EECS 242: Linearization Efficiency Enhancement and Power Combiners

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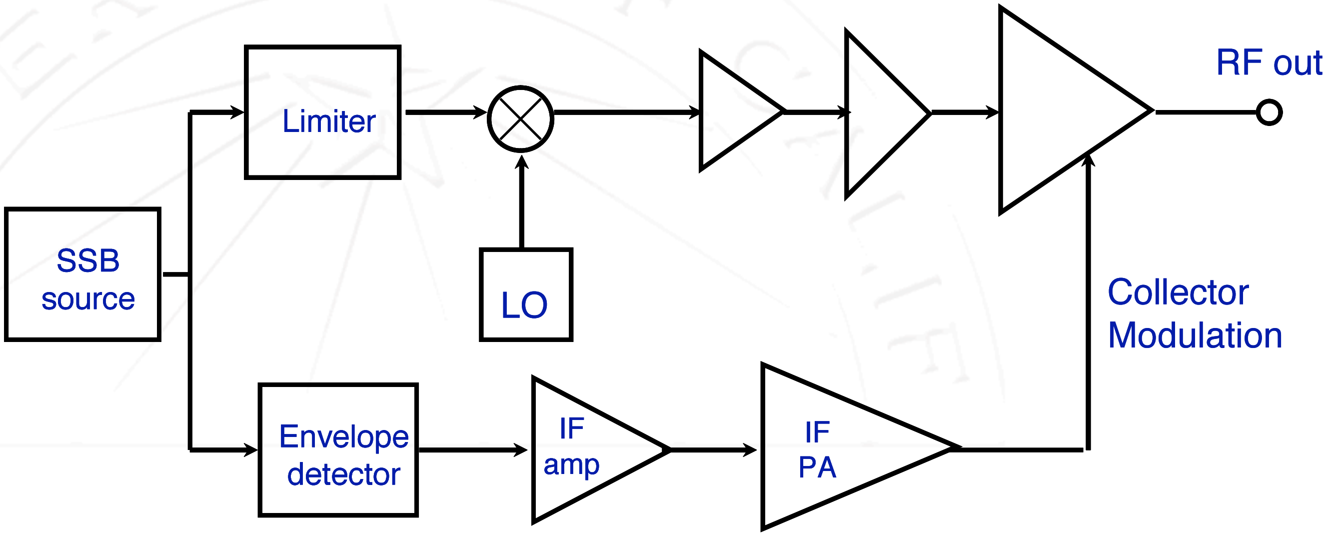
Linearization

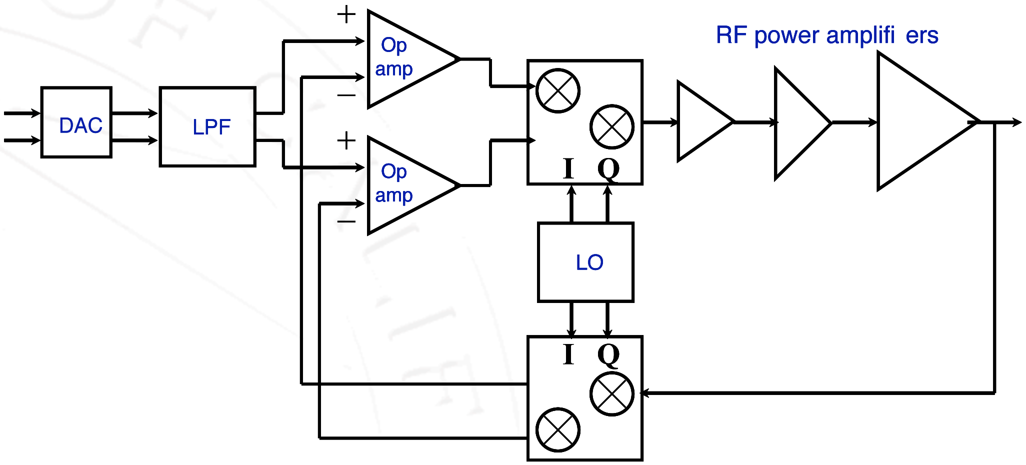
Polar Modulators

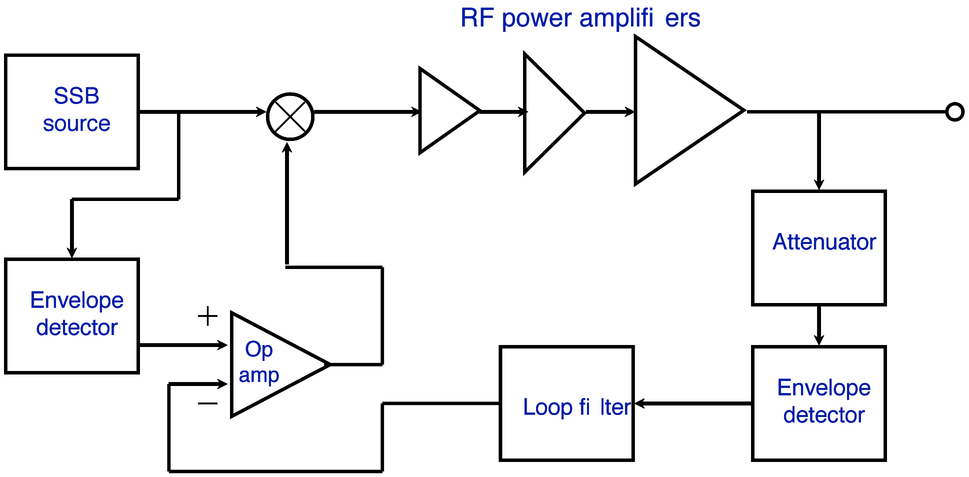


- Polar modulators are gaining popularity by require complex feedback and/or chip to external PA interaction
- Modulation bandwidth is a limiting factor
- In a digital system, the magnitude/phase signal are generated directly and fed into an offset PLL and PA supply voltage

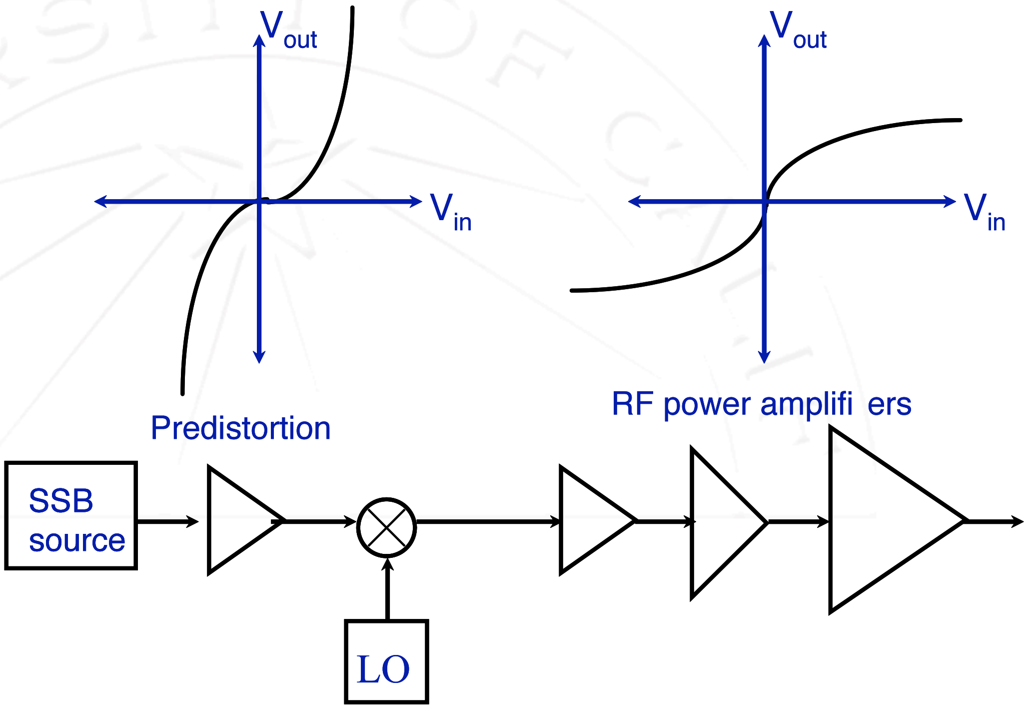
Feedback Loops with PA

- Need loop gain, stability a big concern, modulation bandwidth
- Envelope feedback only works for AM-AM non-linearity
- Cartesian requires linear mixers and good amplitude/ phase matching
- Complexity…



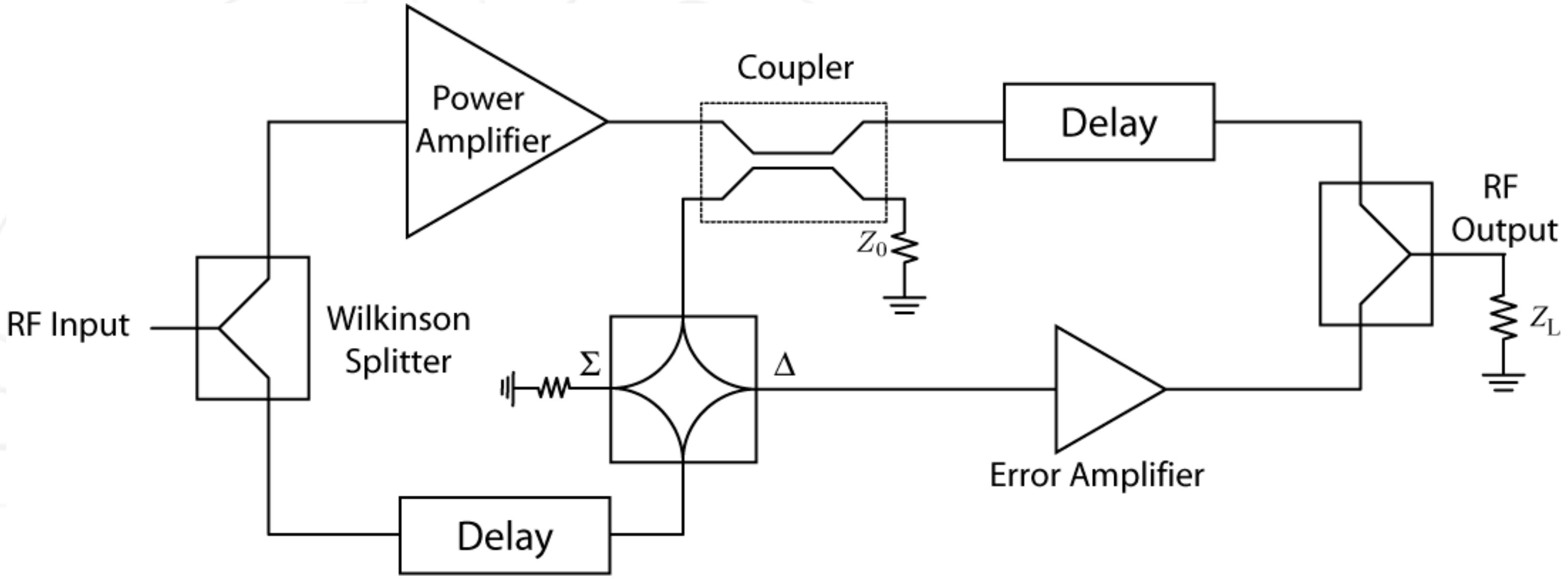


Digital Predistortion



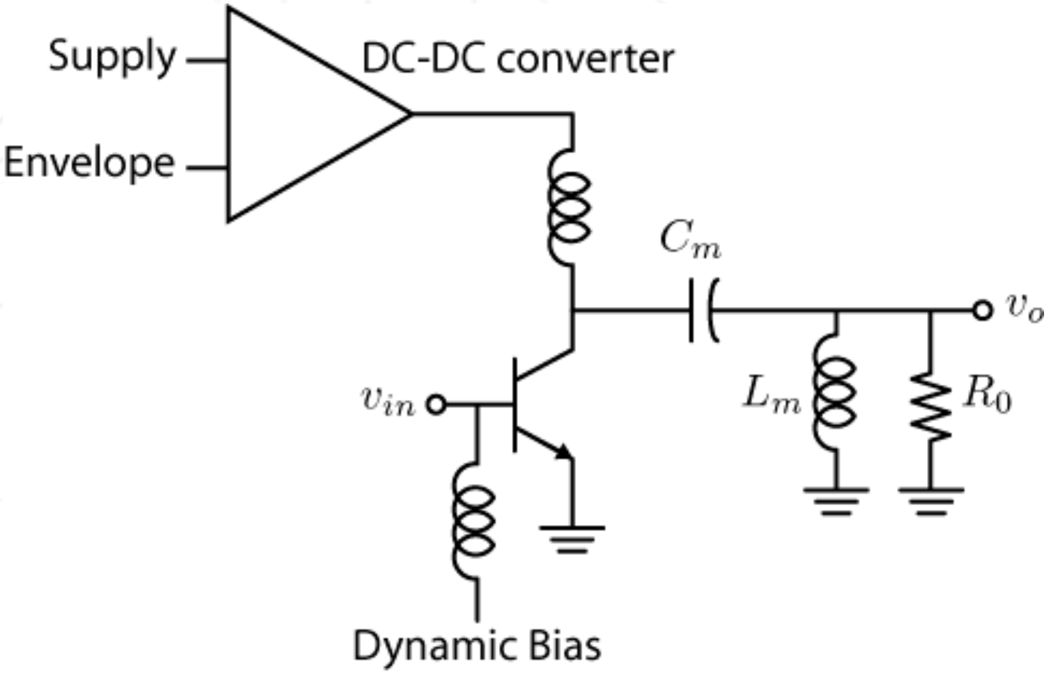
- In a modern system a dynamic predistortion circuit can compensate for process/ temp variations
- Can implement predistortion at baseband
- 100k gates = 1 pad

Microwave Feedforward



- Basestations use feedforward linearization since calibariton is a possibility.
- Use couplers

Dynamic PA



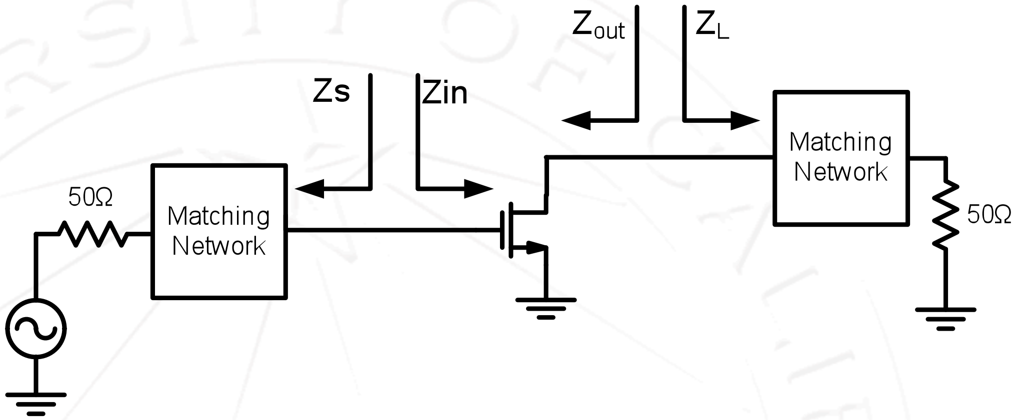
- Envelope tracking supply and dynamic class-A
- Efficiency always close to peak efficiency of amplifier (say 30%) regardless of PAR
- Need a very fast DC-DC converter

Power Combining

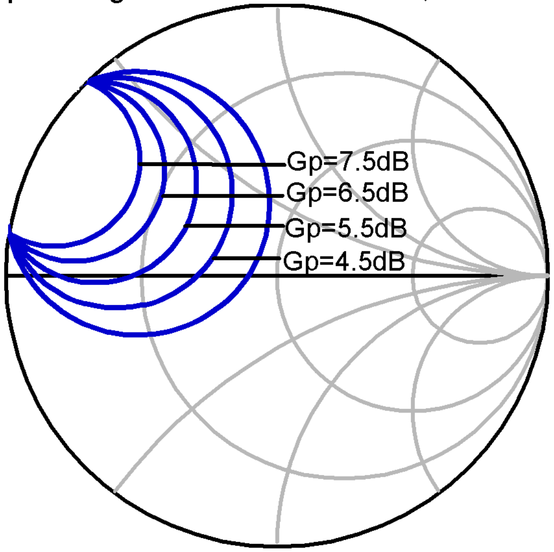
How Big?

- The amount of power that we can extract from a PA device is limited by the output imepdance of the device. As the device is made larger to handle a higher DC current (without compromising the f_T), the lower the output impedance.
- For a “current source” style of PA, eventually the device is so large that power is lost in the device rather than the load. This is the attraction of a switching PA.

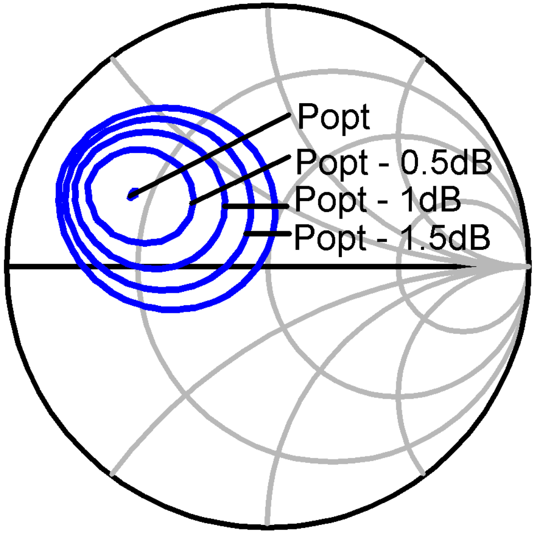
Gain vs. Output Power Tradeoff



Operating Power Gain Circles,F=60GHz



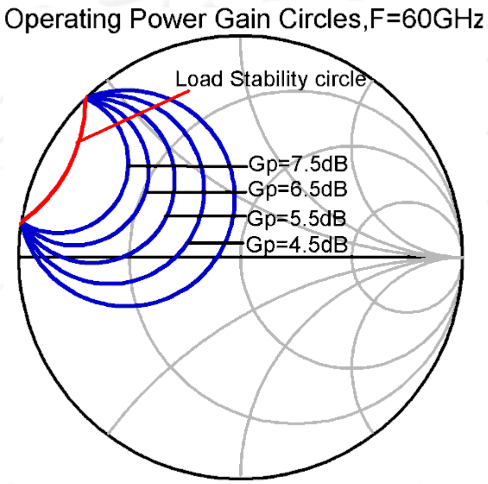
Constant P1dB Contours



Power Devices (cont)

100 fingers

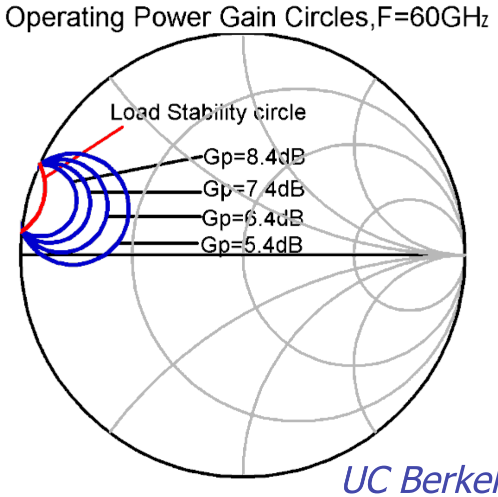
1µm/finger



Finger width	MSG	Idc
1µm	7.6dB	25mA
2µm	8.4dB	47mA
4µm	6.8dB	94mA

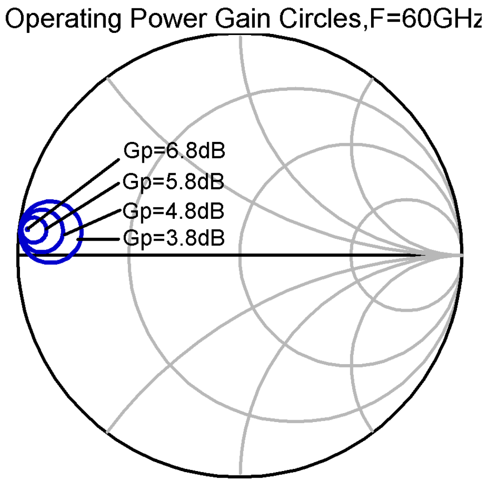
100 fingers

2µm/finger

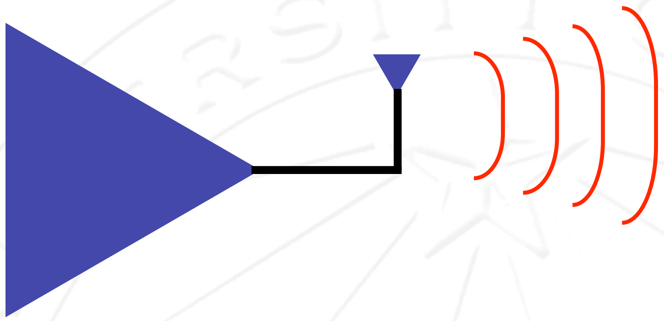


100 fingers

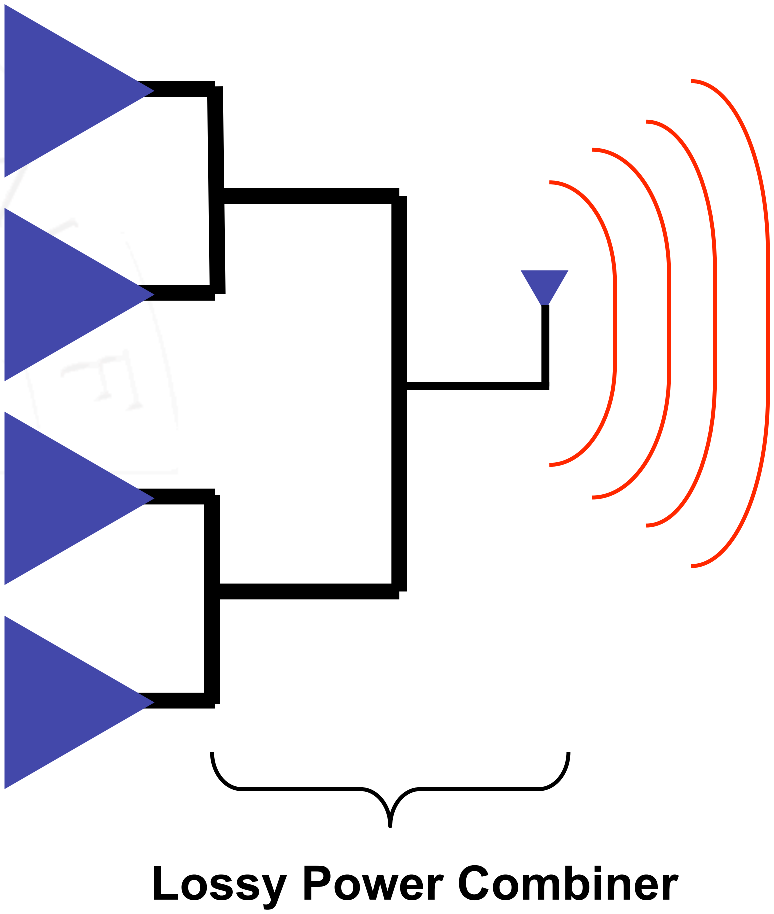
4µm/finger



Power Combining (cont)



- But for a non-switching PA we must perform some power combining to use more than one device. This way we can transform the load into a higher impedance seen by each PA.
- The power combining networks are lossy and large. We'll come back to them later.



Can we "wire" PAs together?

- Note that we cannot simply "wire" PAs together since the impedance seen by each PA increases by *N* if we connect *N* in parallel:

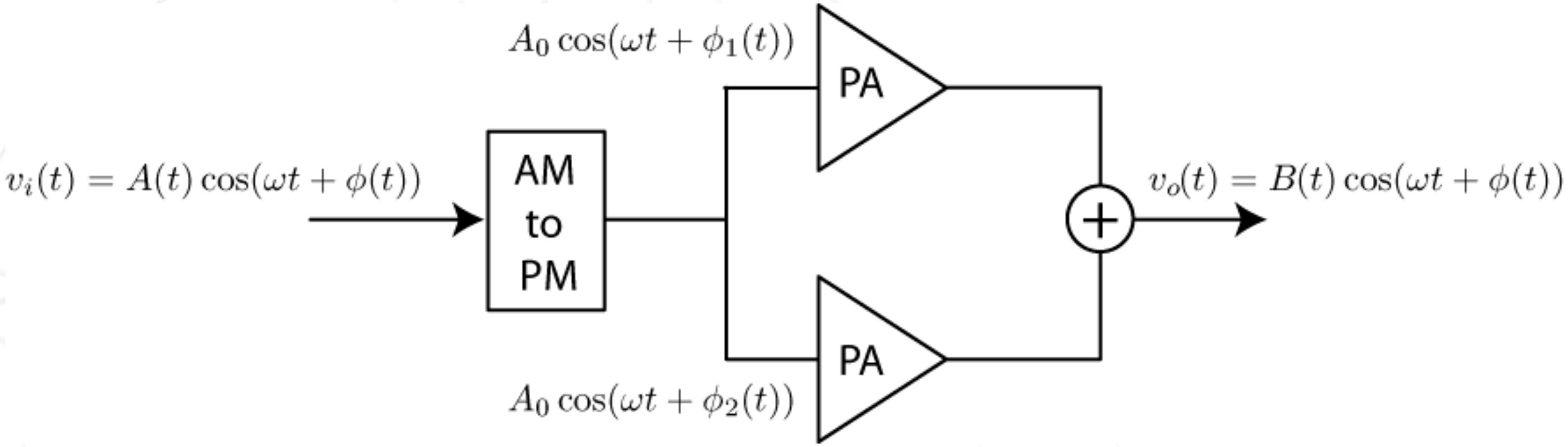
$$R_{PA} = \frac{V_L}{I_L/N} = NR_L$$

- This means that each PA delivers less power for a fixed swing

$$P_{PA} = \frac{V_{swing}^2}{2R_{PA}}$$

- There is also "load pulling" effects if the sub-PAs are not perfectly in phase

Outphasing LINC Amplifier



- Decompose the AM/PM signal into two PM signals
- The two PM signals can get amplified by two non-linear PA's. These can be saturated and efficient amplifiers.
- By combining the two signals, the amplitude modulation is restored at the antenna.
- How to combine signals? Simple current mode will present a time-varying load to each PA. Coupler or isolator will waste power.

Outphasing Math

$$\cos(A) + \cos(B) = 2\cos\left(\frac{A+B}{2}\right)\cos\left(\frac{A-B}{2}\right)$$

$$\cos(\omega t + \phi) + \cos(\omega t - \phi) = 2\cos(\phi)\cos(\omega t)$$

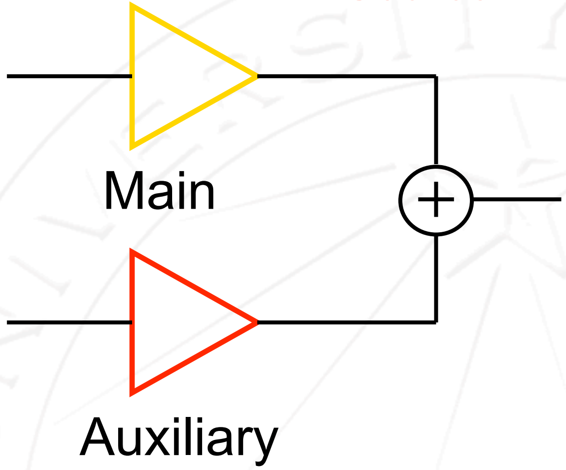
$$\cos\left(\omega t + \cos^{-1} A(t)\right) + \cos\left(\omega t - \cos^{-1} A(t)\right) = 2\cos\left(\cos^{-1} A(t)\right)\cos(\omega t)$$

$$\cos\left(\omega t + \cos^{-1} A(t)\right) + \cos\left(\omega t - \cos^{-1} A(t)\right) = 2A(t)\cos(\omega t)$$

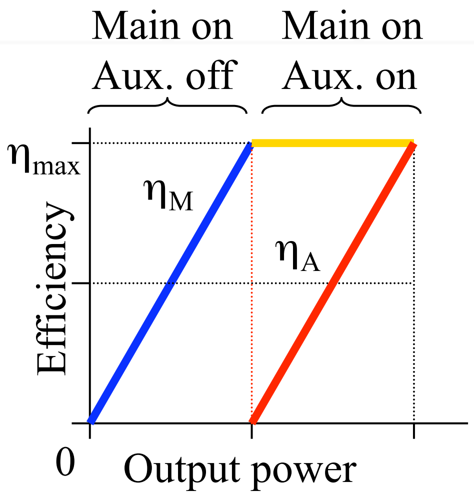
- In theory all we need to do is to compute the inverse cosine of the AM waveform to generate our outphasing signals
- In practice, we can use a DSP to calculate these signals since the envelope rate is at the modulation rate and digital techniques work well
- Power combining is the main difficulty.

