
Revisiting the Doherty PA

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Steve C Cripps, Ph.D
Hywave Associates

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Notes:

1

Introduction to Doherty PA (-1)

- The Doherty PA (DPA) has emerged as one of the “hottest” topics in the PA business
- Originally proposed (by W.H. Doherty) in 1936, it was almost entirely ignored by the modern RF community until just a few years ago
- The DPA offers a solution to the low PBO efficiency problem which all Class AB amplifiers present
- The availability of linearisation techniques such as Digital Predistortion (DPD) can (potentially) solve the key linearity problem with DPAs

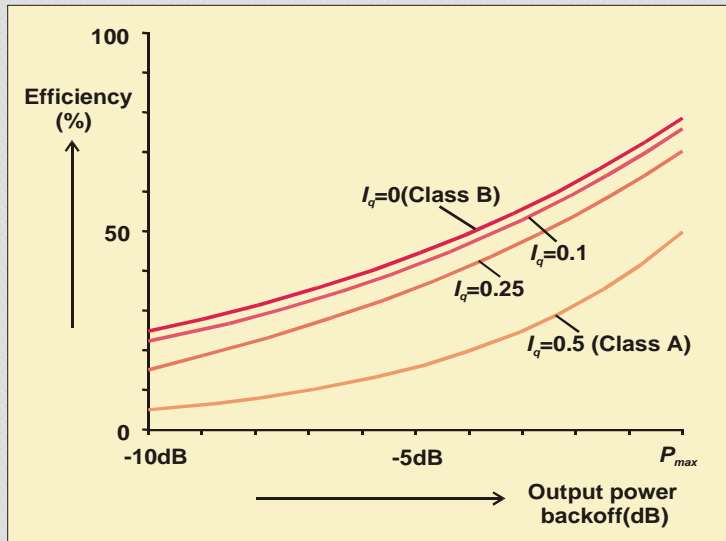
The Doherty amplifier is a classical piece of work dating from the early era of radio engineering (1936). Its implementation in solid state applications has been largely limited to specialized systems such as Satcom. But it clearly has wider uses.

Ref. “A New High Efficiency Amplifier for Modulated Waves”, W.H. Doherty, Proc. IRE, Vol.24, No.9, Sept 1936, pp1163-1182.

Notes:

2

Introduction to Doherty PA (-2)



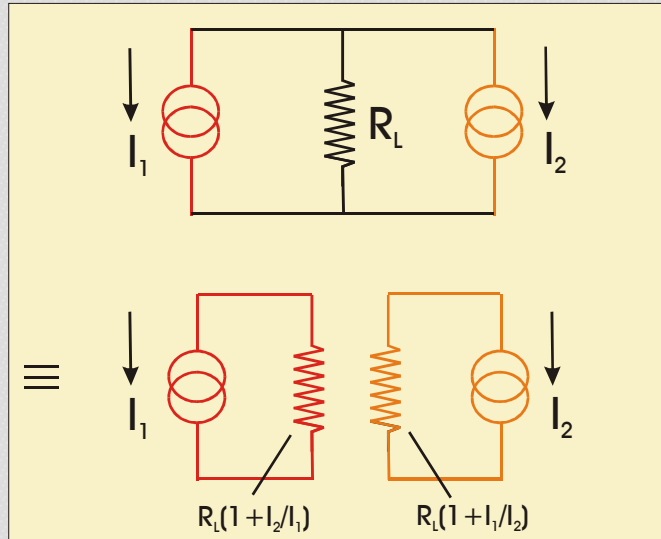
- Efficiency of Class AB PA degrades rapidly as RF carrier amplitude is reduced
- Degradation slows as conduction angle is reduced (from Class A to Class B) but still highly problematical in making high average efficiency for signals having AM
- Need to somehow reduce the power “capacity” at low points in the AM cycle
- Old problem; old solutions exist!

The basic reduced conduction angle modes are, in a sense, already one step along the road of envelope power management. The Class B amplifier efficiency degrades considerably less than the Class A, as the drive level is reduced.

Notes:

3

Introduction to Doherty PA (-3)



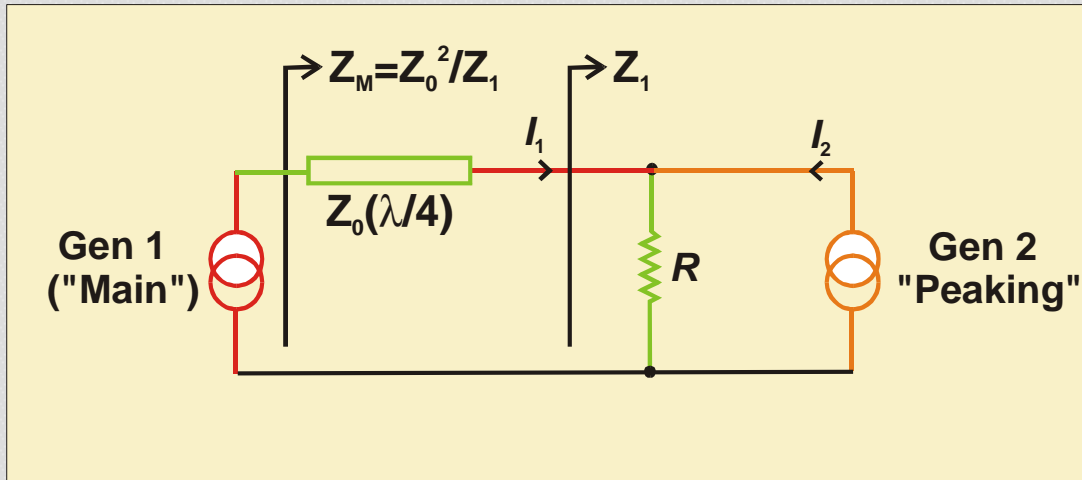
- Impedance “seen” by generator 1 is
$$Z_1 = R_L \cdot (1 + I_2/I_1)$$
- As drive level is backed off from maximum down to the 6dB PBO point, Z_1 decreases from $2R_L$ down to R_L
- This is actually the wrong direction for R_L , but it’s a start!

The other key element of the Doherty scheme is the active “pulling” of the main PA load resistance by the activity of the peaking amp.

