-E_2
f_0	**8.86+j8.86**
$2f_0$	**-j12.28**
$3f_0$	NA
$4f_0$	NA
$5f_0$	NA
$6f_0$	NA
$7f_0$	NA
$8f_0$	NA
$9f_0$	NA
$10f_0$	NA

← $Z_{VD} = R_1 + jR_1$

← $X_2 = -j1.414R_1$

Second harmonic voltage and current in phase quadrature (no power dissipation)

Class-E_2 drain waveforms



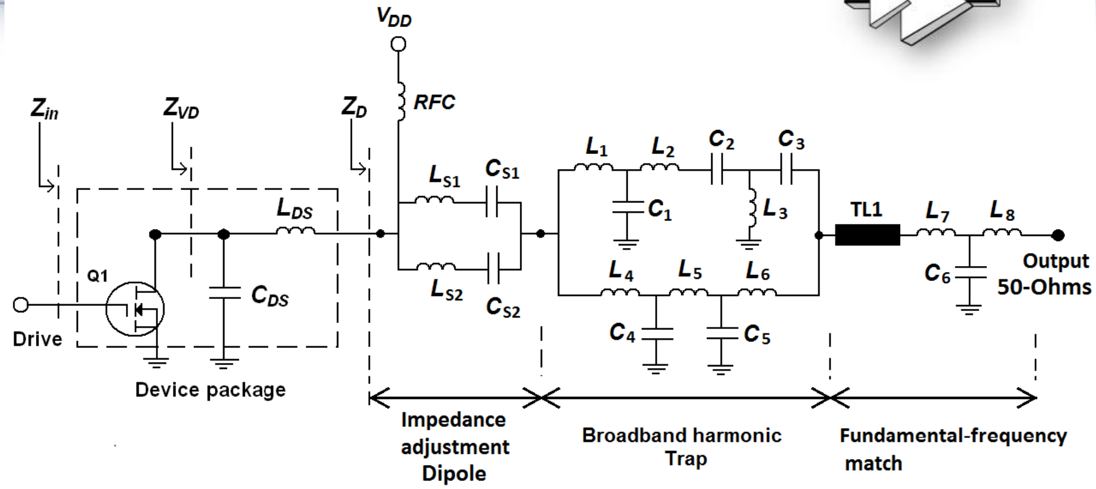
Class-E Multi-harmonic Approximation

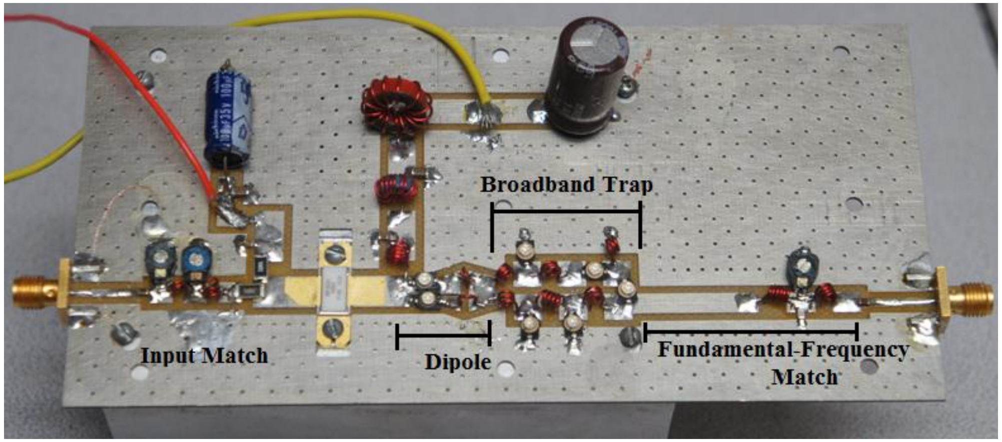
Impedances for Class-E_{10}

Class-E_{10} $\eta = 85\%$

$$Z_{VD} = R_L + jX_L \text{ at } f_0$$
$$= -j5.4466 \cdot R_0/n \text{ at } nf_0$$

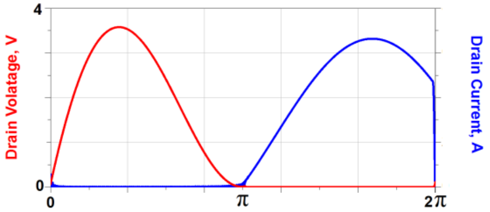
It requires harmonic drain currents and voltages with specific reactance values