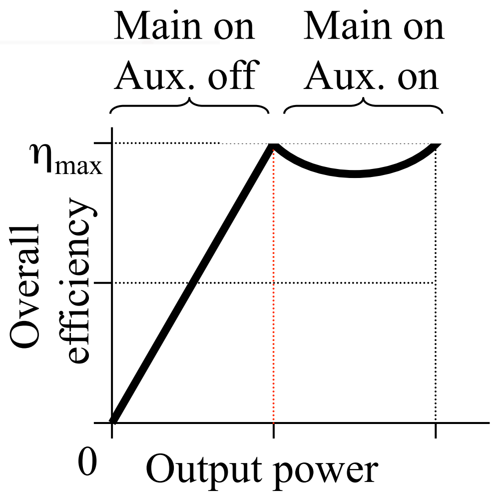
Doherty Amplifier Concept

Source: Naratip Wongkomet and P. Gray (UCB)



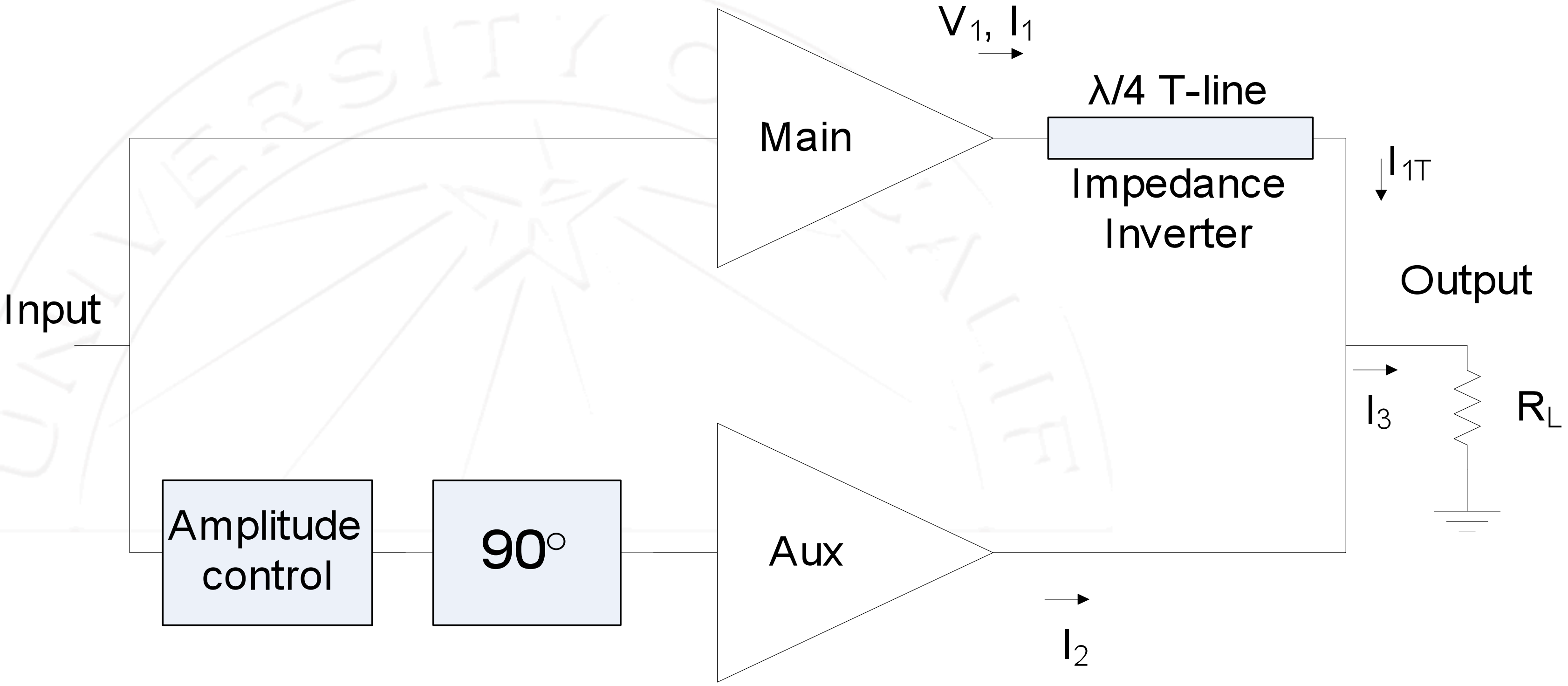
- Invented by W.H. Doherty in 1936
- Good power efficiency over a wide range of output power





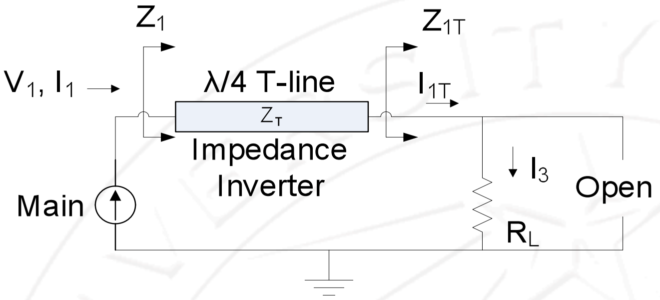
Must efficiently combine power without increasing V_{swing}

Doherty Amplifier Block Diagram



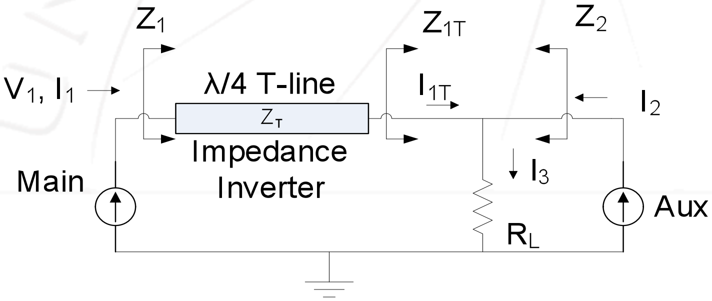
Quarter wave line used as an impedance inverter. Can be realized with LC equivalent.

Doherty Details



(a)

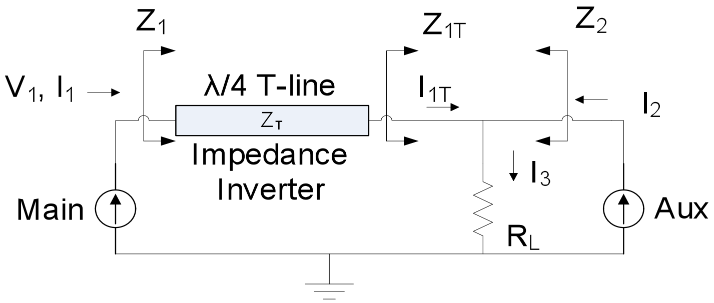
$$Z_1 = \frac{Z_T^2}{R_L}$$



(b)

$$Z_1 = \frac{Z_T^2}{R_L\left(1 + \frac{I_2}{I_{1T}}\right)}$$

$$Z_2 = R_L\left(1 + \frac{I_{1T}}{I_2}\right)$$



(c)

$$I_{1T} = I_2$$

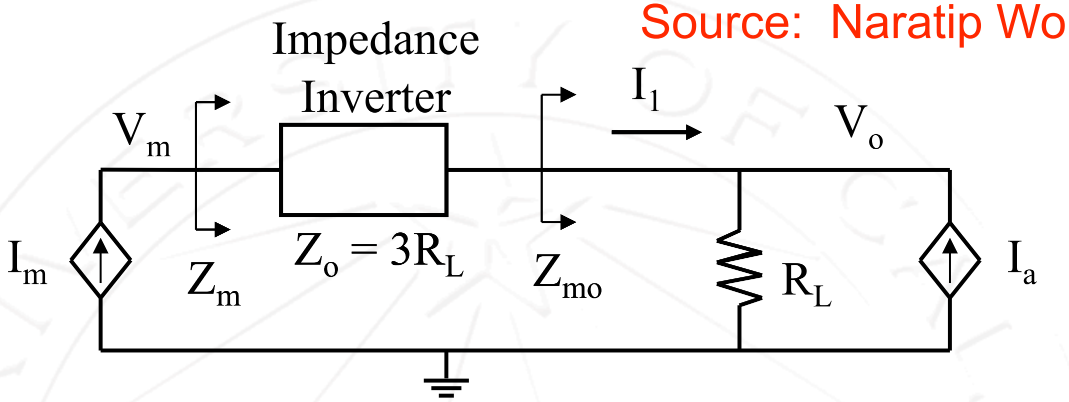
$$Z_1 = \frac{Z_T^2}{2R_L}$$

$$Z_2 = 2R_L$$

- Small signal region: auxiliary amplifier is off
- When the input crosses the threshold, the action of the auxiliary amplifier is to dynamically lower the load seen by the main PA
- Finally, both amplifiers operate at the peak power point

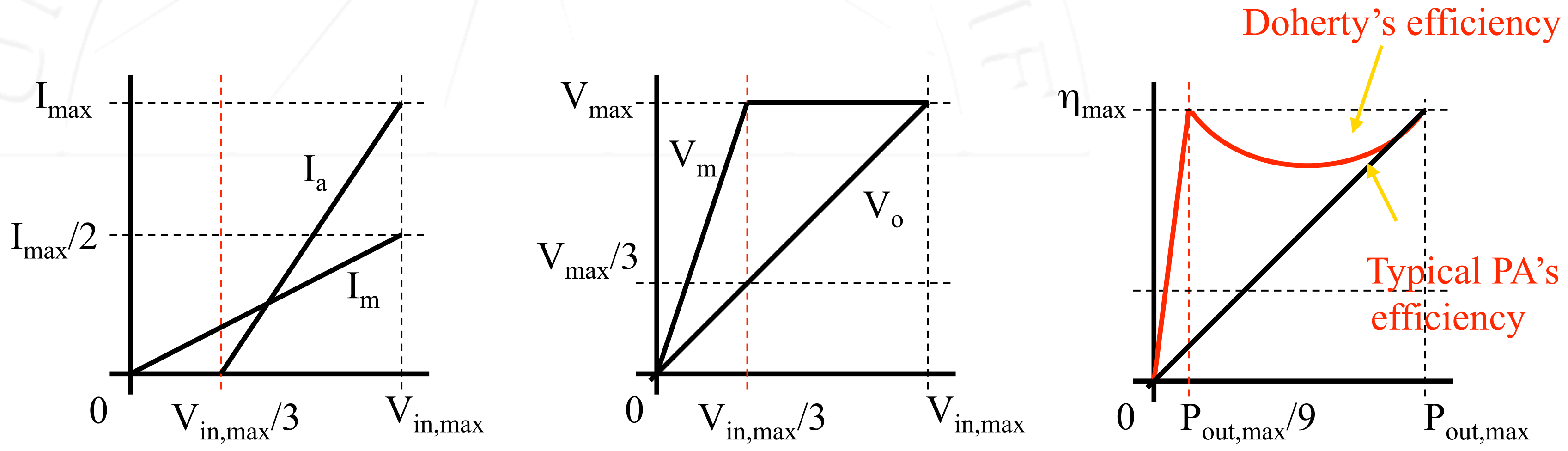
Doherty Amplifier Operation

Source: Naratip Wongkomet and P. Gray (UCB)



$$Z_m = Z_o^2/Z_{mo}$$

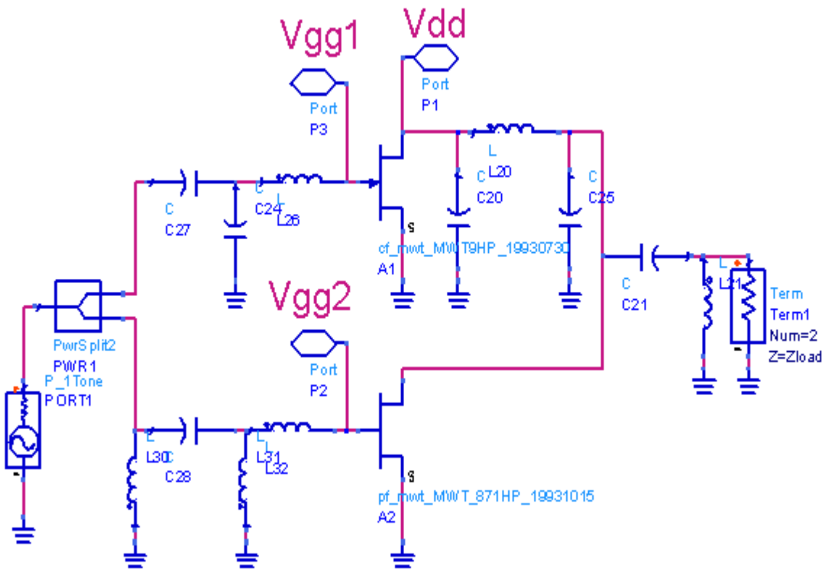
$$Z_{mo} = R_L\,(1+I_a/I_1)$$

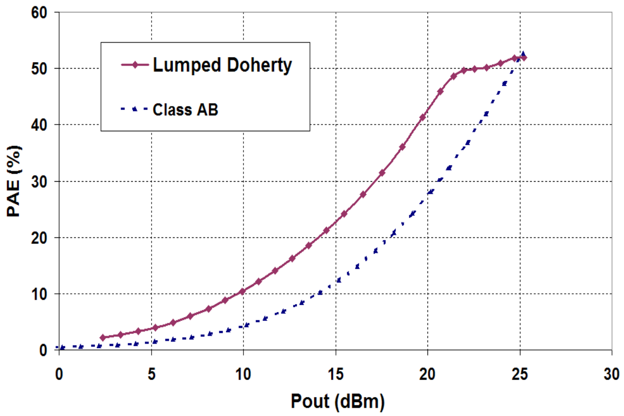


Auxiliary amplifier actively changes load impedance of the main amplifier

Lumped Doherty Implementation

- Can use lumped elements to realize 90° phase shift
- The CLC line is an impedance inverter that also provides VDD for the aux amp
- The LCL line is embedded into the matching network and provides 90° phase shift
- Simulations show an improved efficiency





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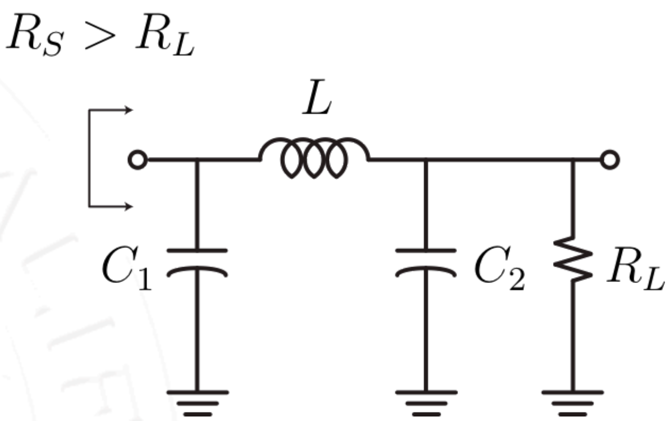
LC Matching Networks

- Matching networks are needed to drive output power to the load, which has a fixed impedance.
- Large output powers require a large transformation ratio, and low voltage operation means high currents in the CMOS stage (sensitive to series resistance).
- 30 dBm of output power requires a matching ratio of 100 !



$$P_L = m\frac{V_{SW}^2}{2R_L} < m\frac{V_{DD}^2}{2R_L}$$

$$P_L < m \cdot \frac{1\text{V}^2}{2 \cdot 50\Omega} = m \times 10\text{mW}$$

LC Matching Network Loss

- The power loss of integrated matching networks is important.
- The insertion loss can be derived by making some simple approximations
- The final result implies that we should minimize our circuit Q factor and maximize the component Q_c

$$P_{in} = P_L + P_{diss}$$

$$IL = \frac{P_L}{P_{in}} = \frac{P_L}{P_L + P_{diss}} = \frac{1}{1 + \frac{P_{diss}}{P_L}}$$

$$W_m = \frac{1}{4} L i_s^2 = \frac{1}{4} \frac{v_s^2}{4 R_S^2} L$$

$$\omega_0 \times W_m = \frac{1}{4} \frac{v_s^2}{4 R_S} \frac{\omega_0 L}{R_S} = \frac{1}{2} \frac{v_s^2}{8 R_S} Q = \frac{1}{2} P_L \times Q$$

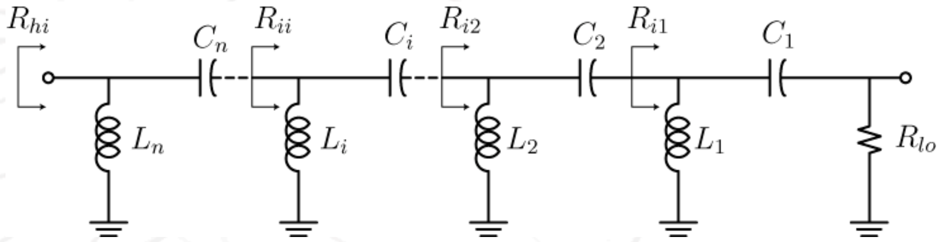
$$P_L = \frac{v_L^2}{2 R_S} = \frac{v_s^2}{4 \cdot 2 \cdot R_S} = \frac{v_s^2}{8 R_S}$$

$$\omega_0 (W_m + W_e) = Q \times P_L$$

$$P_{diss} = \frac{P_L \cdot Q}{Q_c}$$

$$IL = \frac{1}{1 + \frac{Q}{Q_c}}$$

Multistage Matching



$$Q = \frac{\omega(W_{s1} + W_{s2})}{P_{d1} + P_{d2}} = \frac{\omega W_{s1}}{2P_d} + \frac{\omega W_{s2}}{2P_d} = \frac{Q_1 + Q_2}{2}$$

$$R_{i,\text{opt}} = \sqrt{R_L R_S}$$

$$Q = \tfrac{1}{2}\left(\sqrt{\frac{R_i}{R_L} - 1} + \sqrt{\frac{R_S}{R_i} - 1}\right)$$

$$Q_{opt} = \sqrt{\sqrt{\frac{R_S}{R_L}} - 1} \approx m^{1/4}$$

$$\frac{R_{i1}}{R_{lo}} = \frac{R_{i2}}{R_{i1}} = \frac{R_{i3}}{R_{i2}} = \cdots = \frac{R_{hi}}{R_{in}} = 1 + Q^2$$

$$\frac{R_{i1}}{R_{lo}} \cdot \frac{R_{i2}}{R_{i1}} \cdot \frac{R_{i3}}{R_{i2}} \cdot \cdots \cdot \frac{R_{hi}}{R_{in}} = \frac{R_{hi}}{R_{lo}} = (1 + Q^2)^N$$

$$Q = \sqrt{\left(\frac{R_{hi}}{R_{lo}}\right)^{1/N} - 1}$$

- lti-stage design
- Since the Q of each stage is lowered, the insertion can improve

Approximate Insertion Loss

$$P_{diss} = \frac{NQP_L}{Q_u}$$

$$IL = \frac{1}{1 + N\frac{Q}{Q_u}}$$

$$IL = \frac{1}{1 + \frac{N}{Q_u}\sqrt{\left(\frac{R_{hi}}{R_{lo}}\right)^{1/N} - 1}}$$

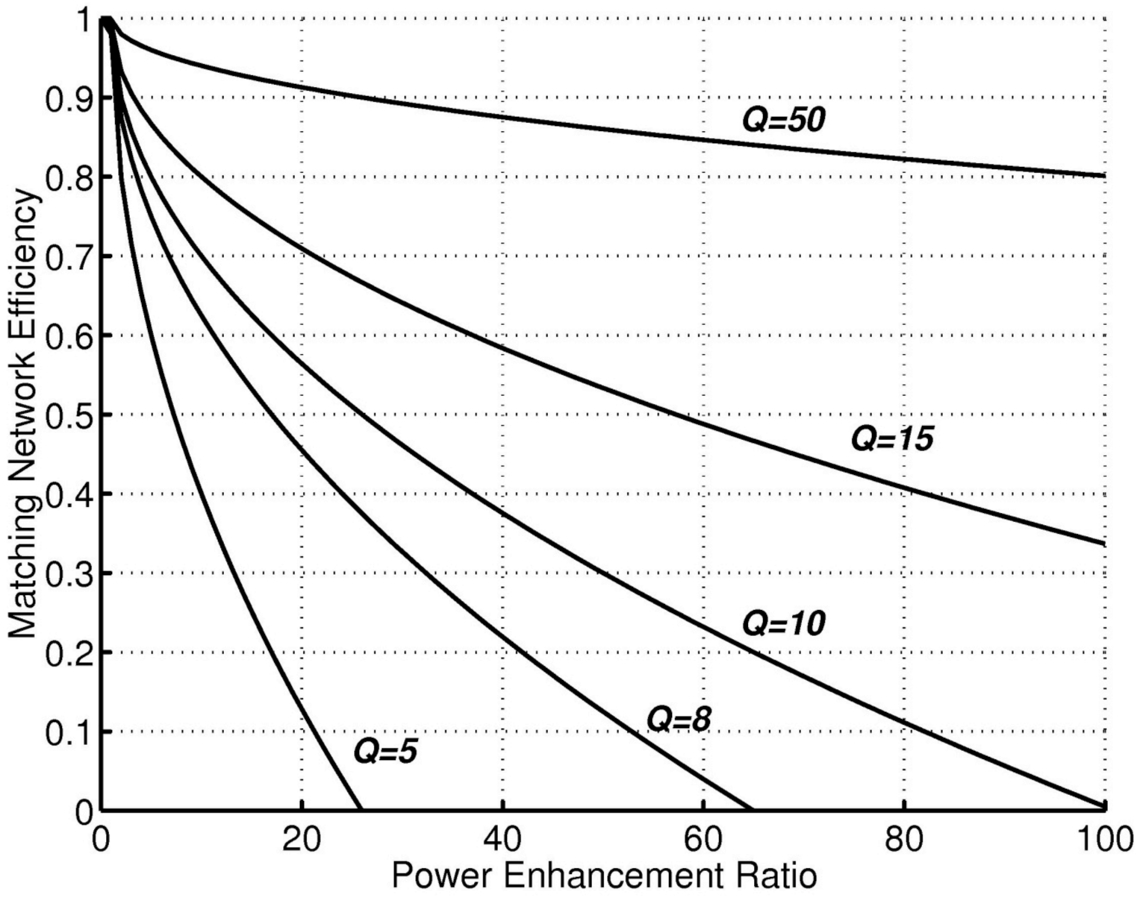
N	Q (Eq. 7.125)	IL (dB) (Eq. 7.128)
1	9.95	−1.24
2	3	−0.79
3	1.91	−0.76
4	1.47	−0.78
5	1.23	−0.81
6	1.07	−0.85

- Suppose a power amplifier delivering 100 W of power has an optimal load resistance of .5, but needs to drive a 50 IΩ antenna.
- Design a matching networkassuming that the component Q’s of 30 are available.
- First note that a matching factor of m = 50/.5 = 100 is needed.
- Table above shows that 3 stages is optimum

Technology Scaling

- Power Enhancement Ratio

$$PER = r \cdot \eta$$

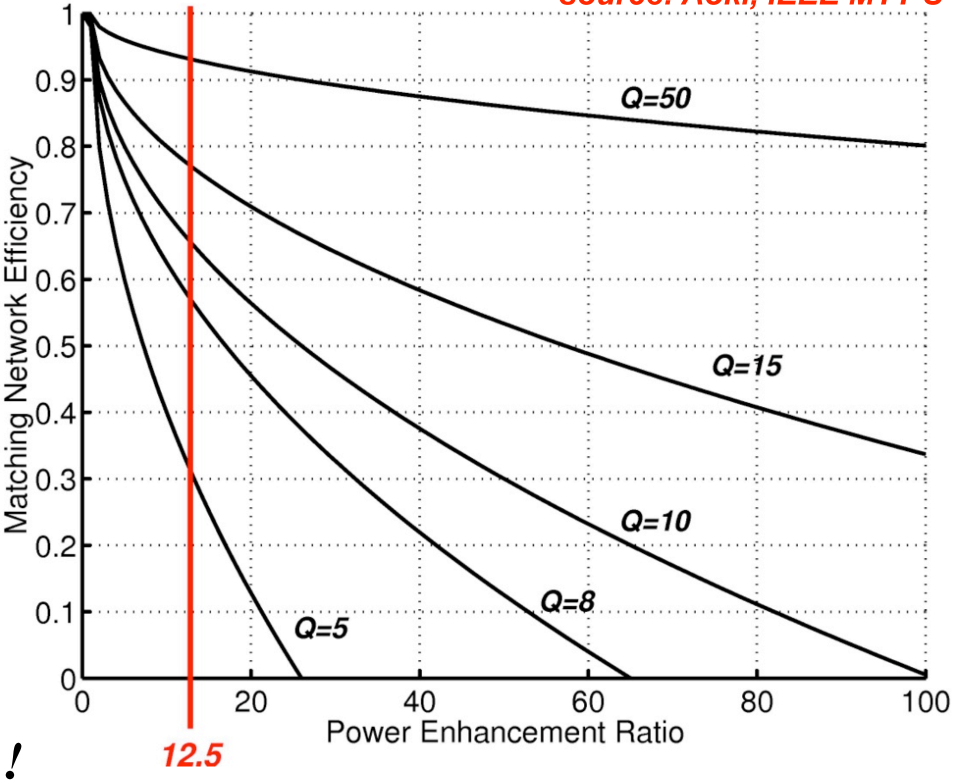


source: Aoki, IEEE MTT-S

Technology Scaling

- Example Class E
  - 0.13 um → $V_{PEAK} = 3$ V
  - $P_{OUT,50} = 8$ mW
  - Required $P_{OUT} = 100$ mW
  - $R_{IN} = 4\ \Omega$
  - PER = 50/4 = 12.5
  - Q of 5 → $\eta = 32\%$
  - Q of 10 → $\eta = 65\%$

source: Aoki, IEEE MTT-S

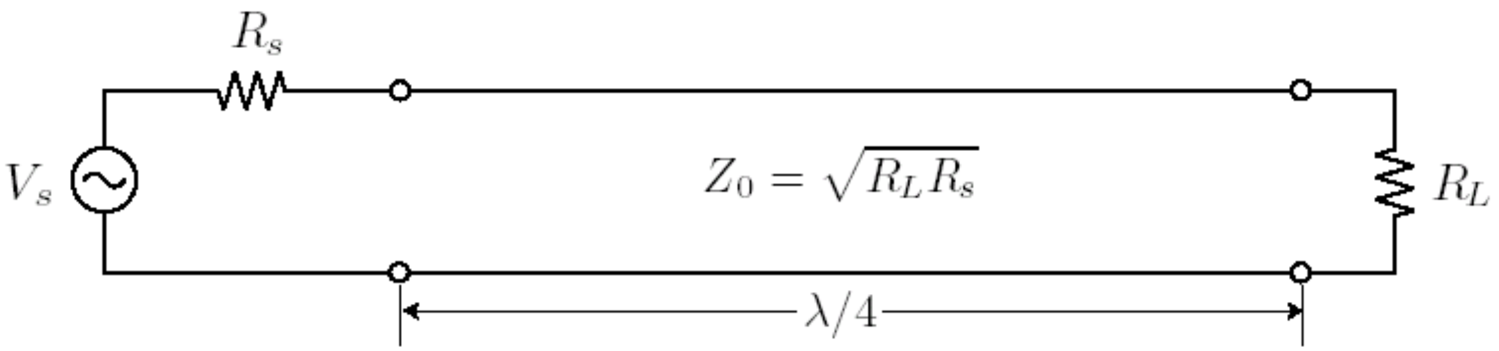


  - *…For the matching network alone !*
    → impedance matching is limited
    → problem for low-voltage operation

$$PER = r \cdot \eta$$

source: Reynaert

Quarter Wave Transformer



$$P_{in} = \frac{|V^+|^2}{2Z_0}\left(e^{2\alpha\ell} - |\rho(\lambda/4)|^2 e^{-2\alpha\ell}\right) \qquad |\rho(\lambda/4)| = |\rho_L| e^{-2\alpha\lambda/4}$$

$$P_L = \frac{|V^+|^2}{2Z_0}\left(1 - |\rho_L|^2\right) \qquad IL = \frac{P_L}{P_{in}} = \frac{1 - |\rho_L|^2}{e^{2\alpha\lambda/4} - |\rho(\lambda/4)| e^{-2\alpha\lambda/4}}$$

- Quarter wave line is a nice way to impedance match source and load. T-line comes for free since we can use the board trace at high frequency.
- How does this vary with matching ratio?

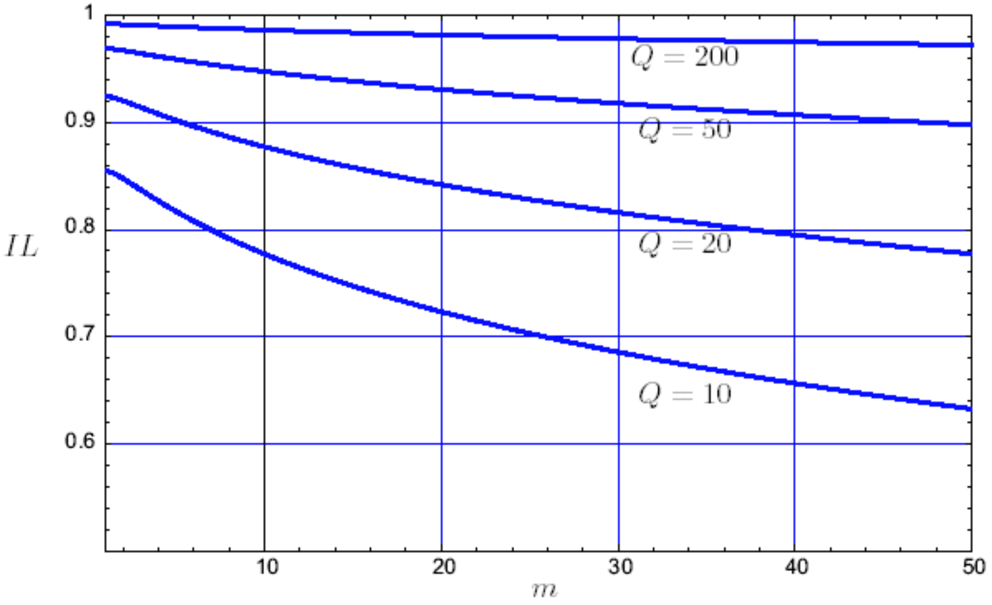
T-Line Loss

$$m = \frac{R_{hi}}{R_{lo}} \geq 1$$

$$IL = \frac{1}{\cosh(2\alpha\lambda/4) + \frac{1+m}{2\sqrt{m}}\sinh(2\alpha\lambda/4)}$$

$$2\alpha\lambda/4 = \frac{\alpha\lambda}{2} = \frac{\beta}{2Q}\lambda 2 = \frac{\pi}{2Q}$$

$$IL(Q,m) = \frac{1}{\cosh(\frac{\pi}{2Q}) + \frac{1+m}{2\sqrt{m}}\sinh(\frac{\pi}{2Q})}$$

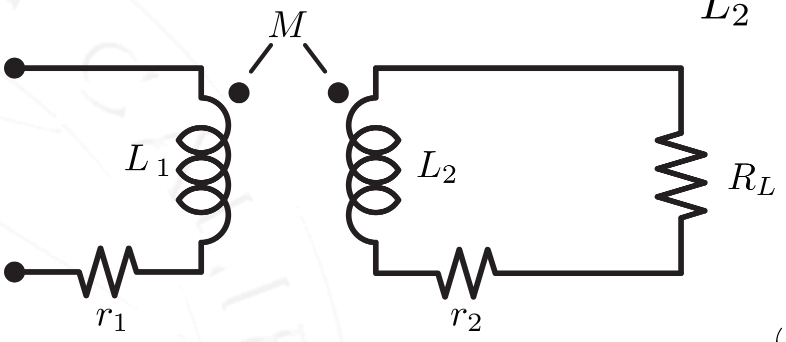


- For FR4 and other lossy dielectrics, the IL can be quite high. Multi-section T-line helps (lower Q) but area is a big constraint.