Notes:

4

Introduction to Doherty PA(-4)



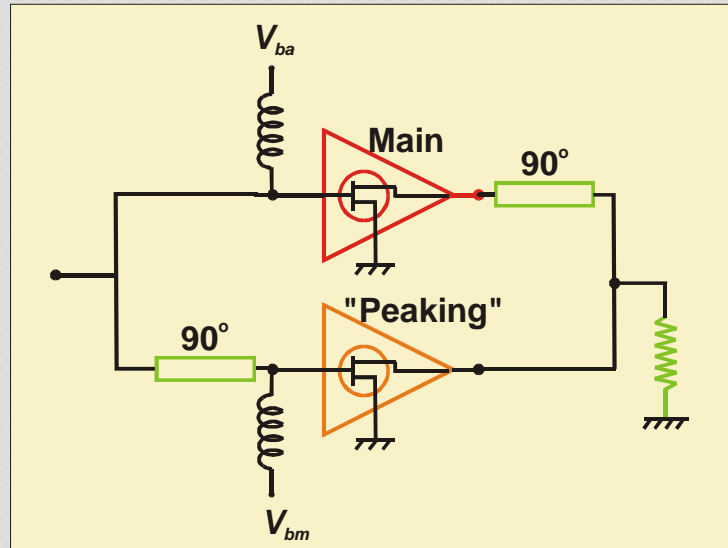
- Impedance inverter can be realised using quarterwave transformer
- Further analysis shows that transformer must have $Z_0 = 2R$
- $R = R_{opt}/2$ (R_{opt} is loadline value for a single device)
- Phase compensation on peaking amplifier conveniently done at input (giving a "quasi balanced" configuration and associated VSWR advantages)
- Output Doherty circuitry can be done after matching devices closer to 50 Ohm

The impedance movement needs to be "inverted". This is usually indicated by a quarter wave transmission line, in which case the inputs to the two amplifiers needs to be differentially phase compensated by 90 degrees. The input arrangement then looks reminiscent of a balanced amplifier, but in this case the two amplifiers are not well matched and only limited "balanced" effects can be obtained.

Notes:

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Introduction to Doherty PA (-5)

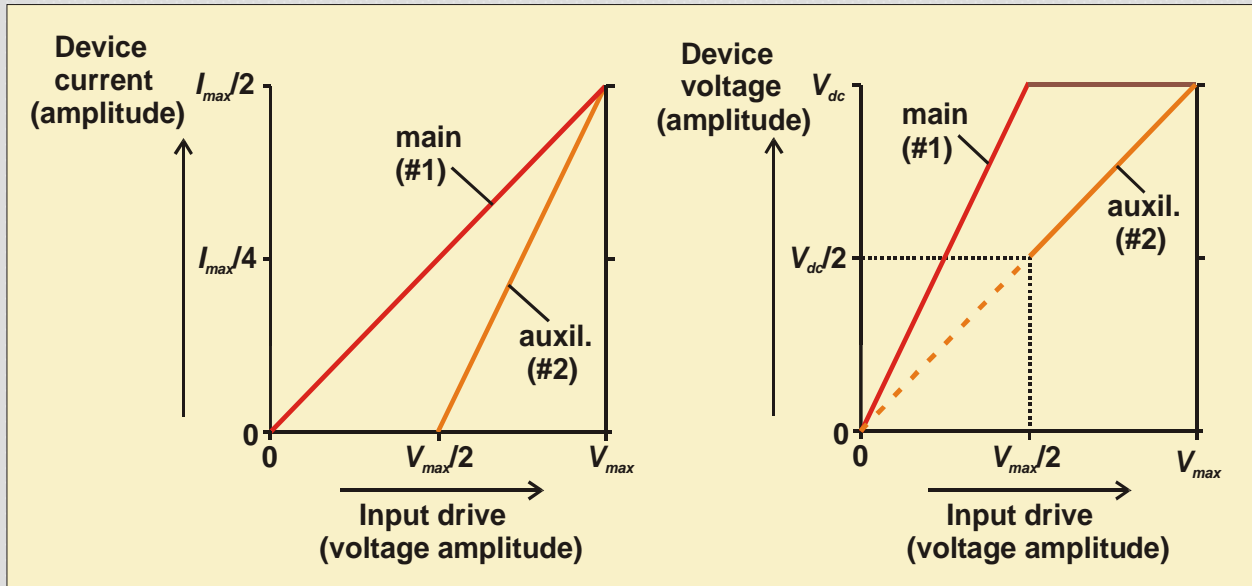


- Uses 2 devices with common load
- "Peaking" device only active for upper few dB of range (6dB typically)
- Overall efficiency can be maintained close to maximum for initial 6dB PBO

Notes:

6

Introduction to Doherty PA (-6)



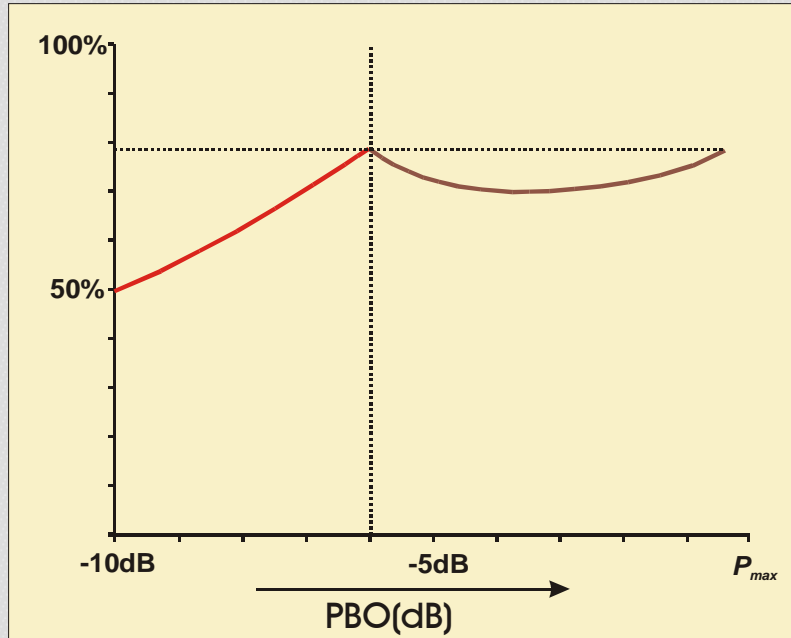
- Main device maintains maximum efficiency for all the active regime of the peaking device
- Peaking device does not have maximum efficiency in the mid range, but is contributing correspondingly less power

The other key aspect of the Doherty scheme is the creation of a “constant voltage, maximum efficiency” range of operation for the main PA. As the drive backs off 6dB, the load is “pulled” upwards by the action of the peaking amp and the impedance inverter, maintaining maximum peak-to-peak voltage swing at the main PA output.

