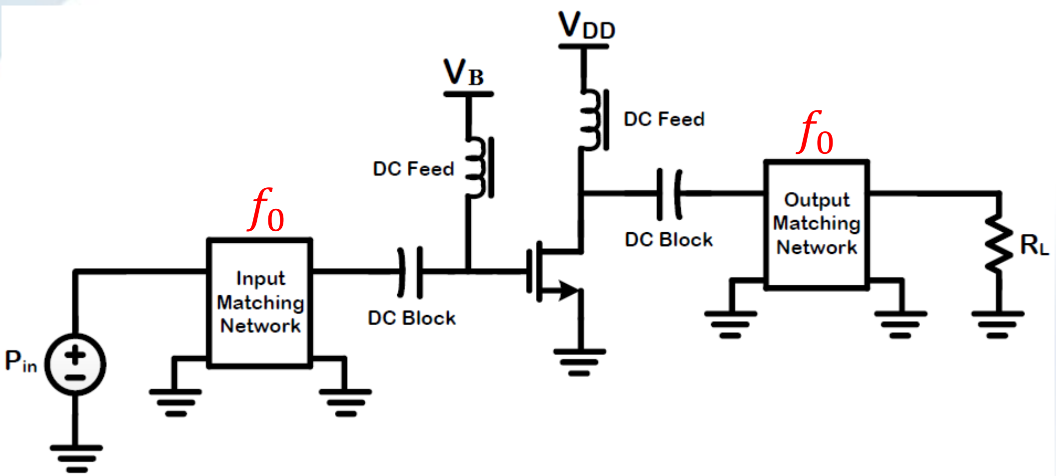
Class J Power Amplifiers

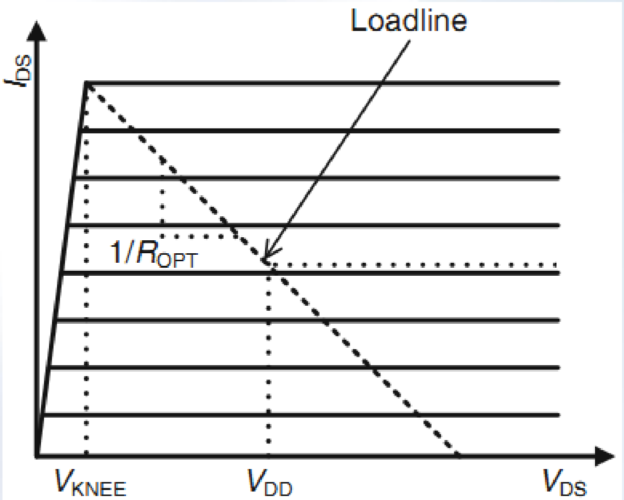
Overview

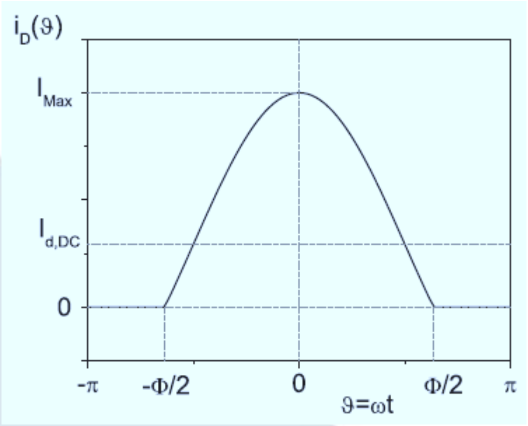
- Review
  - Tuned Load Power Amplifiers (TLPAs)
  - Harmonically Tuned Power Amplifiers (HTPAs)
- Second Harmonic Tuning Theory
- Class J Family
  - Wide-Band Designs
  - Dual-Band Designs
  - Back-Off Efficiency Improvement

Tuned Load Power Amplifiers (TLPAs)

- TLPAs: Class B, Class AB, …





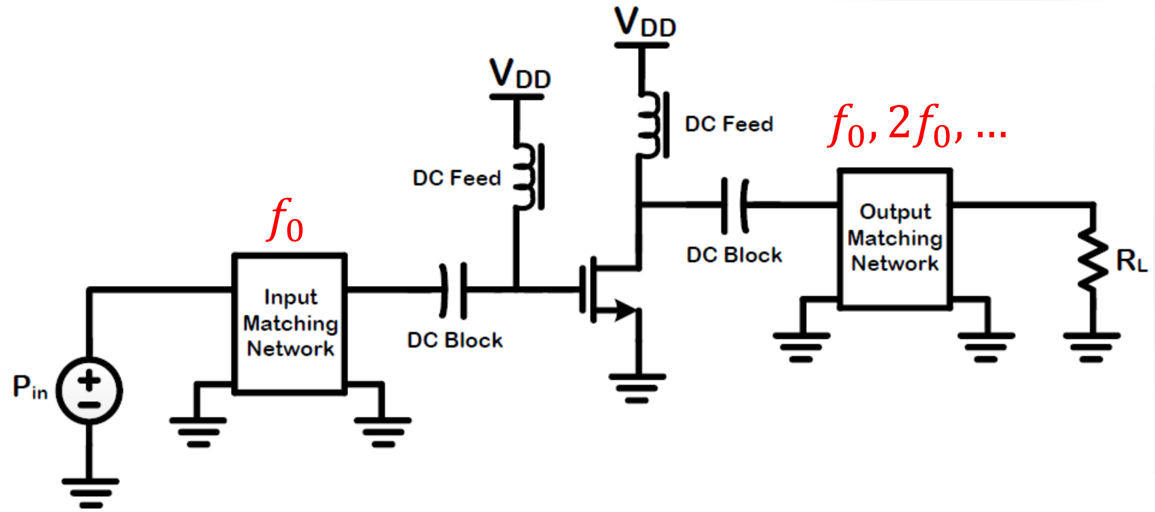


$$i_d(\theta) = \begin{cases} \dfrac{I_{max}}{1-\cos\frac{\alpha}{2}}\left(\cos\theta - \cos\frac{\alpha}{2}\right) & -\frac{\alpha}{2} < \theta < \frac{\alpha}{2} \\ 0 & -\pi < \theta < \frac{\alpha}{2}\ ;\ \frac{\alpha}{2} < \theta < \pi \end{cases}$$

$$i_D(t) = I_0 + \sum_{n=1}^{\infty} I_n \cos(n\omega t + \xi_n)$$

$$v_{DS}(t) = V_{DD} - V_{TL}\cos\omega t \qquad V_{TL} = \min[V_{DD} - V_{knee}, V_{BR} - V_{DD}]$$

Harmonicly Tuned Power Amplifiers-Theory



$i_D(t) = I_0 + \sum_{n=1}^{\infty} I_n \cos(n\omega t + \xi_n)$ → Same as TL!

$v_{DS}(t) = V_{DD} - \sum_{n=1}^{\infty} V_n \cos(n\omega t + \psi_n)$ → $V_{knee} \leq v_{DS}(t) \leq V_{BR}$

$$P_{diss} = \frac{1}{T}\int_0^T v_{DS}(t) i_D(t) dt = V_{DD} I_0 - \frac{1}{2}\sum_{n=1}^{\infty} V_n I_n \cos(\phi_n)$$

$$P_{DC} = P_{diss} + P_{out_f} + \sum_{n=2}^{\infty} P_{out_{nf}}$$

$\eta = \frac{P_{out_f}}{P_{DC}} = \frac{P_{out_f}}{P_{diss} + P_{out_f} + \sum_{n=2}^{\infty} P_{out_{nf}}}$ $P_{diss} + \sum_{n=2}^{\infty} P_{out_{nf}} = 0$ → 100% Efficiency

$Y_{L_n} = 0 \text{ or } Z_{L_n} = 0$ $\cos(\phi_n) = 0$

High Frequency HT PAs-Theory

- HTPAs: Class F, Class F^{-1}, J, and High Frequency Class E
- Only three harmonics could be controlled:
  - Device parasitic capacitance
  - Increased circuit complexity and matching losses

$$v_{DS}(t) = V_{DD} - V_1(\cos\omega t - k_2\cos 2\omega t - k_3\cos 3\omega t) \qquad k_2 \equiv \frac{V_2}{V_1}\ ,\quad k_3 = \frac{V_3}{V_1}$$

$$v_{DS_{nor}}(\tau, k_2, k_3) = \frac{v_{DS}(\tau) - V_{DD}}{V_1} = -\cos\tau - k_2\cos 2\tau - k_3\cos 3\tau \qquad \tau = \omega t$$