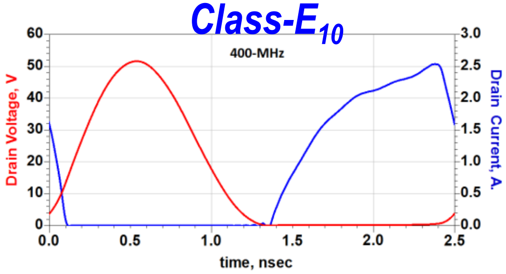


GaN FET RF3931

Class-E, All harmonics



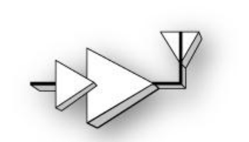
Class-E_{10}



Efficiency: 85%; Output power: 10 Watts; Frequency 400-MHz

Class-E Multi-harmonic Approximation

Impedances for Class-E_{10}



Comparison between ideal class-E and class-E_{10}

V_{DD} = 15 V

Pout = 11.5-W

Freq.	Ideal Class-E	Class-E_{10}	Ratio E_{10}/E
f_0	15.26+j11.064	**15.26+j11.064**	1
$2f_0$	-j27.23	**-j27.23**	1
$3f_0$	-j18.155	**-j9.881**	0.544
$4f_0$	-j13.616	**-j5.144**	0.377
$5f_0$	-j10.893	**-j3.952**	0.363
$6f_0$	-j9.038	**-j3.226**	0.357
$7f_0$	-j7.781	**-j2.684**	0.345
$8f_0$	-j6.778	**-j2.269**	0.335
$9f_0$	-j6.052	**-j1.892**	0.312
$10f_0$	-j5.420	**-j1.378**	0.254