Notes:

7

Introduction to Doherty PA (-7)



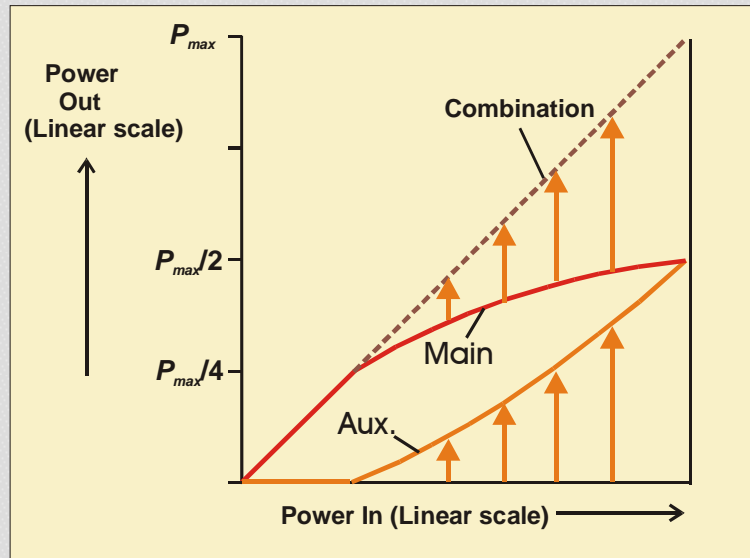
- Composite efficiency shows close to maximum value maintained over upper 6dB power range
- Depth of dip (at 3dB PBO point) dependent on implementation of peaking amp

The Doherty amplifier is always shown to have this characteristic efficiency/pbo plot. The depth of the dip in the middle of the peaking amp range is very much dependent on how the peaking amp is controlled.

Notes:

8

Introduction to Doherty PA (-8)



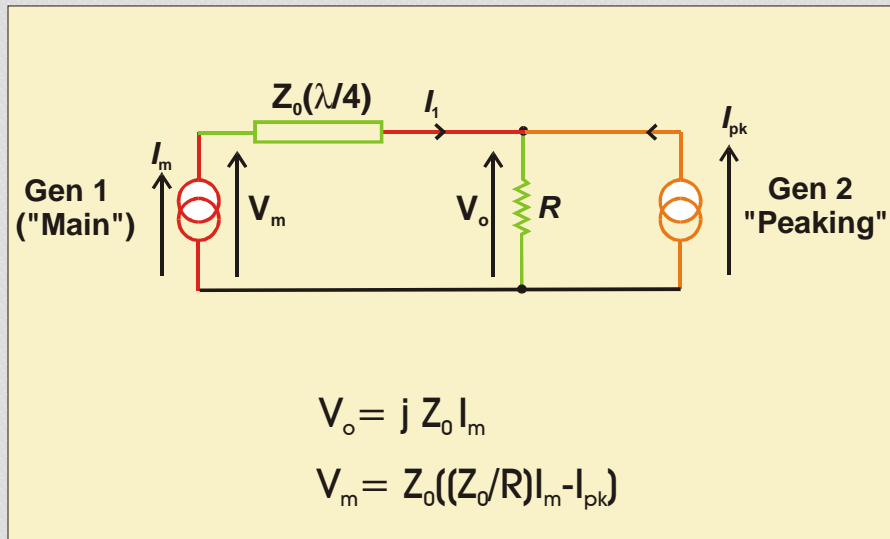
- Key aspect of DPA analysis is *linearity* of final response
- Power contributed by auxiliary PA is exactly the power required to restore the square-law characteristic of the main PA in the “load modulation” regime
- Note linear power scales on diagram

The ability of the two devices to act together as a linear amplifier is another remarkable feature of the Doherty configuration. In practice, of course, things may not look quite so “pristine”.

Notes:

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Doherty PA Analysis (-1)



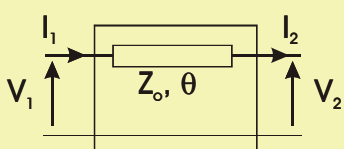
- More detailed analysis (see ref.) gives above expressions for the output voltage (V_o) and the main PA device output voltage (V_m)
- Expression for V_o shows that the output voltage is a simple linear function of I_m .
- Function of peaking device is to keep V_m below clipping level
- So peaking amp does not have to be linear!

Ref: Cripps, "Advanced Techniques in RF PA Design", Artech House, p45

Notes:

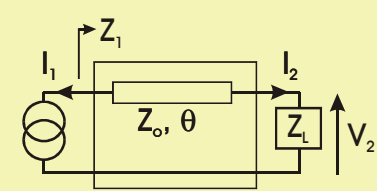
10

Doherty PA Analysis (-2)



$$\begin{bmatrix} \cos \theta & jZ_0 \sin \theta \\ (j/Z_0) \sin \theta & \cos \theta \end{bmatrix}$$

$(\theta = \pi/2)$
 $\begin{bmatrix} 0 & jZ_0 \\ j/Z_0 & 0 \end{bmatrix}$
 $(\omega^2 LC = 1)$



$$V_1 = (0 \cdot V_2) + jZ_0 I_2$$

$$-I_1 = (j/Z_0) V_2 + (0 \cdot I_2)$$

\Rightarrow

$$V_2 = jZ_0 I_1$$

$$Z_1 = Z_0^2 / Z_L$$

- An ideal impedance inverter transforms a current source into a voltage source
- It is also a useful impedance transformer!

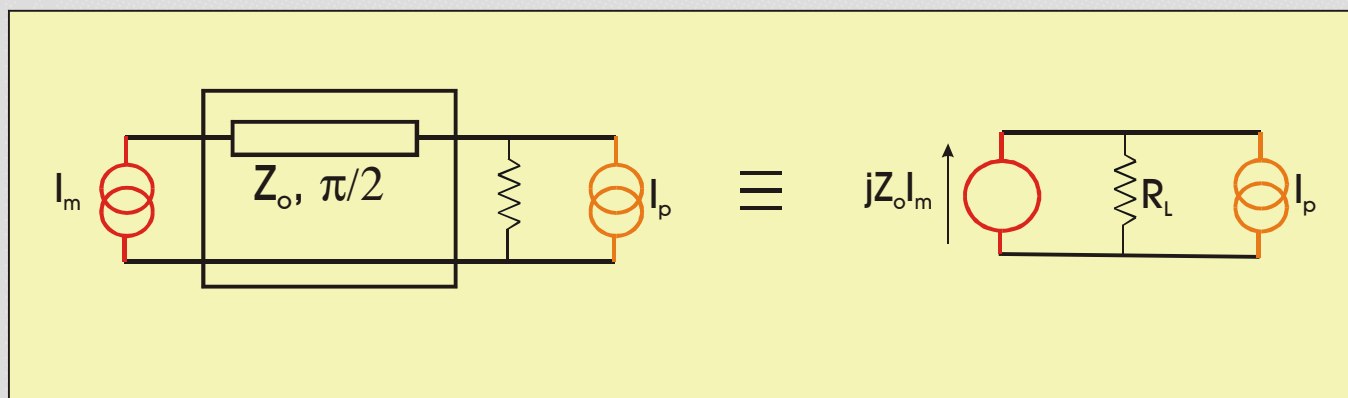
This is the core of a basic DPA circuit.