Transformer Matching

- Simple model of transformer as coupled inductors with series loss.

$$N = \frac{M}{L_2} = k\sqrt{\frac{L_1}{L_2}}$$



$$IL = \frac{P_L}{P_L + P_{diss}}$$

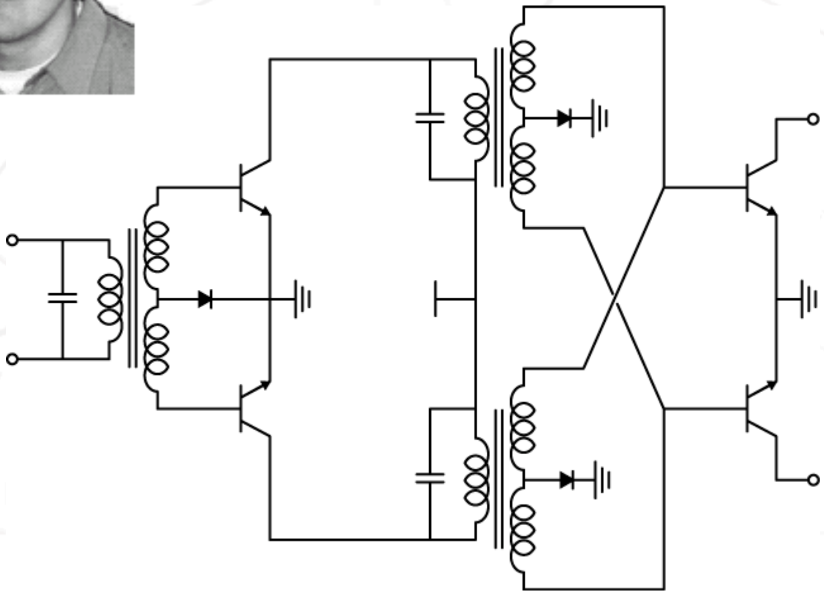
$$Q_L = \frac{\omega L_2}{r_2 + R_L}$$

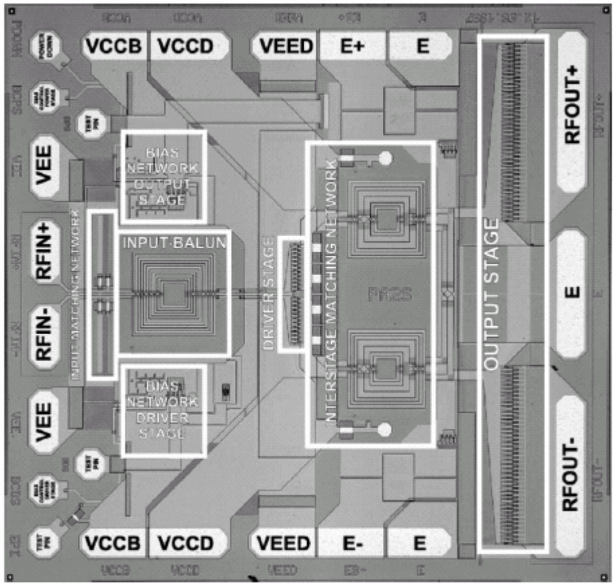
$$IL = \frac{R_L}{r_1 + r_2 + R_L + \left(\frac{L_2}{M}\right)^2 r_1 + \frac{r_1(r_2+R_L)^2}{\omega^2 M^2}}$$

- Key result: loss is nearly independent of the matching ratio!

$$IL \approx \frac{R_L}{r_1 + r_2 + R_L + \frac{r_1}{N^2 Q_2^2}}$$

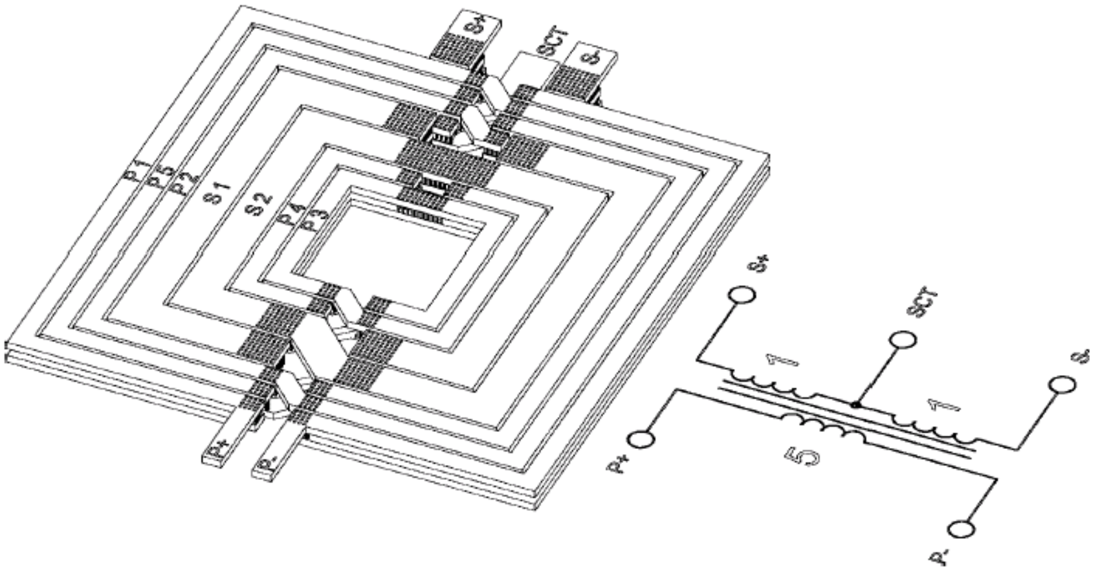
Simbürger PA Interstage Drive





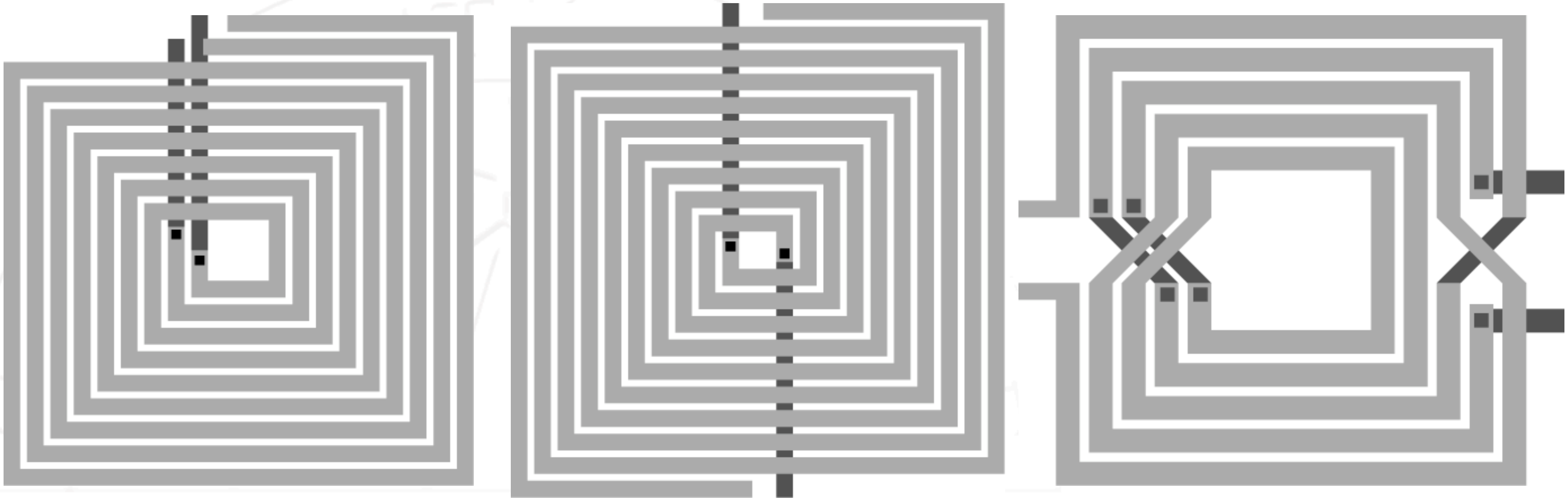
- Simburger and co-authors demonstrated that on-chip transformer can be used to drive large bipolar PA devices
- Output power ~ 5W, 55% PAE

Simbürger Transformer



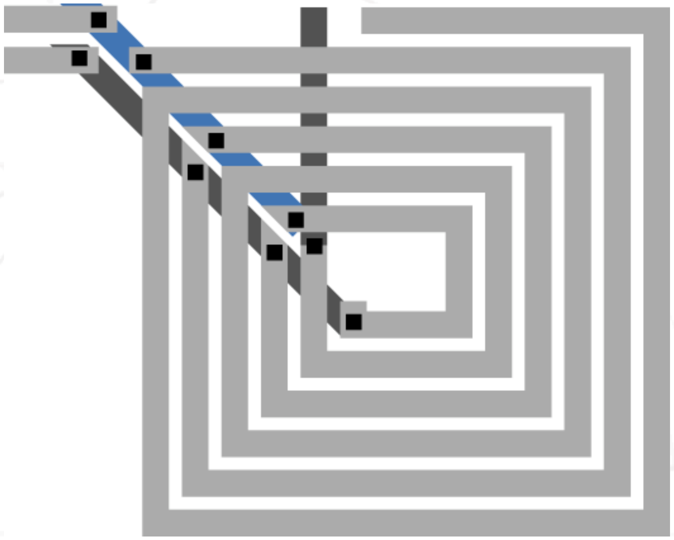
- Siemens team showed that on-chip transformers were useful for PA interstage matching.
- Can they be used for the output stage as well? … Caltech DAT

Planar Transformer Layout



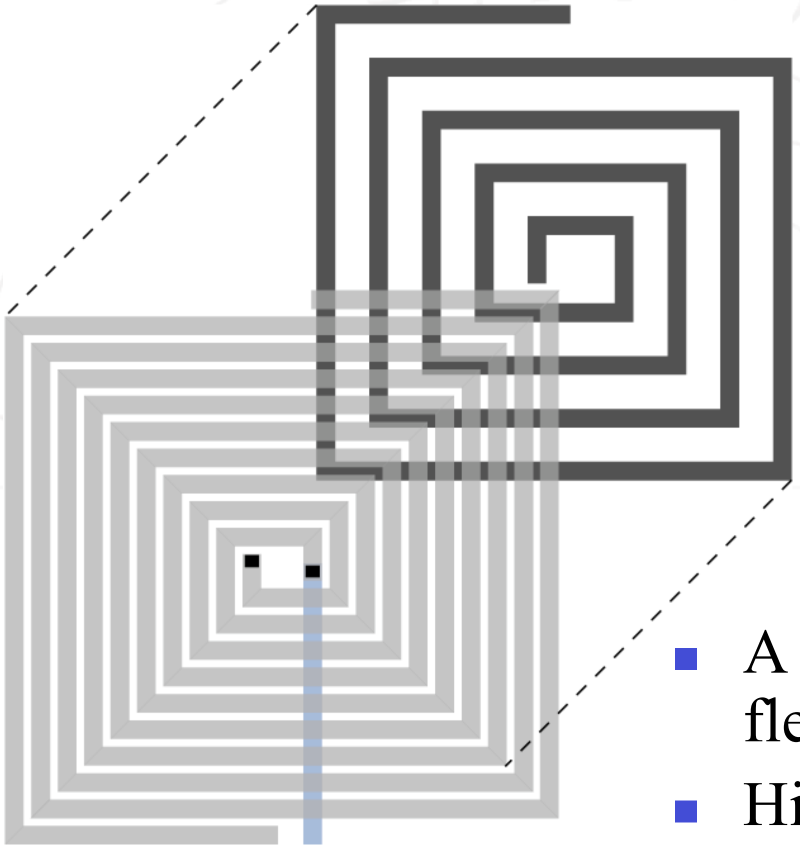
- Moderately high *k* factor transformers can be realized using two metal layers
- Different layout styles offer an asymmetric primary/secondary, a symmetric prim/sec, and a fully balanced and symmetric prim/sec

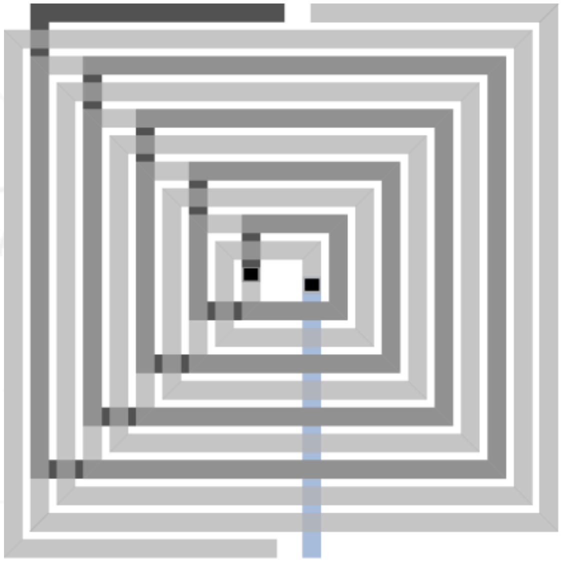
Transformer Turns Ratio



- With a planar layout, turns ratio can be obtained from omitting turns on the secondary or by connecting secondary turns in parallel
- Parallel connection offers lower loss on secondary

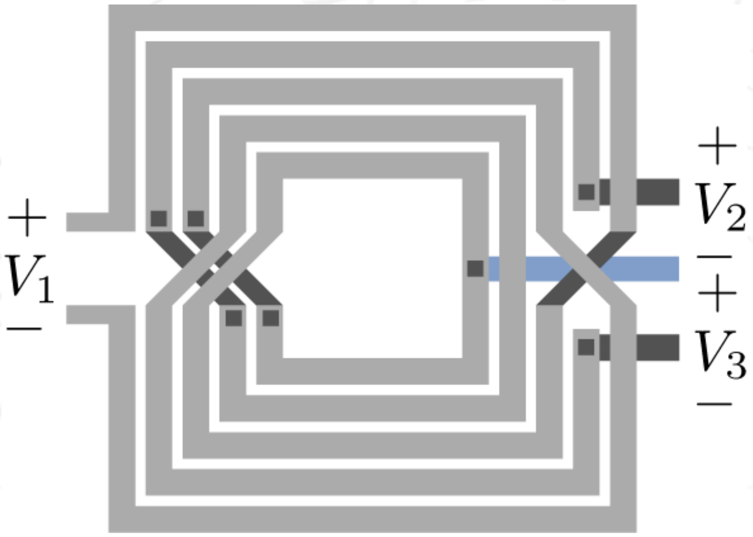
High Turns 3D Ratio Transformers

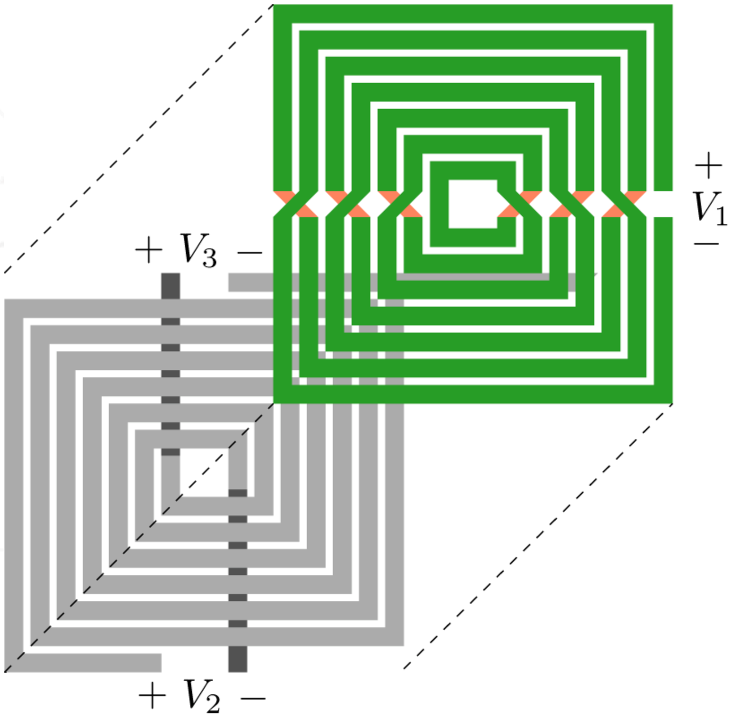




- A 3D layout allows much more flexibility.
- High turns ratio and higher coupling factor can be implemented in a simple way

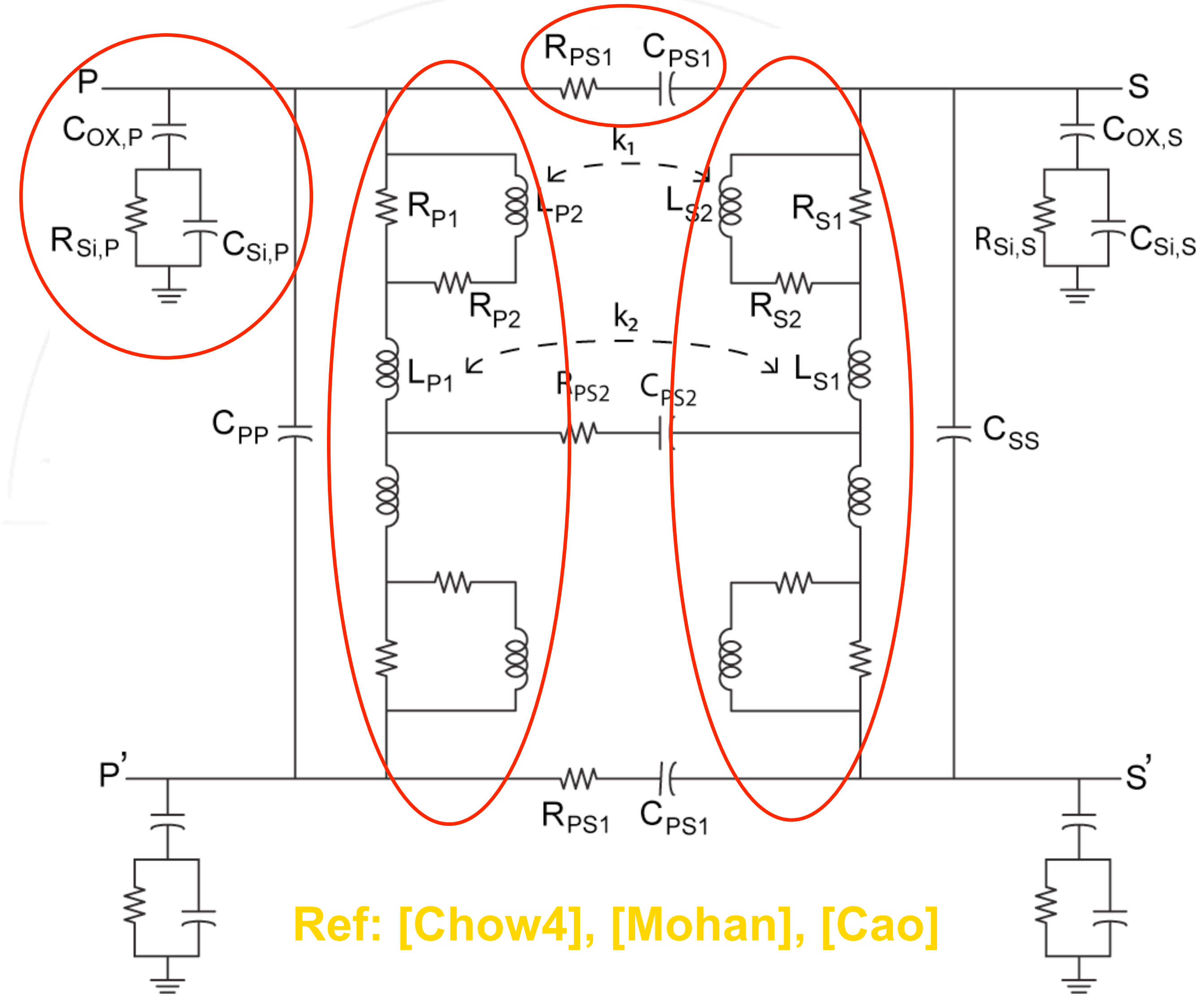
Balun Layout





- Symmetric structures can be used to build baluns.
- Baluns are a natural fit in fully differential circuits.

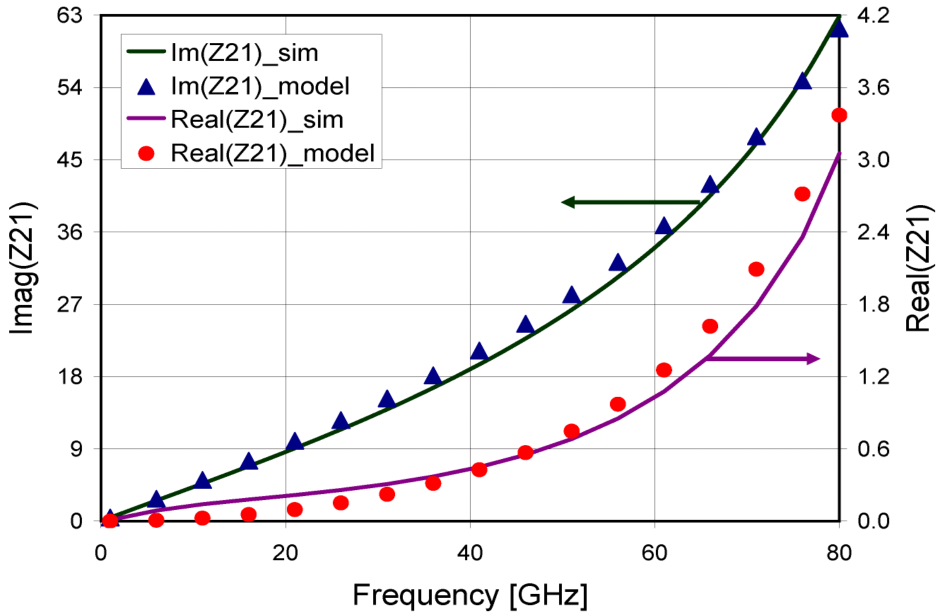
Lumped Modeling of Transformer

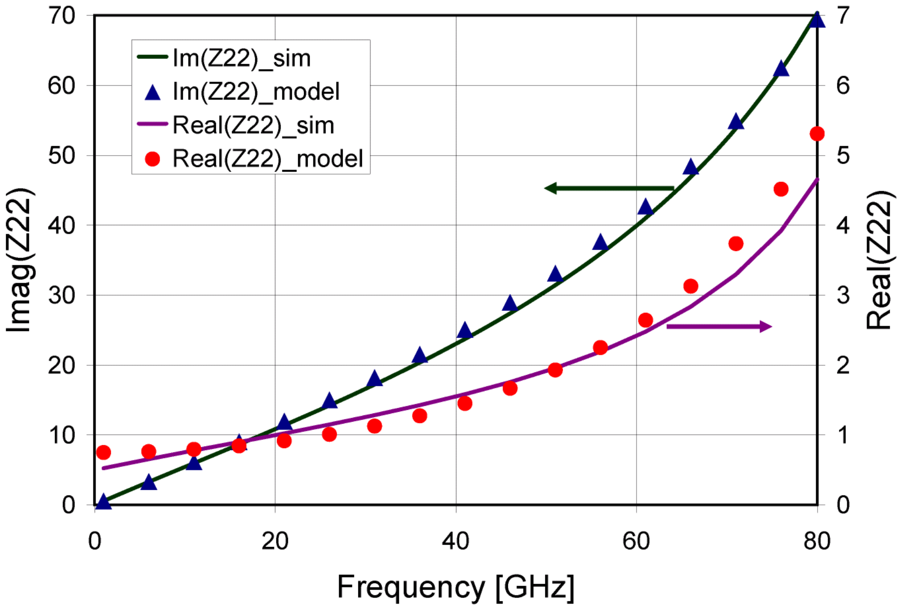


Ref: [Chow4], [Mohan], [Cao]

- Symmetric 2π model
- RL network models frequency-dependent loss
- Winding capacitance for SRF
- Asymmetric substrate network

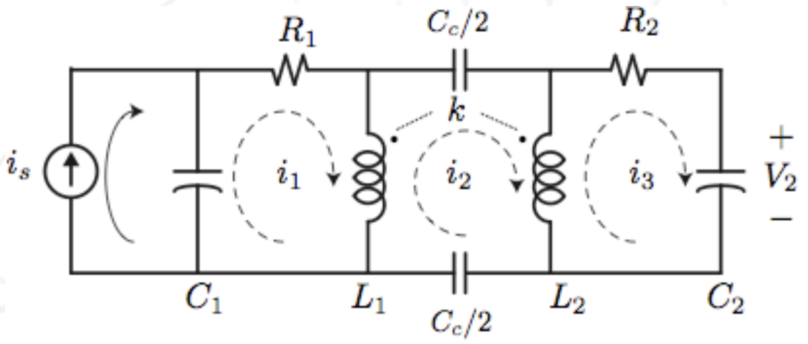
Comparison of Results





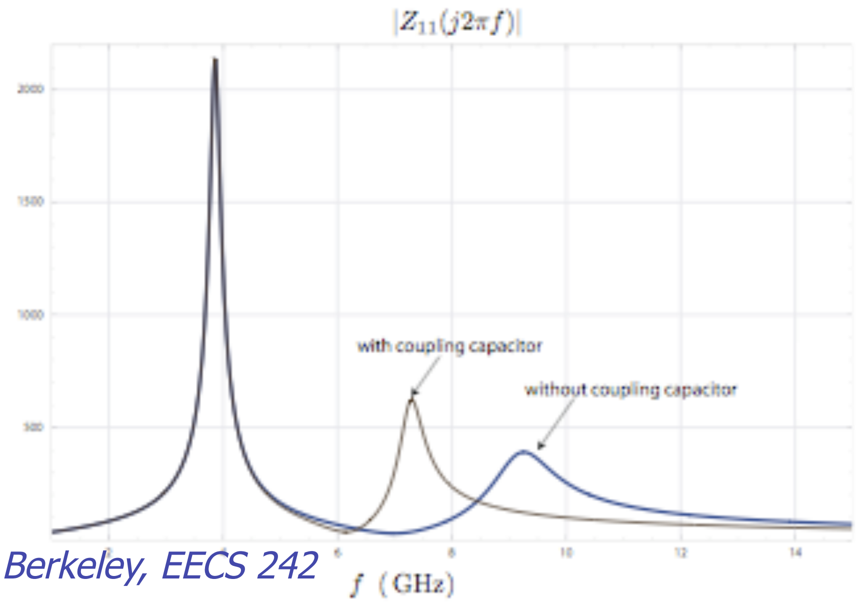
- Necessary to match both y, z parameters instead of s-parameters only
- Good match up to high frequencies

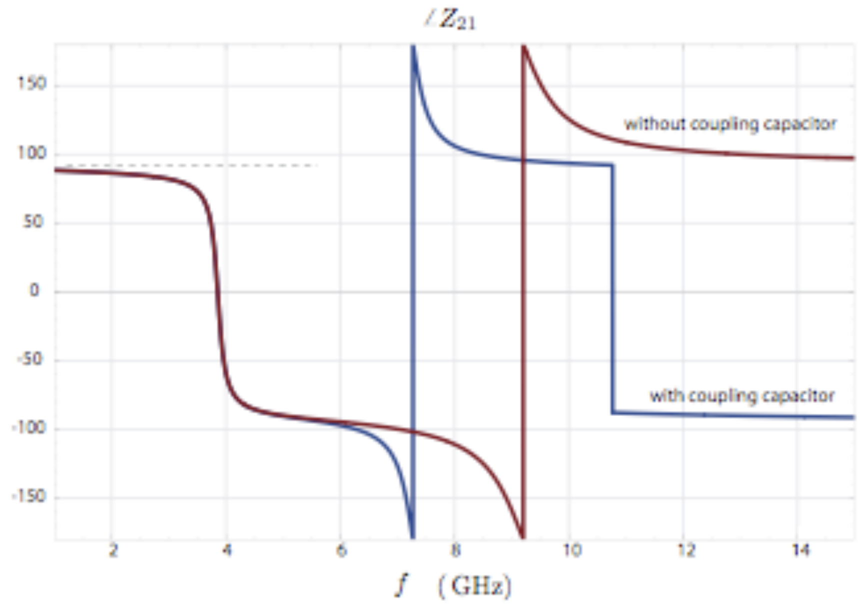
Transformer Resonant Modes



$$\omega^+ = \sqrt{\frac{1}{C_0(L_1+L_2+2M)}} \qquad \omega^- = \sqrt{\frac{1}{(C+2C_c)(L_1+L_2-2M)}}$$

- Two modes due to odd and even excitation.
- In “even” mode the coupling capacitor Cc is not excited.