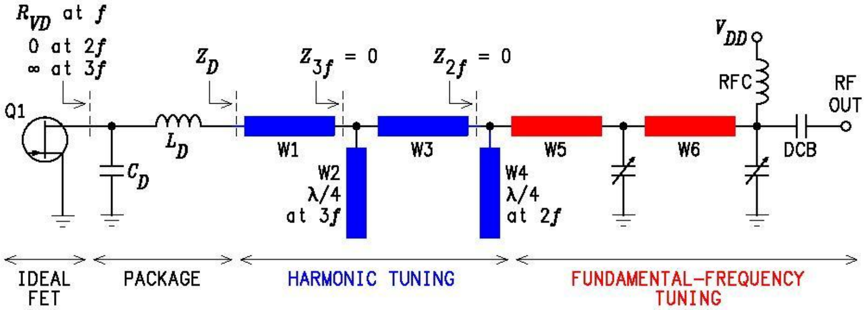
Class-F$_{2,3}$ Power Amplifier

Second and third harmonic

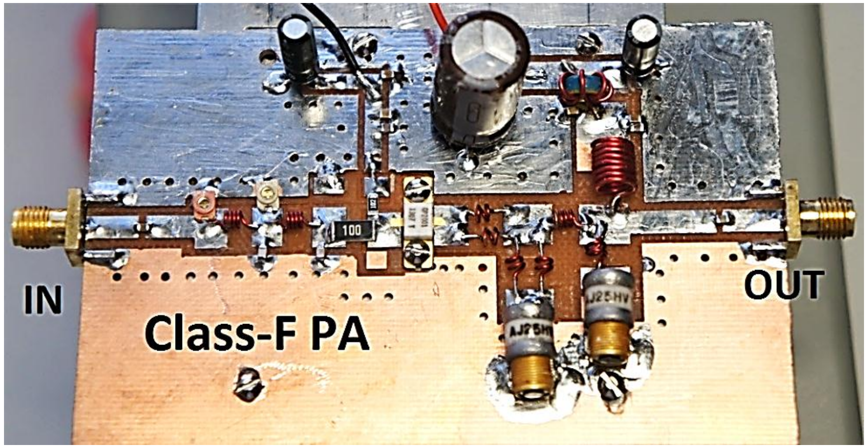
Class-F$_{2,3}$ η = 81.65%

$Z_{VD} = R_L$ at f_0
$= 0$ at $2f_0$
$= \infty$ at $3f_0$

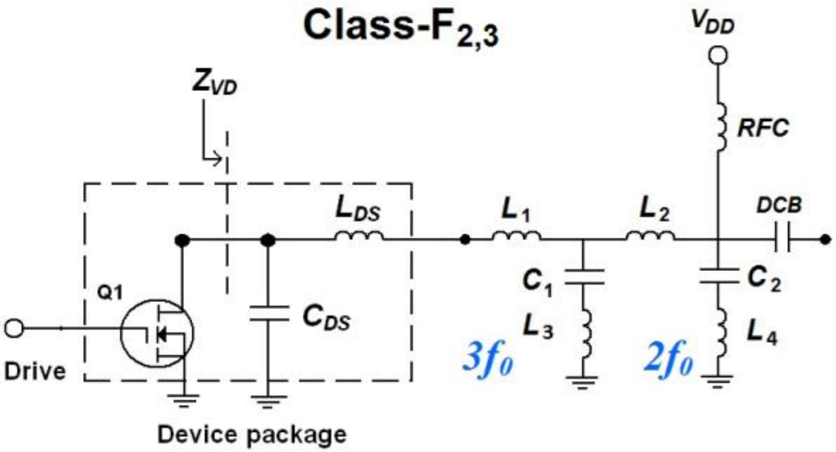
$$\gamma_V = 1.1547$$
$$\gamma_I = 1.4142$$



It requires harmonic voltage and current at drain waveforms.



GaN FET GP2001 PolyFET



Efficiency: 81%; Output power: 17 Watts; Frequency 300-MHz

Inverse Class-$F_{2,3}$ Power Amplifier

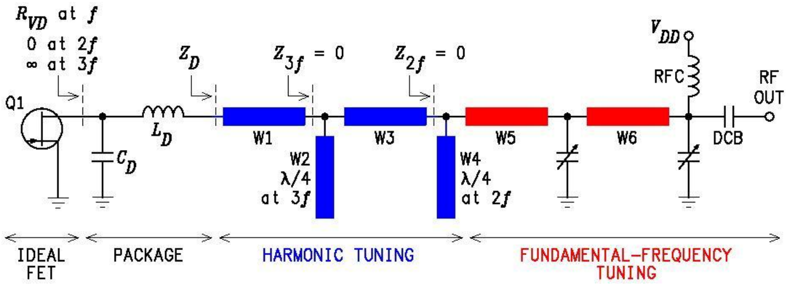
Second and third harmonic

Class-$F_{2,3}$ η = 81.65%

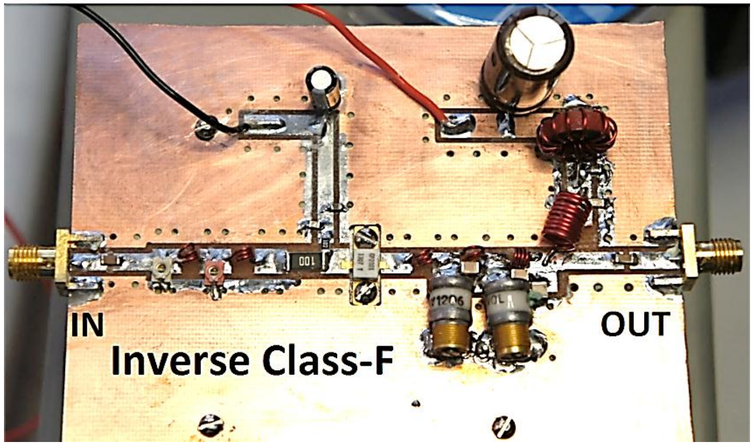
$Z_{VD} = R_L$ at f_0
$= \infty$ at $2f_0$
$= 0$ at $3f_0$

$$\gamma_V = 1.1547$$

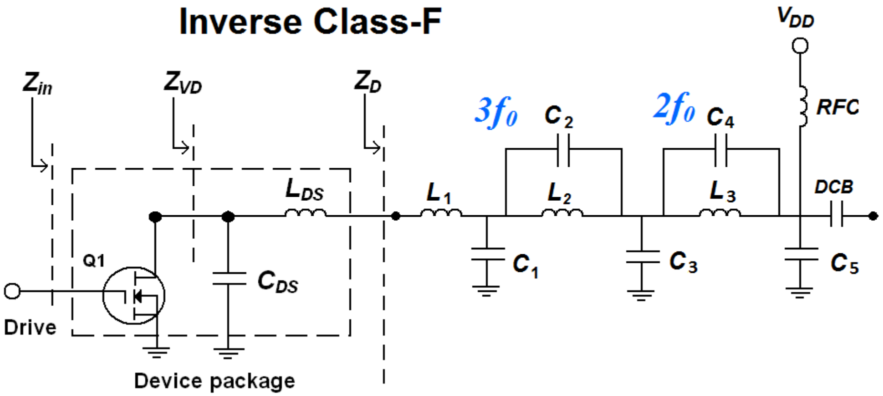
$$\gamma_I = 1.4142$$



It requires harmonic voltage and current at drain waveforms.