We normally consider transistors to behave as current sources, but the main PA device will behave like a voltage source in the DPA.

Notes:

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Doherty PA Analysis (-3)



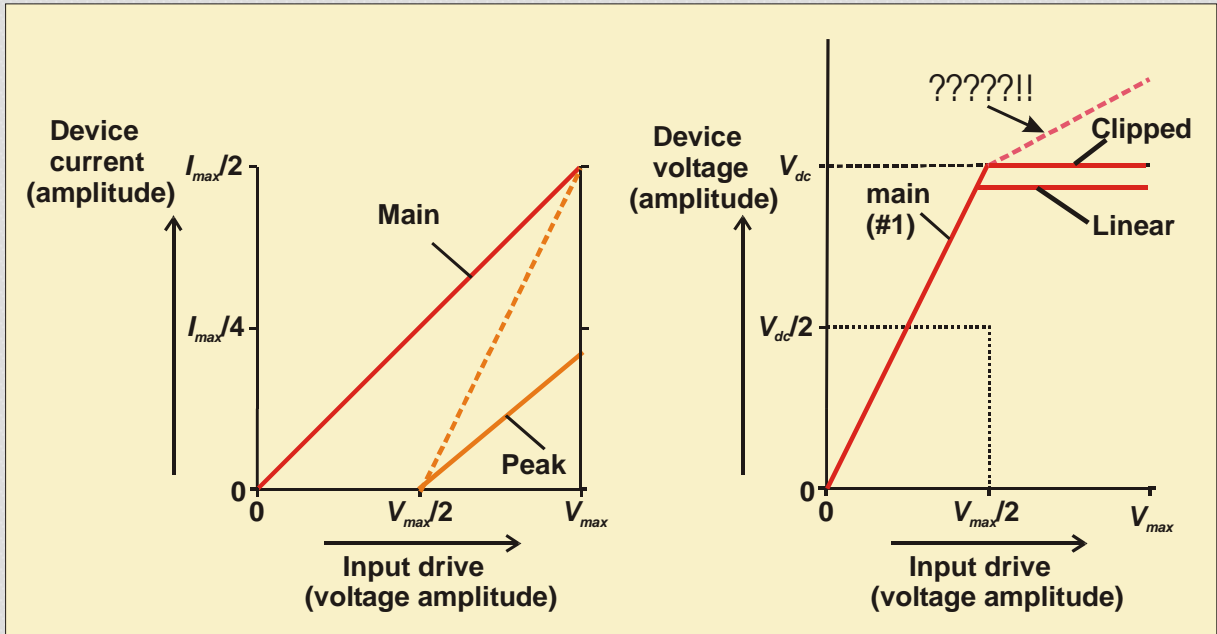
- The basic DPA schematic can be redrawn as shown
- Since the MPA current I_m has a linear relationship to the input voltage, linear output is “mathematically” guaranteed!
- But there is a crucial caveat which has been missed by many: ***If the MPA voltage starts to clip, it immediately becomes a voltage source and the analysis is invalid!***

An important caveat! Everything changes if the MPA device voltage reaches the clipping level.

Notes:

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Doherty PA Analysis (-4)

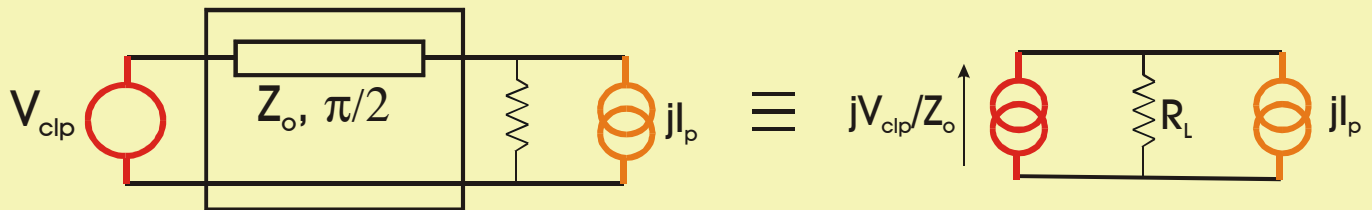


- If the Peaking current is too low, the conventional analysis shows the MPA voltage climbing above V_{ss}
- This clearly doesn't actually happen, it just clips on the rail

Notes:

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Doherty PA Analysis (-5)



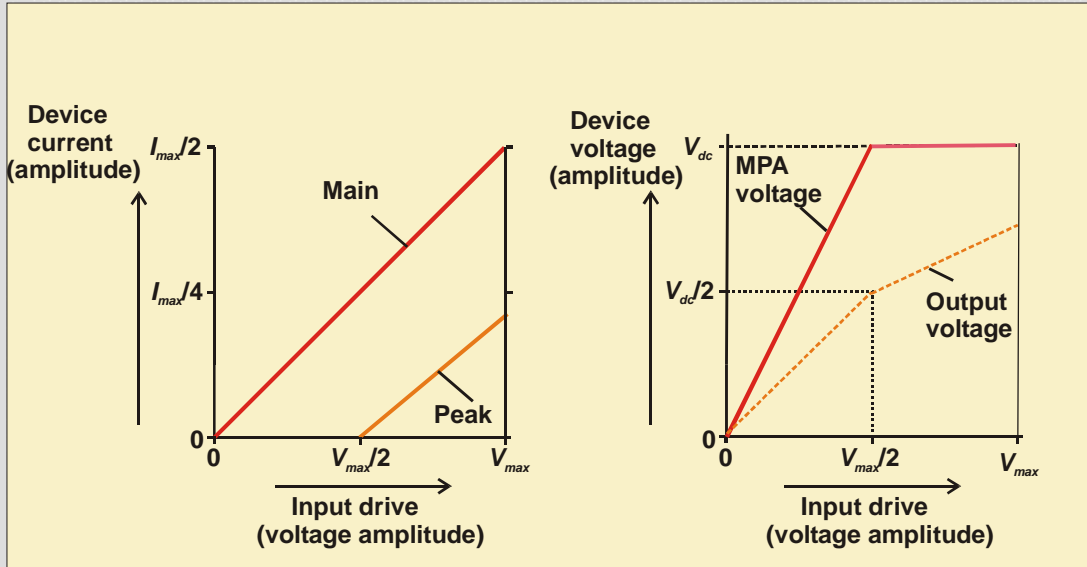
- A device which is clipping on the supply lines can be regarded as a constant voltage source (approximately)
- So the DPA circuit now transforms to a simple pair of current sources
- This can *seriously degrade* most of the useful features of Doherty PA operation!
- It can also *explain* allegedly "quirky" behaviour observed in practice

Herein lies much of the problems exhibited by many practical implementations. Allowing the MPA to clip is a disaster, and is mainly caused by "scrimping" on the peaking PA device current and/or incorrect PPA control arrangements.