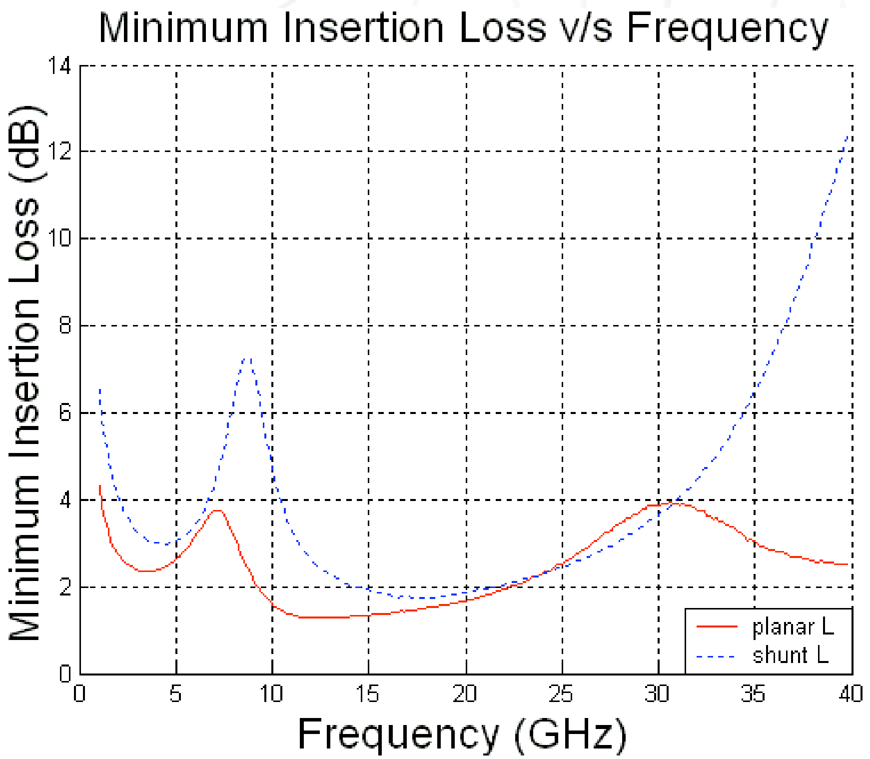


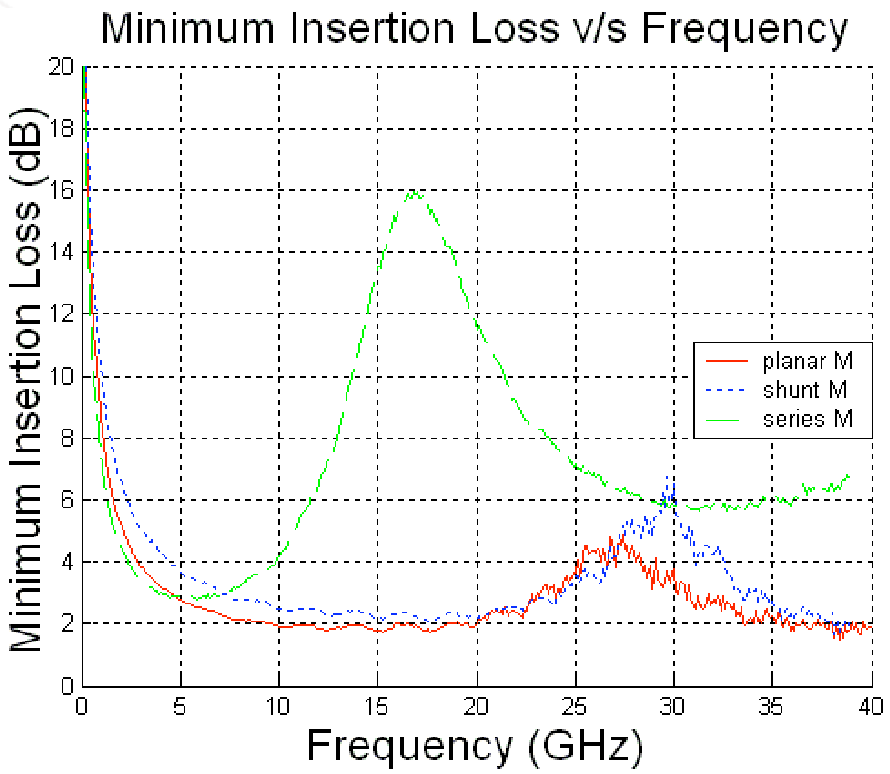


Transformers Comparison

- Paper published at RFIC 2004:
  - "Microwave Performance of Monolithic Silicon Passive Transformers", Mounir. Y. Bohsali and Ali. M. Niknejad
- Compare various transformer layouts
- Define metric that takes into account bandwidth

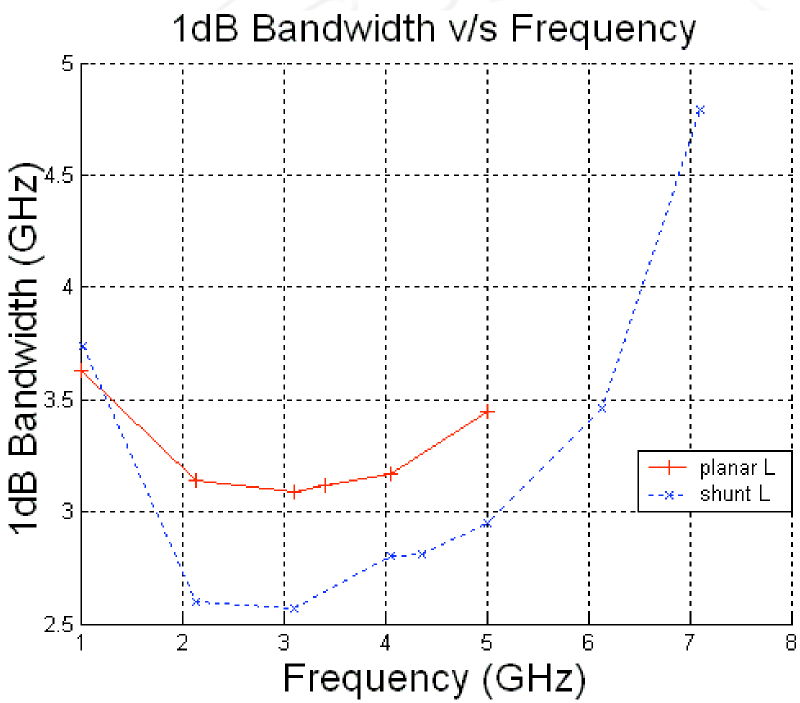
Shunt versus Planar

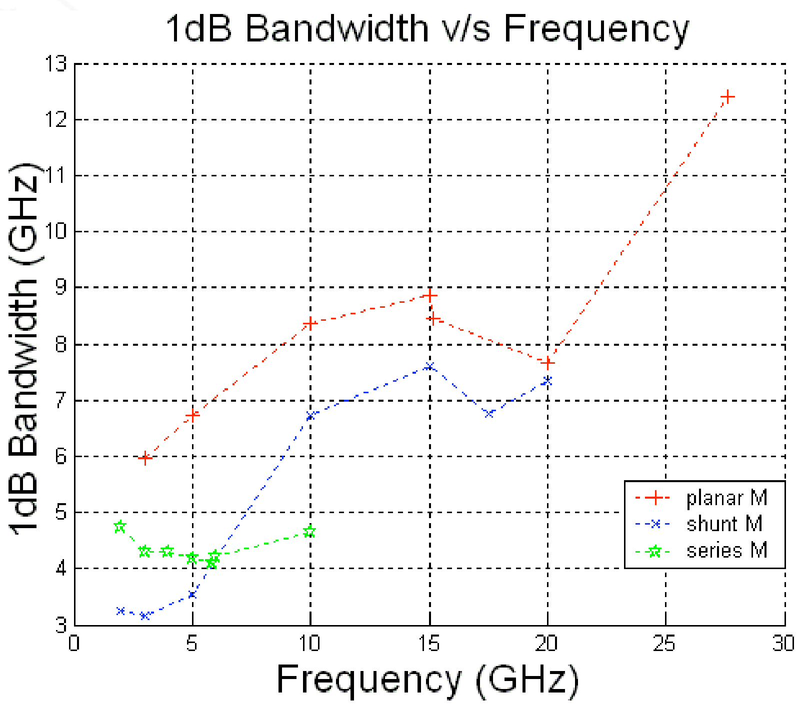




- Planar versus shunt have similar behavior below “resonance” with 2-3 dB of loss.
- Series structure has much lower resonance frequency.

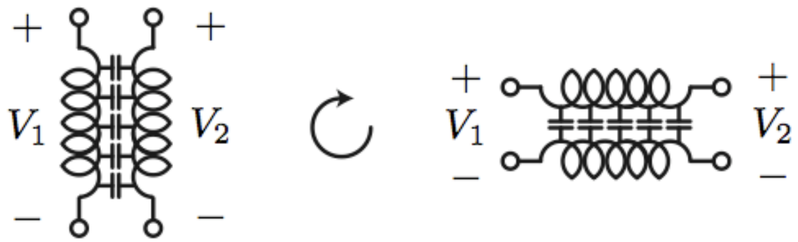
Transformer Bandwidth



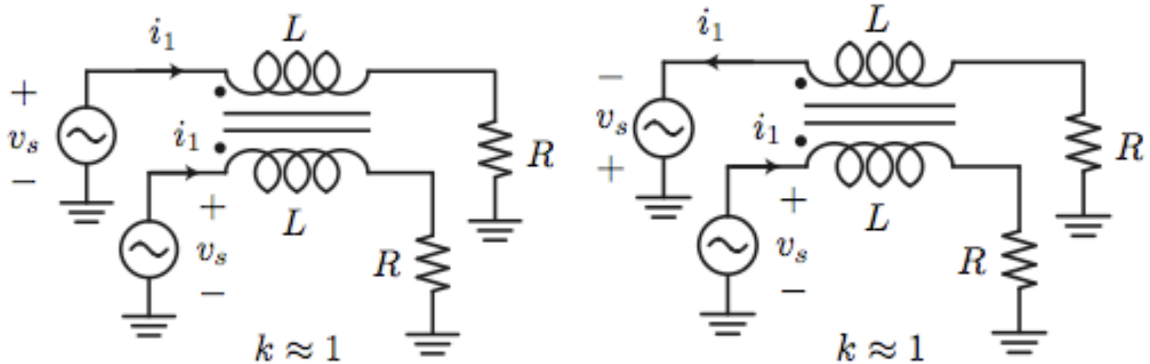


- Define a new metric: bandwidth over which gain is within 1 dB of "optimal" gain (for a bi-conj. match)
- Planar structure has very good bandwidth (50-150%), and other structures are worse, but series structure is significantly worse.

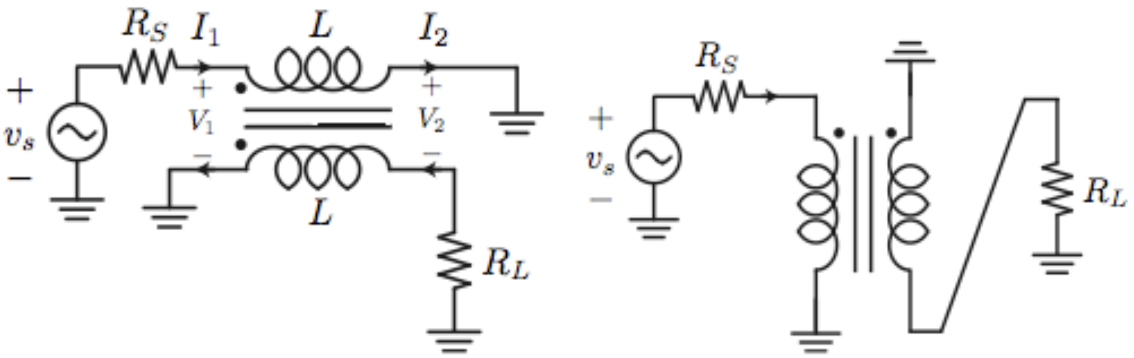
Transmission Line Balun



- Turn parasitic coupling capacitance into a distributed broadband transmission line!
- Excite the differential mode rather than the odd mode.



Broadband Inverter



$$V_1 = (\cosh\gamma\ell + \sinh\gamma\ell)\, V_2 = e^{\gamma\ell} V_2$$

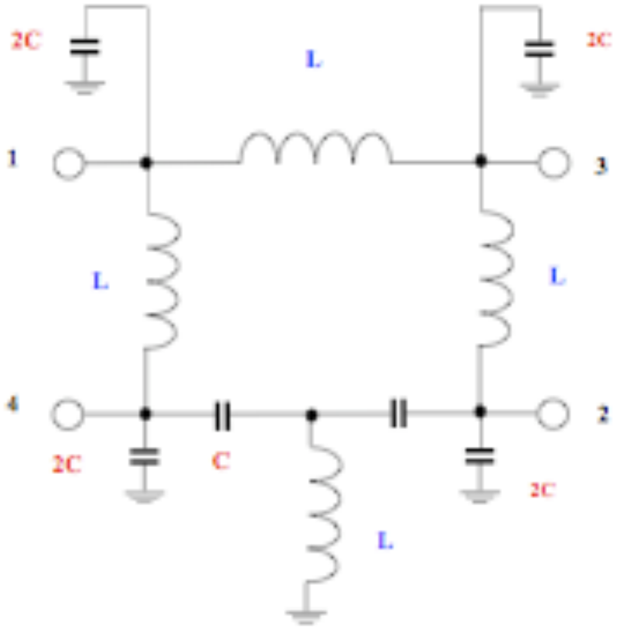
$$v_L = -V_2 = -e^{-\gamma\ell} V_1$$

- The voltage at the load is inverted if the length of the line is small (~1/10 wavelength)
- Note that line excited with both odd and even mode at source but higher Z0 and loss of line rejects even mode.

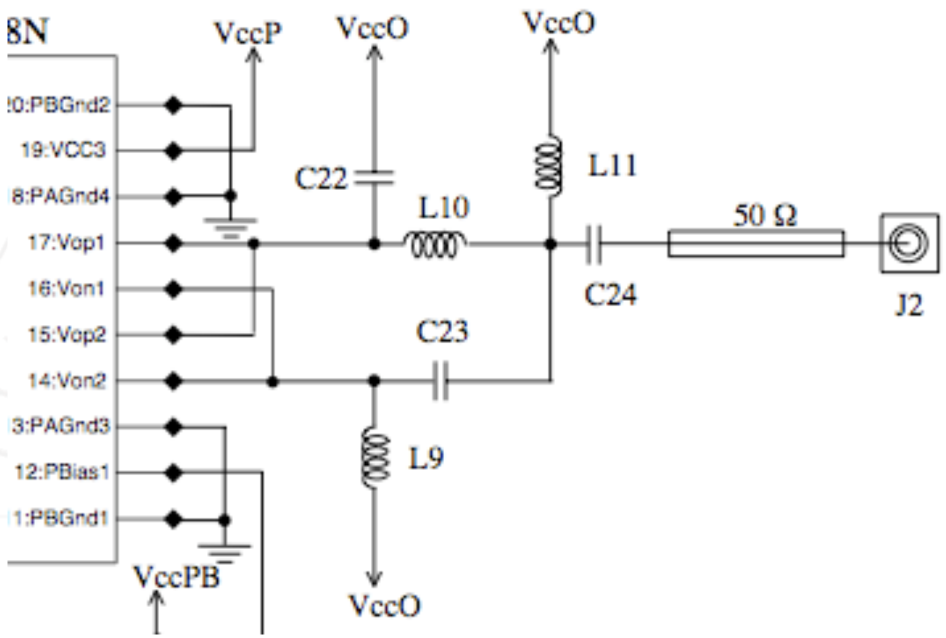
LC Coupler

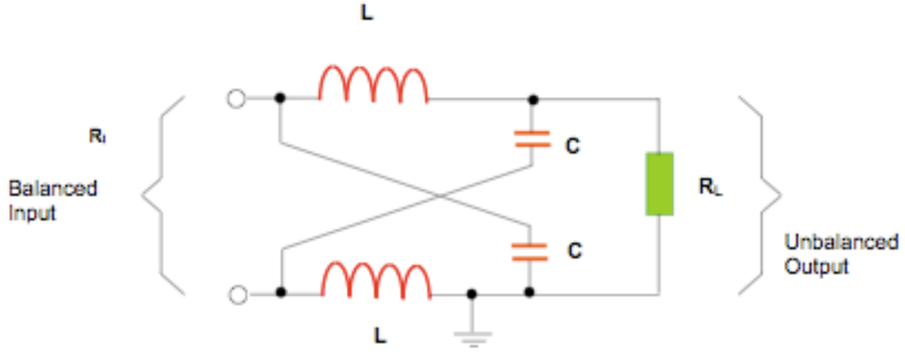
- Lumped 180º coupler
- Low bandwidth (20%)
- Element values

$$\frac{1}{\omega C} = \omega L = \sqrt{2} Z_0$$



LC Balun





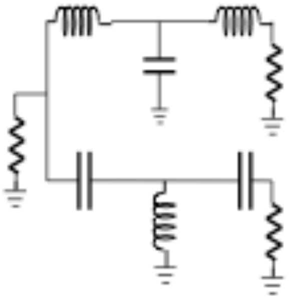
- Essentially a bridge with phase lead and lag networks.
- Bandwidth? Depends on Q of match since this is just a high-pass and low-pass matching network.

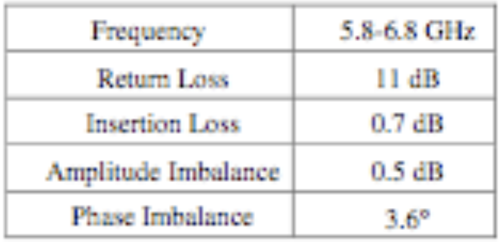
$$Z_c = \sqrt{R_i R_L}$$

$$L = \frac{Z_c}{\omega} \quad C = \frac{1}{\omega Z_c}$$

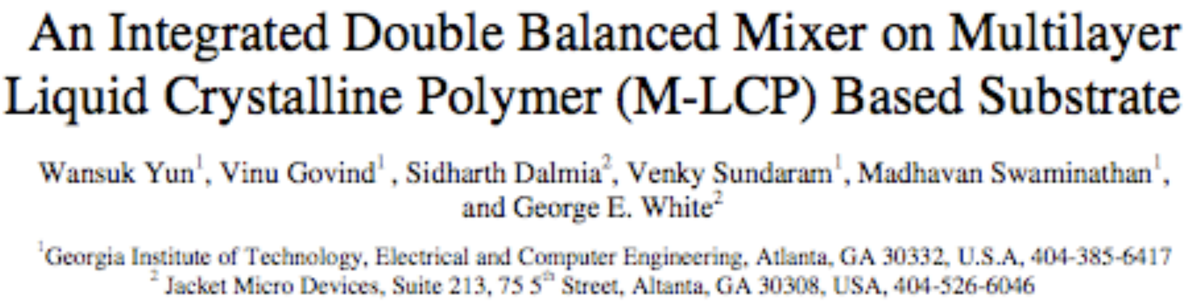
Measured Lumped Balun

- 20% fractional bandwidth
- IL low due to substrate
- Phase/amplitude balance relatively poor.





Frequency	5.8-6.8 GHz
Return Loss	11 dB
Insertion Loss	0.7 dB
Amplitude Imbalance	0.5 dB
Phase Imbalance	3.6°

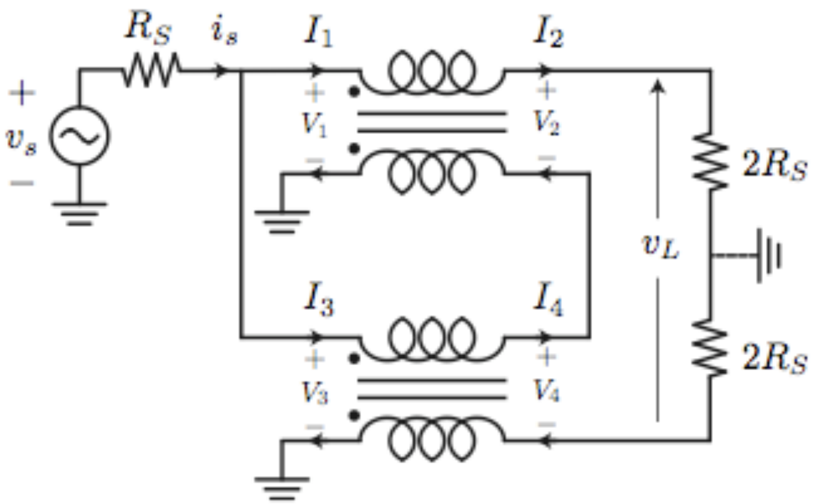


An Integrated Double Balanced Mixer on Multilayer Liquid Crystalline Polymer (M-LCP) Based Substrate

Wansuk Yun[1], Vinu Govind[1], Sidharth Dalmia[2], Venky Sundaram[1], Madhavan Swaminathan[1],
and George E. White[2]

[1]Georgia Institute of Technology, Electrical and Computer Engineering, Atlanta, GA 30332, U.S.A, 404-385-6417
[2] Jacket Micro Devices, Suite 213, 75 5th Street, Altanta, GA 30308, USA, 404-526-6046

Transmission Line Balun



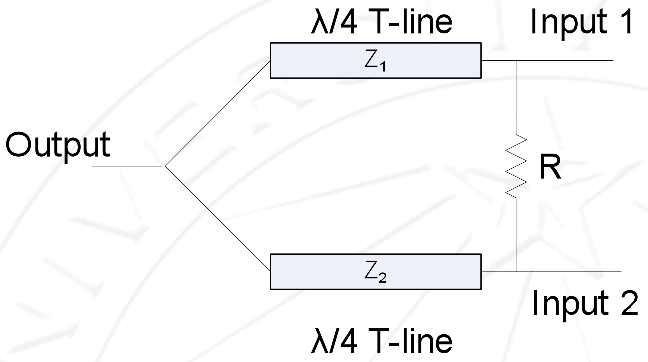
- This works as a balun over a very broad band. If length is quarter wavelength, the even mode is rejected at center frequency.

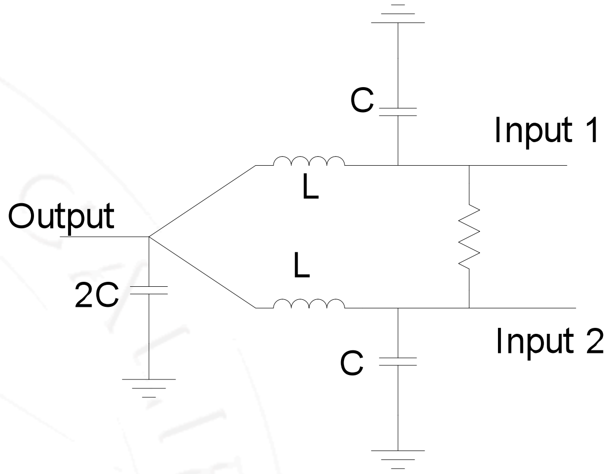
$$G_v = \frac{v_L}{v_s} = \frac{2}{\cos k\ell + j\sin k\ell\frac{Z_0}{2R_S}} = \frac{2}{e^{jk\ell}} = 2e^{-jk\ell}$$

Marchand Balun

- Improved bandwidth
- Less sensitivity to even-mode impedance
- Requires two quarter wave structures.

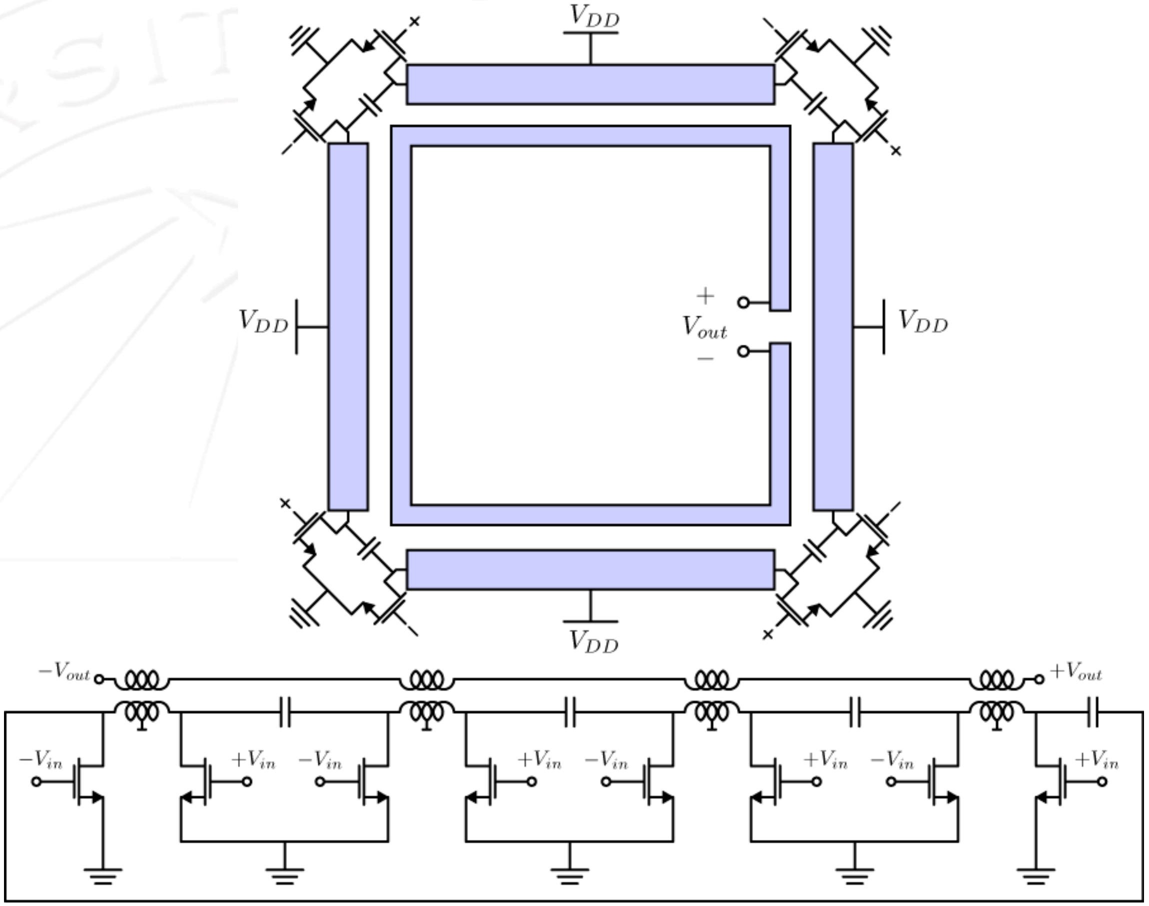
Wilkinson Power Combiner





- Theoretically we cannot build a *lossless* 3 port device with isolation and power combining.
- The Wilkinson uses a resistor that is normally "open circuited" (even mode) and does not generate loss.
- Effective for high frequency designs or using LC circuit at low frequency.

Cal Tech DAT



- Use virtual grounds wisely to turn 1:1 coupled lines into a transformer loop.