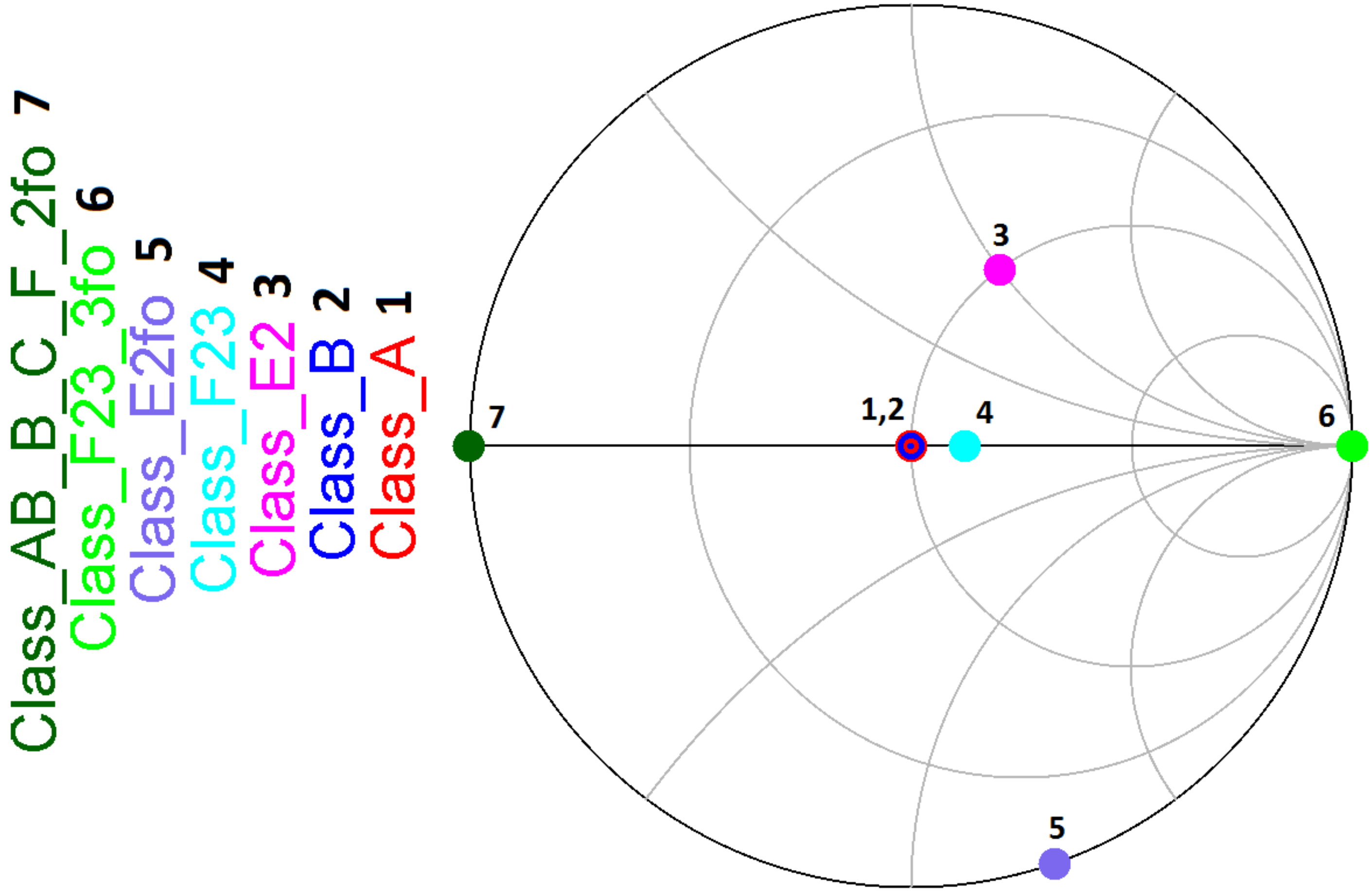
GaN FET GP2001 PolyFET



Efficiency: 79%; Output power: 17 Watts; Frequency 300-MHz

Impedances for PA classes

Impedances at intrinsic drain



Continuous Class-E_2 and $F_{2,3}$

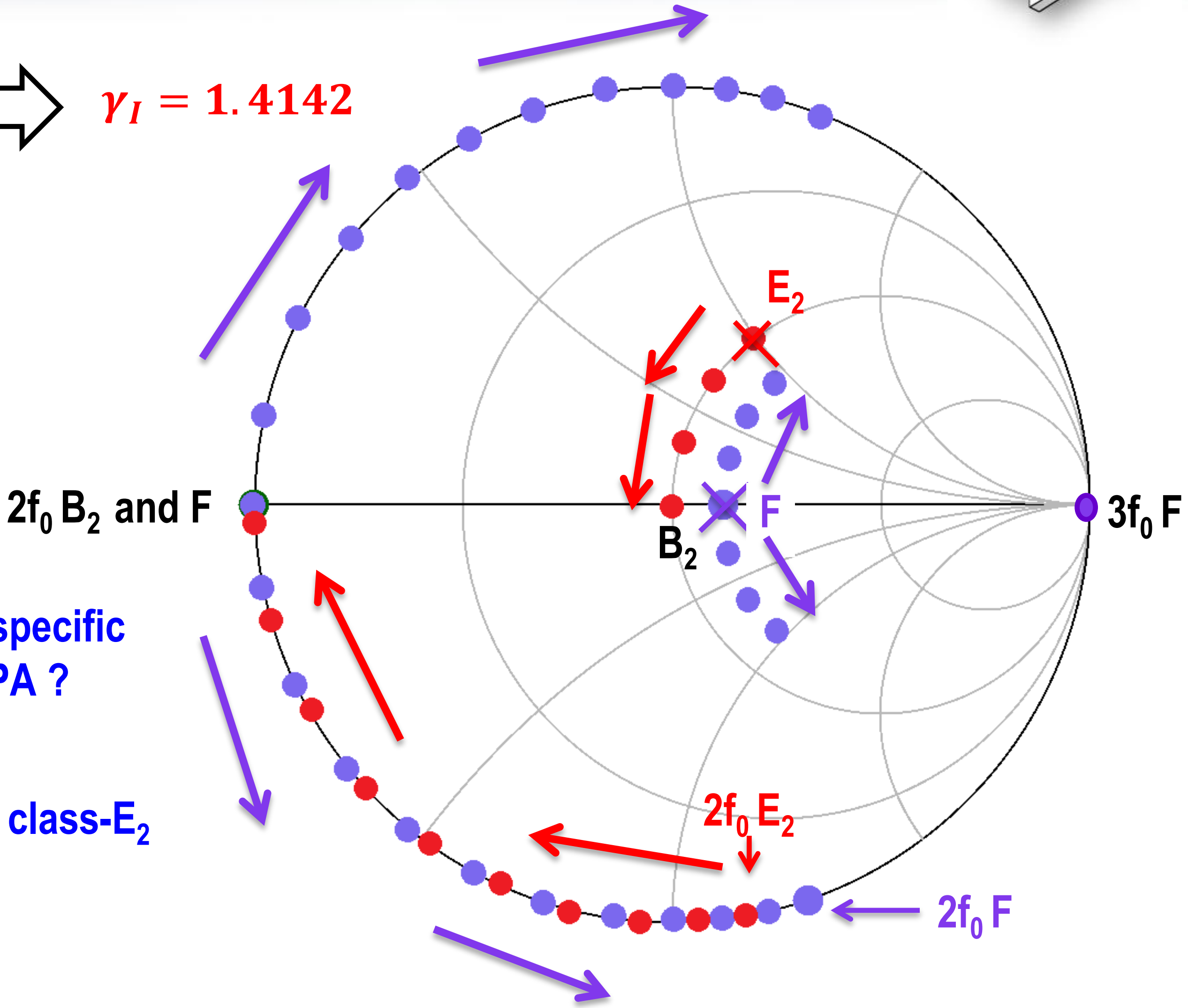
Impedance locus

Do you remember the waveform factor for class-B_2 and class-E_2 are the same?

$\gamma_I = 1.4142$

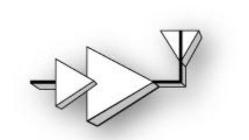
There is a transition from class-E_2 to class-B_2 PAs.