Notes:

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Doherty PA Analysis (-6)



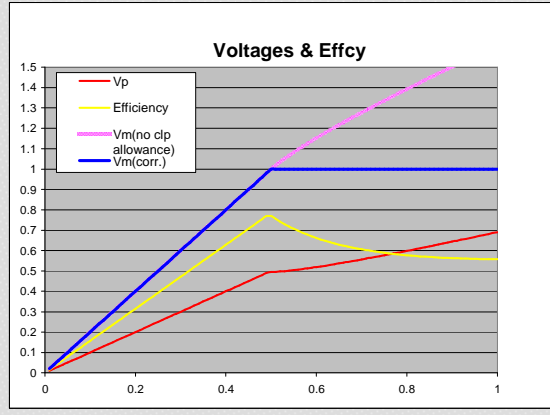
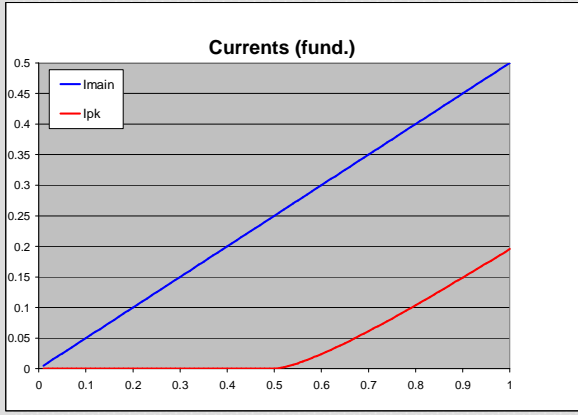
- If the MPA saturates (=“clips”), it starts behaving like a voltage source, its output “pegged” at the supply voltage
- The result is a highly non-linear characteristic at the output
- This is probably very common in practice

Beware the conventional DPA analysis! It falls apart when either device starts to saturate.

Notes:

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DPA Simulator ("Doughnut" -1)



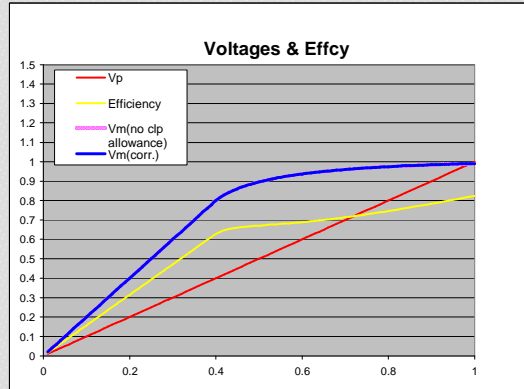
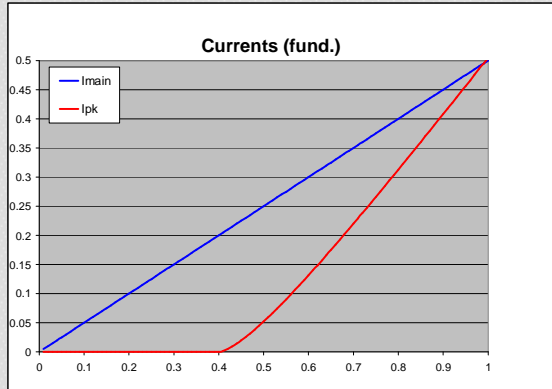
Vknee	0.01	main amp	Vq	0.	ZT=	2	Calculate
Vdc	1	Peaking amp	X MPA	1	RL=	1	
			Vq	-5	PUF(dB)=	-3.22	

- "Doughnut" is an Excel spreadsheet which simulates the main action of a DPD, including clipping of the MPA
- Peaking amp is Class C and can be set using "Vq" and "xVm") text box entries
- Different tuning conditions can be set using ZT,RL

Notes:

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Doughnut (-2)



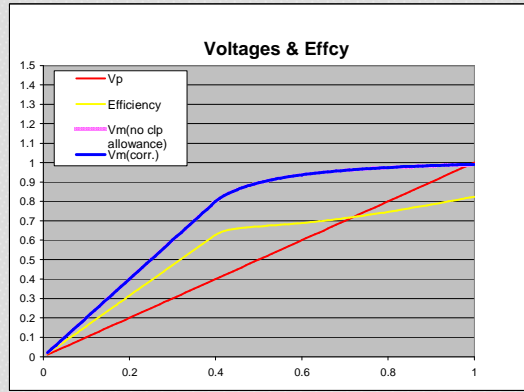
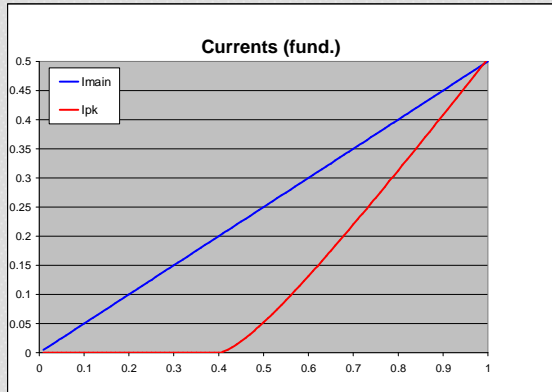
Vknee	0.01	main amp	Vq	0.	ZT=	2	Calculate
Vdc	1	Peaking amp	XMPA	2	RL=	1	
			Vq	-4	(X Vs)	1	
					PUF(dB)=	-1.77	

- Obvious solution to low PPA current is to increase the periphery compared to MPA ("X MPA" textbox)
- Although in principle this does not require higher drive to the PPA, in practice a larger device will have lower gain and higher matching Q factor
- The increased power of the PPA is "wasted"

Notes:

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Doughnut (-3)



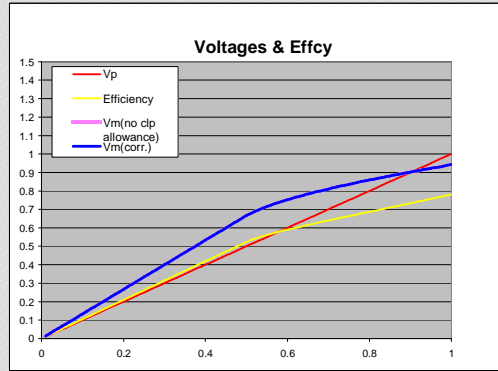
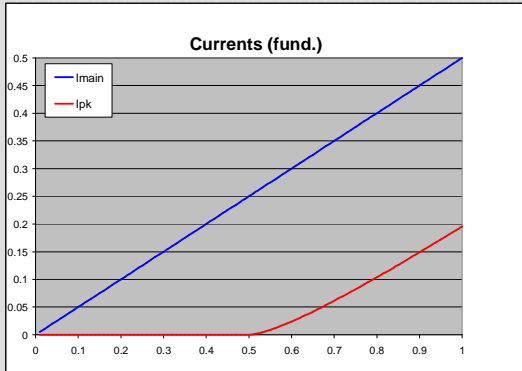
Vknee	0.01	main amp	Vq	0.	ZT=	2	Calculate		
Vdc	1	Peaking amp	XMPA	1	(X Vs)	2		RL=	1
		Vq	-8	PUF(dB)=	0				

- Alternative approach is to have *asymmetrical* drive, higher input to PPA and then PPA at lower bias
- This can restore linear performance (almost) but requires a 6dB offset between MPA and PPA
- This is probably too much loss of gain at GHz frequencies (ie 6dB higher drive power)

Notes:

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Doughnut (-4)



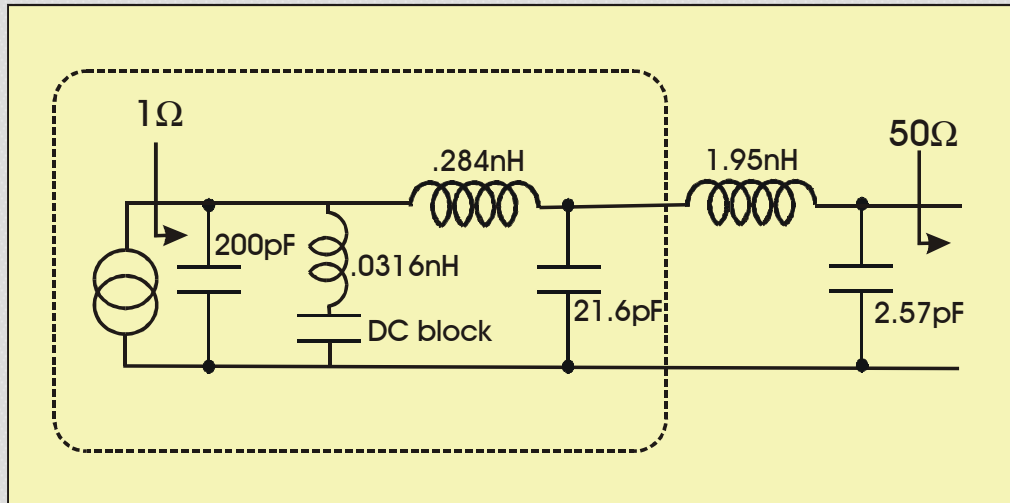
Vknee	0.01	main amp	Vq	0.	ZT=	2	Calculate
Vdc	1	Peaking amp	XMPA	1	RL=	1.5	
			Vq	-5	PUF(dB)=	-1.77	

- Another approach, probably commonly practiced (but not realised?!) is to retune the two PAs
- This can be demonstrated on Doughnut by increasing the value of RL .
- So we are decreasing the MPA load (below the peaking region) and increasing the PPA load
- Efficiency is lower in the breakpoint region; **commonly observed in practice ?!**

Notes:

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DPA design (-1)

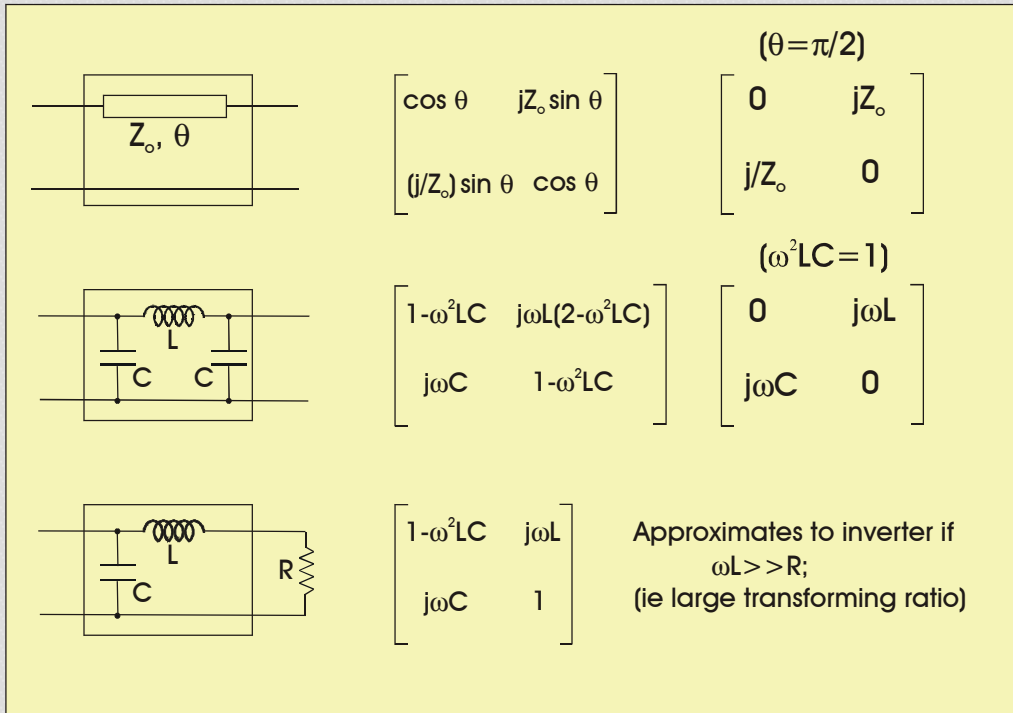


- A typical high power device (LDMOS, GaAs, >50Watt) will require this kind of a matching topology
- The large device output capacitance is shunt resonated and a 2-section (usually Chebchev) network follows
- The shunt resonator and first matching section will usually (and necessarily) be placed inside the package
- We need to examine how well this network inverts!

