Development of a Concurrent Dual-Band Switch-Mode Power Amplifier Based on Current-Switching Class-D Configuration

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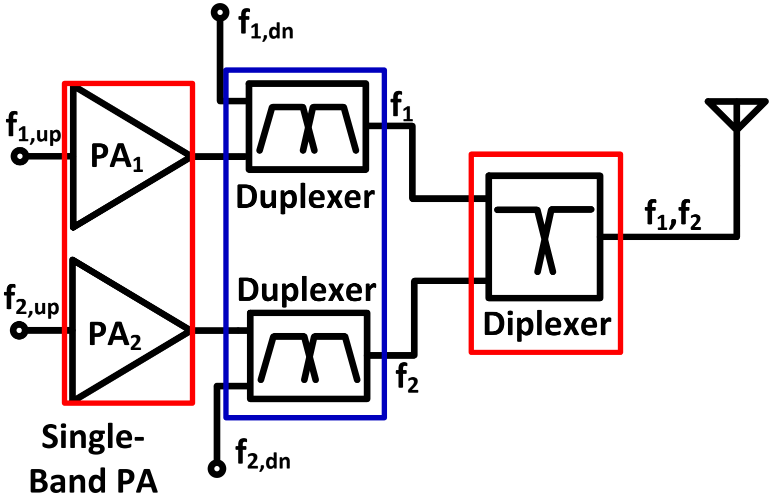
Contents

- Background and Motivation
- Theoretical Analysis of Proposed Concurrent Dual-band Class-D Power Amplifier
- Design Method and Considerations
- Measurement Results and Discussion

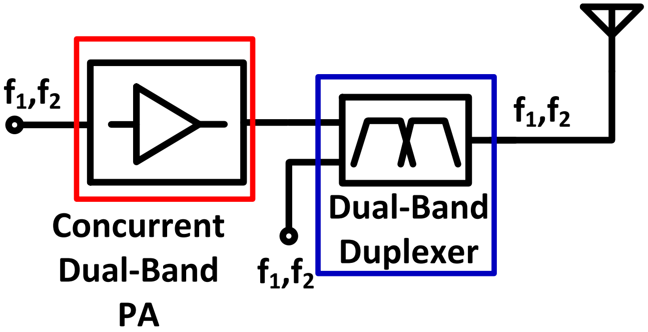
Demand for Concurrent Multi-Band PAs

- Higher data rate (carrier aggregation)
- By using concurrent (multi-)dual-band PAs, we are trying to reduce area, cost, design complexity and increase efficiency as well.



Currently Used TX Schematic for CA

Improve



Proposed TX Schematic for CA

Existing Concurrent Dual-Band PAs

- Linear PAs are used to accommodate the varying envelope of concurrent dual-band signals
- Theoretical Maximum Drain efficiency of Linear PAs

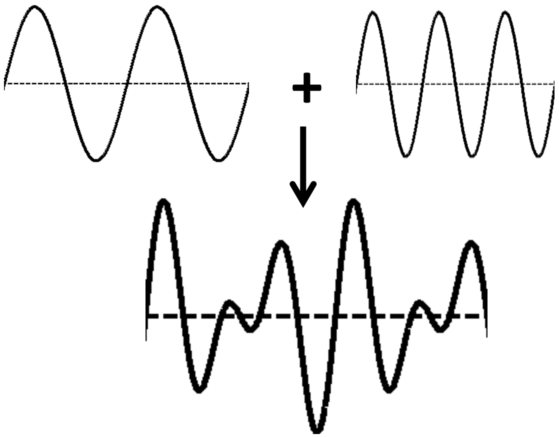
$$\eta = \frac{P_o}{P_{DC}} = \frac{P_{o1} + P_{o2}}{V_{DD} * I_{DC}} = \frac{2 * \frac{1}{2} * \frac{V_{ds,max}}{2\boldsymbol{\alpha}} * \frac{I_{ds,max}}{2\boldsymbol{\alpha}}}{V_{ds,max}/2 * I_{ds,max}/2} = 25\%$$

Concurrent Dual-Band Class A

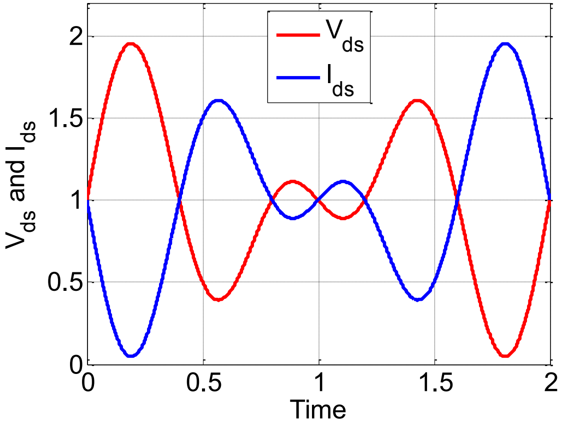
$$\eta = \frac{P_o}{P_{DC}} = \frac{P_{o1} + P_{o2}}{V_{DD} * I_{DC}} = \frac{2 * \frac{1}{2} * \frac{V_{ds,max}}{2\boldsymbol{\alpha}} * \frac{I_{ds,max}}{\boldsymbol{\beta}}}{V_{ds,max}/2 * I_{ds,max}/\boldsymbol{\gamma}} = 62\%$$

Concurrent Dual-Band Class B

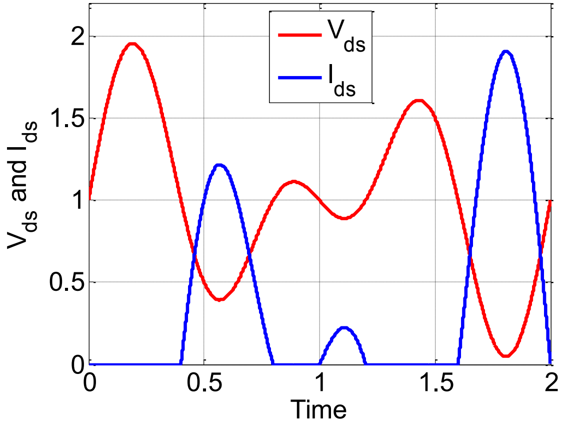
Note: α, β, γ are about 2, 4, and 5 respectively in most cases (non-harmonic related frequency ratio).



Input Waveform



Concurrent Dual-Band Class A



Concurrent Dual-Band Class B

Z. Zhang, MWCAS, 2015.
X. Chen, MTT 2013

Existing Concurrent Dual-Band PAs in Literatures

◆ Switchless Dual-Band PA: IMs not considered

	Frequency (GHz)	Pout @ Single Mode	Pout @ Concurrent Mode	Efficiency @ Single Mode	Efficiency @ Concurrent Mode	Signal
IET MAP, 2011	1.96/3.5	39.5/40 dBm	39.5 dBm	60%/55%	49%	CW
WAMICON, 2012	1.8/2.4	35.5/35.5 dBm	33 dBm	34.7%/32.7%	24.7%	WCDMA/LTE
T-MTT, 2012	1.8/2.4	36.2/34.5 dBm	33.4 dBm	54.2%/40.7%	34.4%	LTE/WiMax
TCAS I, 2014	0.85/2.33	44/42.5 dBm	31.4 dBm	60%/53%	26.7%	CW/LTE

◆ Linear Concurrent Dual-Band PAs: IMs shorting

	Frequency (GHz)	Pout @ Single Mode	Pout @ Concurrent Mode	Efficiency @ Single Mode	Efficiency @ Concurrent Mode	Signal
T-MTT, 2012	1.9/2.6	41.5/41.2 dBm	39.5 dBm	73%/67.5%	56%	CW
IMS, 2014	1.9/2.6	44.5/44 dBm	42 dBm	65%/60%	53%	CW

◆ Switch-Mode Concurrent Dual-Band PAs?

- Higher concurrent-mode output power
- Higher concurrent-mode efficiency

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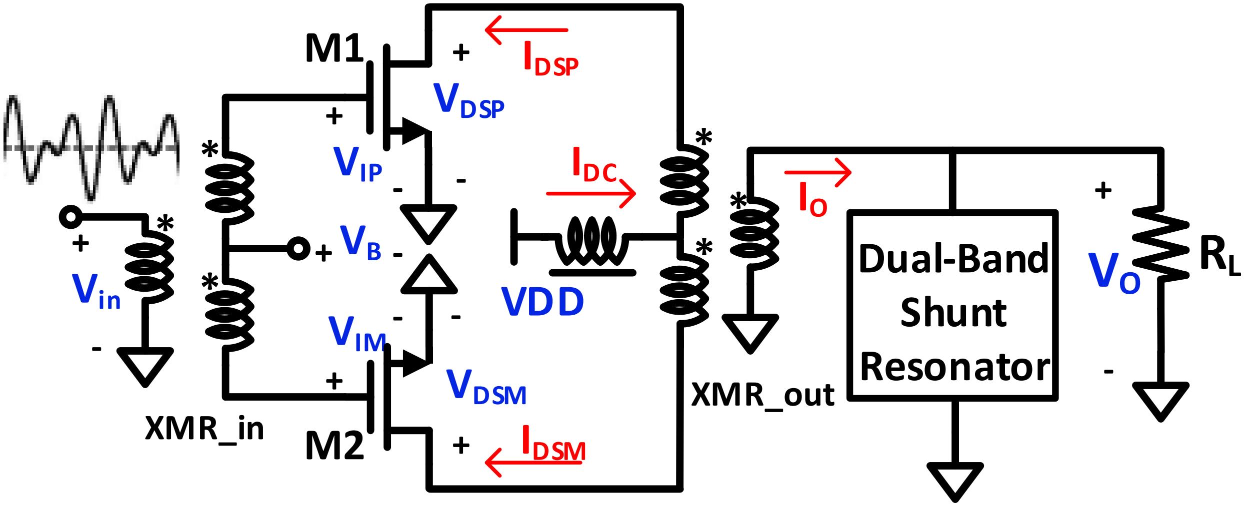
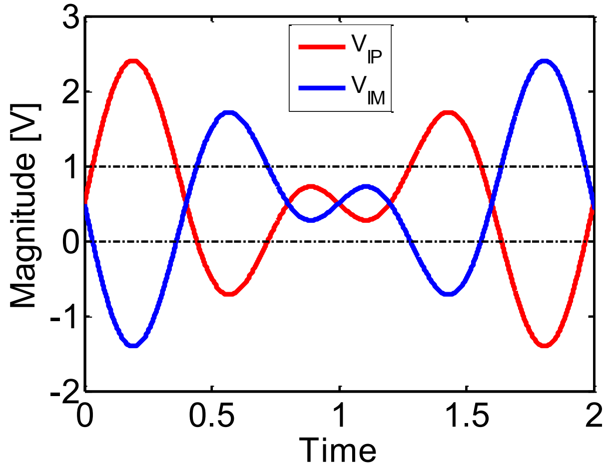
Proposed Concurrent Dual-Band Current-Switching Class-D PA





Idealized analysis: zero knee voltage, zero threshold voltage

- **Input signal**

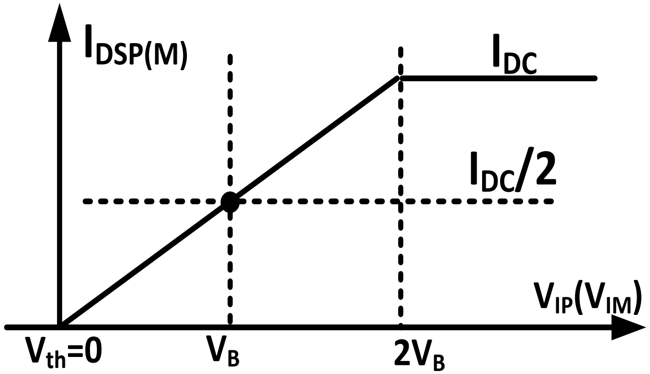
$$V_{IP}(t) = A\,sin(\omega_1 t) + A\,sin(\omega_2 t) + V_B$$

$$V_{IM}(t) = A\,sin(\omega_1 t + \pi) + A\,sin(\omega_2 t + \pi) + V_B$$

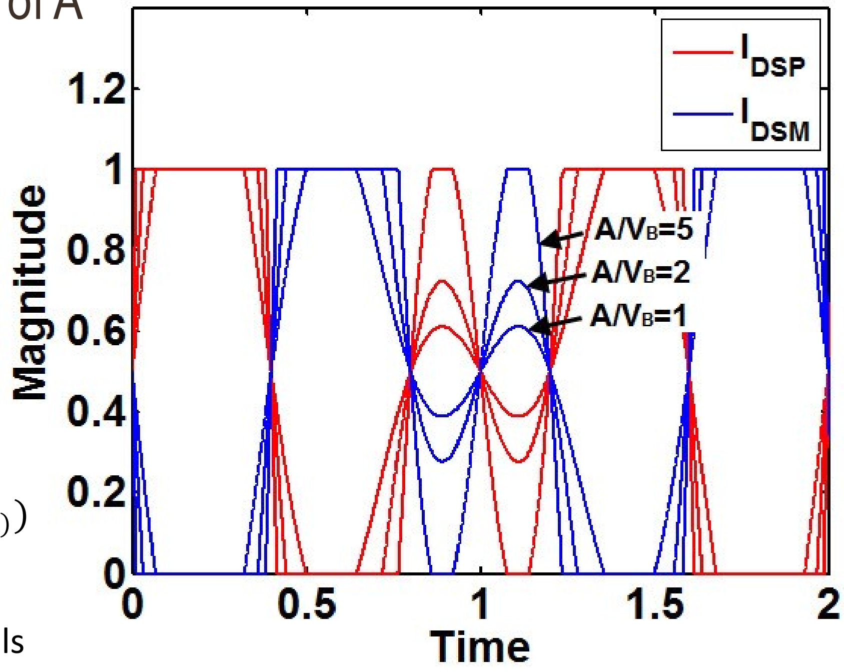
Harmonic related frequencies, ω_2/ω_1=2, 3, are avoided.

- **Transistor transfer function**

$$I_{DSP(M)}(t) = \begin{cases} 0, & V_{IP(M)}(t) < V_{th} = 0 \\ \frac{I_{DC}}{2V_B} V_{IP(M)}(t), & V_{th} < V_{IP(M)}(t) < 2V_B \\ I_{DC}, & V_{IP(M)}(t) > 2V_B \end{cases}$$



- **Assuming the PA is overdriven, I_{DC} is fixed**
  - Determined by V_{DD} and R_L, independent of A
  - I_{DC} can be accommodated by changing V_{DD} or R_L when V_B changes

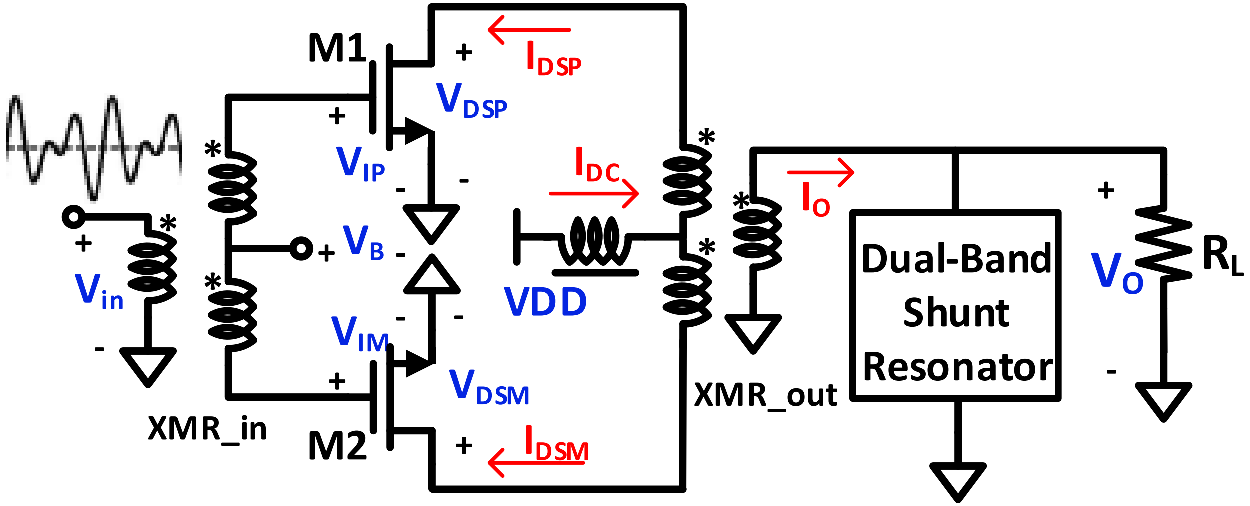


- **Drain Current and Output Current**

$$I_0 = I_{DSP} - I_{DSM}$$

$$I_o(t) \approx \sum_{n=0}^{N} \sum_{m=0}^{M} I_{(m,n)} * \sin\left((m\omega_1 \pm n\omega_2)t + \theta_{(m,n)}\right)$$

Where $I_{(0,0)}, I_{(0,1)}, I_{(1,0)}$ represent DC and two fundamentals respectively.



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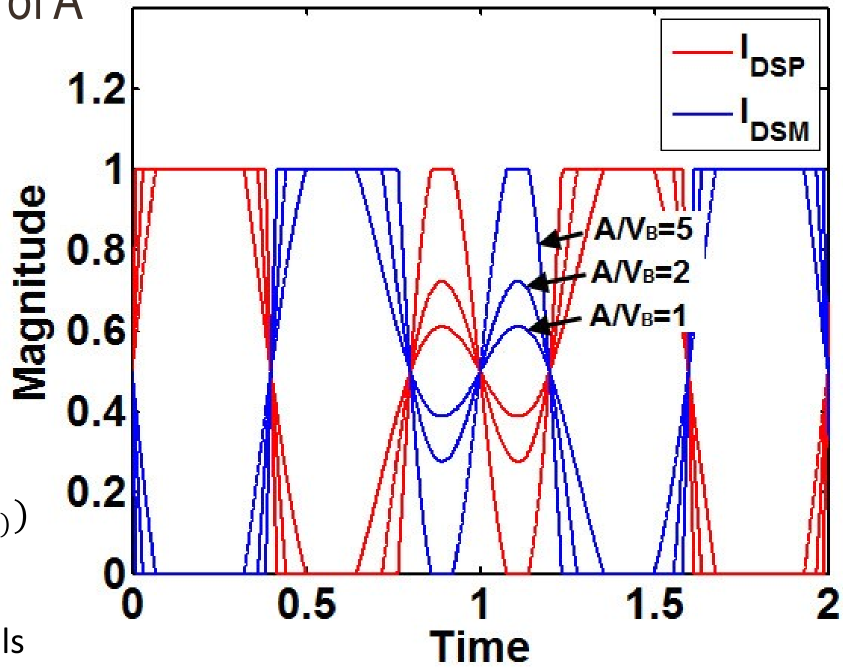

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Where $I_{(0,0)}$, $I_{(0,1)}$, $I_{(1,0)}$ represent DC and two fundamentals respectively.

Output Voltage and Drain Voltage

$$V_o(t) = R_L\left(I_{(1,0)}\sin\left(\omega_1 t + \theta_{(1,0)}\right) + I_{(0,1)}\sin\left(\omega_2 t + \theta_{(0,1)}\right)\right)$$

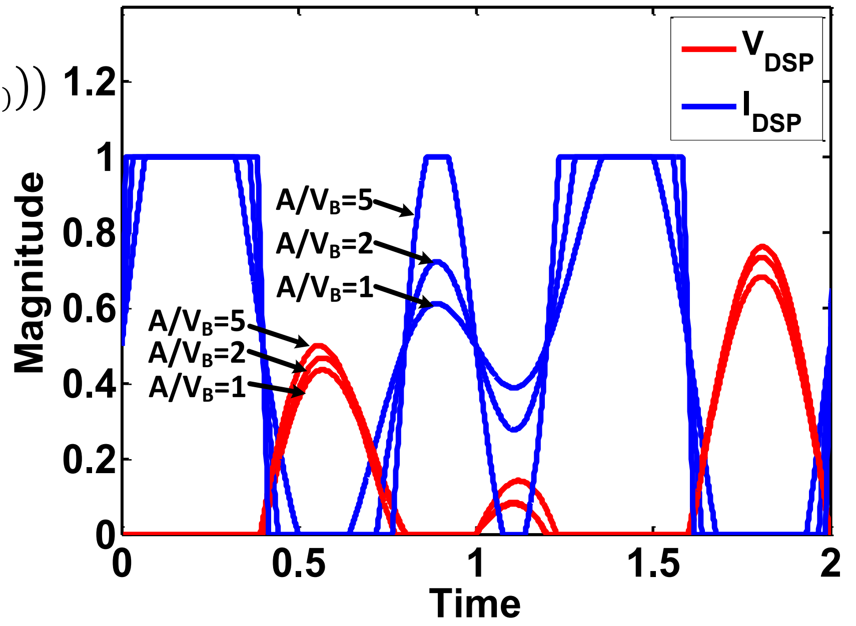
$$V_{DSP(M)}(t) = 0.5\left(|V_o(t)| \pm V_o(t)\right)$$

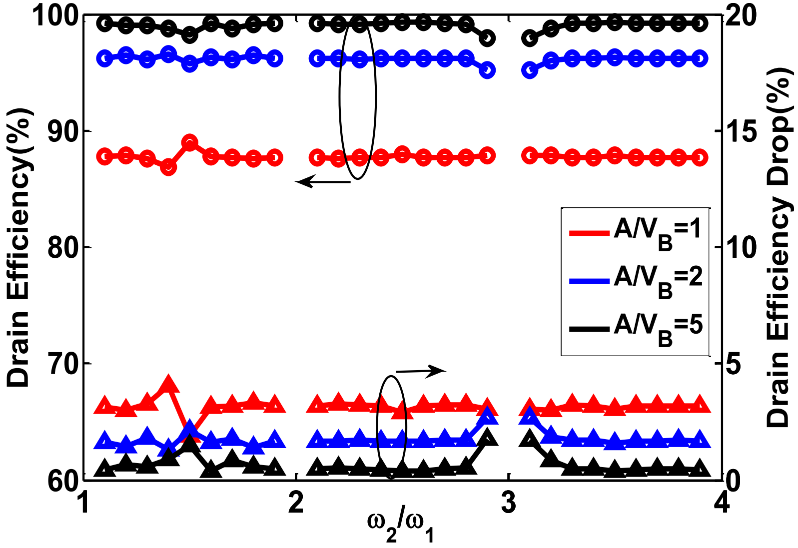
Drain Efficiency

$$V_{DD} = \frac{1}{T}\int_0^T 0.5\left(V_{DSP}(t) + V_{DSM}(t)\right)dt$$

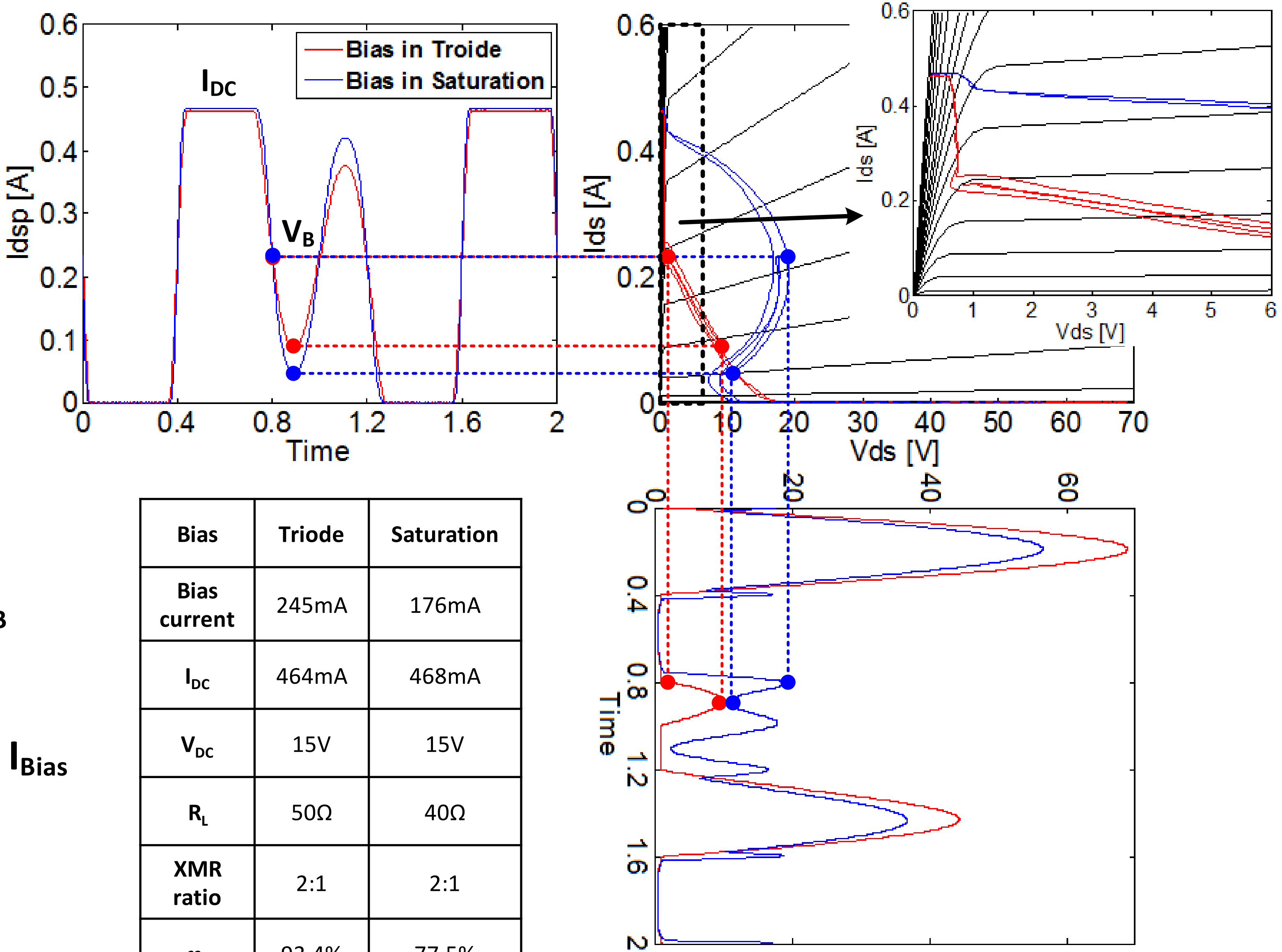
$$\eta = \frac{P_{RF}}{P_{DC}} = \frac{\left(I_{(0,1)}^2 + I_{(1,0)}^2\right)R_L}{2\left(V_{DD}I_{DC}\right)}$$

What will happen with non-zero knee voltage?

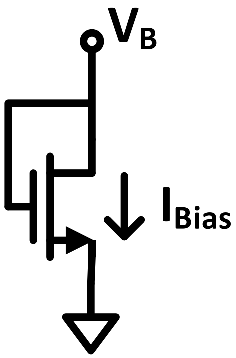




Non-Zero Knee Voltage



Bias	Triode	Saturation
Bias current	245mA	176mA
I_{DC}	464mA	468mA
V_{DC}	15V	15V
R_L	50Ω	40Ω
XMR ratio	2:1	2:1
η	93.4%	77.5%



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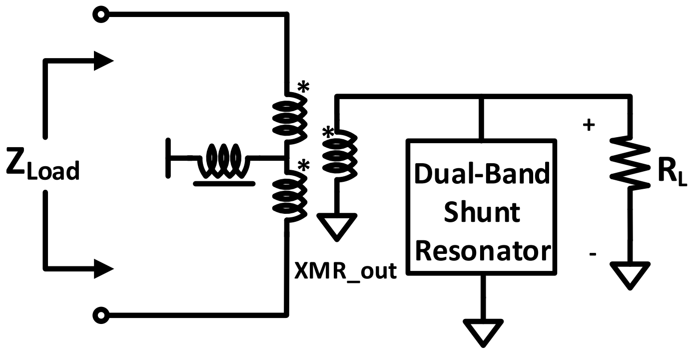
Design Method

Ideal transformer and shunt resonator provides:

- Z_{Load} = Ideal open @ even harmonics and IMs
- Z_{Load} = Ideal short @ odd harmonics and IMs
- Z_{Load} = R_{opt} @ fundamentals

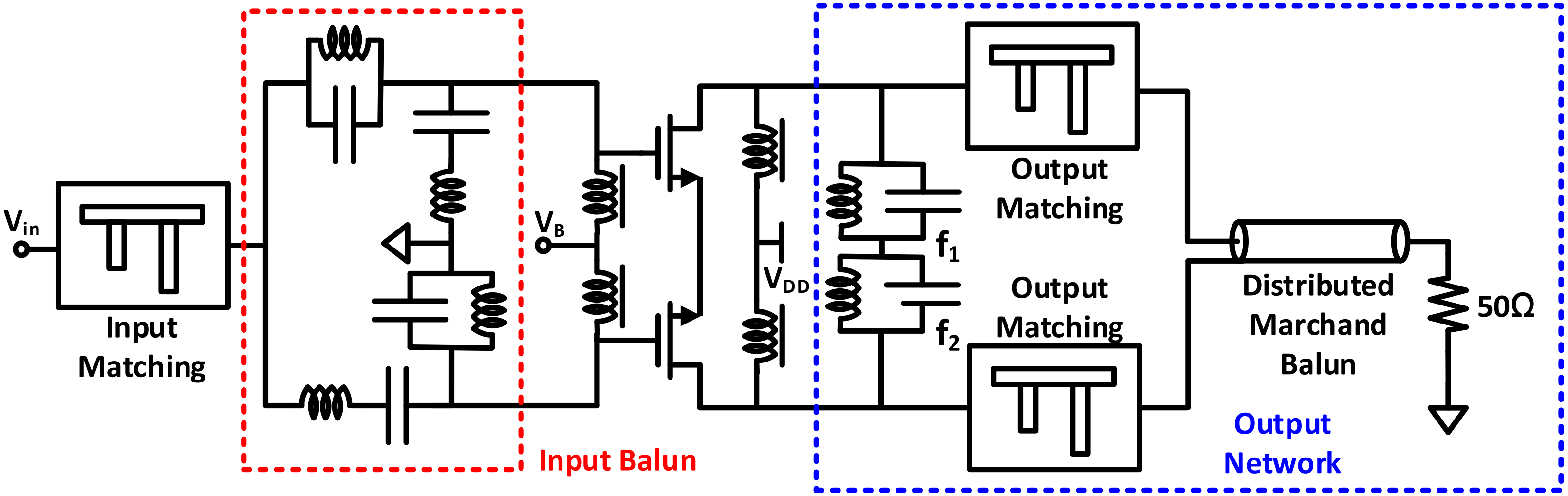
Frequency	Order of Nonlinearity	I_{DSP} (A)	V_{DSP} (V)
DC	0	0.5	0.155
$\omega_{1(2)}$	1	0.38	0.19
$\omega_2 \pm \omega_1$	2	0	0.1
$2\omega_{1(2)}$	2	0	0.04
$2\omega_{1(2)} - \omega_{2(1)}$	3	0.09	0
$2\omega_{1(2)} + \omega_{2(1)}$	3	0.1	0
$3\omega_1$	3	0.02*	0
$3\omega_2$	3	0.008*	0



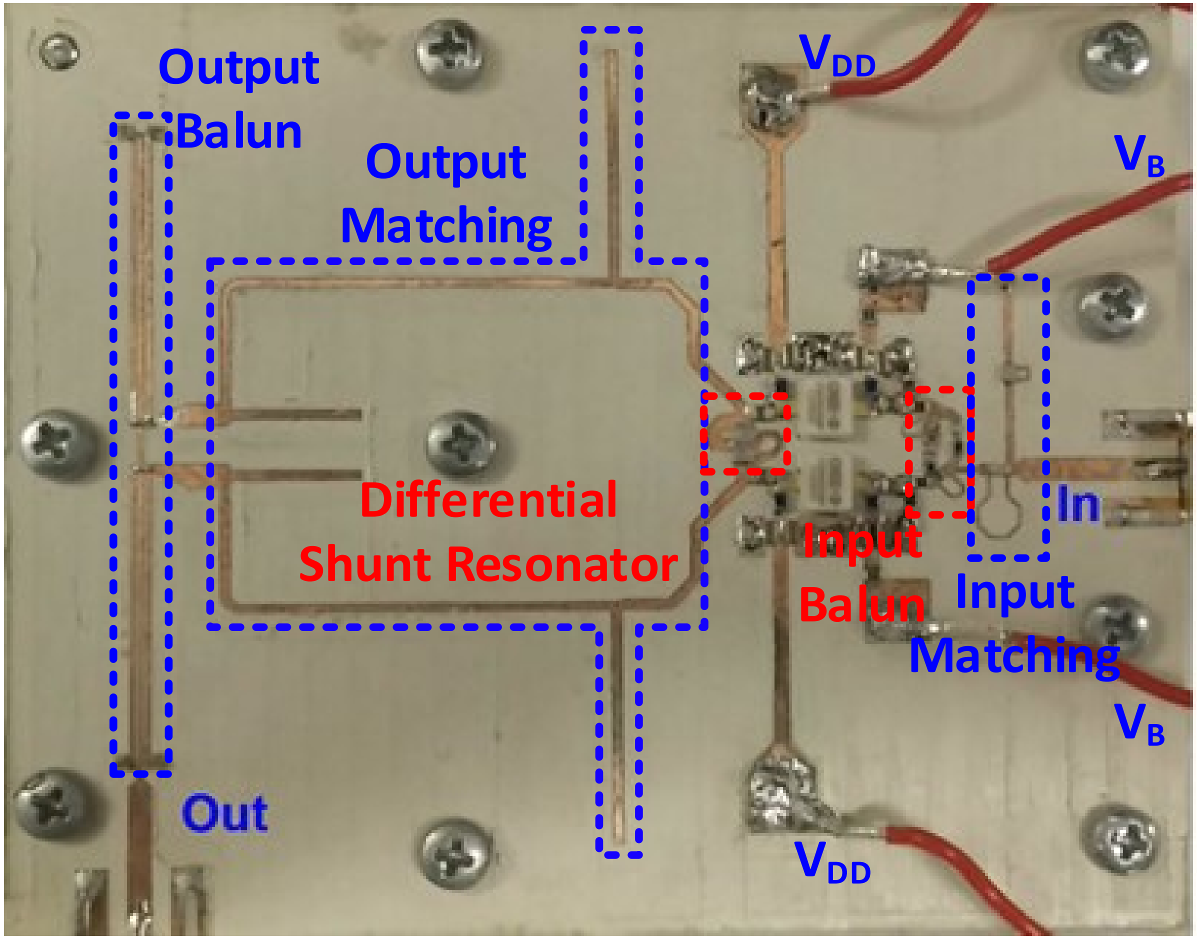
Ideal Load Network

Implementation Considerations

- **Output network target:**
  - Z_{opt} @ fundamentals;
  - high impedance @ even-order harmonic and IM (especially 2nd-order);
  - low impedance @ odd-order harmonic and IM
- **C_{out}**
  - Differential: absorbed in to dual-band shunt resonator
  - Common-mode: needs to be resonated out by the output network



Board Layout



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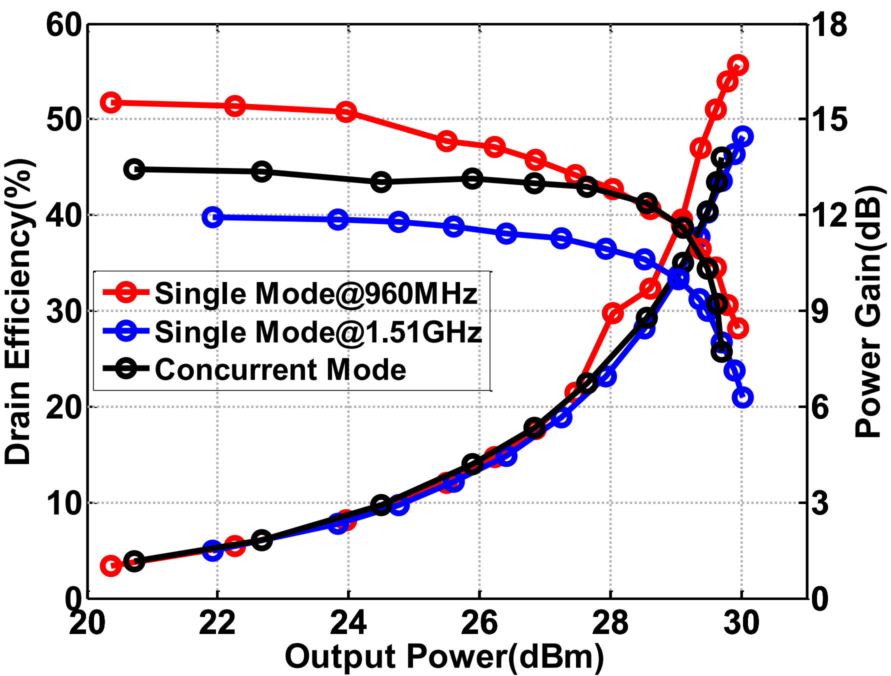
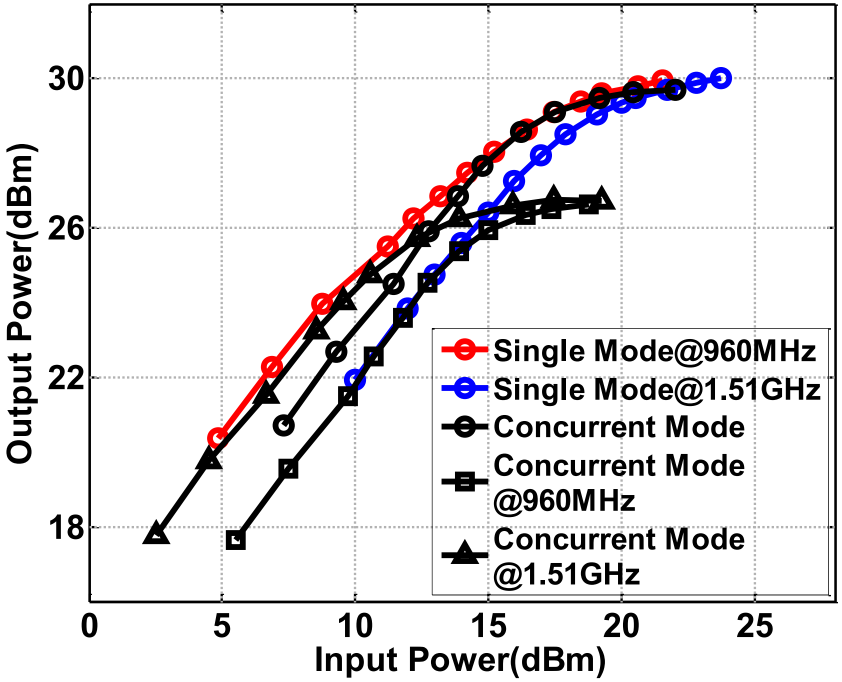
Measurement Results

- **Single Mode**
  - Low band: $\eta = 55.6\%$ @ Pout=30dBm; 6dB over drive
  - High band:$\eta = 48.2\%$ @ Pout=30dBm; 6dB over drive
- **Concurrent Dual-Band Mode**
  - $\eta = 46\%$ @ Pout=29.7dBm; 6dB over drive





Comparison to State of Art Concurrent Dual-Band PAs

- Minimum drain efficiency drop: 9.6% and 2.2%
- Minimum output power drop: 0.3dB
- Efficiency Improvement

	f (GHz)	Pout (dBm) @ Single Mode	Pout (dBm) @ Concurrent Mode*	Efficiency @ Single Mode	Efficiency @ Concurrent Mode**	Signal
IET MAP, 2011	1.96/3.5	39/40	36.5	57%/49.5% ‡	44.1% ‡	CW
WAMICON, 2012	1.8/2.4	35.5/35.5	33	34.7%/32.7% ‡	24.7%	WCDMA/LTE
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TCAS I, 2014	0.85/2.33	44/42.5	31.4	60%/53% †	26.7% †	CW/LTE***
T-MTT, 2012	1.9/2.6	41.5/41.2	39.5	73%/67.5% †	56% †	CW
This Work	0.96/1.51	30/30	29.7	55.6%/48.2% †	46% †	CW

* Total output power, ** Total efficiency, *** CW for single mode, LTE for concurrent mode, † Drain efficiency, ‡ PAE

Acknowledgements

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Thank You

- [1] K. Rawat, F. Ghannouchi, "Dual-band matching technique based on dual-characteristic impedance transformers for dual-band power amplifiers design", IET Microw. Antennas Propag., 2011
- [2] P. Saad, et al, “Concurrent dual-band GaN-HEMT power amplifier at 1.8 GHz and 2.4 GHz,” *2012 IEEE WAMICON*, pp. 1-5, Apr. 2012.
- [3] P. Saad, et al, “Design of a Concurrent Dual-Band 1.8-2.4-GHz GaN-HEMT Doherty Power Amplifier,” *IEEE Trans. Microwave Theory & Tech.*, vol. 60, no. 6, pp. 1840-1849, Apr. 2012.
- [4] Wenhua Chen, …, F. Ghannouchi, "A Concurrent Dual-Band Uneven Doherty Power Amplifier with Frequency-Dependent Input Power Division", TCAS I, 2014.
- [5] Xiaofan Chen, …, F. Ghannouchi, "Enhanced Analysis and Design Method of Concurrent Dual-Band Power Amplifiers With Intermodulation Impedance Tuning", TMTT, 2013
- [6] Xiaofan Chen, Wenhua Chen, …, F. Ghannouchi, "A Concurrent Dual-band 1.9-2.6-GHz Doherty Power Amplifier with Intermodulation Impedance Tuning", IMS 2014