- **Does class-J look like an specific solution case of class-E_2 PA ?**
- **A harmonic load-pull for a class-E_2 PA will reveal the true.**



Power Amplifiers for RF Transmitters

Enhancing efficiency at back-off



$$Efficiency = \frac{P_o}{P_{DC}}$$

Maximize Po

Minimize or keep same P_{DC}

ET, EER, DC-DC

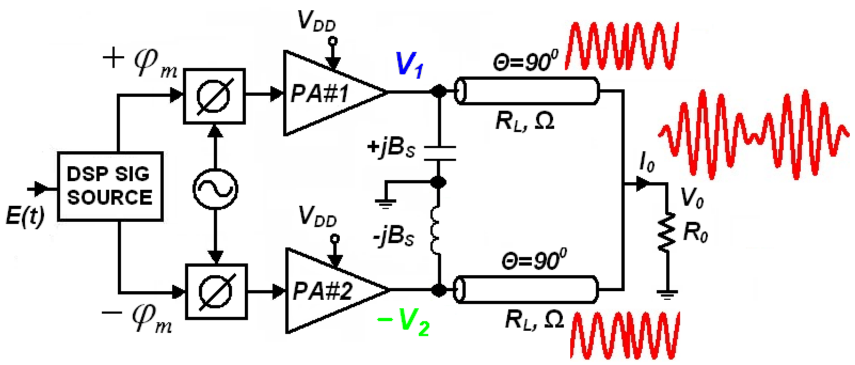
$$\mathbf{Po} = \frac{\left(\gamma_V \cdot V_{eff}\right)^2}{2R_L}$$

Doherty and Outphasing

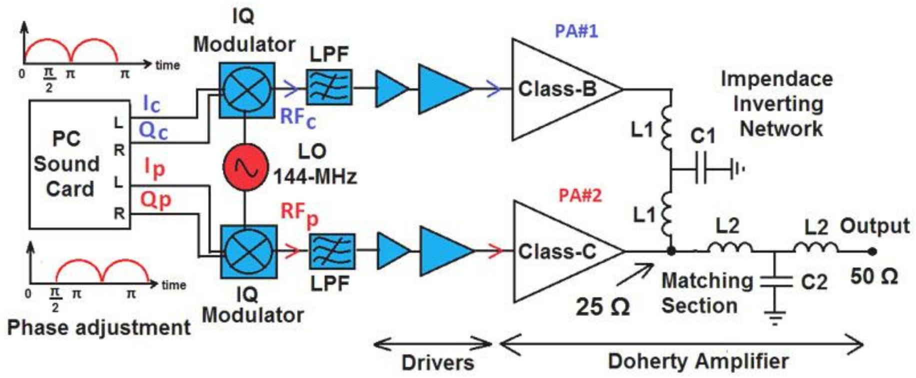
Using PAs in Outphasing and Doherty

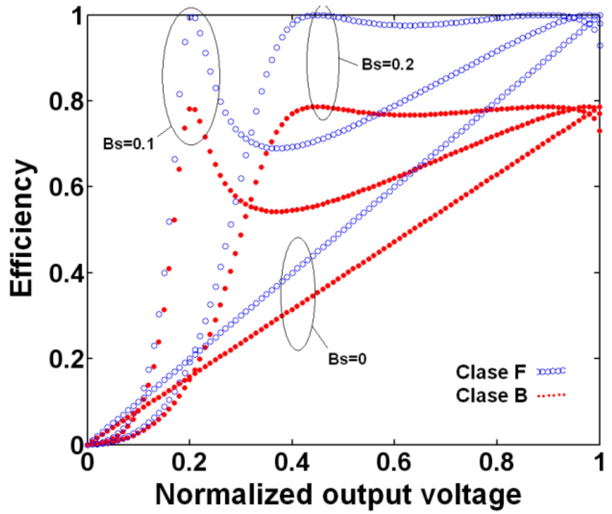
Load modulation for PAs

H. Chireix



W. Doherty

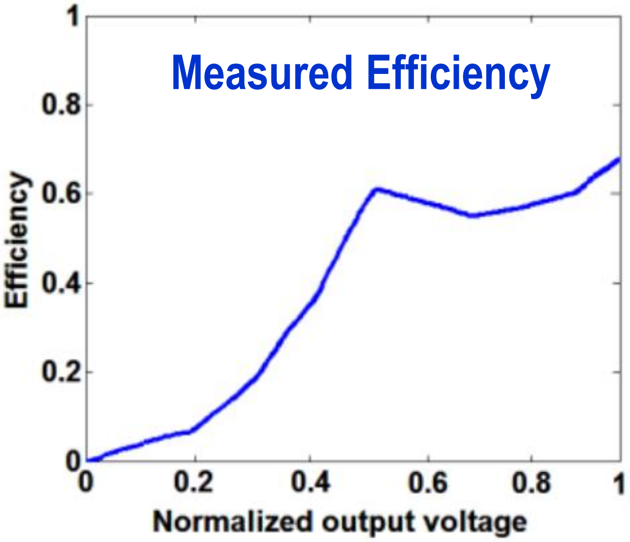




Class-B PAs

and/or

Class-F PAs

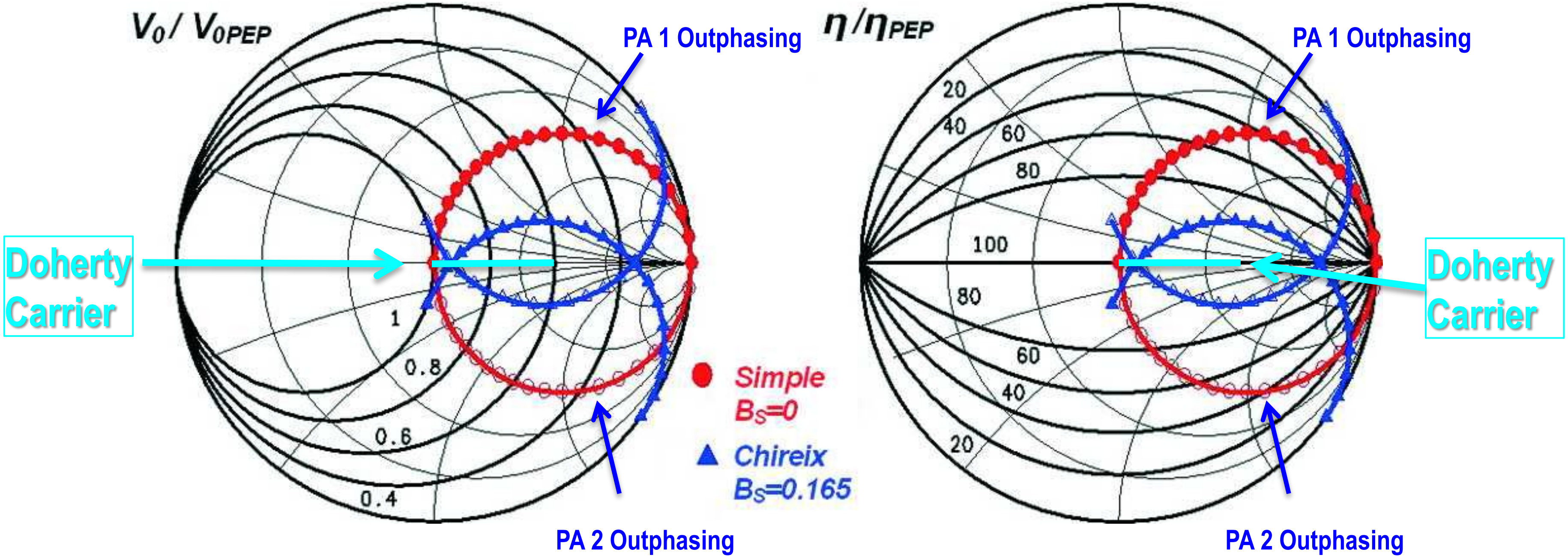


Load Modulation for PA classes

Impedance locus for a voltage source PA

Why a real amplifier does not work as expected for Outphasing or Doherty transmitters?

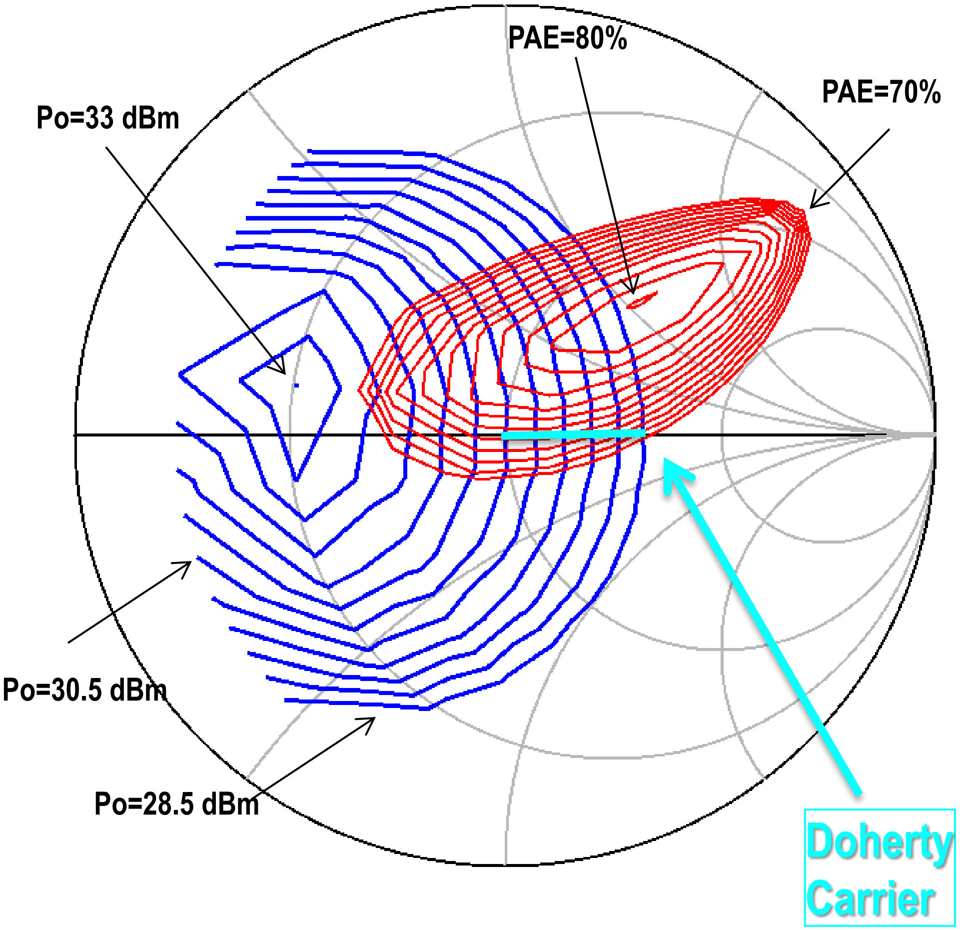
Don’t use a real PA assuming ideal load-pull contours

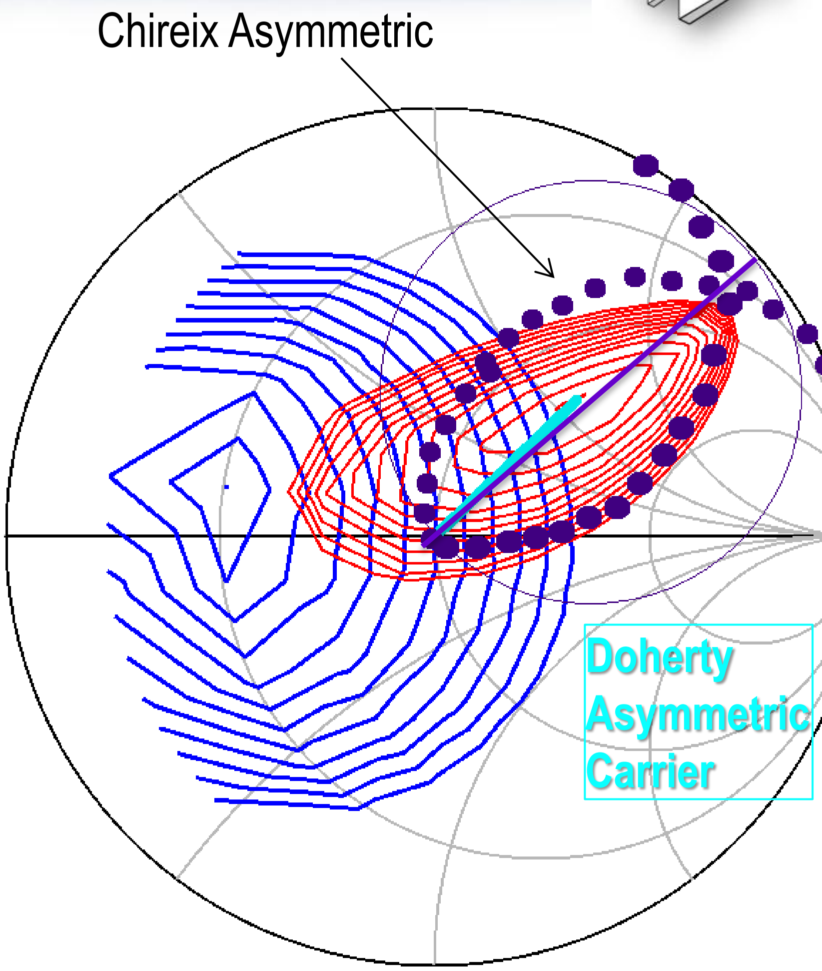


Symmetric combiner

However, this is not the case for a real amplifier…

Load Modulation for real PAs and Asymmetric Combining





Asymmetric combiner

Summary -

- The power amplifier efficiency depends upon the number of controlled harmonics.
- The harmonic impedances define the amplifier’s output power capabilities and waveform shapes.
- Lumped-element output networks can serve for a wide frequency range.
- For a load modulated amplifier (i.e Doherty or Outphasing) take a look at the amplifiers load-pull contours, since they may need asymmetric combining.
- Not all real amplifiers can operate in either classic Doherty or Outphasing. However, DSP assisted PAs systems could overcome practical limitations by compensating phase and amplitude unbalance as well as other parameters such as linearity through pre-distortion.
- The transition between PA classes is one of the most common confusion in a real amplifier when it is tuned in the measurement bench.

Power Amplifier Classes Based upon Harmonic Approximation and Lumped-element Loading Networks

Thank you all

Questions?