Notes:

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DPA design (-2)



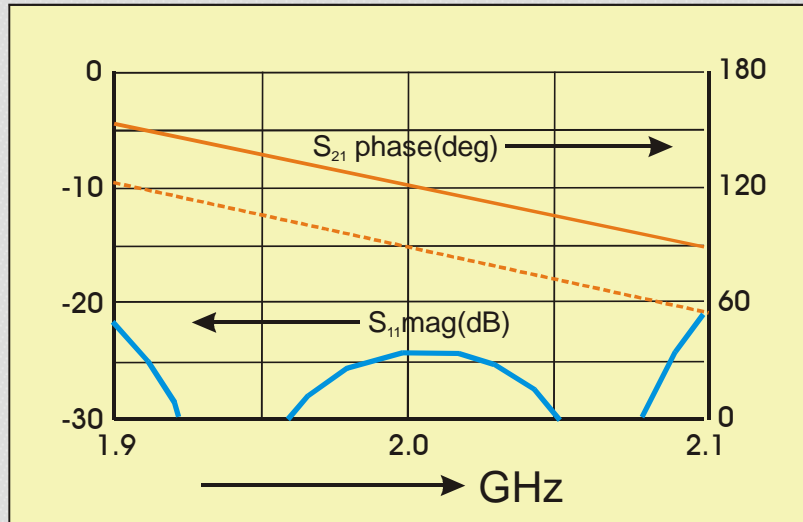
- A $\lambda/4$ line is an ideal impedance inverter at resonance
- High transformation matching networks also behave as inverters!

In order to implement a DPA, the active devices are usually matched to a 50 Ohm environment. The matching networks will themselves behave as inverters.

Notes:

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DPA Design (-3)

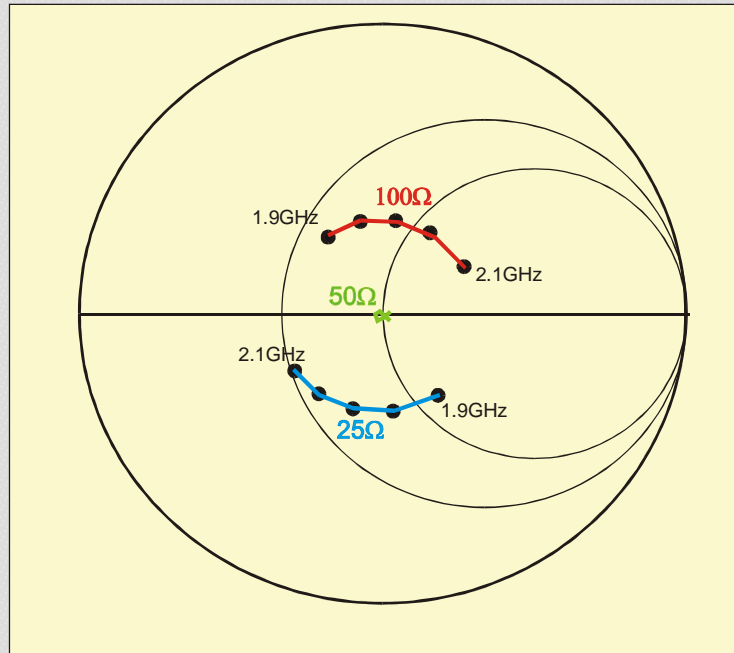


- Although showing an excellent match (< -20 dB ret. Loss) this network has inferior inverting action compared to simpler elements
- The necessary 90 degree phase shift can be restored with a phase “tweak” line section but this further reduces the bandwidth
- Even over 100MHz b/w, the phase deviates by ± 20 degrees (see MWO file doh_2sec)

Notes:

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DPA Design (-4)

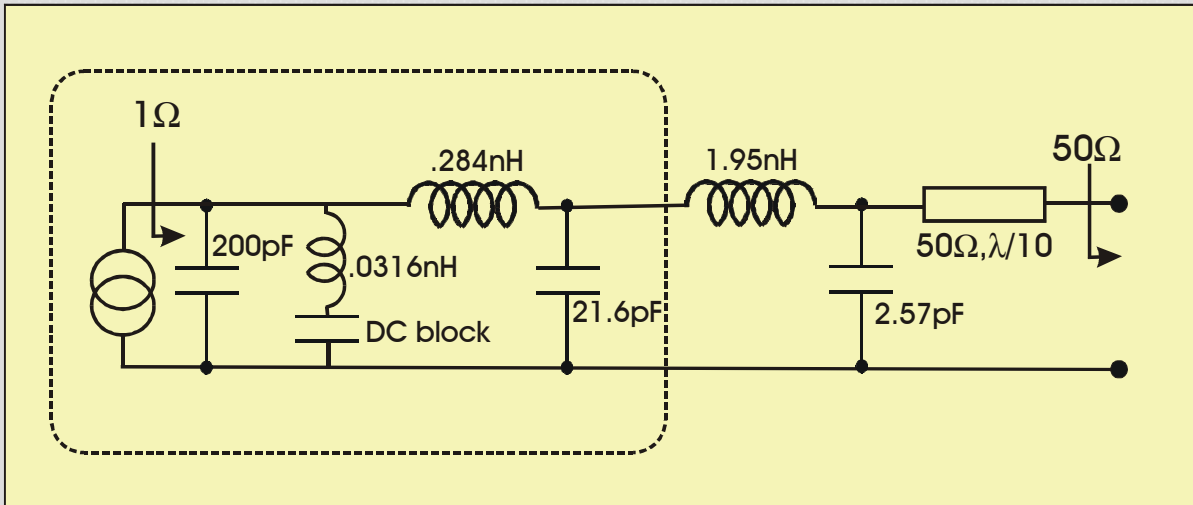


- Impedance trajectory as network termination varies from 25 to 100 Ohm viewed at device plane)
- Double section would imply “non-inversion” but actual impedance trajectory is neither inverting or non-inverting!