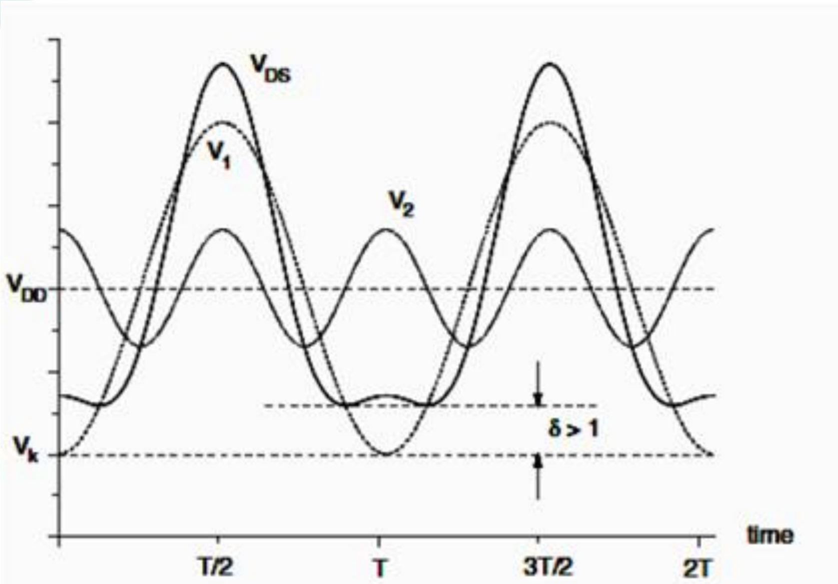
$$g(k_2, k_3) = \frac{V_1}{V_{TL}}$$ → HT Gain

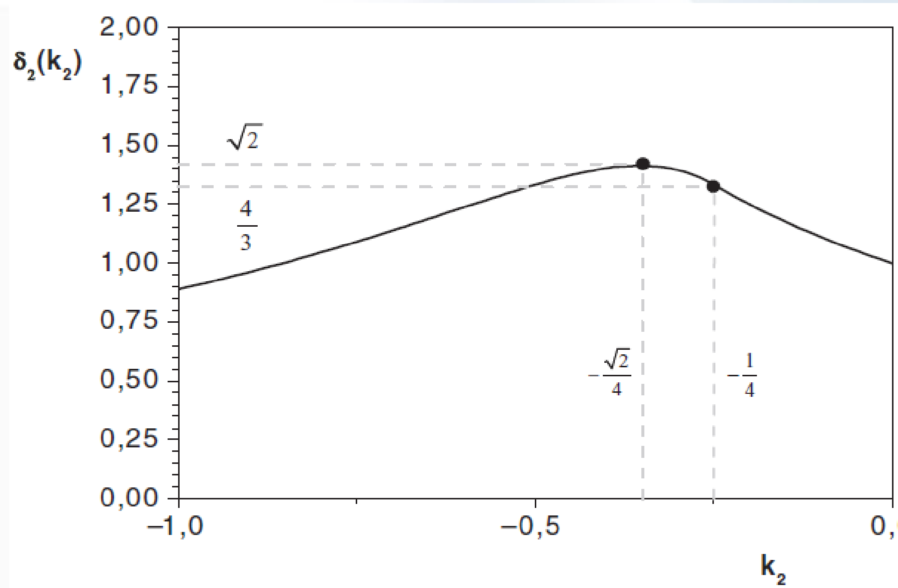
$$p(k_2, k_3) = \frac{\max(v_{DS}(\tau)) - V_{DD}}{V_{DD} - V_{knee}}$$ → HT Peaking

$$\eta_{HT}(k_2, k_3) = g(k_2, k_3)\eta_{TL}$$

High Frequency 2nd HT PAs-Theory

$$v_{DS_{nor}}(\tau, k_2, k_3) = -\cos\tau - k_2 \cos 2\tau$$





$$\frac{\partial v_{DS_{nor}}(\tau,k_2,k_3)}{\partial \tau} = \sin\tau + 2k_2 \sin 2\tau = 0$$

$$\tau_1 = 0 \quad , \quad \tau_2 = \pi \quad , \quad \tau_3 = \cos^{-1}\frac{-1}{4k_2}$$

$$g_2(k_2) \equiv g(k_2, k_3 = 0) = \begin{cases} \dfrac{-1}{k_2 + \frac{1}{8k_2}} & k_2 \le -\frac{1}{4} \\ \dfrac{1}{1+k_2} & -\frac{1}{4} \le k_2 \le 0 \end{cases}$$

$$k_{2_g} = -\frac{1}{2\sqrt{2}} \quad , \quad g_{2_{max}} = \sqrt{2}$$

$$v_{ds}(\theta) = V_{DC} - (V_{DC} - V_{knee})\left(\sqrt{2}\cos\theta - 0.5\cos 2\theta\right)$$

→ 111% Efficiency

High Frequency 2nd HT PAs-Peaking

$$v_{DS_{nor}}(\tau, k_2, k_3) = -\cos\tau - k_2\cos 2\tau$$

$$\frac{\partial v_{DS_{nor}}(\tau,k_2,k_3)}{\partial \tau} = \sin\tau + 2k_2\sin 2\tau = 0$$

$$\tau_1 = 0 \quad , \quad \tau_2 = \pi \quad , \quad \tau_3 = \cos^{-1}\frac{-1}{4k_2}$$

$$p_2(k_2) \equiv p(k_2, k_3 = 0) = \begin{cases} \frac{k_2-1}{k_2+\frac{1}{8k_2}} & k_2 \le -\frac{1}{4} \\ \frac{k_2-1}{k_2+1} & -\frac{1}{4} \le k_2 \le 0 \end{cases}$$

$$k_{2_p} = -\frac{1}{2} \quad \text{و} \quad p_{2_{max}} = 2$$

↓

V_{DD} should be in order of $\frac{V_{BD}}{3}$

Lower Output Power

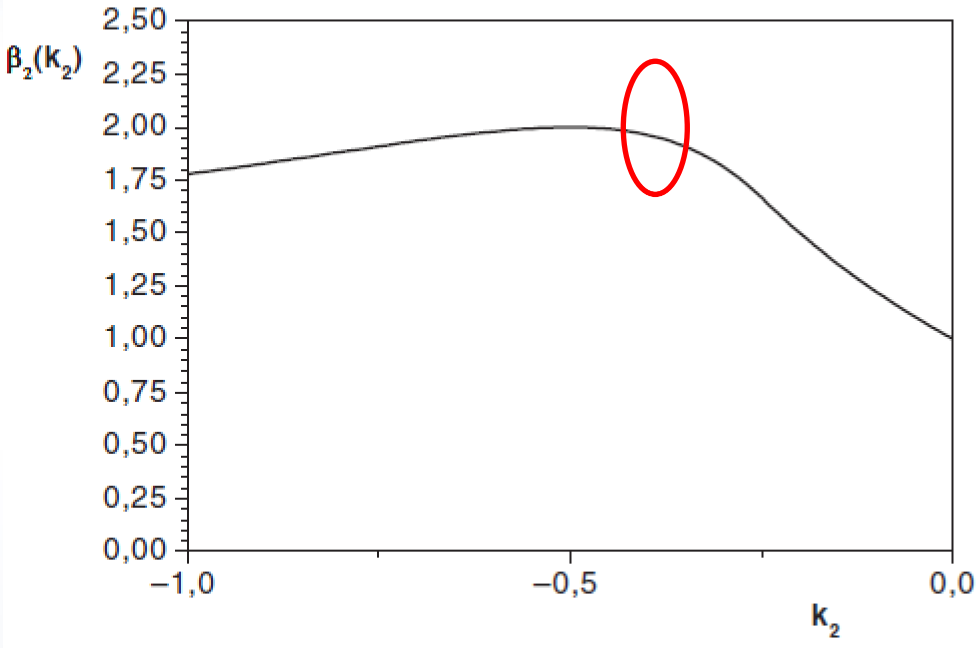
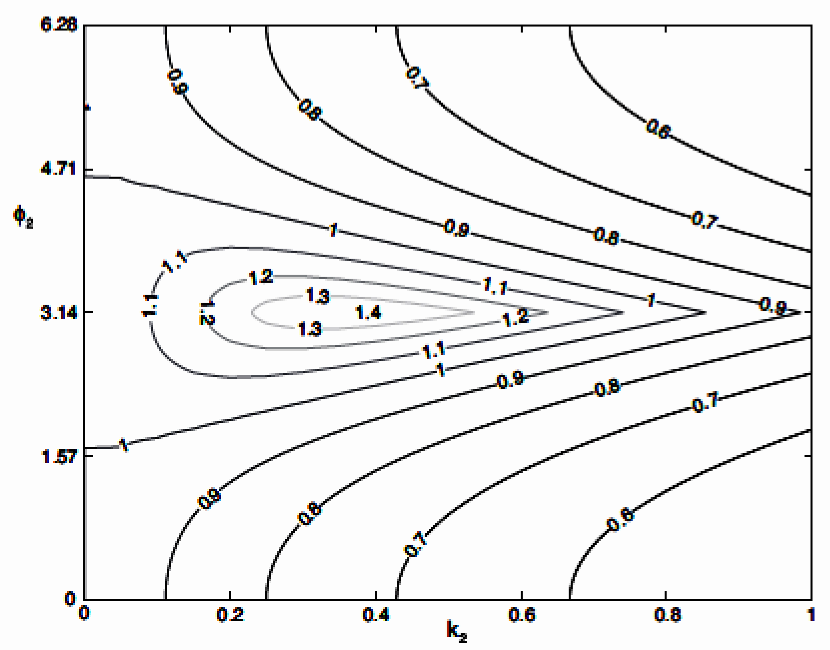


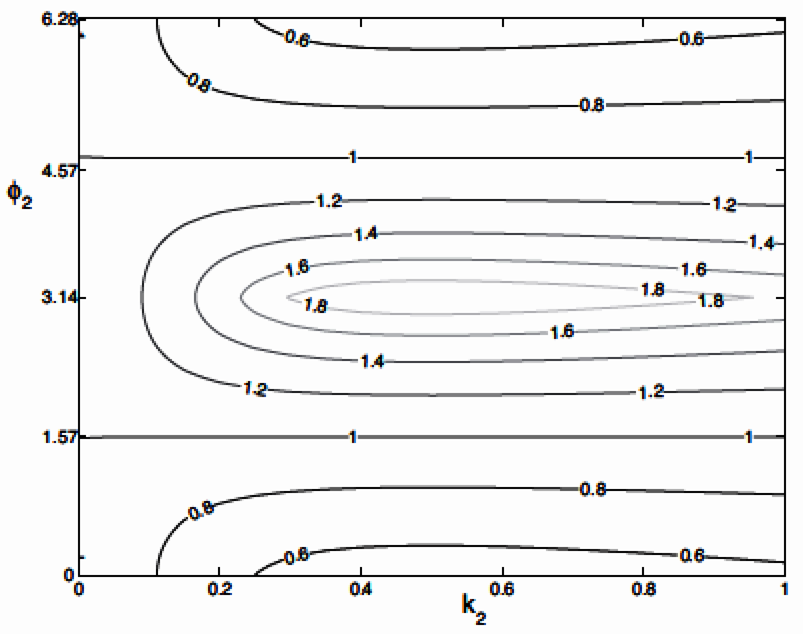
Figure Voltage overshoot function β_2 for different k_2 values.

High Frequency 2nd HT PAs-Complex Termination

$$v_{DS}(t) = V_{DD} - V_1 \cos(\omega t) - V_2 \cos(2\omega t + \psi_2)$$

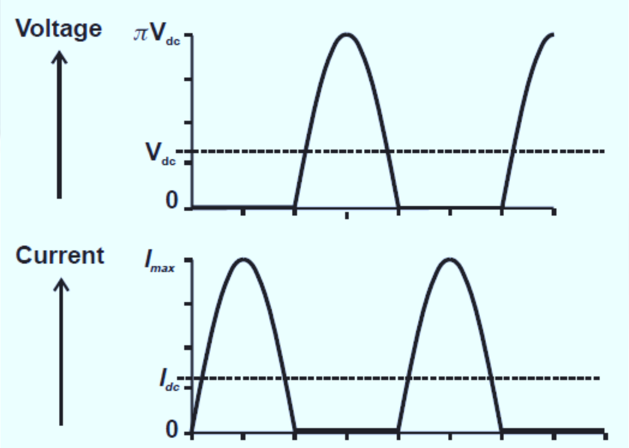


Gain



Peaking

High Frequency 2nd HT PAs-Theory



$$v_{ds}(\theta) = V_{DC} - (V_{DC} - V_{knee})(\sqrt{2}\cos\theta - 0.5\cos 2\theta)$$

↓

$$v_{DS}(t) = V_{DD} - V_1\cos(\omega t + \psi_1) - V_2\cos(2\omega t + \psi_2)$$

$$\alpha = \varphi = \frac{\pi}{2}:$$

$$i_D(\theta) = \frac{I_{Max}}{\pi} + \frac{I_{Max}}{2}\sin\theta - \frac{2I_{Max}}{3\pi}\cos 2\theta + \cdots$$

$$v_D(\theta) = V_{DC} - \frac{\pi V_{DC}}{2}\sin(\theta + \delta) - \frac{2V_{DC}}{3}\cos 2(\theta + \delta) + \cdots$$

$$Z_1 = \frac{\pi V_{DC}}{I_{Max}}\measuredangle\delta \quad , \quad Z_2 = \frac{\pi V_{DC}}{I_{Max}}\measuredangle(2\delta - \pi) \quad \rightarrow \quad \frac{\pi}{4} < \delta < \frac{3\pi}{4}$$

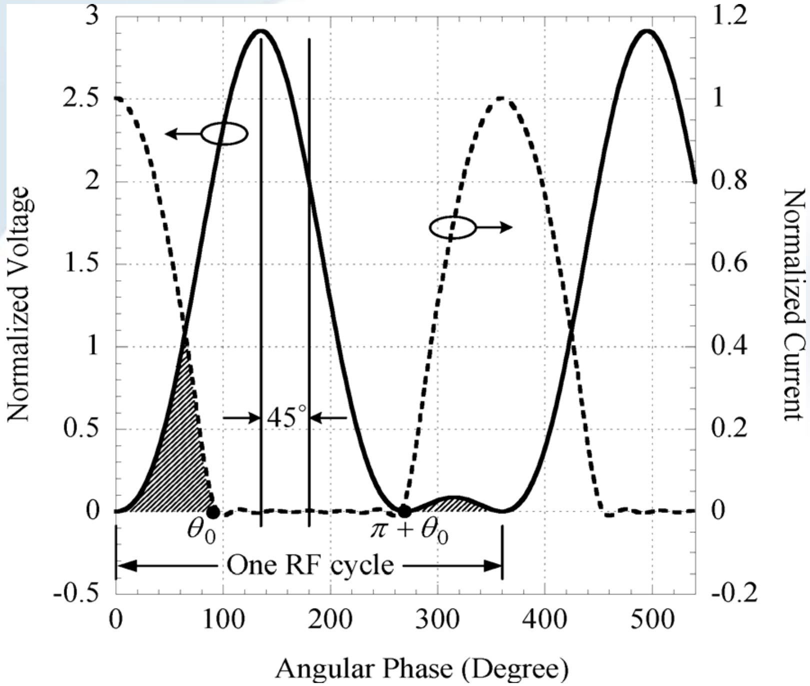
$\delta = \frac{\pi}{4}$, $\delta = \frac{3\pi}{4}$

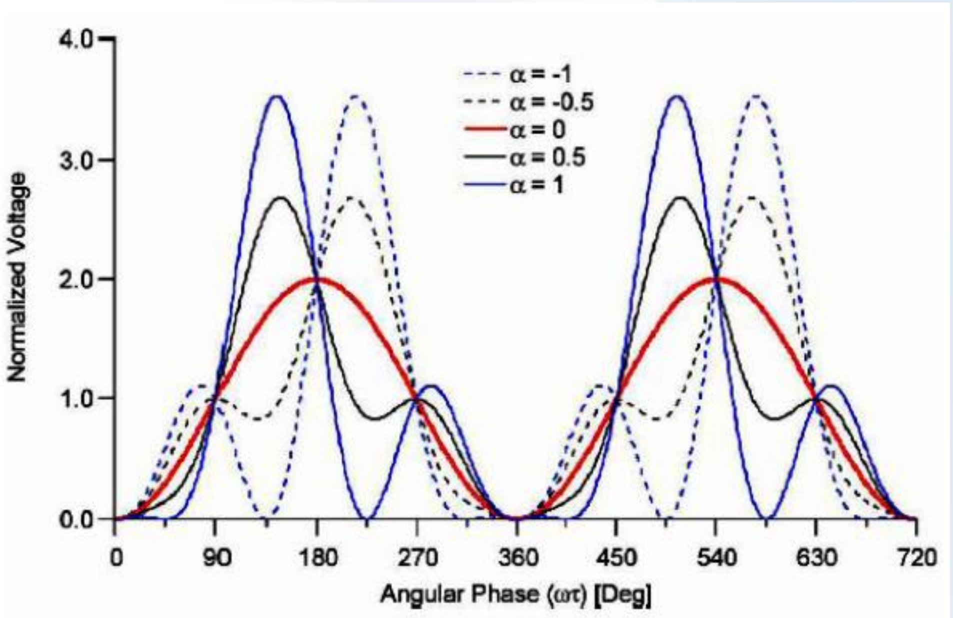
↓ ↓

$Class\ J$, $Class\ J^{-1}$

$$\eta_J = \sqrt{2}\eta_{TL} cos\left(\frac{\pi}{4}\right) = \eta_{TL}$$

Class J Operation -Theory





$$v_{DS}(\theta) = 1 - v_{1r}\cos\theta + v_{1q}\sin\theta + \sum_{n=2}^{\infty} v_{nq}\sin n\theta$$

$$v_{DS}(\theta) = 0 \quad , \quad v'_{DS}(\theta) = 0$$

$$v_{DS}(\theta) = (1 - \beta\cos\theta)(1 - \alpha\sin n\theta), \quad (-1 < \alpha < 1, 0 < \beta < 1)$$

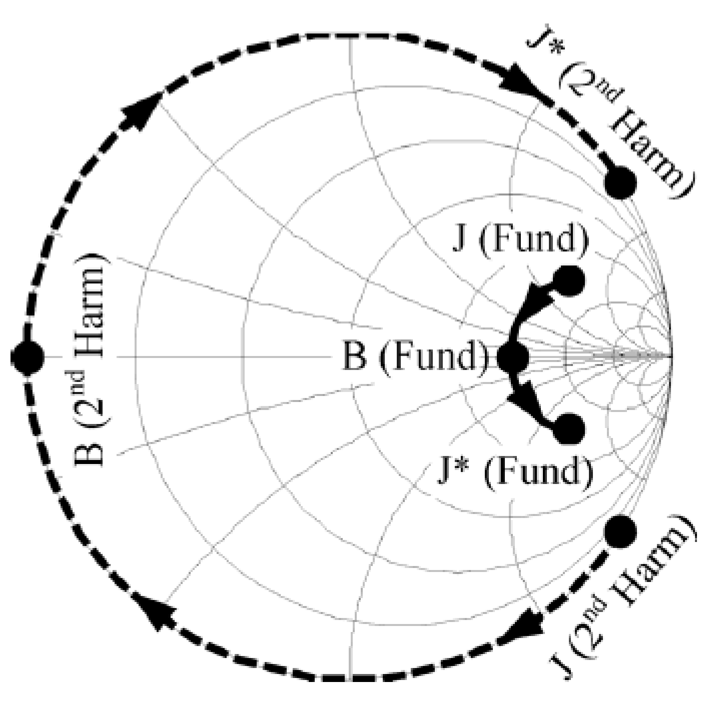
$$v_{d|_J}(\theta) = V_{\mathrm{DC}} - (V_{\mathrm{DC}} - V_K)[\cos(\theta) - \sin(\theta) + 0.5\sin(2\theta)]$$

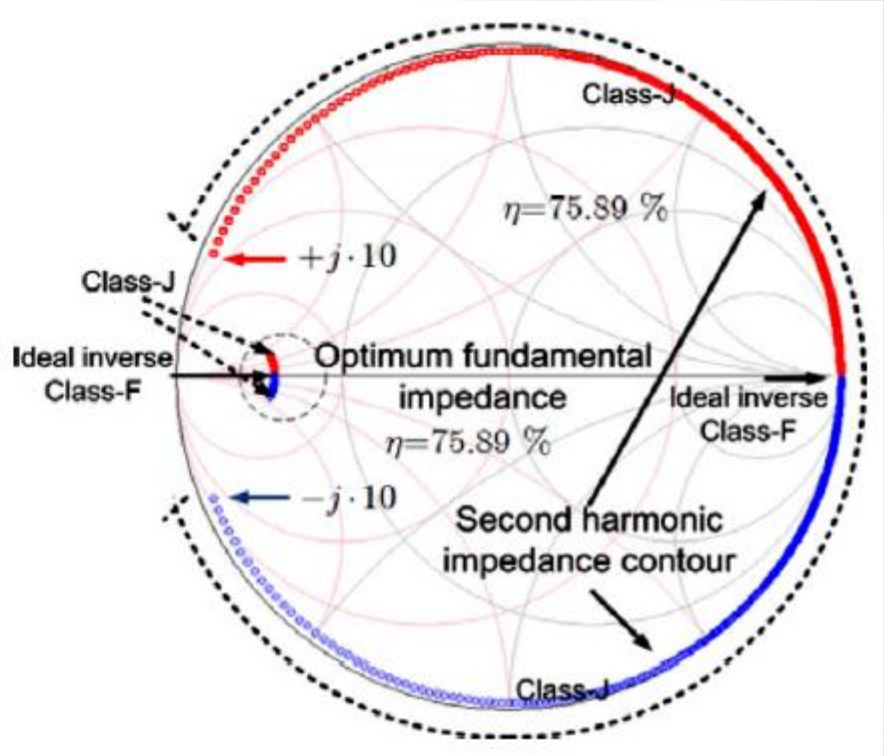
$$Z_{L1}^{J} = -\frac{a_{v1}+jb_{v1}}{a_{i1}+jb_{i1}} = \frac{(V_{DC}-V_{knee})(1+j)}{\frac{I_{max}}{2}} = \frac{2(V_{DC}-V_{knee})}{I_{max}}(1+j)$$

$$Z_{L2}^{J} = -\frac{a_{v2}+jb_{v2}}{a_{i2}+jb_{i2}} = \frac{-0.5(V_{DC}-V_{knee})j}{\frac{2I_{max}}{3\pi}} = -\left(\frac{3\pi}{8}\right)\frac{2(V_{DC}-V_{knee})}{I_{max}}j$$

Cripps, MWCL, 2009

Class J Operation -Theory





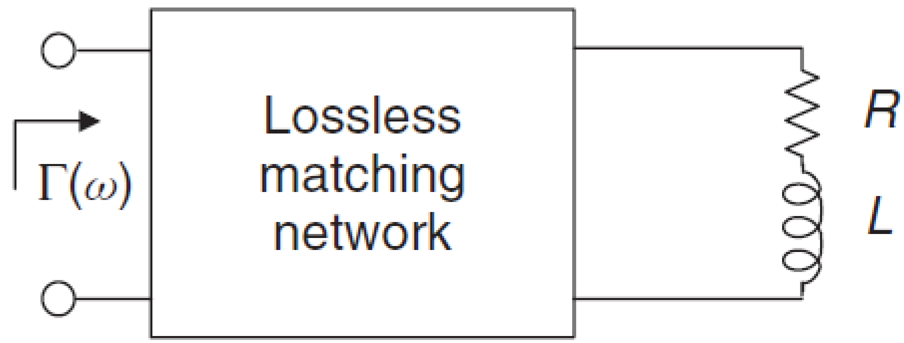
Cripps, MWCL, 2009

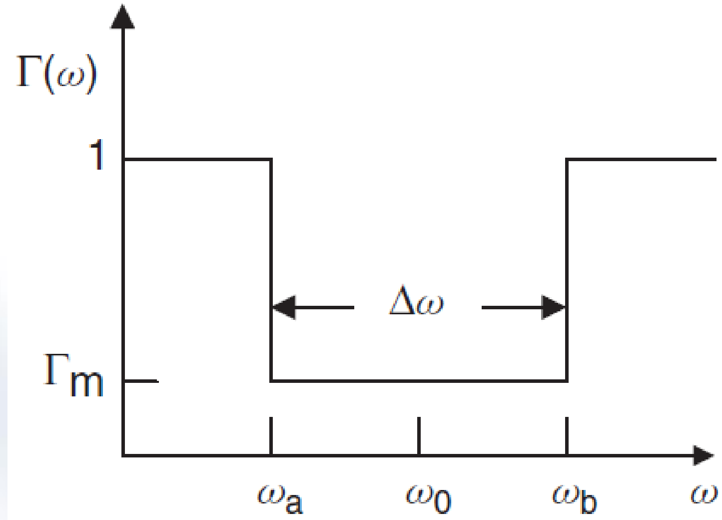
Class J Power Amplifiers

- Simple Matching
  - Wide-Band Designs
  - Multi-Band/Multi-Standard Designs
  - High Frequency Potential
  - Lower Losses

- Peaking
  - Lower Output Power
  - Lower Efficiency Compared to Class F

Wide-Band Class J power Amplifier-Theory





$$\Gamma(\omega) = \frac{Z_{in} - R_G}{Z_{in} + R_G} \quad , \quad \Delta\omega = \omega_b - \omega_a \quad , \quad Q_L = \frac{L\omega_0}{R} \quad , \quad Q_C = \frac{\omega_0}{\Delta\omega}$$

$$\int_0^\infty \ln\left|\frac{1}{\Gamma(\omega)}\right| d\omega \le \frac{\pi R}{L} \quad \to \quad \Delta\omega \ln\left|\frac{1}{\Gamma_m}\right| = \frac{\pi R}{L} \quad \to \quad \frac{\Delta\omega}{\omega_0} = \frac{\pi}{Q_L \ln\left|\frac{1}{\Gamma_m}\right|}$$

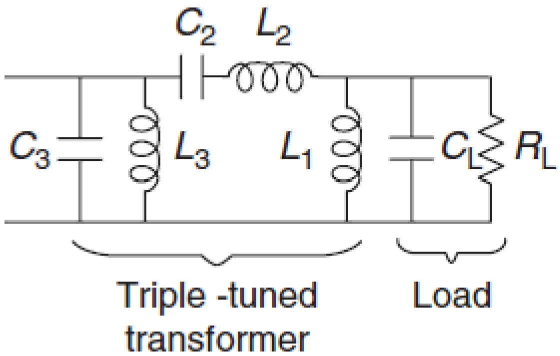
For Class J Operation:

$$Z_{1_{opt}} = R_{opt} + jR_{opt} \quad \to \quad Q_L = 1$$

$$\text{For } \Gamma_m = 10 \text{ dB} \quad \to \quad \frac{\Delta\omega}{\omega_0} = 136\ \%$$

Wide-Band Class J power Amplifier-Theory

Lopez, IEEE APM, 2004, 2005, and 2007



Coefficients a_n and b_n for Various Values of n

n	a_n	b_n
1	1	1
2	2	1
3	2.413	0.678
4	2.628	0.474
5	2.755	0.347
6	2.838	0.264
7	2.896	0.209
8	2.937	0.160
∞	π	0

$$Q_L BW = \frac{1}{b_n \sinh\left[\frac{1}{a_n}\ln\left(\frac{1}{\Gamma}\right)\right] + \frac{1-b_n}{a_n}\ln\left(\frac{1}{\Gamma}\right)}$$

$$n = 1: \quad BW = \frac{1}{Q_L}\frac{2\Gamma_m}{1-\Gamma_m^2} \rightarrow BW \cong 20\ \%$$

$$n = 2: \quad BW = \frac{1}{Q_L}\frac{2\sqrt{\Gamma_m}}{1-\Gamma_m} \rightarrow BW \cong 70\ \%$$

$$n = 3: \rightarrow BW \cong 95\ \%$$

Class J Bandwidth- Clipping Contours

GaN Discrete

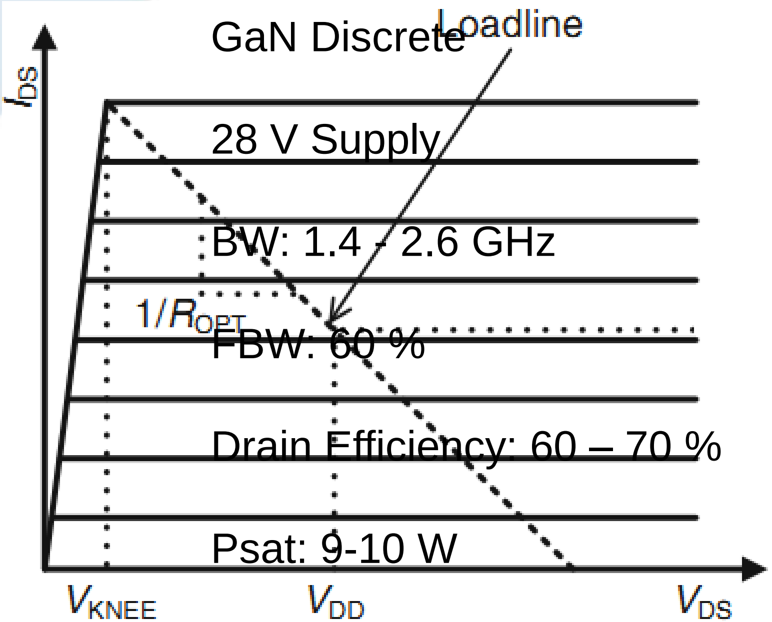
28 V Supply

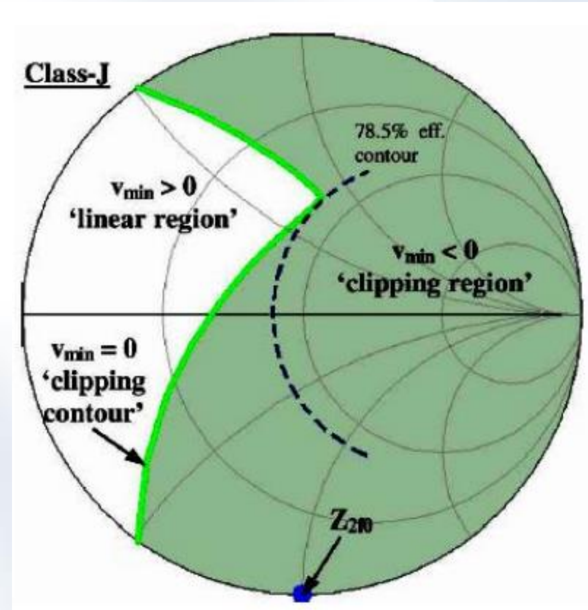
BW: 1.4 - 2.6 GHz

FBW: 60 %

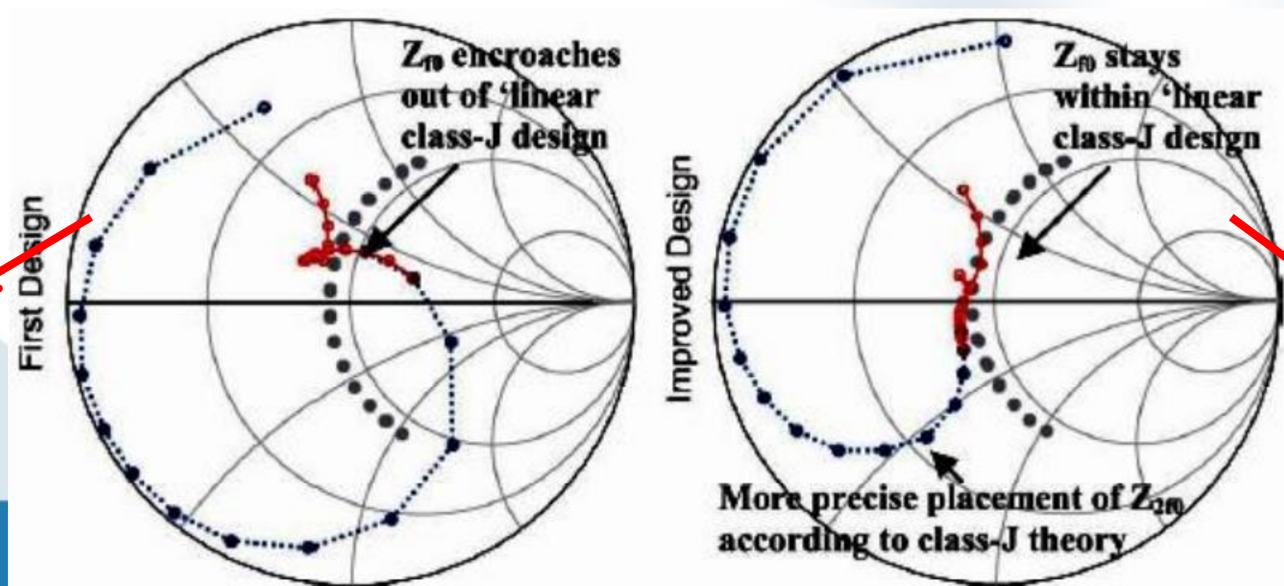
Drain Efficiency: 60 – 70 %

Psat: 9-10 W





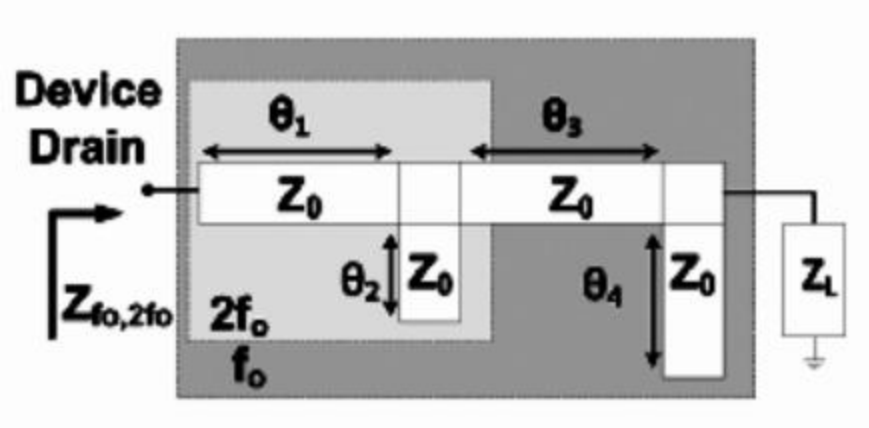
1.5 -2.5 GHz

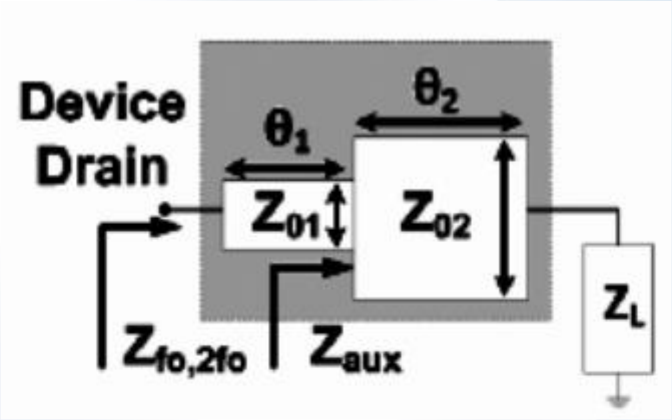


1.4 -2.6 GHz

Wright, MTT, 2009

Class J Bandwidth- Matching Pool





GaN Discrete

28 V Supply

BW: 1.6 - 2.2 GHz

FBW: 32 %

Drain Efficiency: 55 – 68 %

Psat: 10 W

GaN Discrete

28 V Supply

BW: 0.5 – 1.8 GHz

FBW: 113%

Drain Efficiency: 50 – 69 %

Psat: 10 W

Mimis, MTT, 2012

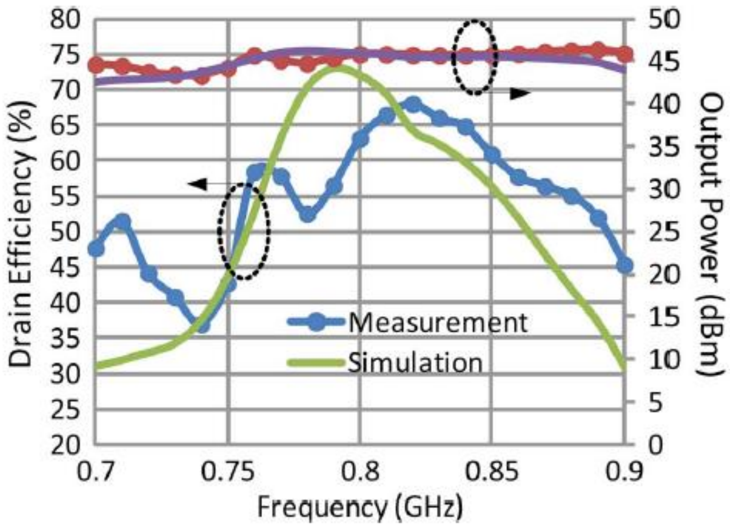


Fig. 19. Measurement and simulation results of output power and drain efficiency for the lower band.

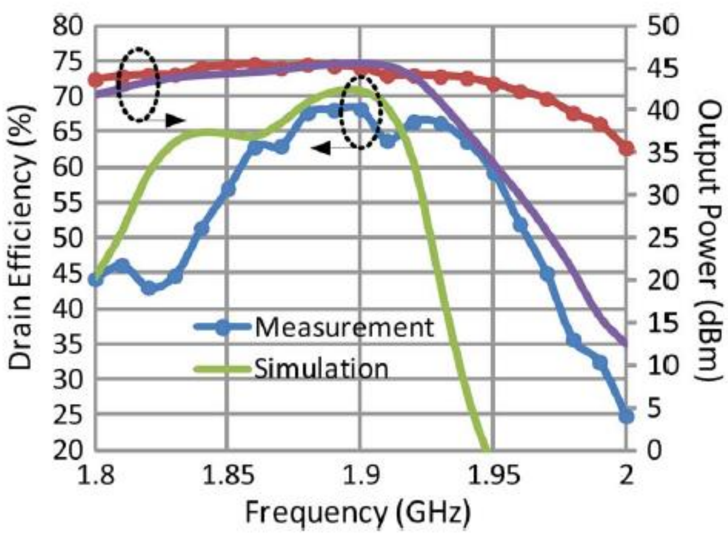


Fig. 20. Measurement and simulation results of output power and drain efficiency for the upper band.

TABLE I
TARGET FUNDAMENTAL IMPEDANCES

Impedance	0.8GHz	1.9GHz
Load side	9.85+j4.8	4+j2.4
Source side	4.68+j3.66	2.1-j2.7

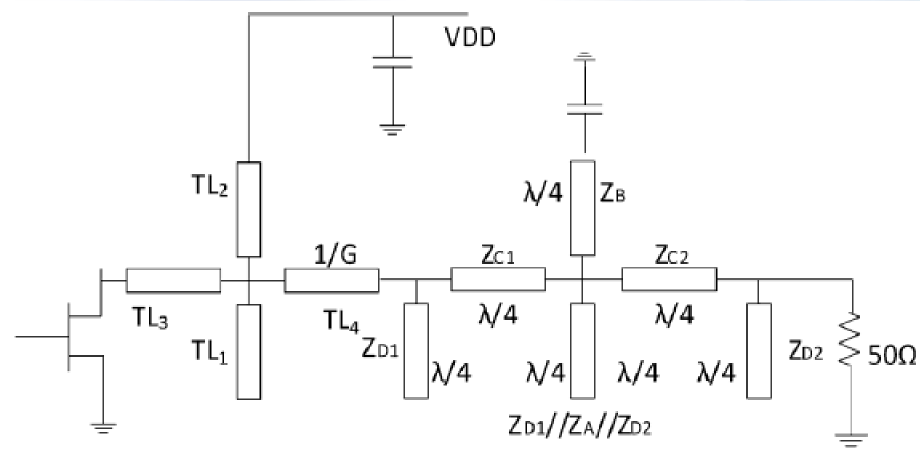
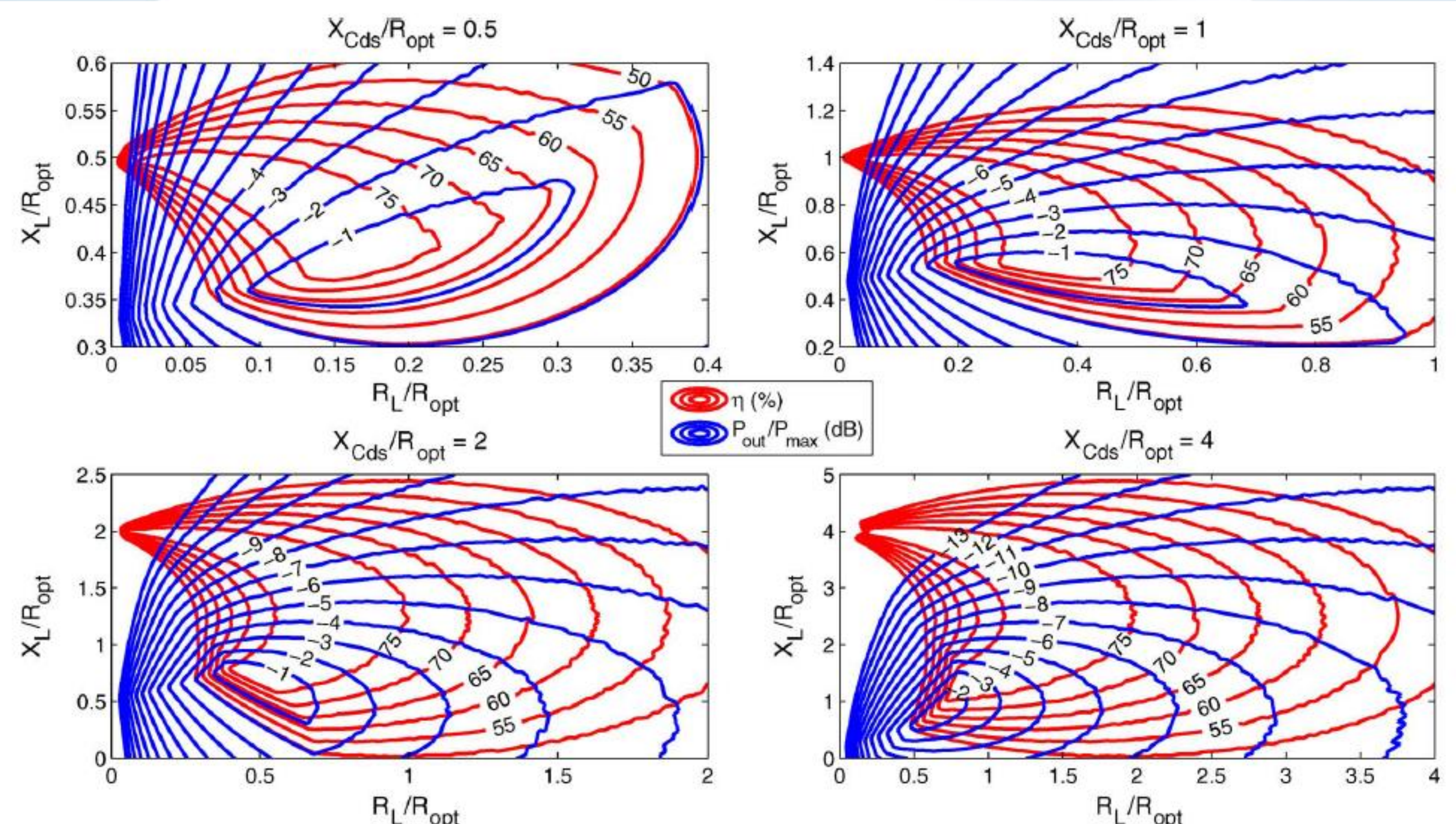


Fig. 14. Dual-band PA topology (load side).

Fu, TCASI, 2014

Class J- High Back-Off Efficiency



Andersson, MTT, 2012

Class J- High Back-Off Efficiency

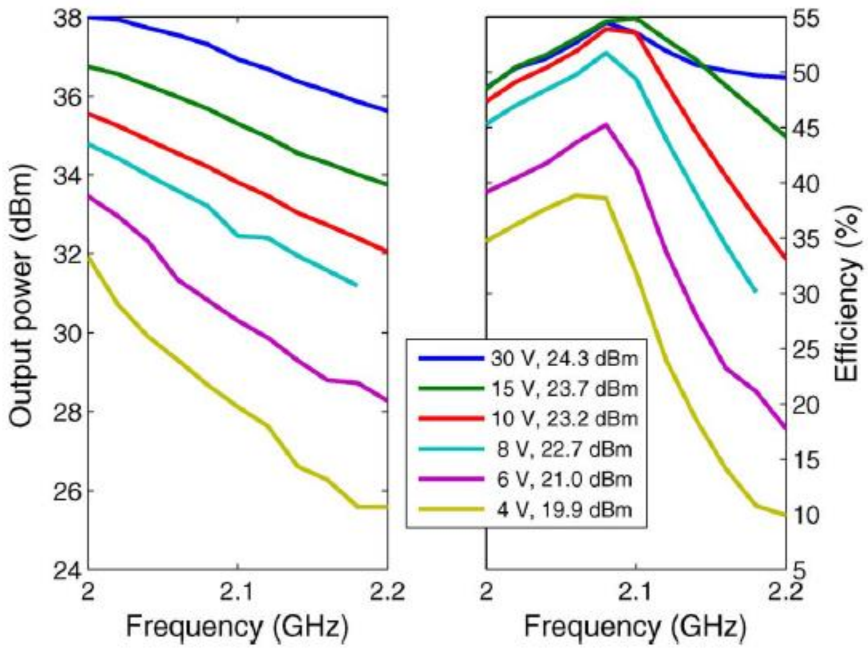
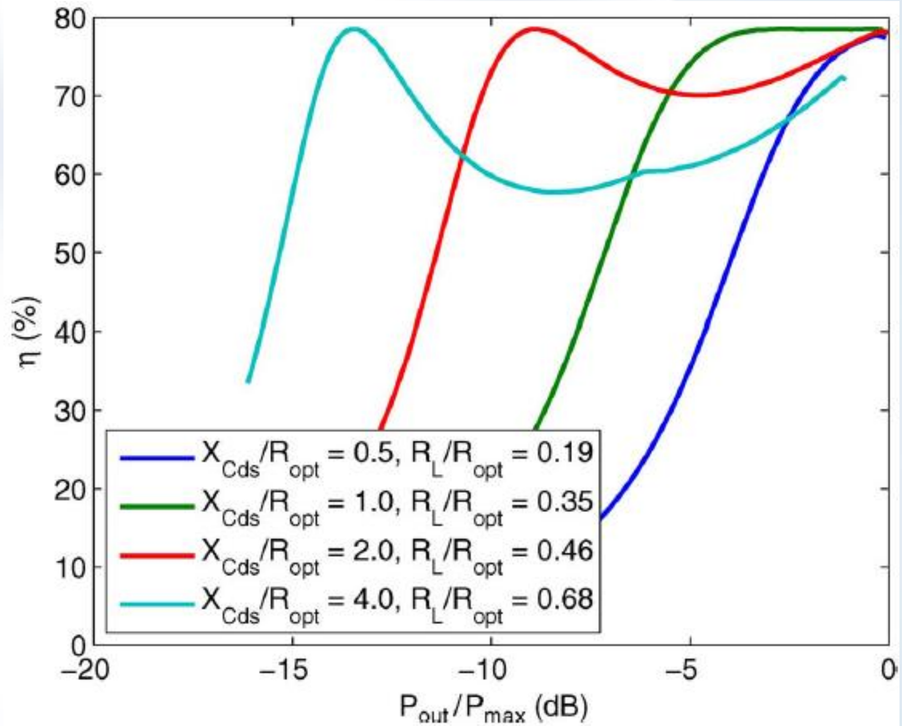
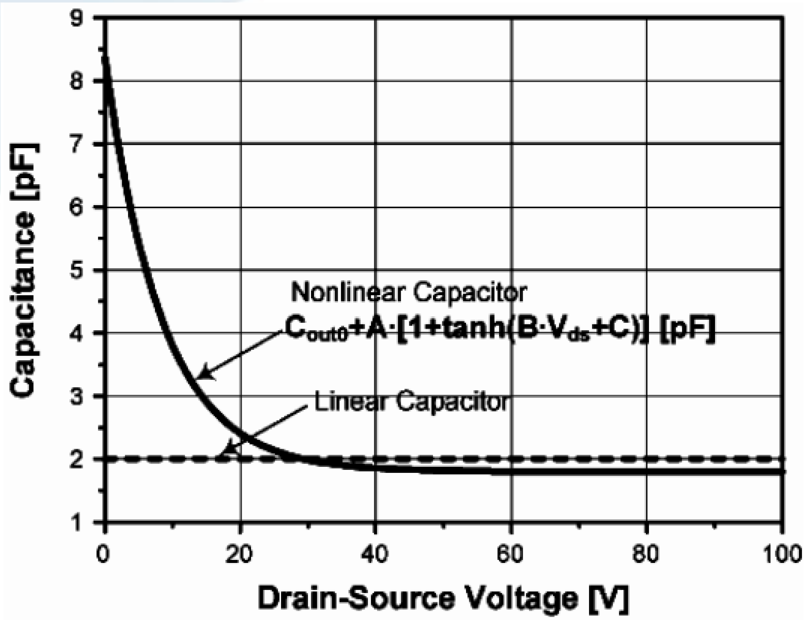


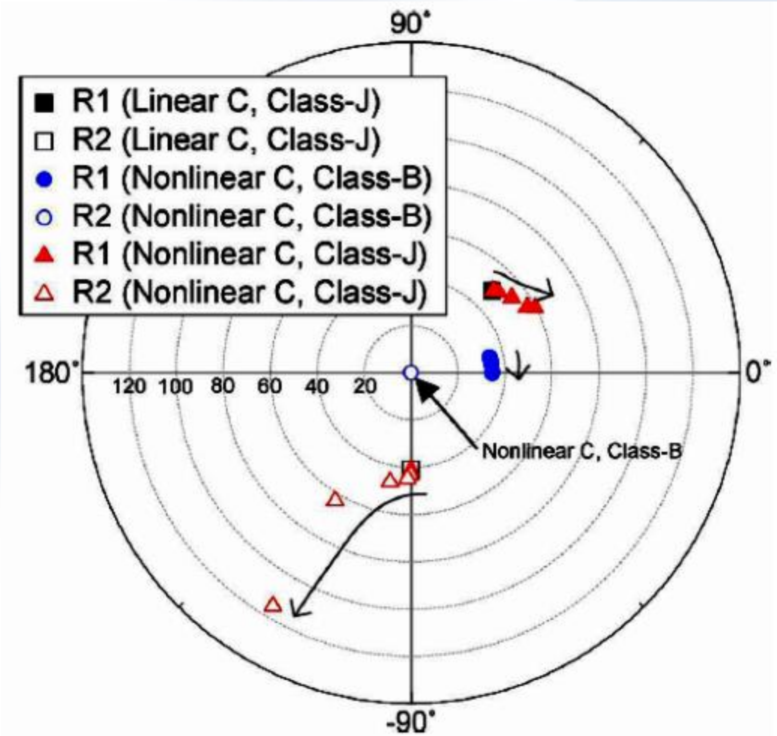
Fig. 11. Amplifier output power and efficiency versus frequency when following the optimum control function at 2.08 GHz, but backing off the input power by 2 dB.

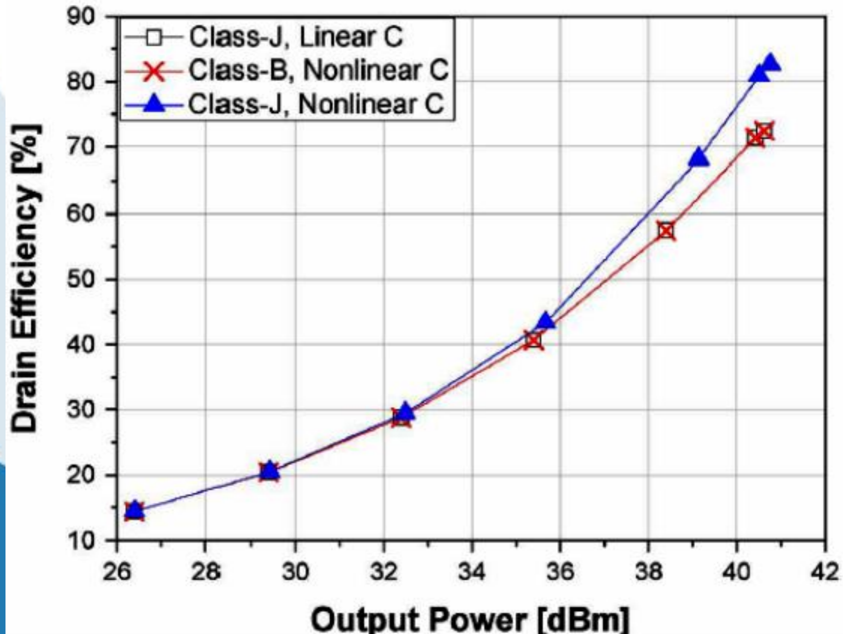


Andersson, MTT, 2012

Class J Efficiency- Negative Resistance







GaN Discrete

30 V Supply

f: 2.14 GHz

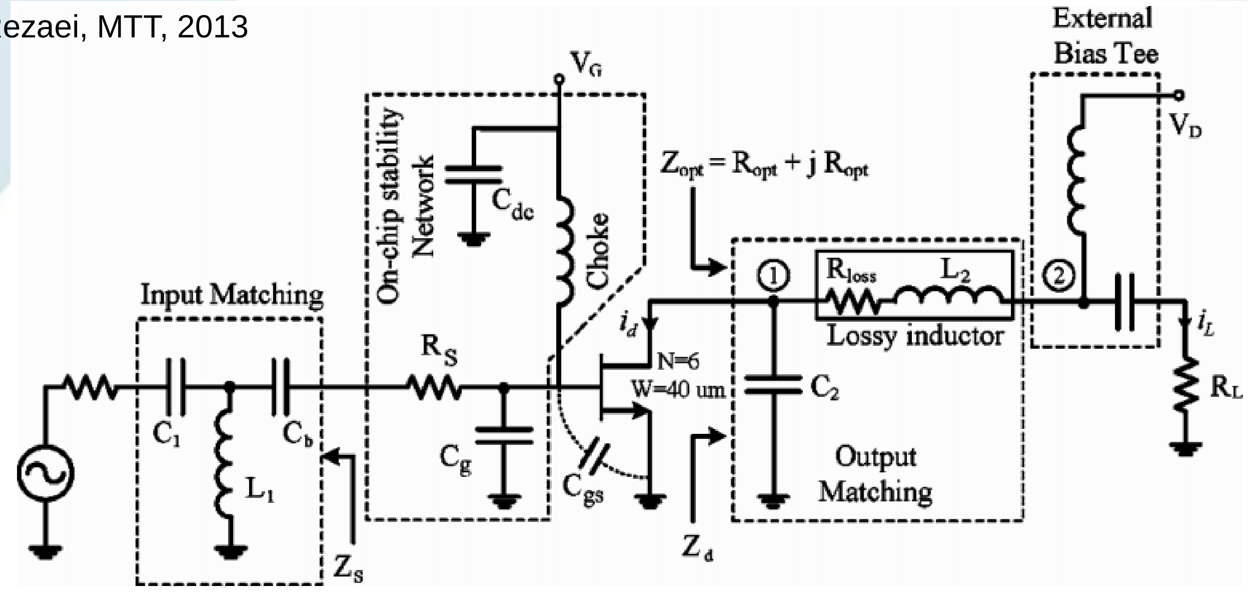
Drain Efficiency: 77%

Psat: 11.5 W

Moon, MTT, 2010

Class J Efficiency- Transistor Sizing

Rezaei, MTT, 2013



GaN Integrated

15 V Supply

f: 2.5 GHz

Drain Efficiency: 58%

Psat: 0.5 W