Transformer FOM

- Unlike inductor Q factor, there is no obvious “silver bullet” FOM for transformers.
- For power combining applications, the maximum power gain (bi-conjugate match) has been used as a figure of merit
- For a simple 1:1 transformer, the maximum gain is a function of only the *Q* and *K* factors

$$G_{max} = \frac{y_{21}}{y_{12}}\left(k - \sqrt{k^2 - 1}\right) = k - \sqrt{k^2 - 1}$$

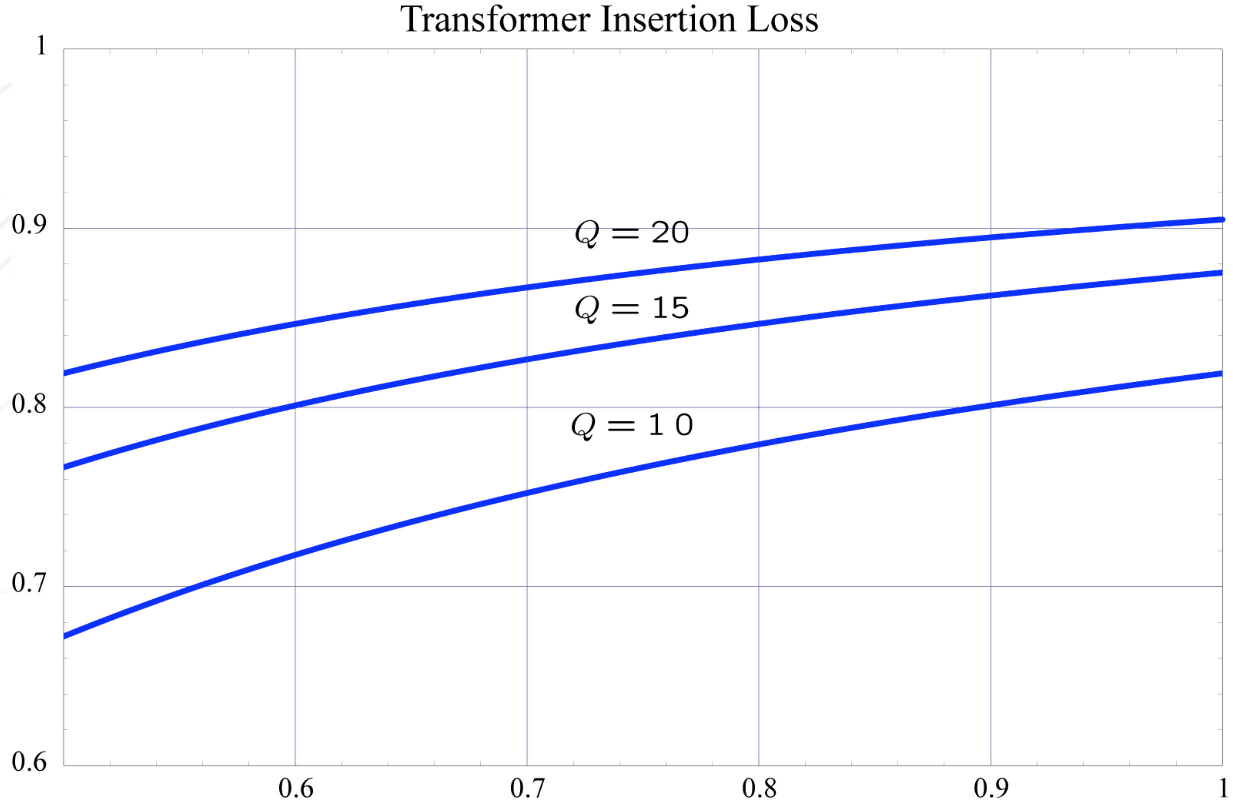
$$Z = \begin{pmatrix} R_p + j\omega L_p & j\omega M \\ j\omega M & R_s + j\omega L_s \end{pmatrix}$$

$$k = \frac{2\Re(z_{22})\Re(z_{11}) - \Re(z_{21}z_{12})}{|z_{21}z_{12}|}$$

$$k = \frac{2R_x^2 + \omega^2 M^2}{\omega^2 M^2} = \frac{2R_x^2 + \omega^2 K^2 L^2}{\omega^2 K^2 L^2}$$

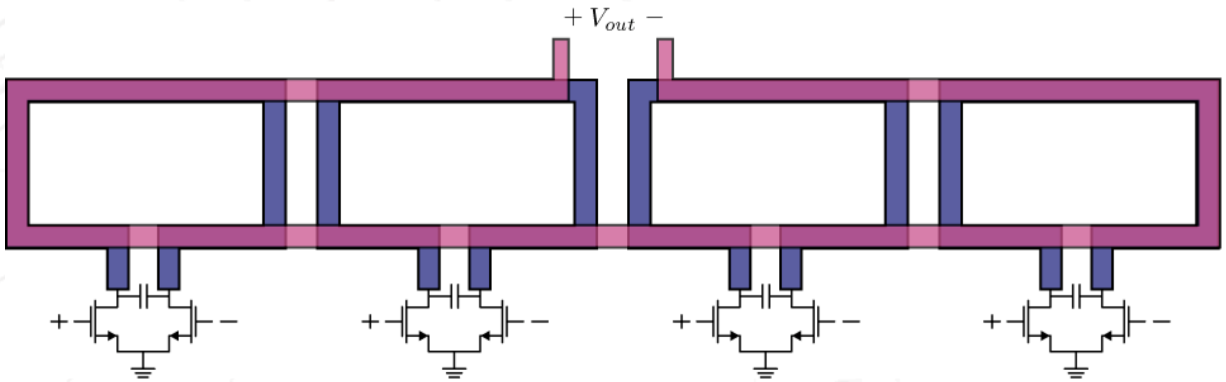
$$G_{max}(Q, K) = 1 + \frac{2}{Q^2K^2} - 2\sqrt{\frac{1}{Q^4K^4} + \frac{1}{Q^2K^2}}$$

Transformers for Power Combining



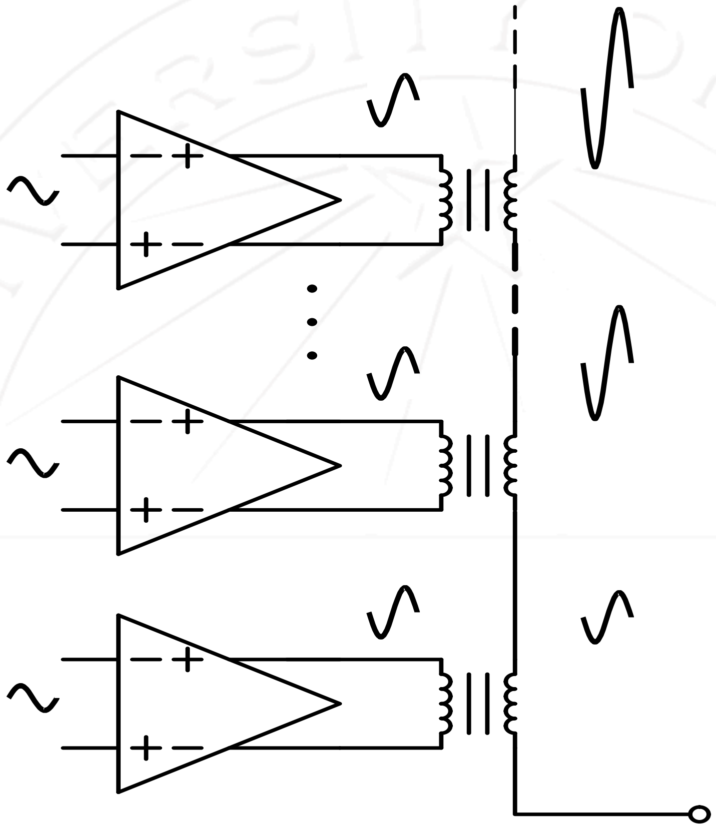
- Notice that relatively low insertion loss is possible with moderate on-chip Q and K factors, thus allowing fully-integrated transformers
- Connecting 1:1 transformers in series and shunt, we can perform efficient power combining *independent* of the number of sections [Caltech DAT architecture]

Transformer Power Combining Layout

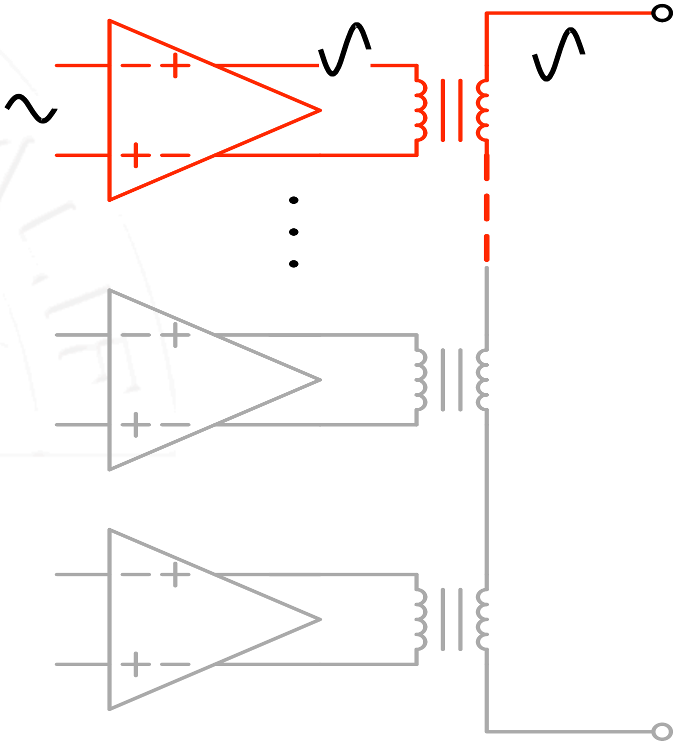


- Very simple layout
- Don't get DAT benefit → have extra "leads" that waste power
- But can turn off individual stages for power back-off
- Can easily scale power by adding more stages: design core driver stage

Fully Integrated Dual Mode CMOS PA



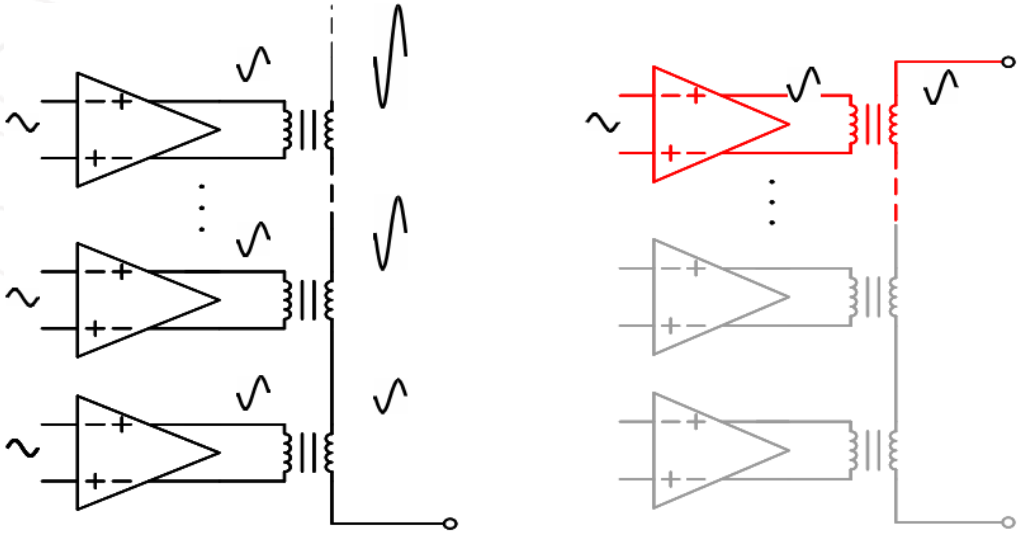
Peak Output Power Mode

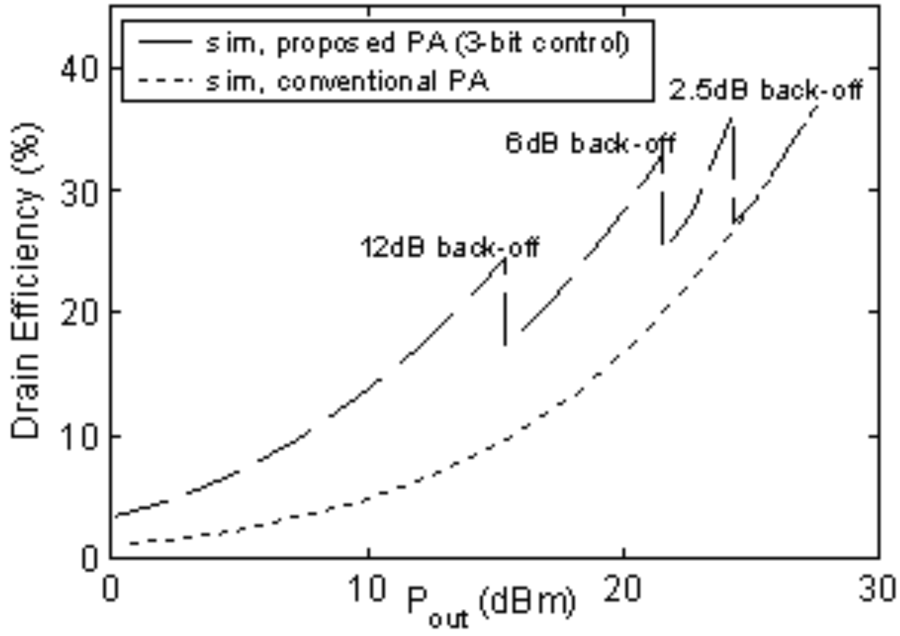


Power Back-off Mode

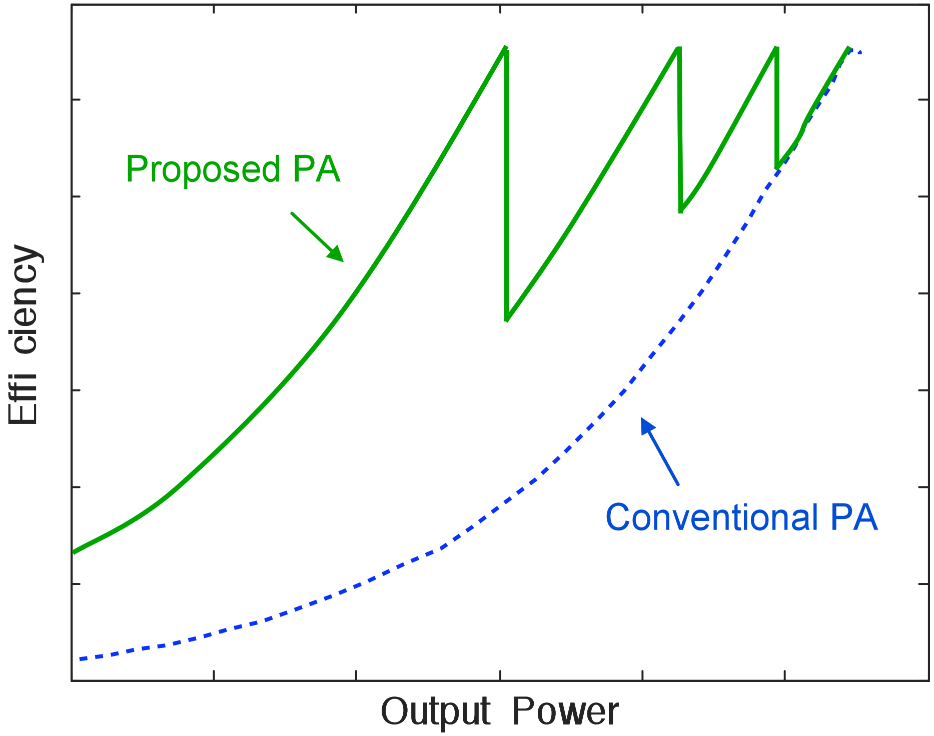
Power Combining and Control

- Use transformer to perform efficient power combining
- Can also use structure for efficient power back-off to improve average power efficiency
- At moderate back-off (6 dB), efficiency close to peak level





Power Control and Efficiency Enhancement



$$\eta_D = \frac{P_{OUTPUT}}{P_{SUPPLY}} = \frac{1}{2}\frac{V_{RF} I_{RF}}{V_{SUPPLY} \cdot I_{DC}}$$

At power back-off

Reduce DC current

Modulate load

Load Modulation

$$Z_{m,j} = \frac{\left(R_L + \sum_{i=1}^{N} m_i^2 \cdot R_{PA,i}\right) \cdot V_{pa,j}}{m_j \cdot \sum_{i=1}^{N} m_i \cdot V_{pa,i}} - R_{PA,j} \longrightarrow R_m = \frac{R_L}{N \cdot m^2}$$

$$P_o = N^2 \cdot m^2 \cdot \frac{V_p^2}{2R_L}$$

- In general there is no isolation in the transformer so the load current of one primary will “pull” the impedance of another primary.
- It’s only under the special circumstance that all windings are driven in phase that we obtain isolation.

Efficiency at Back-Off

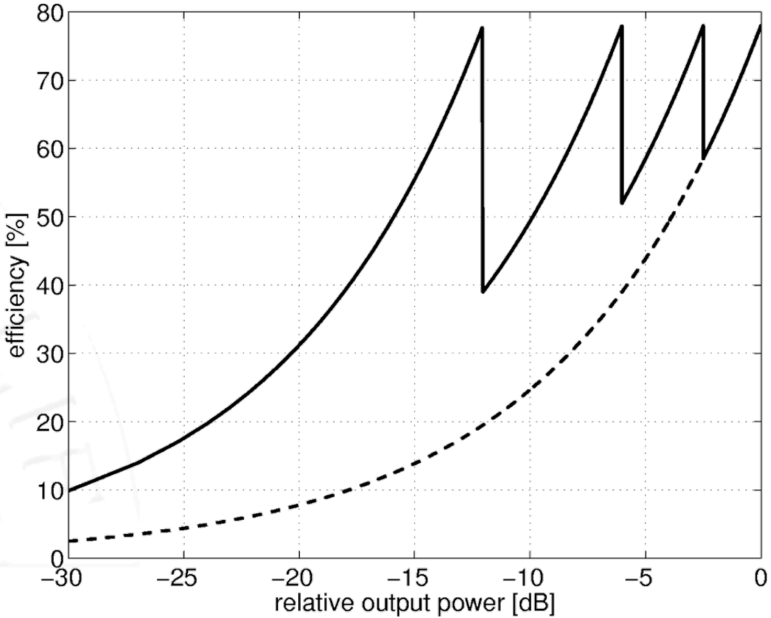
$$V_p = \frac{g_m R_L}{4} \cdot V_i = \frac{1}{4} g_m R_L \cdot V_i$$

$$\eta_B = \frac{\pi}{4} \frac{V_p}{V_{DD}}$$

$$V_{out} = 4V_p = g_m R_L \cdot V_i$$

$$V_p = \frac{g_m R_L}{2} \cdot V_i/2 = g_m R_L \cdot V_i/4$$

$$V_{out} = 2V_p = \frac{g_m R_L V_i}{2}$$



- When all four stages are on, each PA see’s ¼ of the load.
- Suppose 2 stages are turned off. Then the PA’s see ½ the load. The voltage swing at the output drops, but the voltage on each primary remains the same!
- For Class B operation, we can theoretically achieve the same efficiency at back-off.

Power Back-Off Mode

$$R = \frac{1}{3} R_L$$

$$A_{unit} = gm \cdot \frac{1}{3} R_L$$

$$V_o = A_{unit} \cdot V_i = gm \cdot \frac{1}{3} R_L \cdot \frac{3}{4} V_{i,\max} = V_{o,\max}$$

$$\eta_{overall} = \eta_{unit} = \eta_{\max}$$

$$A_{overall} = N \cdot A_{unit} = gm \cdot R_L$$

$$P_{out} = N \cdot P_{unit} = 3 \cdot \frac{1}{2} \frac{V_o^2}{\frac{1}{3} R_L} = \frac{9}{2} \frac{V_o^2}{R_L} = \frac{9}{16} P_{peak}$$

- Say we back-off the input by 3/4 .
- If we turn off one amplifier, the load seen by each amplifier is now 1/3
- But the output voltage is still at the peak optimal value
- The overall efficiency is therefore at the peak value.

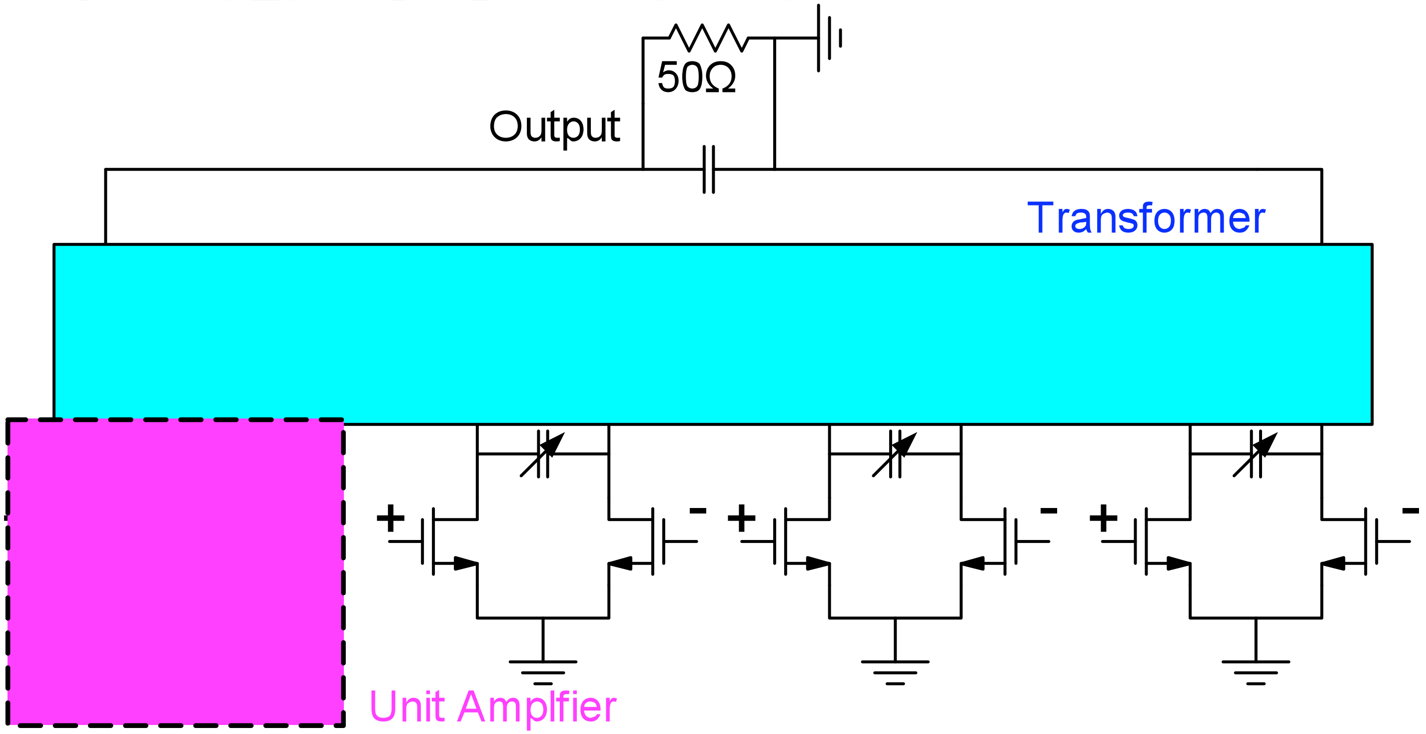
A 1.2V, 2.4GHz Fully Integrated Linear CMOS PA with Efficiency Enhancement

CICC 2006

Gang Liu[1,2], Tsu-Jae King Liu[2]
Ali M. Niknejad[1,2]

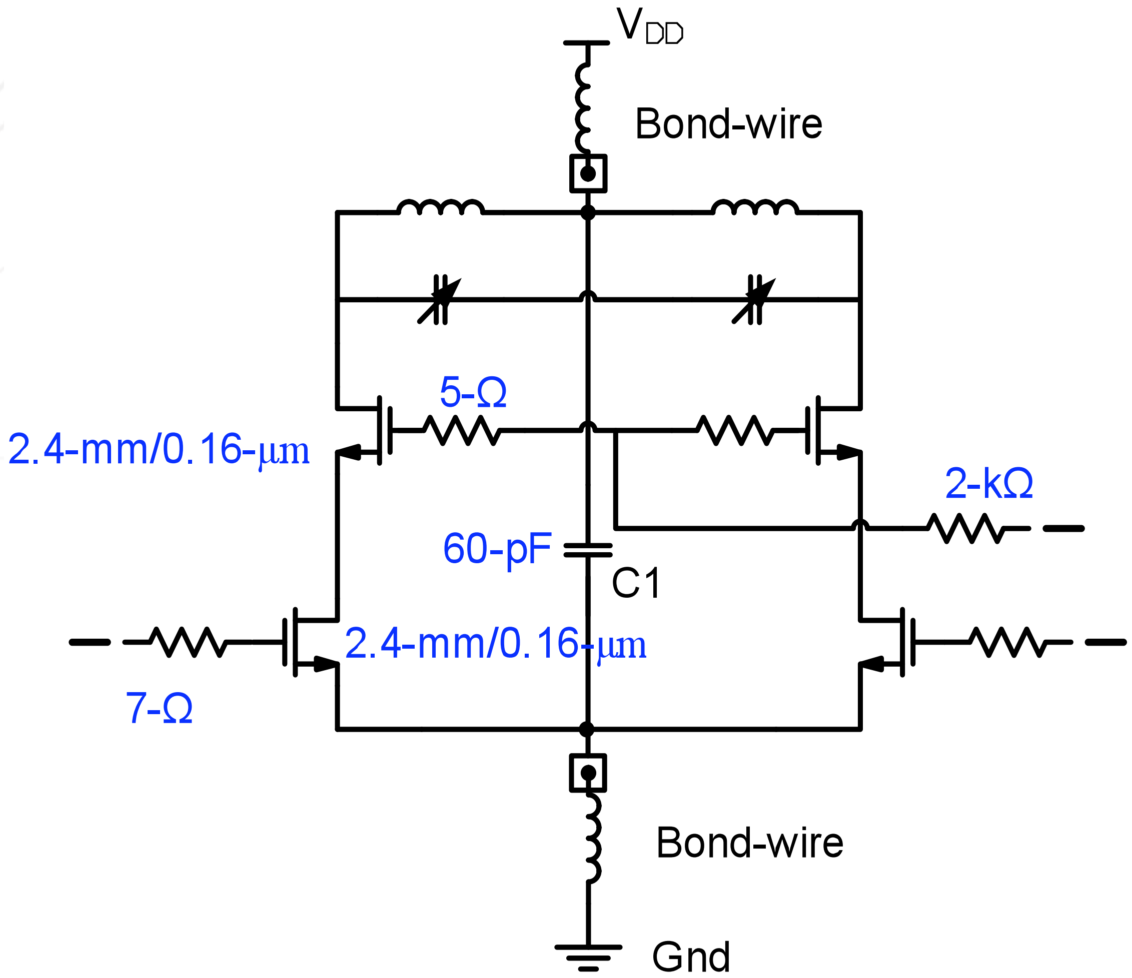
Berkeley Wireless Research Center[1]
Electrical Engineering and Computer Sciences[2]
University of California, Berkeley, CA, USA

Simplified 4-Way Combiner Schematic

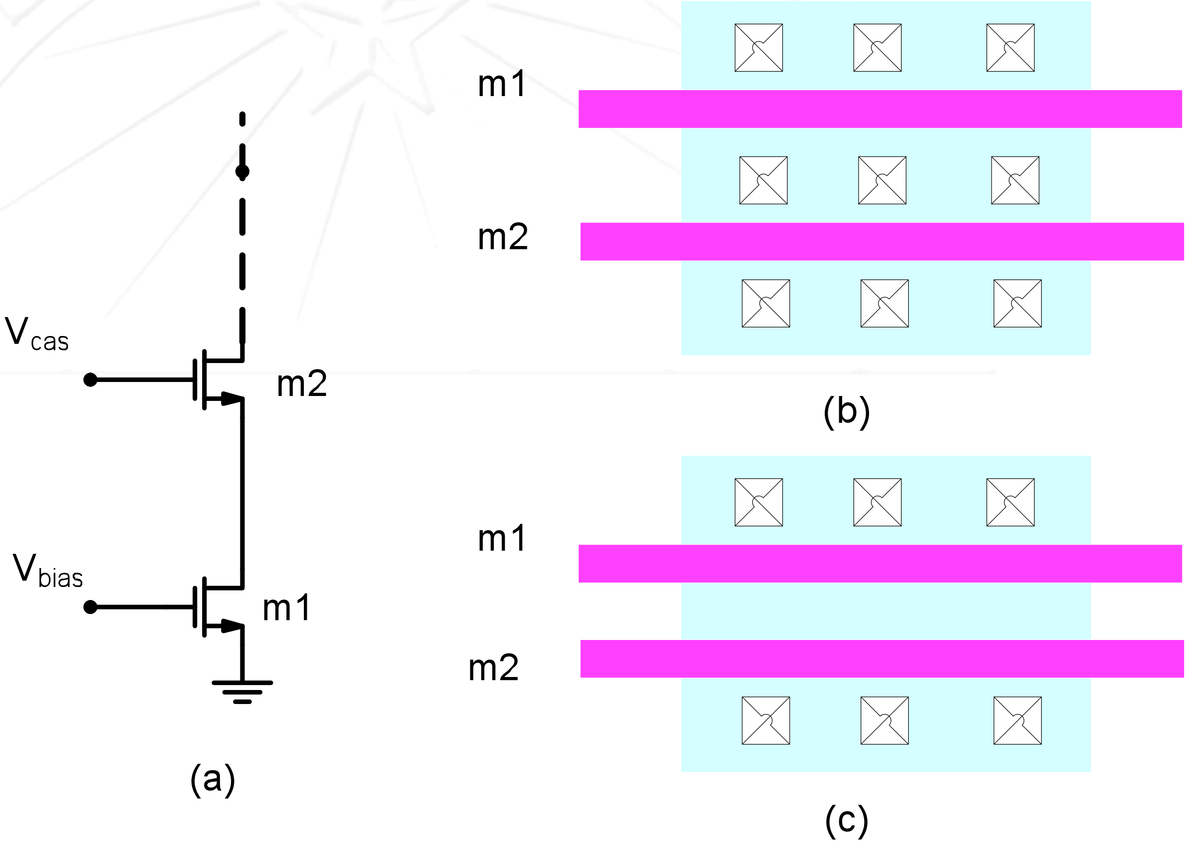


- Combing power from 4 unit amplifiers
- Centering at 2.4-GHz
- Output matching tuned by switched cap at back-off

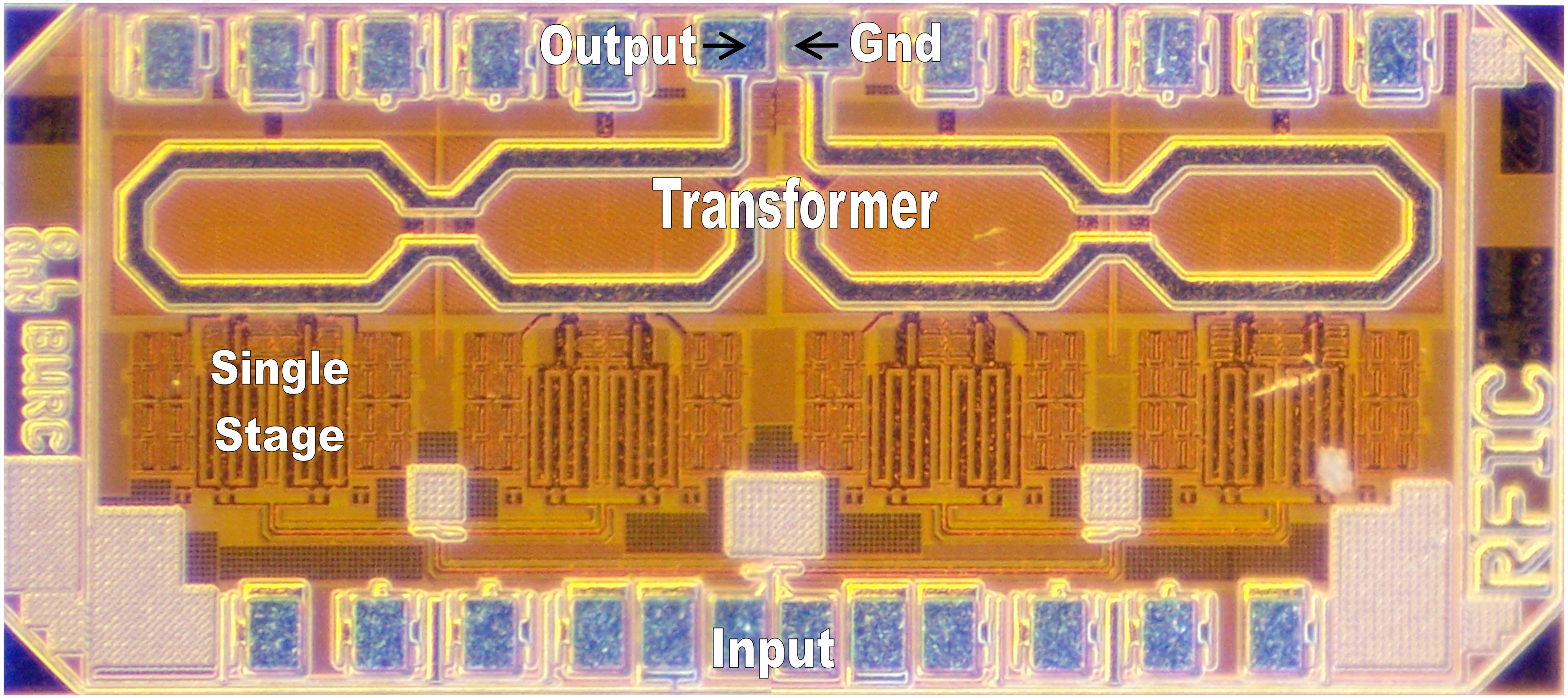
Schematic of Each Unit Amplifier



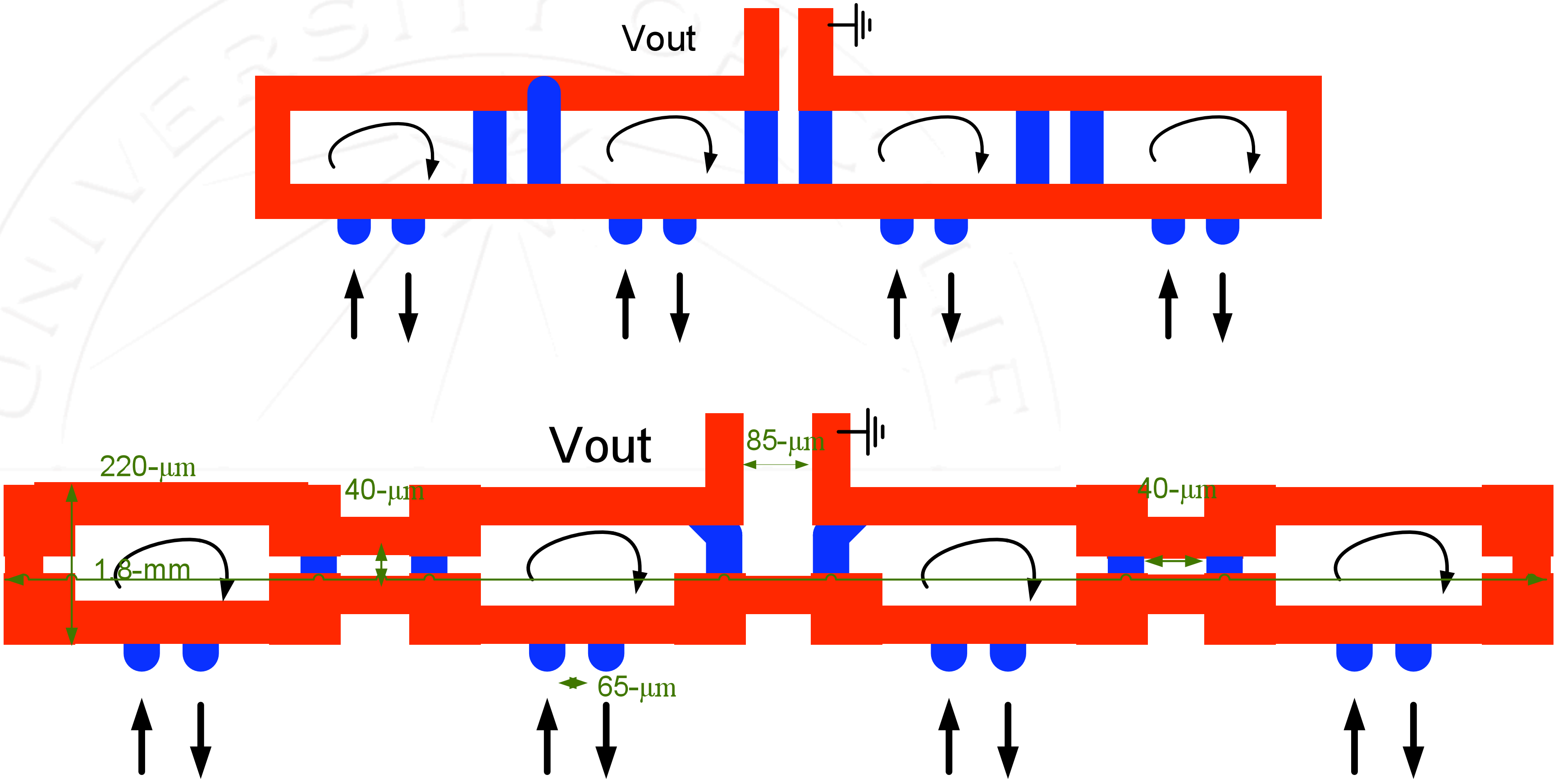
Cascode Layout



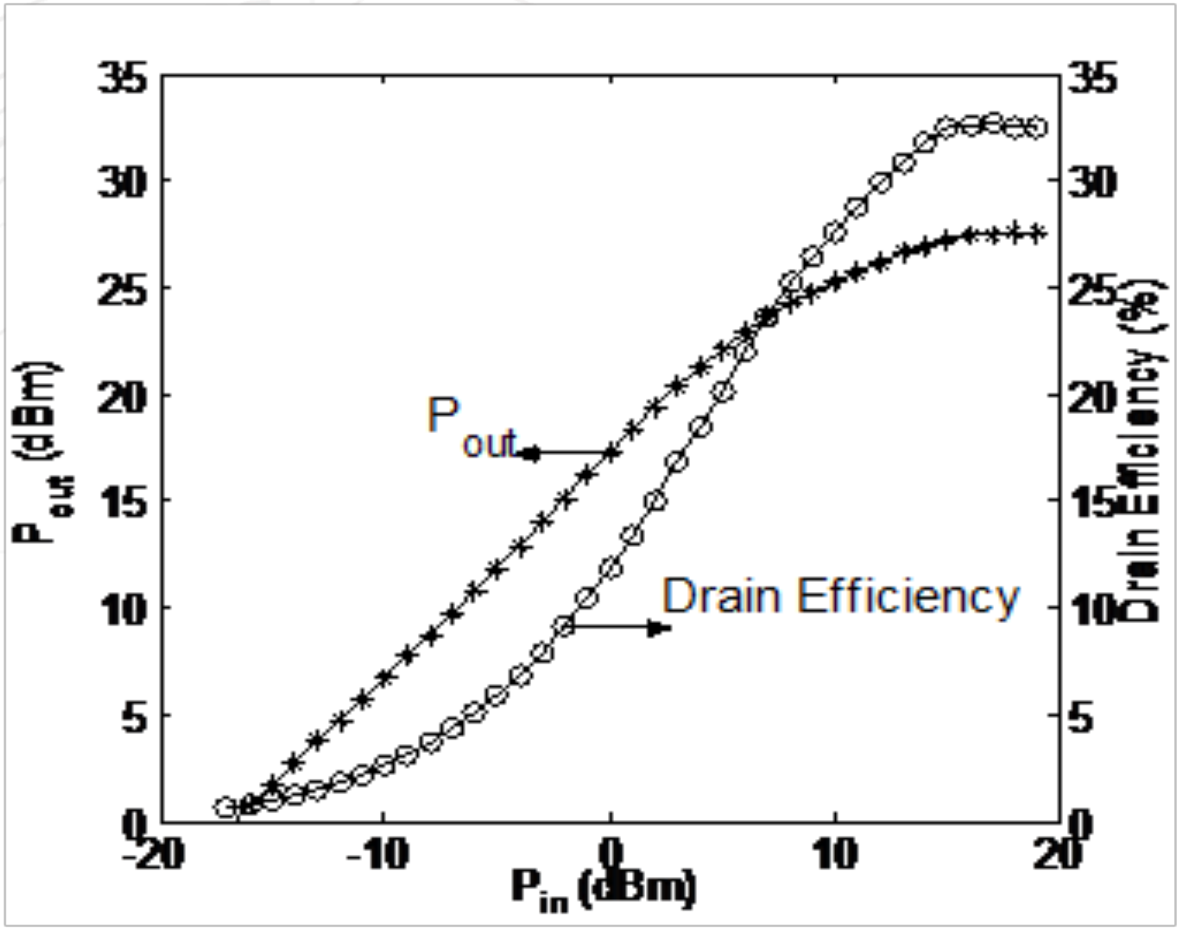
Die Microphotograph



Transformer & Cap Array

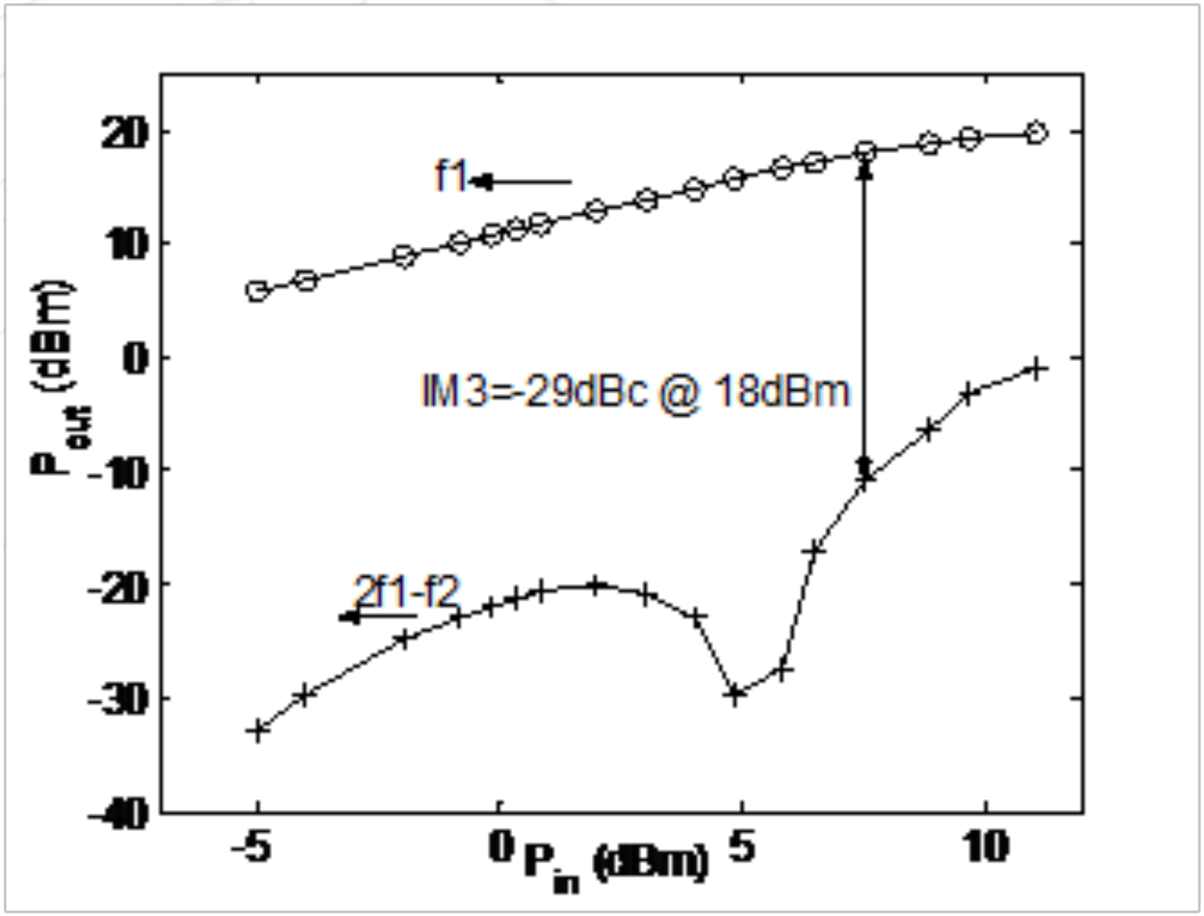


Single-Tone Test



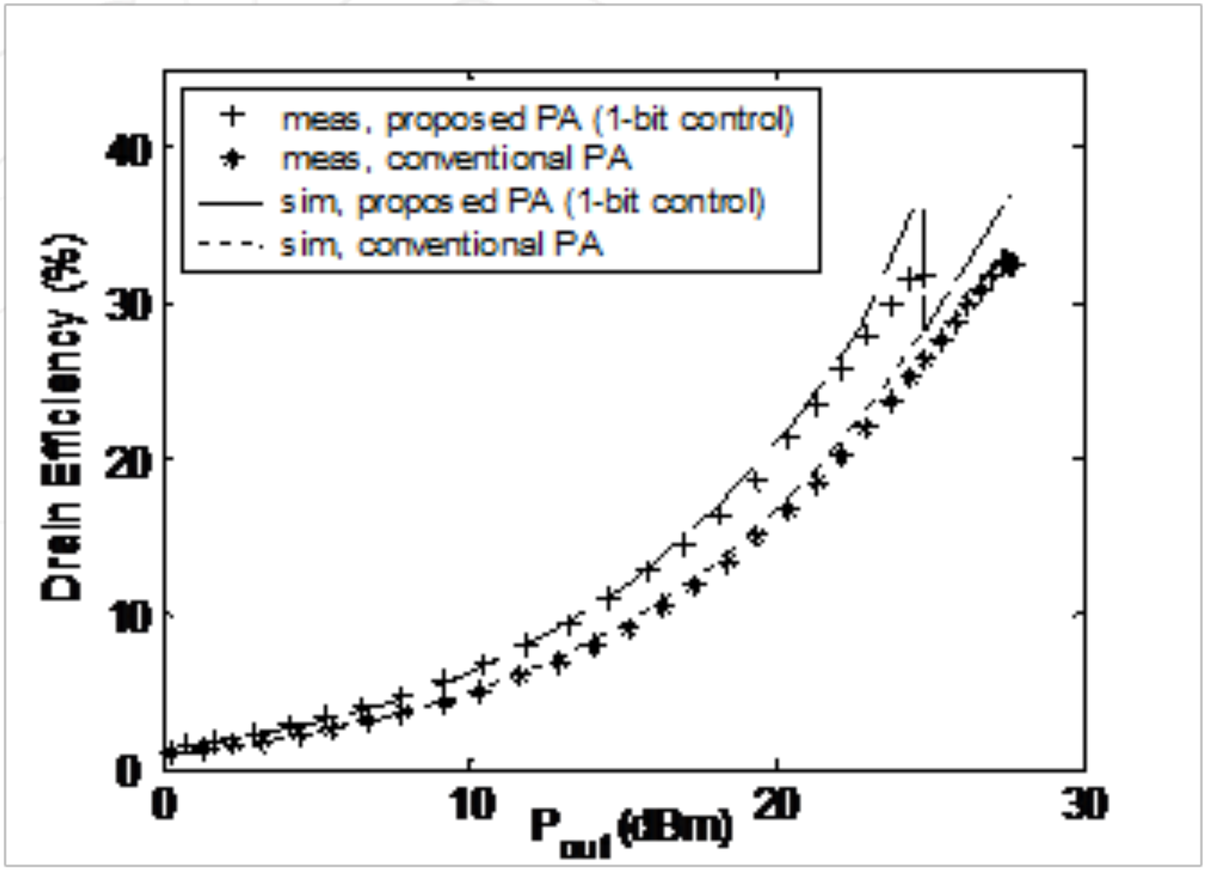
Freq = 2.4-GHz, Peak Power Mode

Two-Tones Test



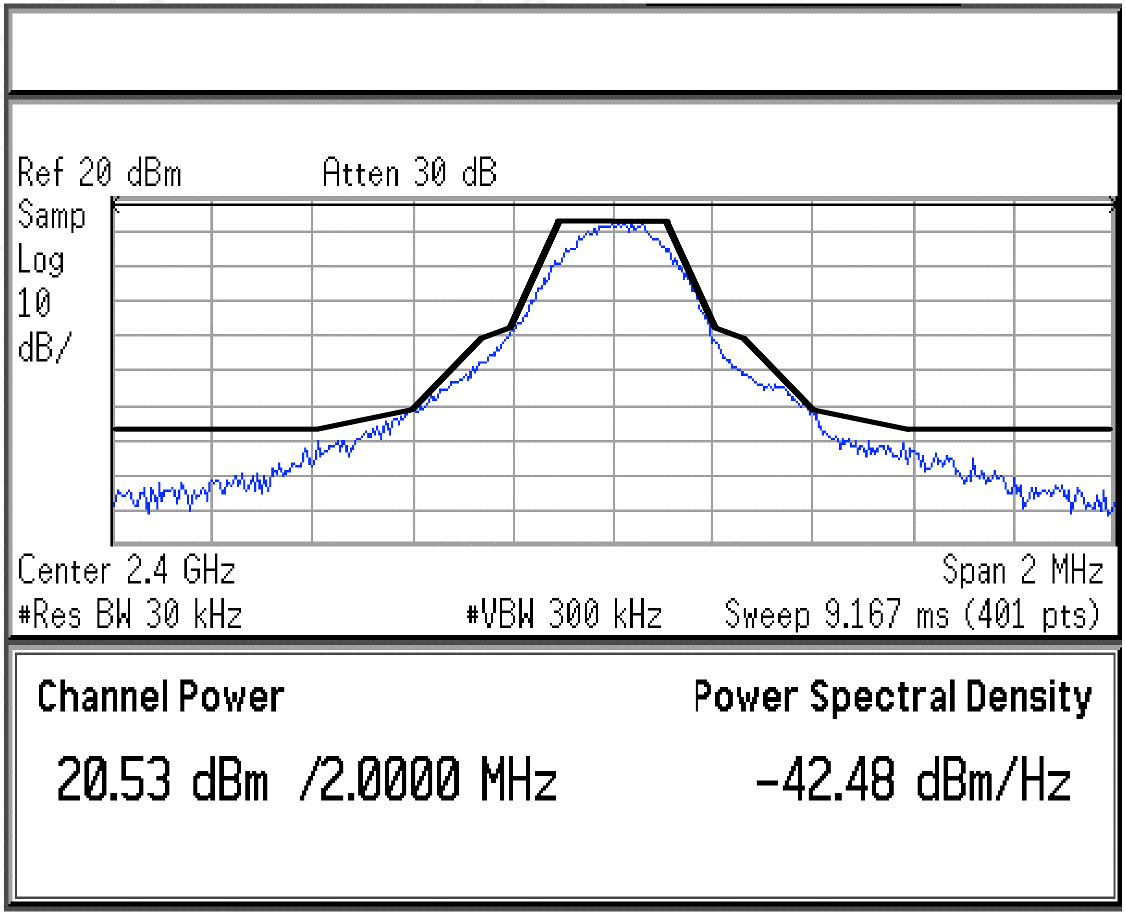
Freq = 2.4-GHz, 1-kHz tone spacing, Peak Power Mode

Measured Efficiency at Back-Off



Note: at 2.5-dB back-off, one unit amplifier was turned off.

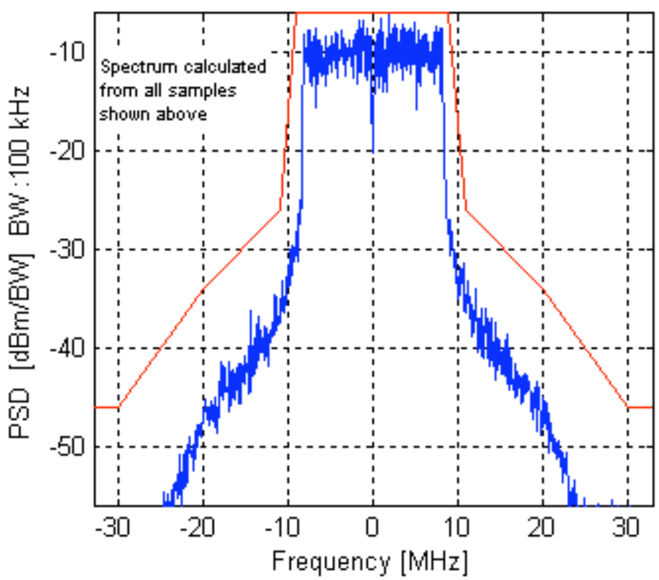
Measurements with EDGE Signals

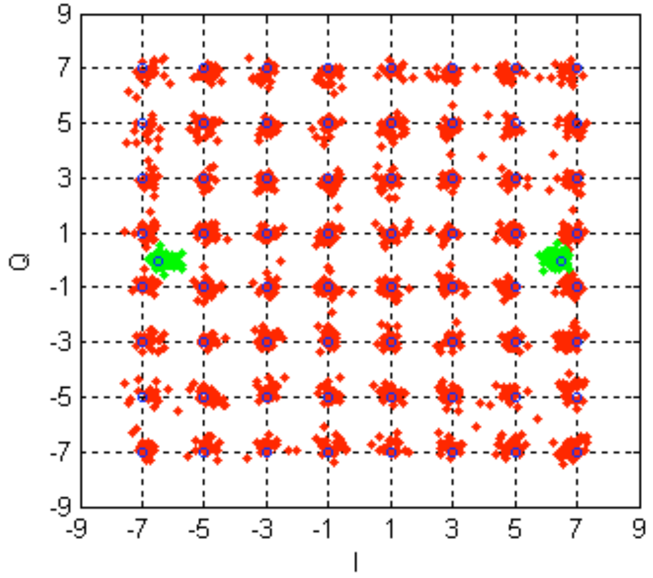


```
Ref 20 dBm          Atten 30 dB
Samp
Log
10
dB/

Center 2.4 GHz                                    Span 2 MHz
#Res BW 30 kHz          #VBW 300 kHz    Sweep 9.167 ms (401 pts)

Channel Power                       Power Spectral Density

 20.53 dBm  /2.0000 MHz               -42.48 dBm/Hz
```

Freq = 2.4-GHz, Peak Power Mode

Measurements with 802.11g Signals





P_{out} = 14.5-dBm EVM = 4.48%

Freq = 2.4-GHz, Peak Power Mode

EVM vs Output Power

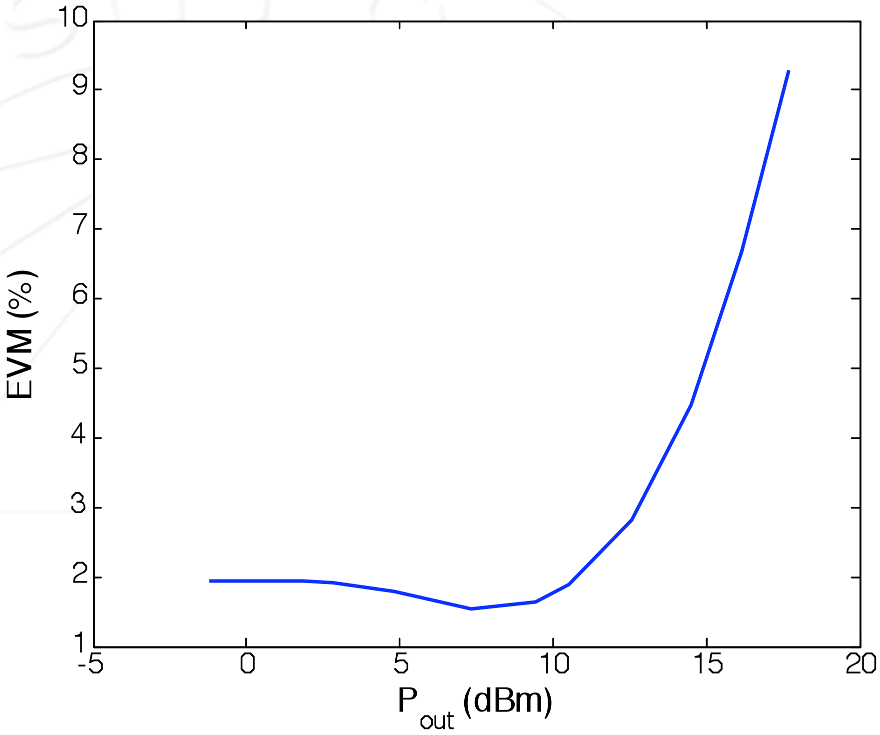


Table of Performance

Technology	0.13-µm RF CMOS
Supply voltage	1.2-V
DC Current	114-mA
P_{-1dB}	24-dBm
Drain efficiency	25%
Saturated Power	27-dBm
Drain efficiency	32%

A 5.8 GHz Linear Power Amplifier in a Standard 90nm CMOS Process using a 1V Power Supply

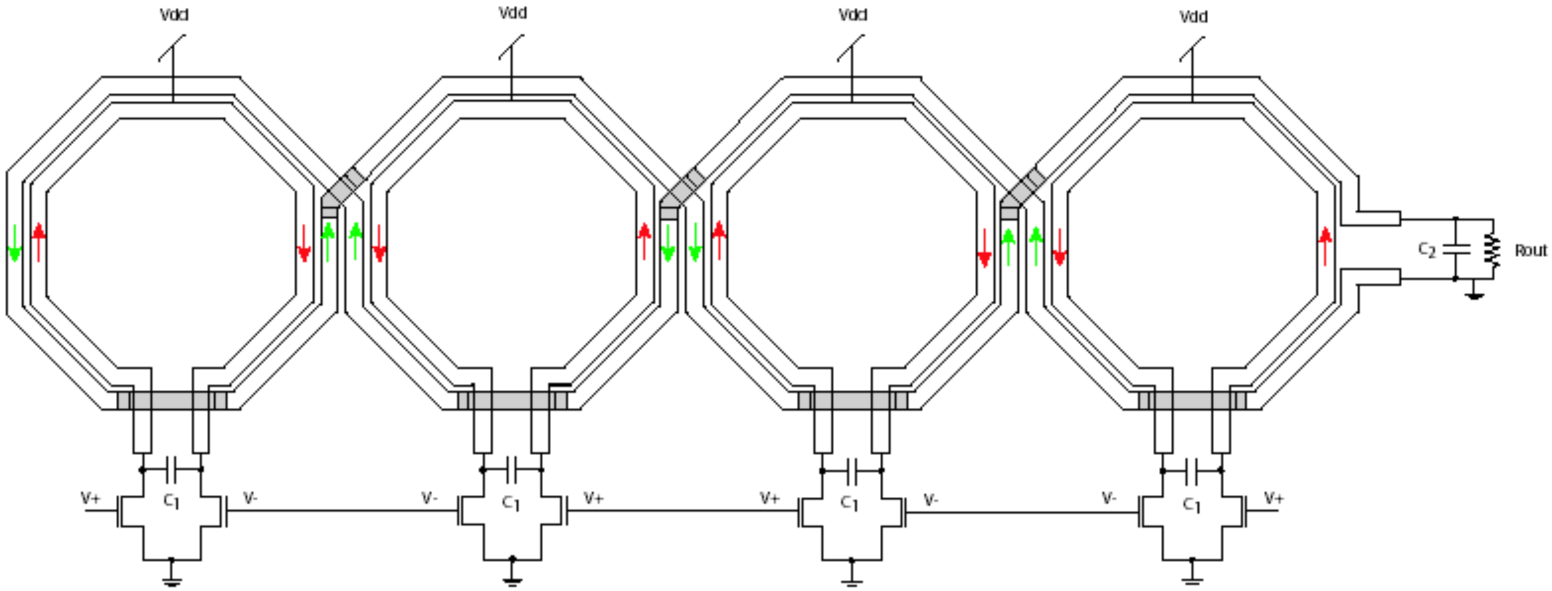
RFIC 2007

Peter Haldi, Debopriyo Chowdhury, Gang Liu and

Ali M. Niknejad

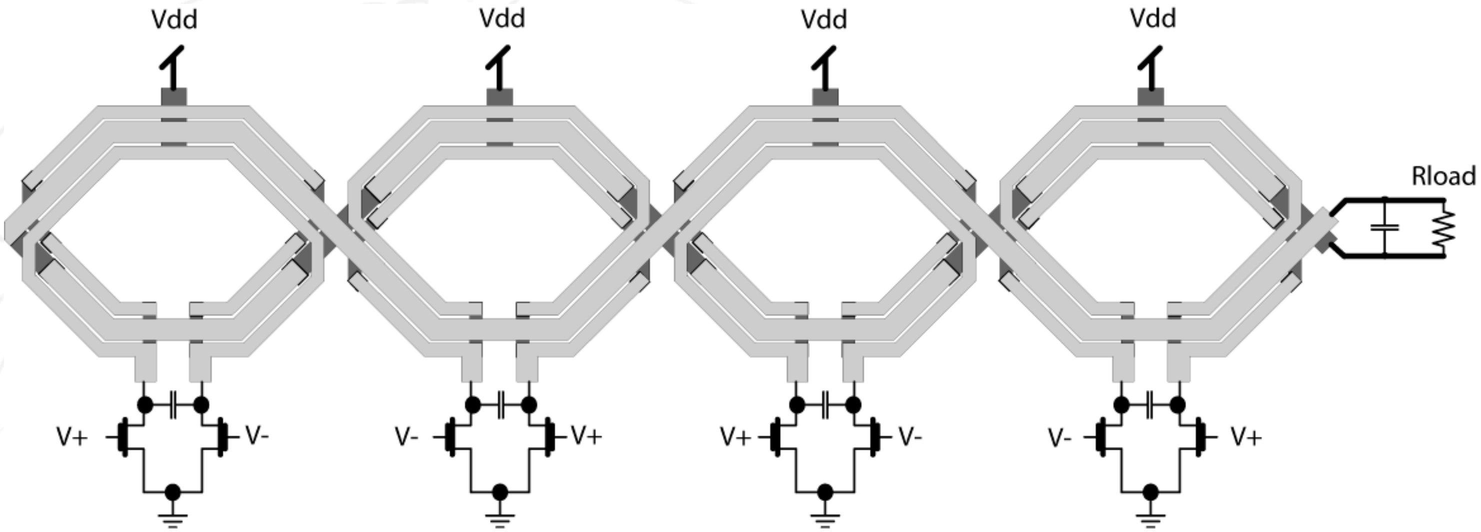
Berkeley Wireless Research Center, Dept. of EECS,
UC Berkeley, Berkeley, CA 94704, USA

New Transformer Network



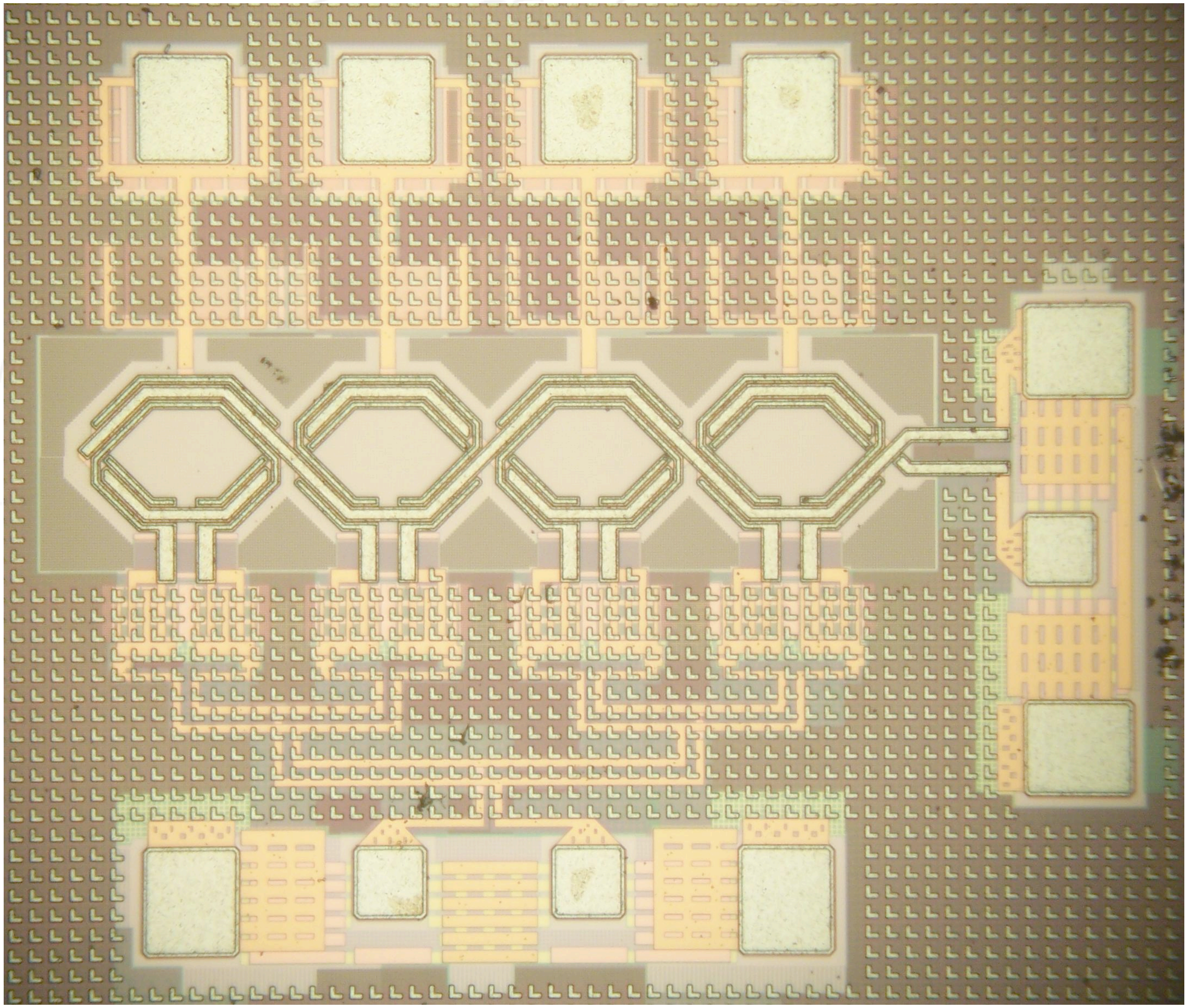
- Figure "8" style layout minimized the impact of lead inductance
- Lateral coupling used since top metal layer is most conductive and most distant from substrate
- Very good isolation characteristic due to flux inversion

Improved Layout…



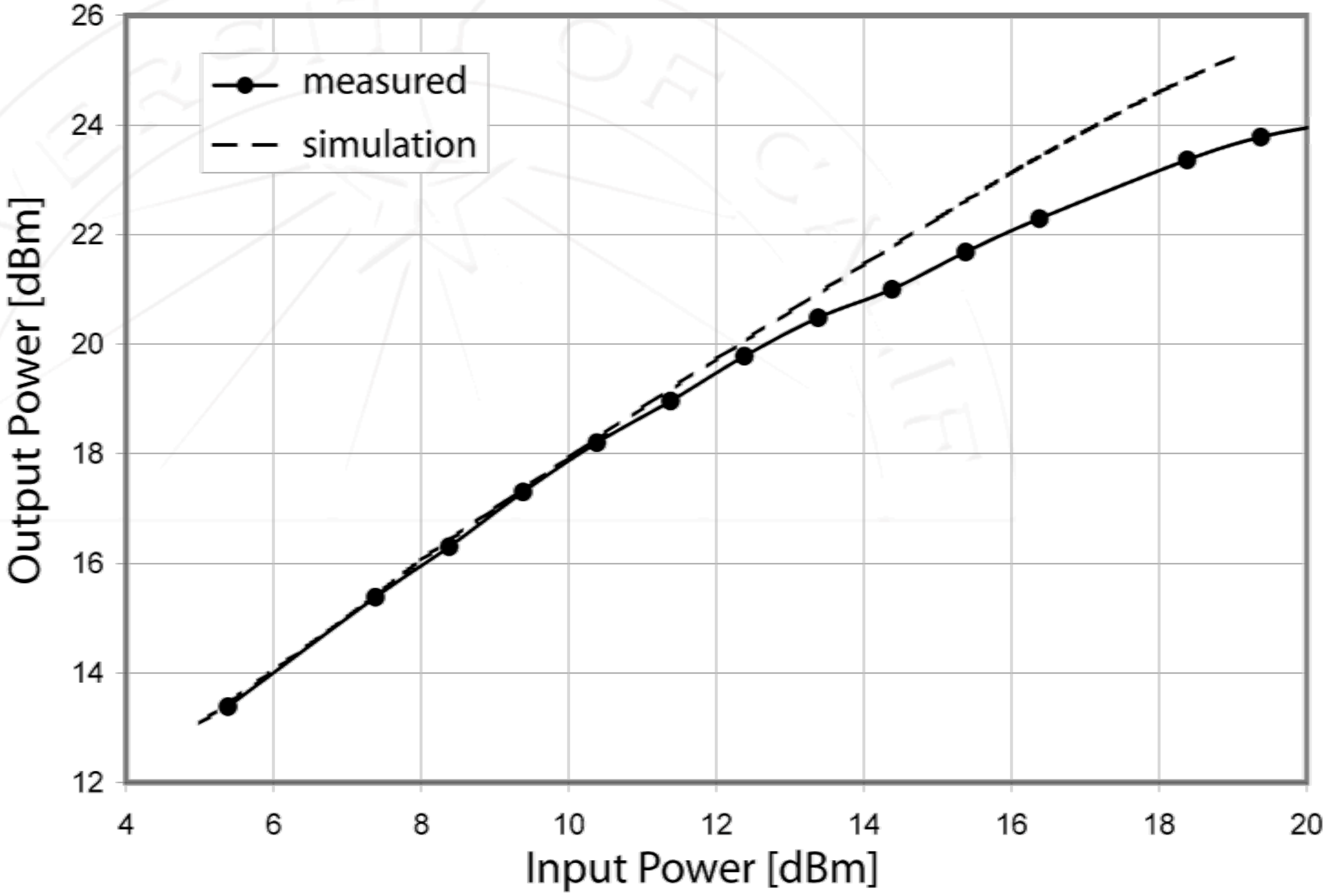
- Using two primary windings
  - Improved coupling
  - Lower loss (current crowding at edge of conductors)
  - More symmetric primary/secondary for optimal power transfer

Prototype PA in Digital CMOS



- Four stage differential design
- Single-ended 50Ω output
- Thin oxide 90nm transistors

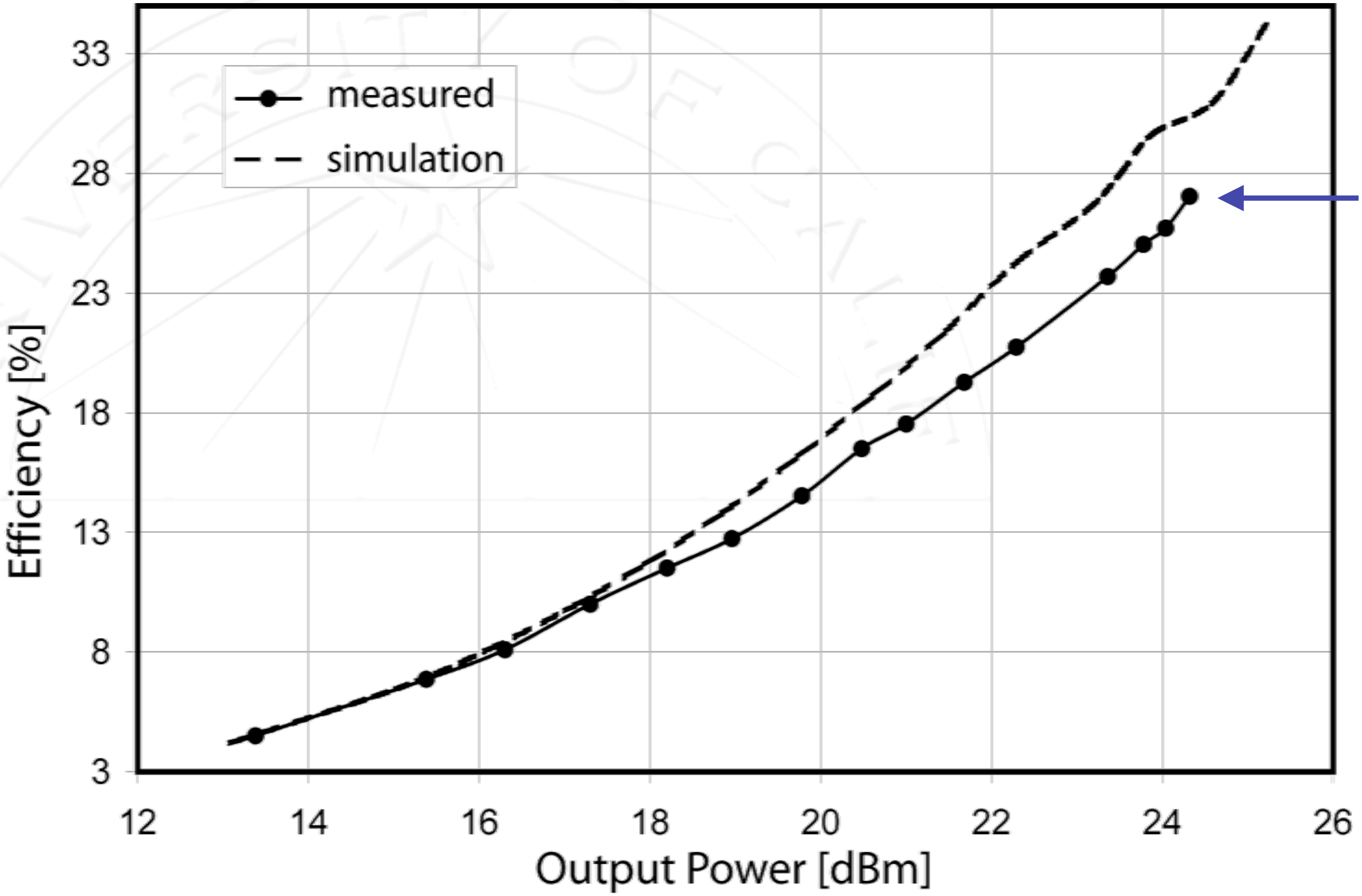
Measured Output Power



24 dBm

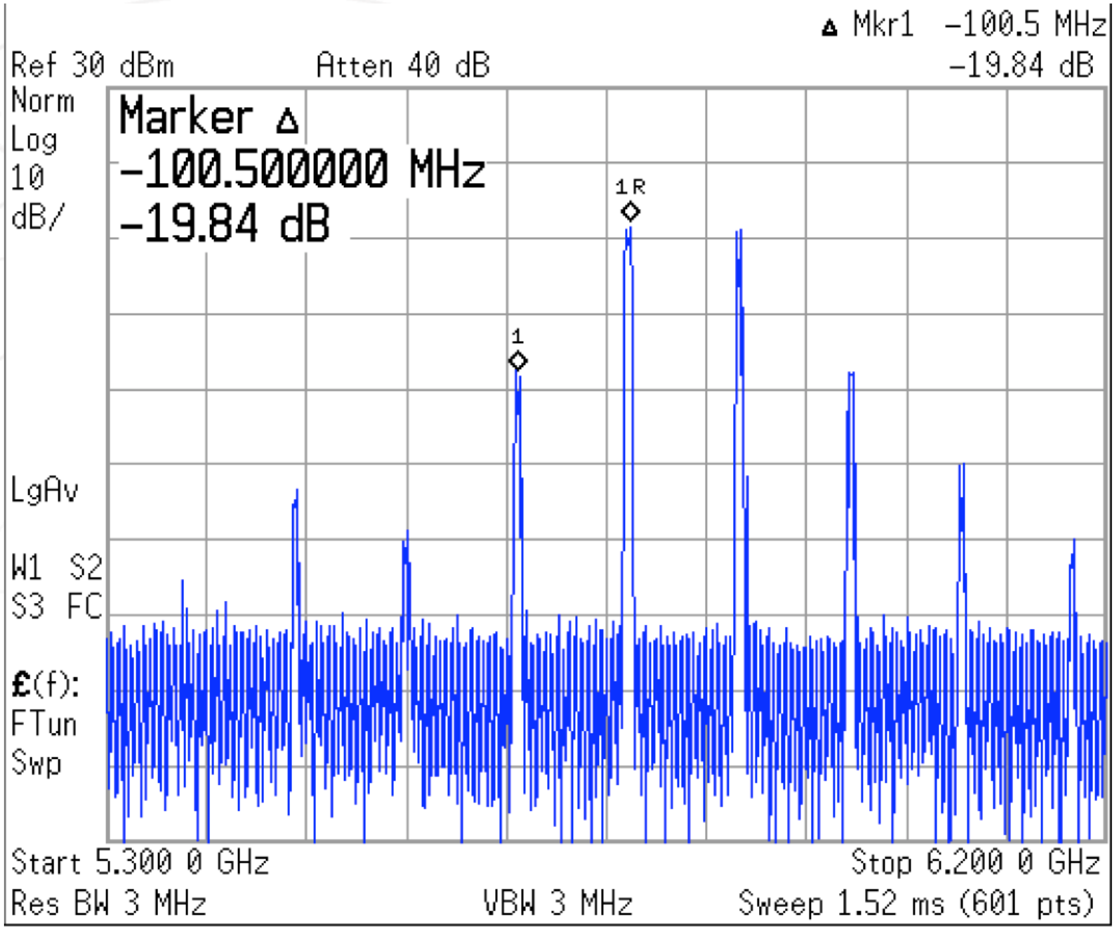
- Peak power is 24 dBm. Good match to simulation up to 1dB compression point.

Measured Efficiency



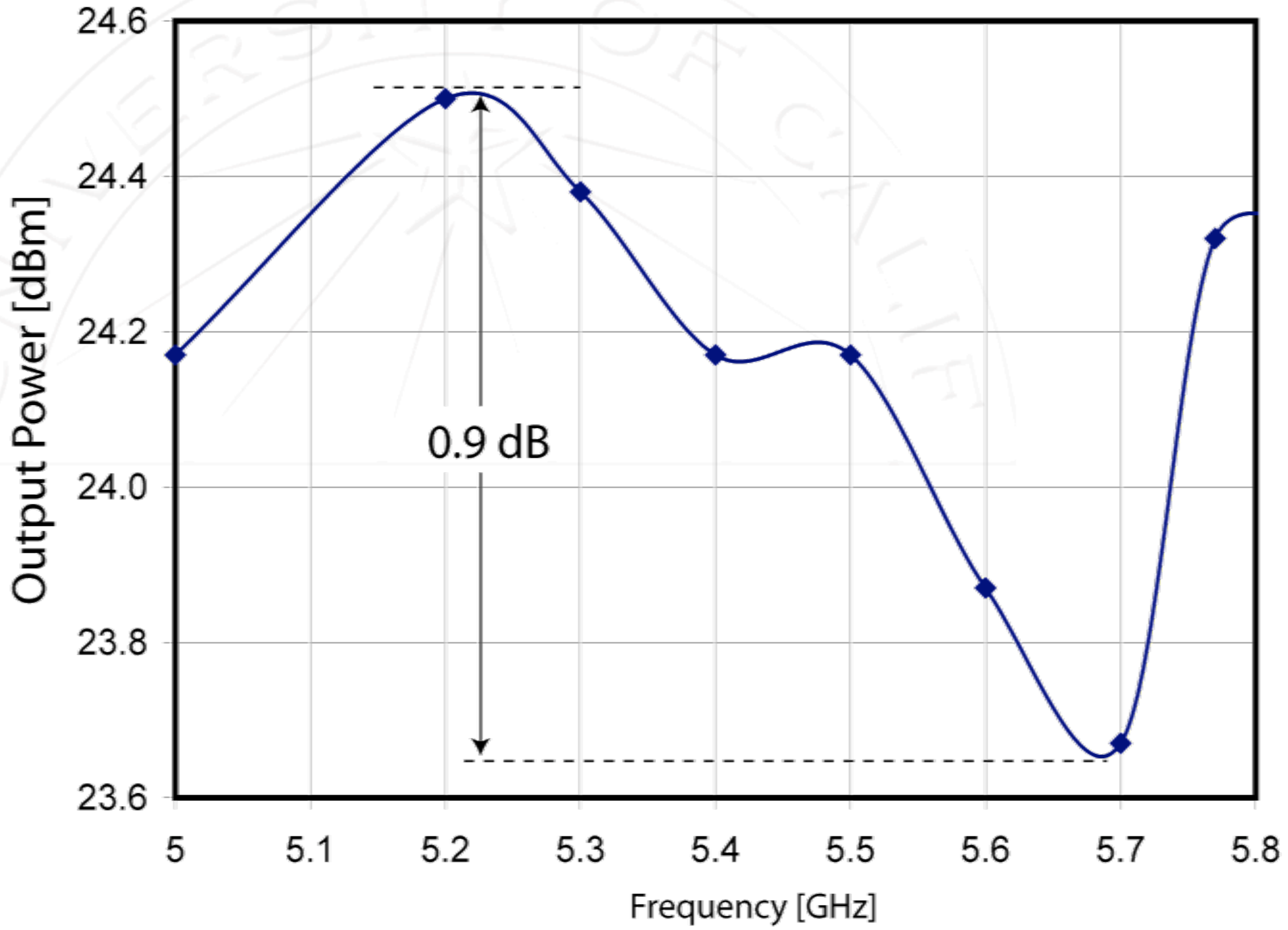
27%

PA Linearity

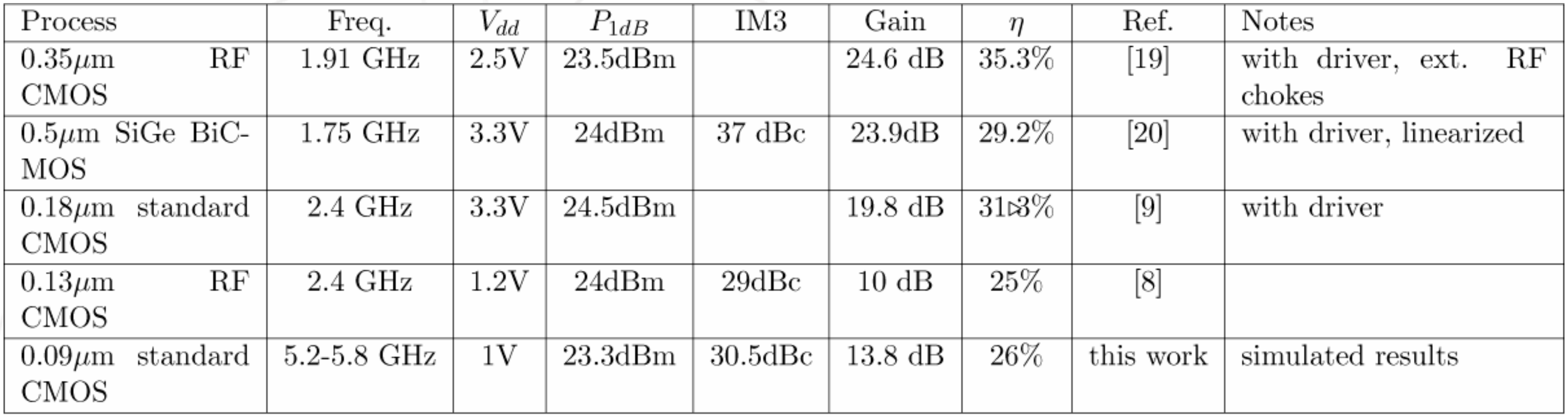


- IM3 = 28 dBc at output power of 20.5 dBm (200 MHz)
- IM3 has tone spacing dependence due to lack of good bypass (class AB stage). Verified with packaged version.

Output Power vs Frequency



CMOS "digital" Prototype

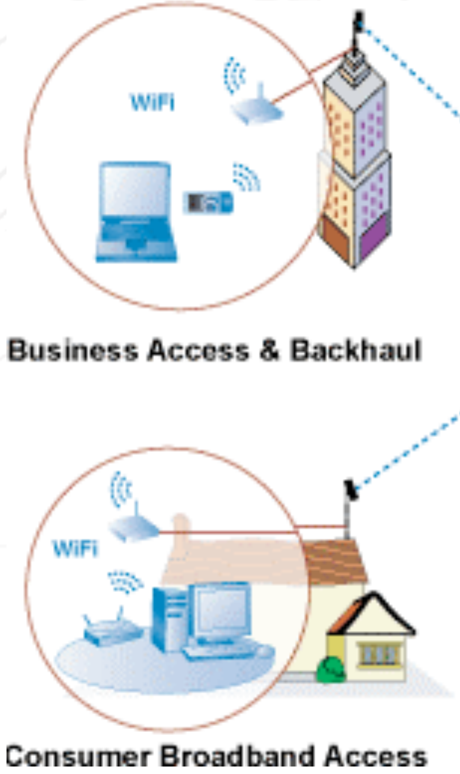


Process	Freq.	V_{dd}	P_{1dB}	IM3	Gain	η	Ref.	Notes
0.35μm RF CMOS	1.91 GHz	2.5V	23.5dBm		24.6 dB	35.3%	[19]	with driver, ext. RF chokes
0.5μm SiGe BiCMOS	1.75 GHz	3.3V	24dBm	37 dBc	23.9dB	29.2%	[20]	with driver, linearized
0.18μm standard CMOS	2.4 GHz	3.3V	24.5dBm		19.8 dB	31.3%	[9]	with driver
0.13μm RF CMOS	2.4 GHz	1.2V	24dBm	29dBc	10 dB	25%	[8]	
0.09μm standard CMOS	5.2-5.8 GHz	1V	23.3dBm	30.5dBc	13.8 dB	26%	this work	simulated results

Table 5.3: Comparison between state of the art linear power amplifiers.

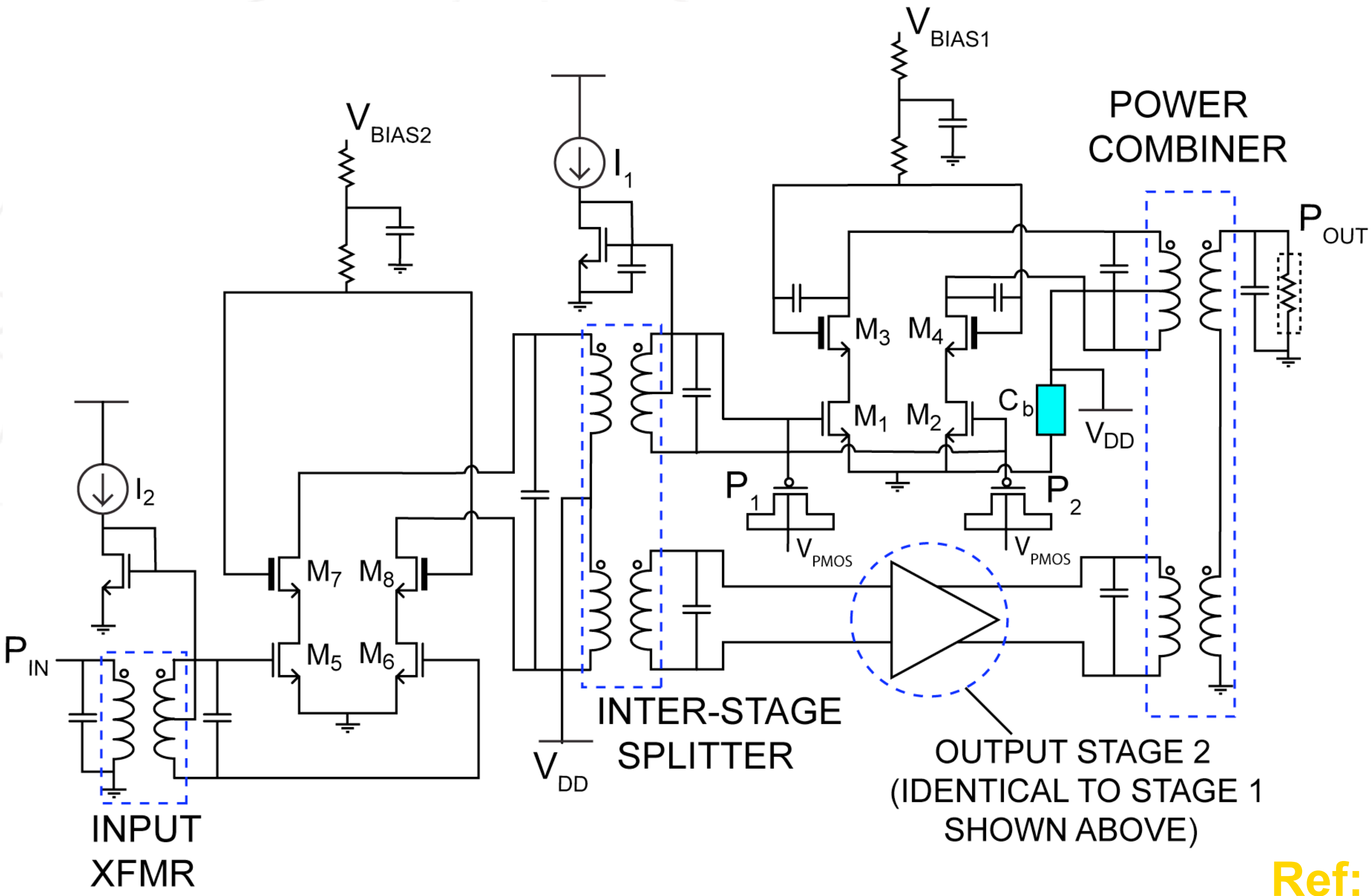
- New transformer layout has simulated efficiency of 75%
- State-of-the-art performance of 5 GHz linear PA
    - 24 dBm with 27% efficiency

4G Wireless Communication



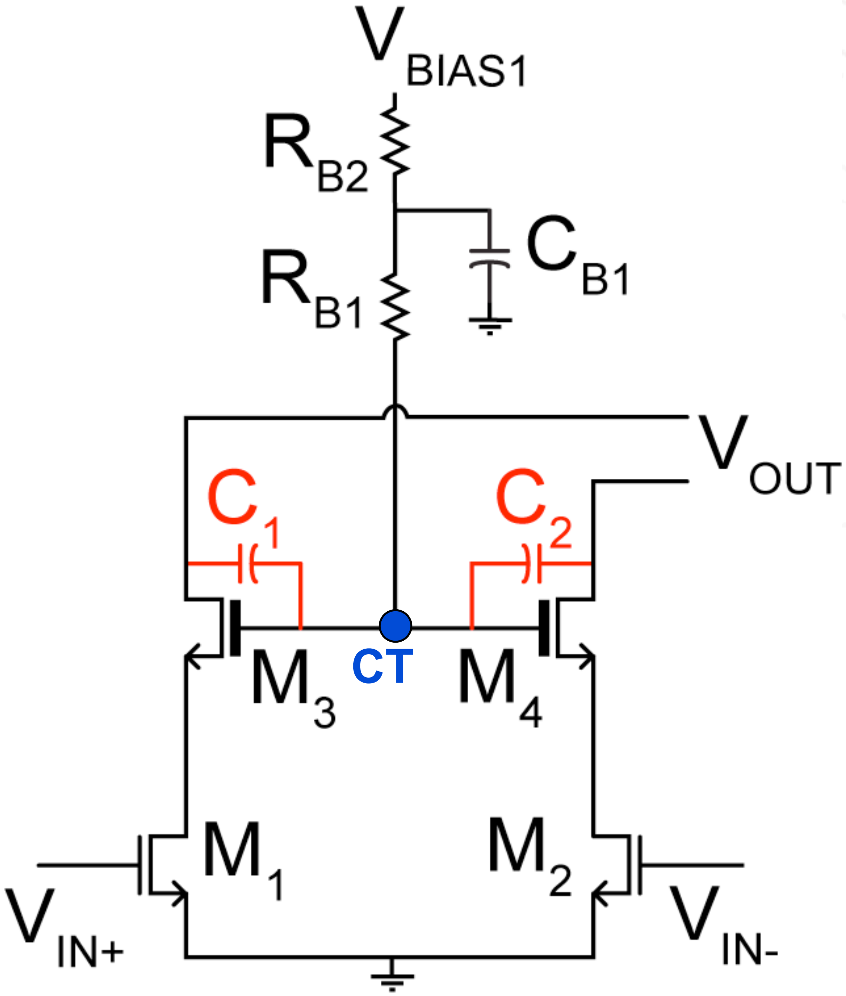
- IEEE 802.16 standard (Wireless MAN)
- Wireless data over long distances in a variety of ways

Two-Stage WiMAX CMOS PA



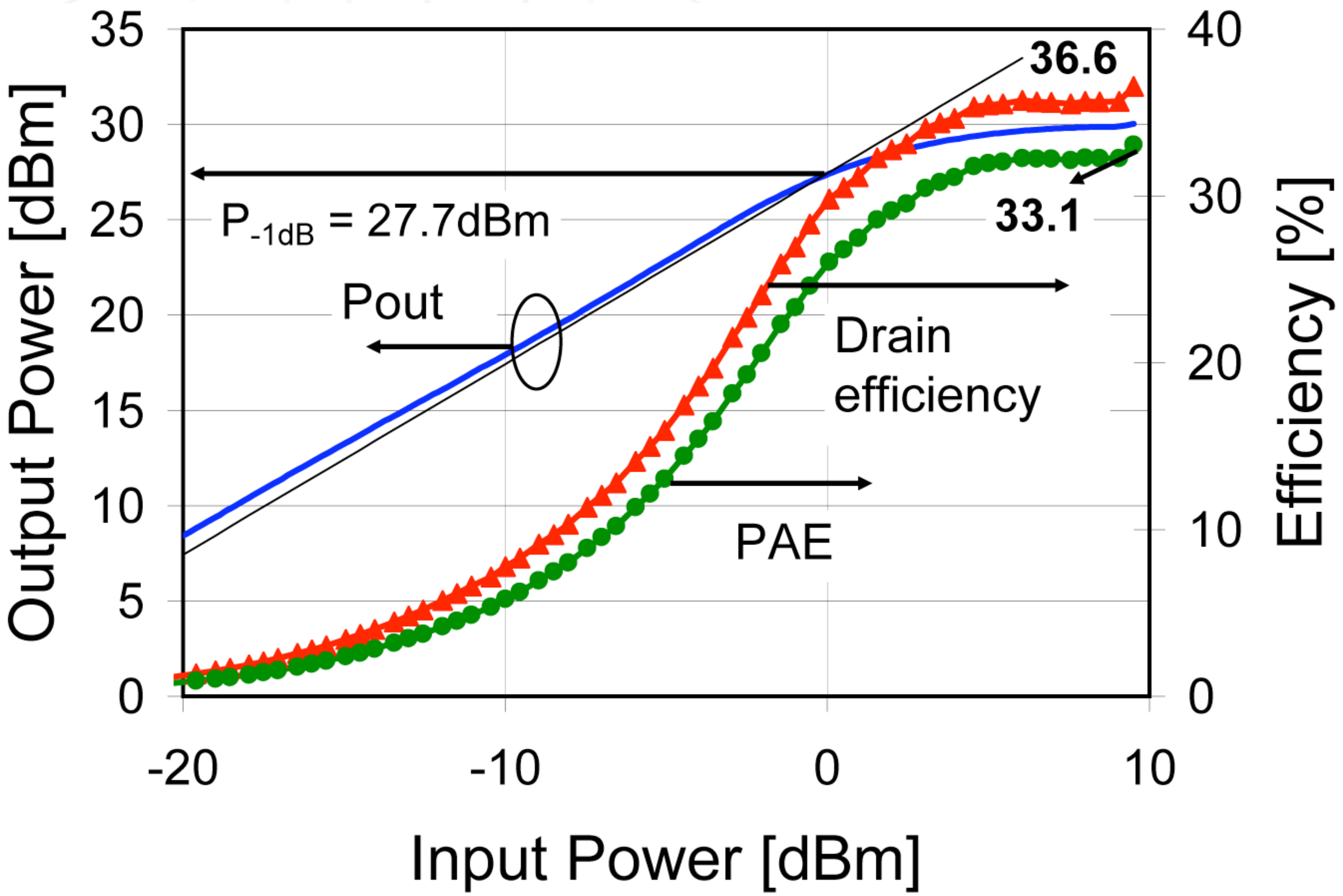
Ref: [Chow2]

Output Stage Design

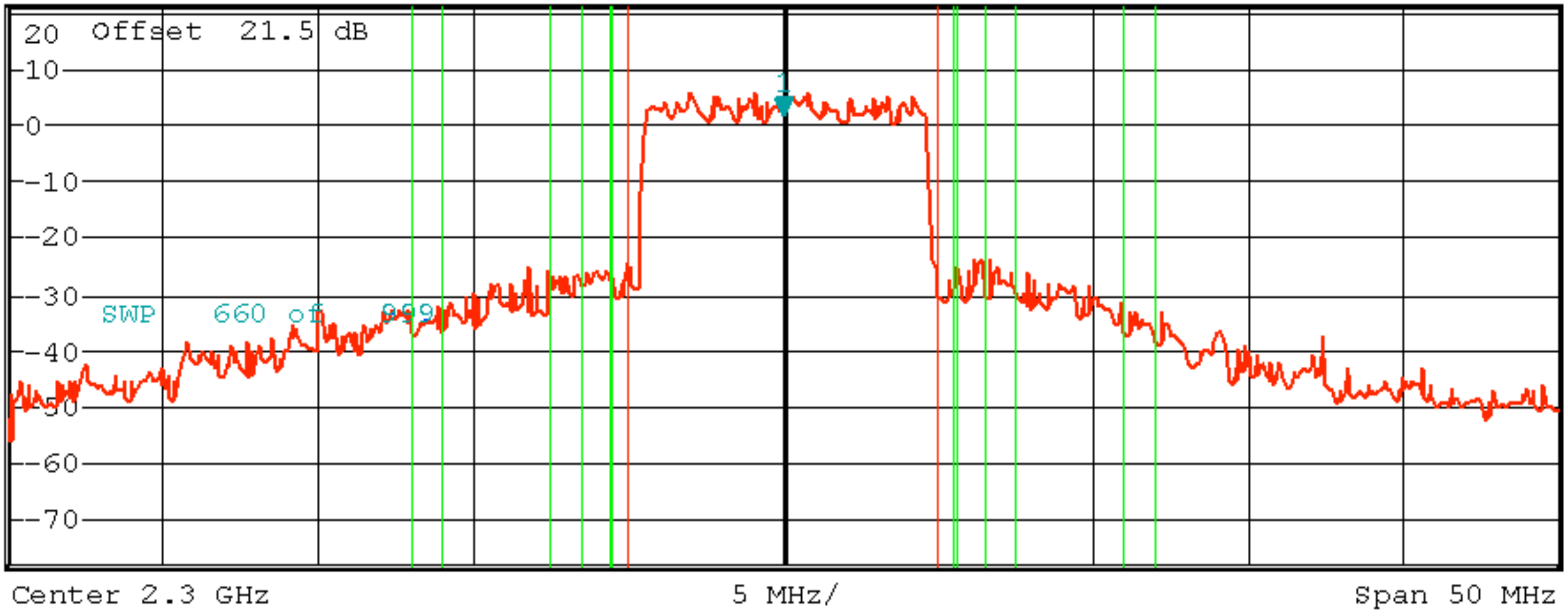


- Thick-oxide CG stage ($V_{DD} = 3.3V$)
- Dynamic gate biasing
- Capacitive divider
- Differential → does not affect small signal gain

Large-Signal CW Measurements

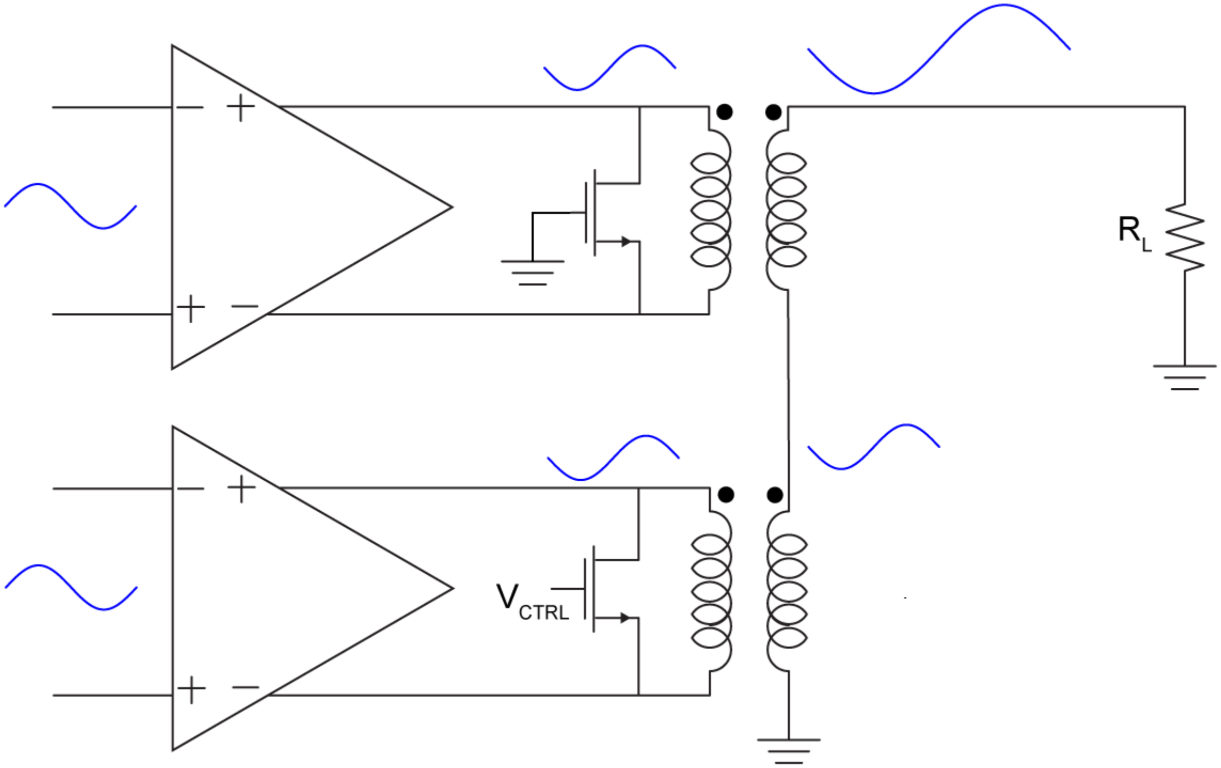


Meeting the WiMAX Mask



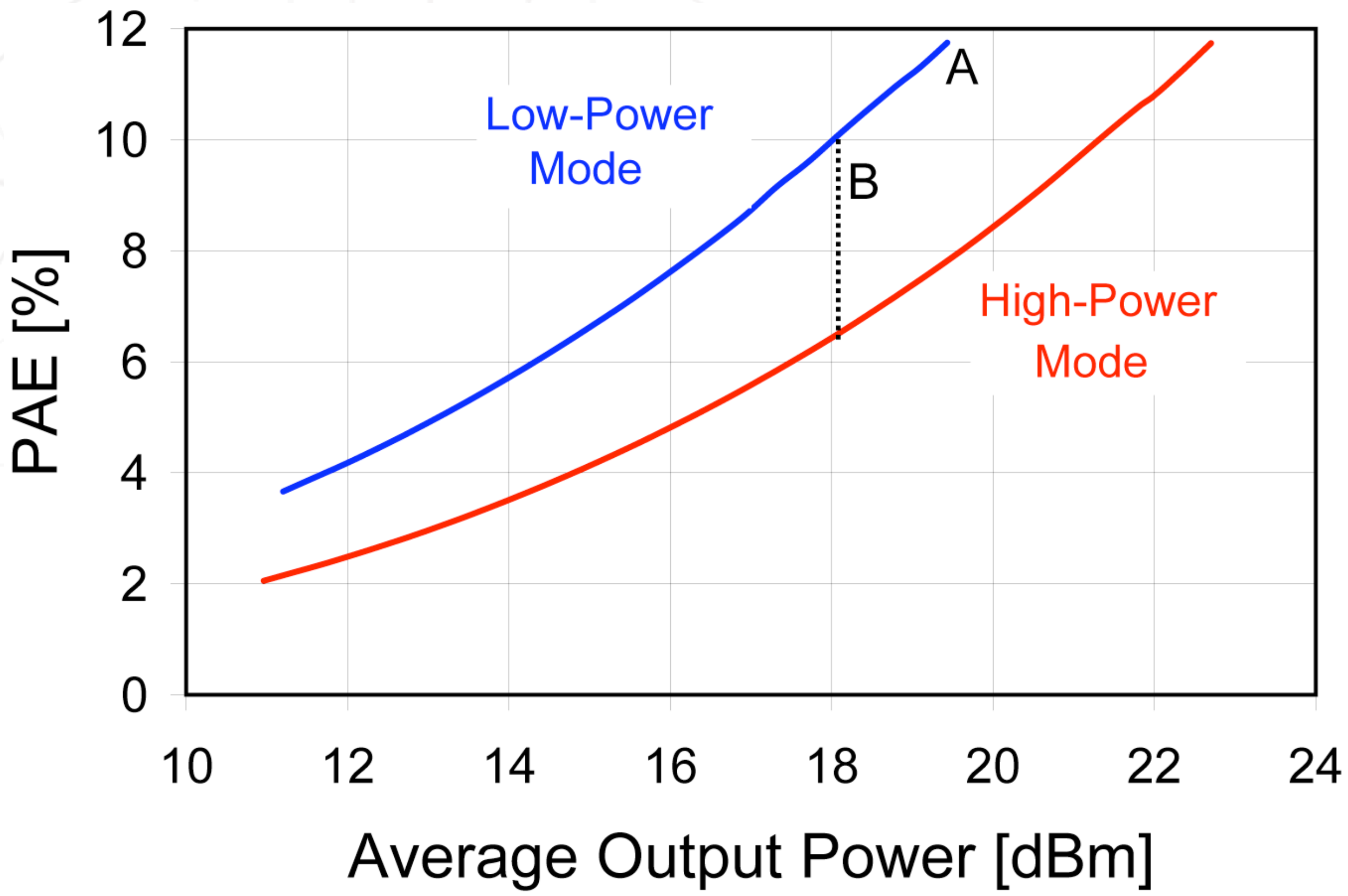
- Average Pout = 22.76 dBm
- Average drain efficiency = 15%, Average PAE = 12%
- Power of 2nd, 3rd and higher harmonics also meet FCC mask → possible to eliminate harmonic filter

Back-Off Mode Implementation

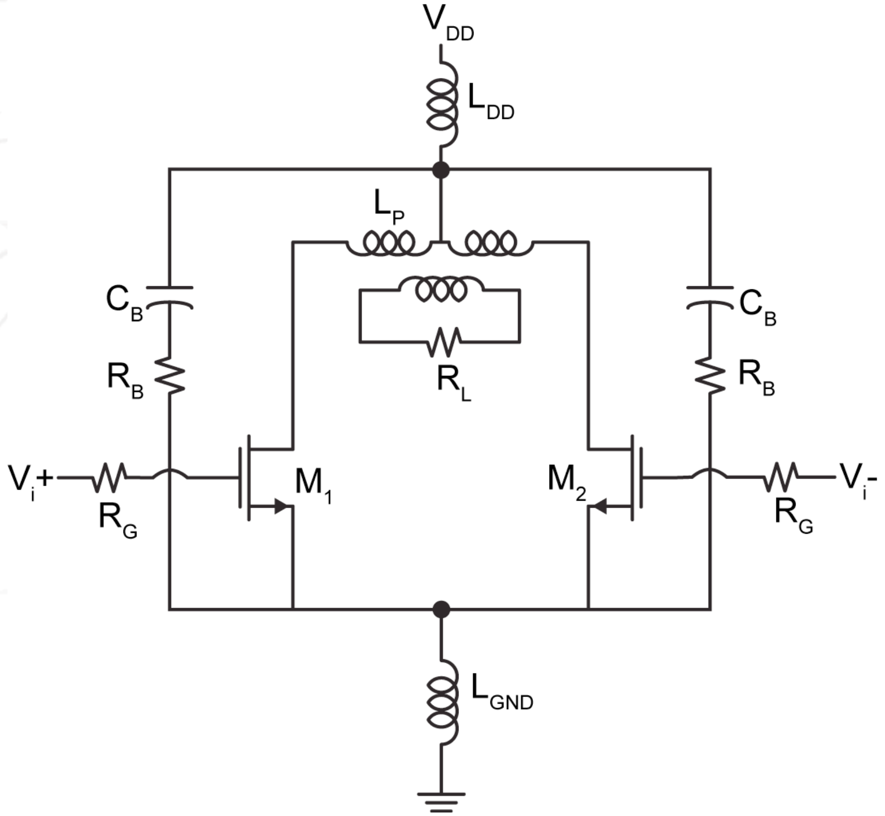


- Bottom stage powered-down for low-power mode
- Vctrl=0 in high-power mode and 2*V_{DD} in low-power mode

Low Power Mode

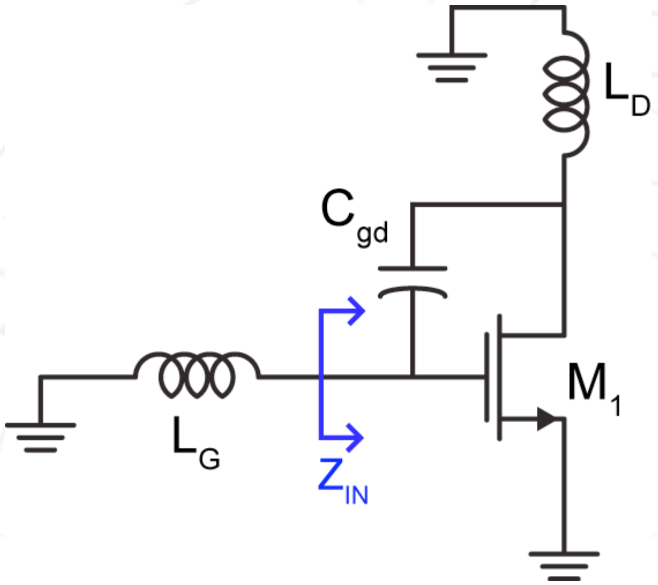


Common-Mode Stability



- Pseudo-differential architecture → common-mode oscillations possible
- Need to consider ground & supply inductances, bypass network

A Simpler Structure



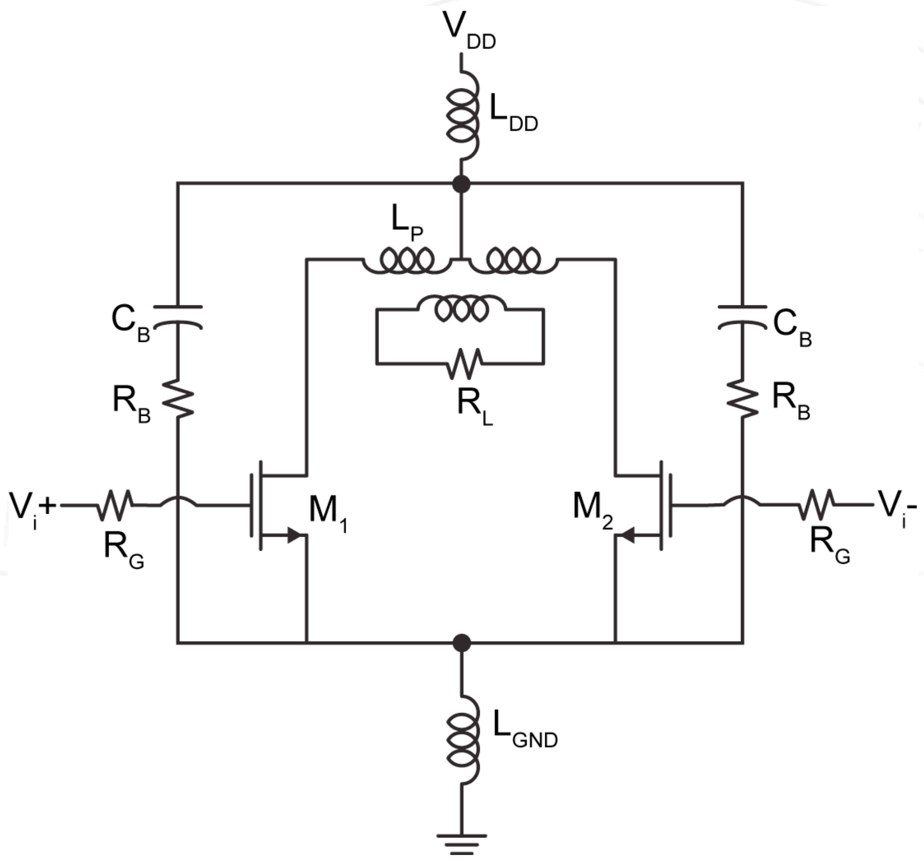
$$Z_{IN} = \frac{j(\omega L - \frac{1}{\omega C_{gd}})}{1 + j\omega g_m L_D}$$

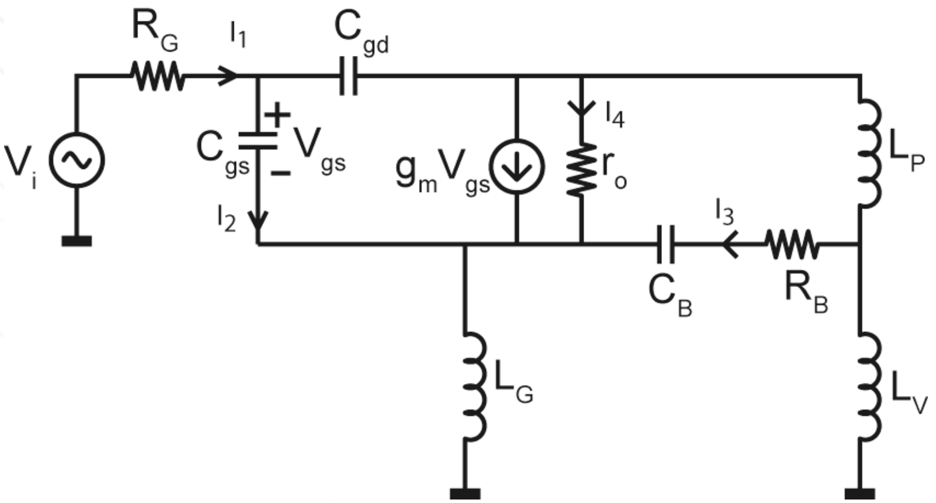
- If $(1/\omega C_{gd}) >> (\omega^* L)$,

$$Z_{IN} = \frac{1}{(1+\omega g_m L_D)^2}[\frac{1}{j\omega C_{gd}} - \frac{g_m L_D}{C_{gd}}]$$

Ref: [Cripps]

Stability Analysis





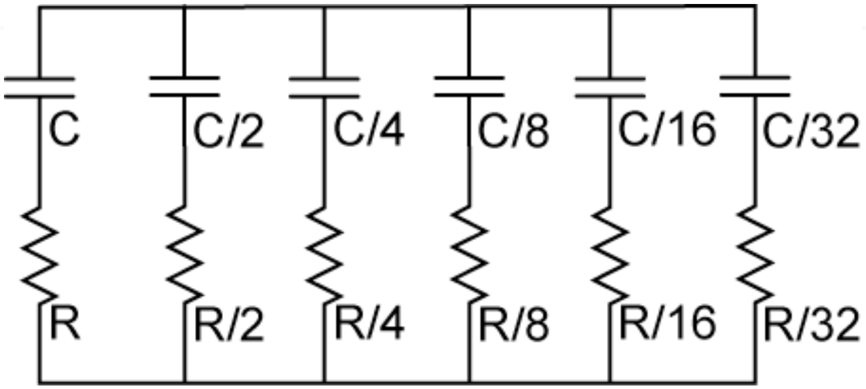
$$\begin{bmatrix} V_i \\ 0 \\ V_i \\ V_i \\ 0 \end{bmatrix} = [A] \times \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ V_{gs} \\ I_4 \end{bmatrix}$$

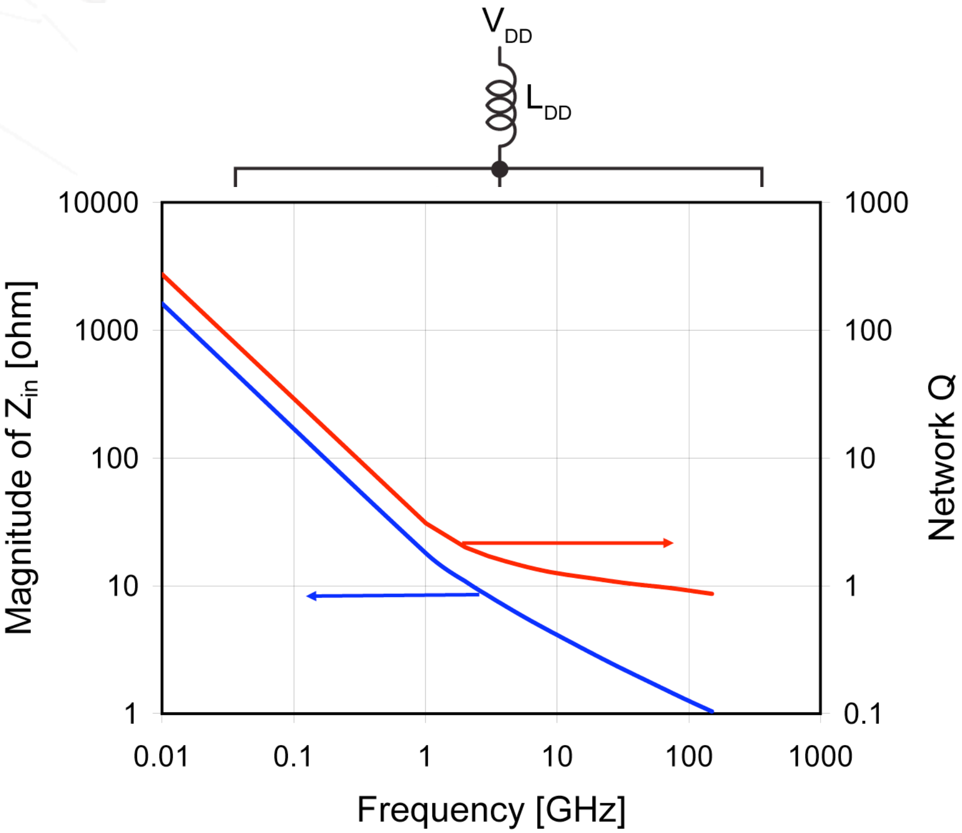
- For oscillation, [A] is singular

Ref: [Chow3]

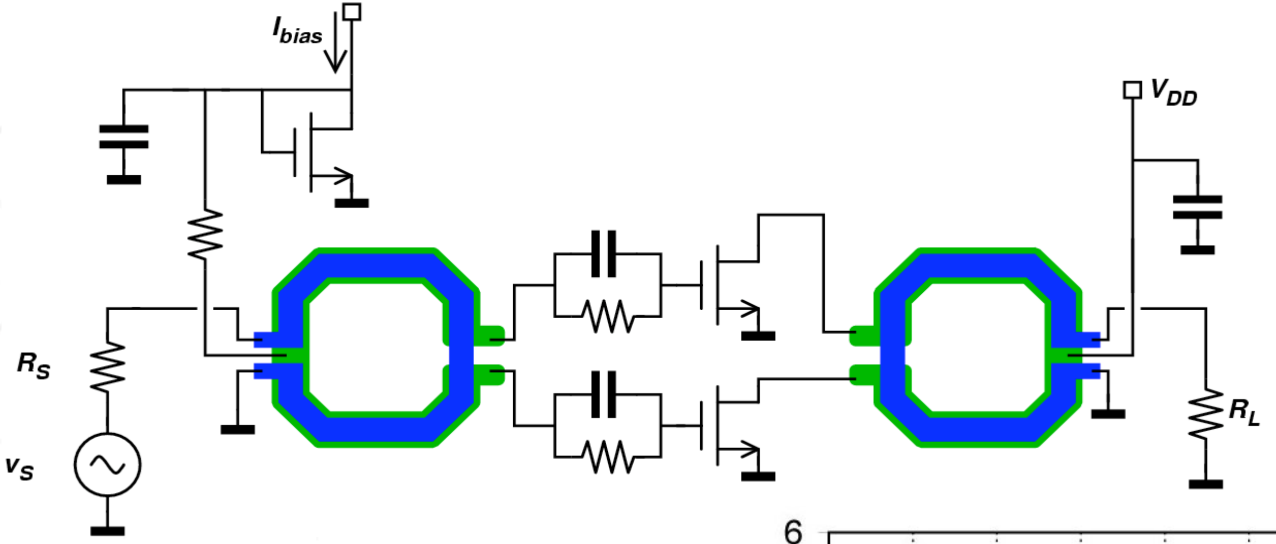
Stabilizing the PA

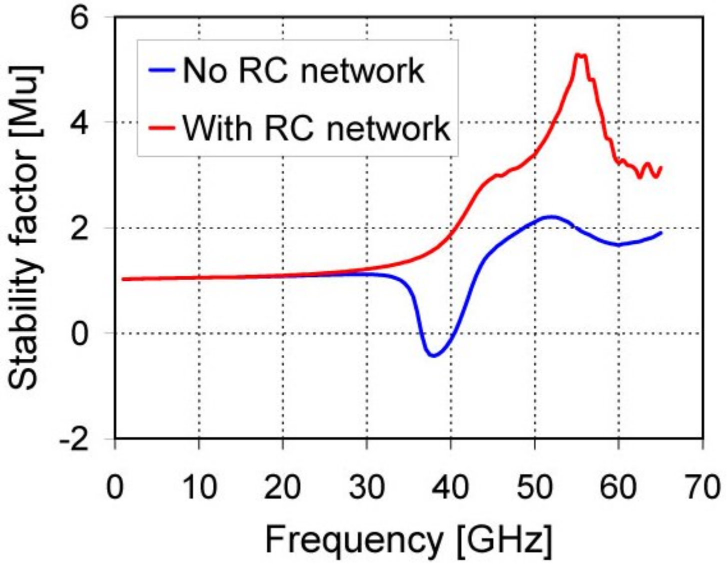
- Resistor in series with gate
- Resistor in series with bypass capacitor
- Staggered-RC bypass network
- Series RC-pair





Series RC Pair





- Transistors have higher gain at lower frequency, transformers are wideband
- RC network → loss around 35GHz without impacting 60GHz

Ref: [Kom]