Notes:

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DPA Design (-2)

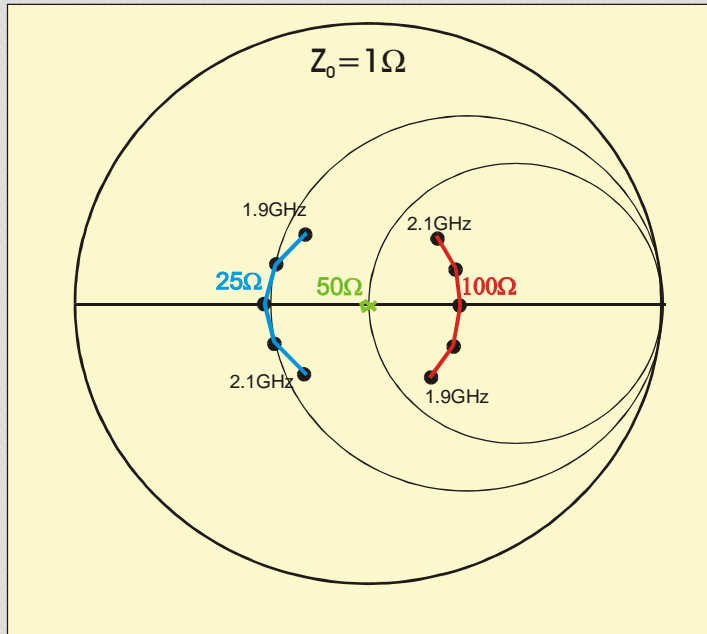


- “Expected” inverting behaviour (= non-inverting for 2-section network) can be restored using a short compensating line length
- This could be viewed as making the network more like a symmetrical (“Pi”) network

Notes:

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DPA Design (-4)

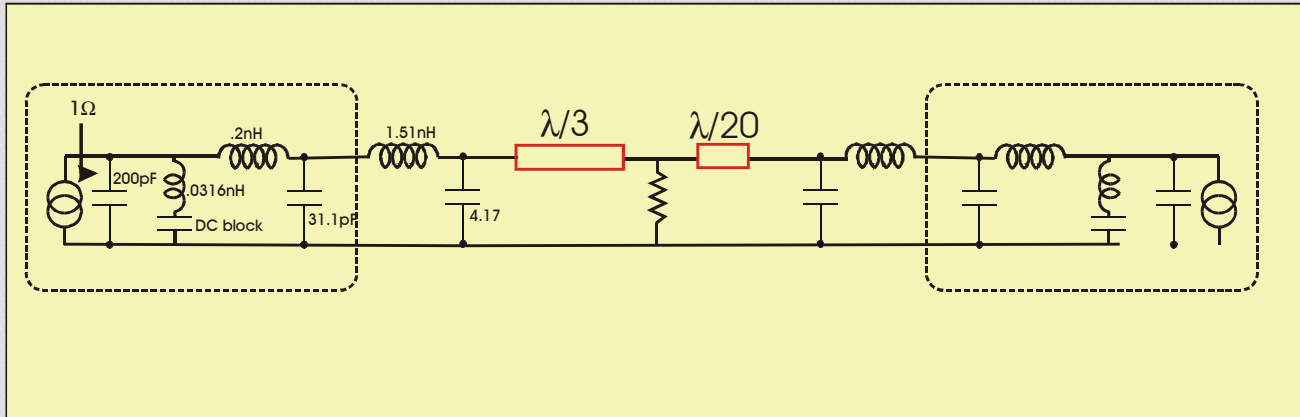


- Non-inverting behaviour can be restored midband using compensatory line length ($\lambda/10$ approx here)
- But double section matching network not nearly so effective in its (non-) inverting properties over design bandwidth!

Notes:

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DPA Design(-5)



- Double matching networks require additional phase “tweaks” in order to get intended DPA action
- Note also, the matching element values have been changed to give more of a maximally flat matching response
- Chebychev networks are harder to “tame” for correct impedance inversion

Notes:

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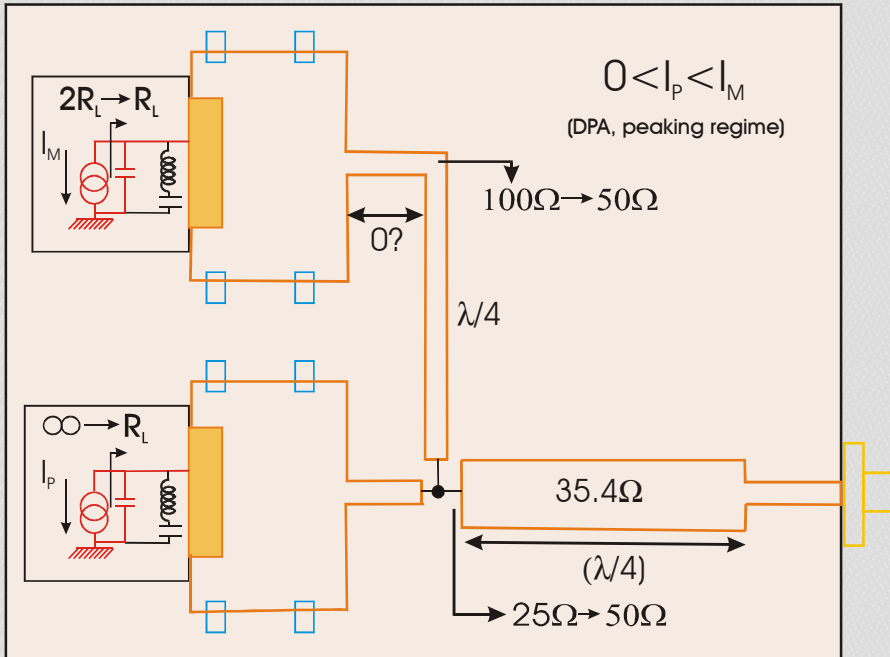
DPA design (-6)

- Bandwidth issues in DPAs need more attention!
- Much published work uses conventional matching networks which have poor inverting properties over 10% bandwidths
- Manufacturers of internally matched devices need to tell us more for DPA design!
- In any event, phase adjustment lines will always be required on both MPA and PPA

Notes:

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Doherty PA Design (-7)



- Typical high power DPA design
- 50Ω "routing" lines can no longer be made of arbitrary, "convenient" lengths due to the inverting requirement

Notes:

Conclusions (-1)

- DPA offers attractive solution for major efficiency improvement in Class AB (quasi-linear) PAs used in higher PAR applications.
- "Quirky" linearity behaviour is not "fundamental" and can often be explained in practice by incorrect control of Peaking PA current
- Classical matching design is at odds with the impedance inversion requirement; more work needed here to realise broader band DPA designs
- Internally matched RF power devices will not necessarily behave well in DPA configurations

Notes:

Conclusions (-2)

- The potential of the Doherty PA is being widely underestimated due to flawed designs based on overly idealistic assumptions
- This applies especially when the bandwidth exceeds about 5% in higher power designs

Notes: