Power Amplifiers (2/2)

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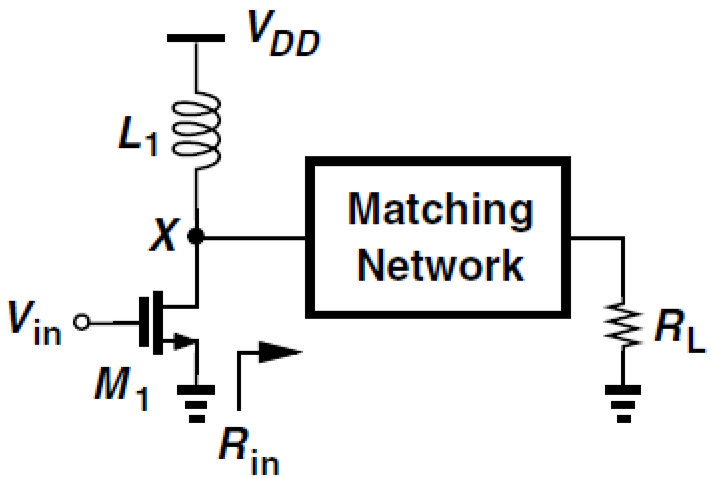
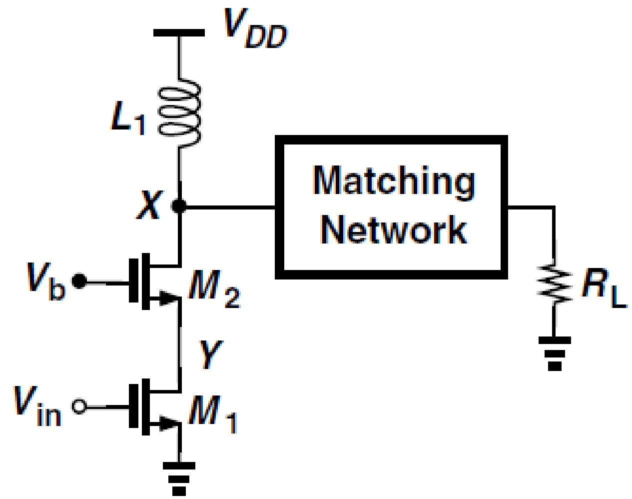
Problem of Single-Transistor PA

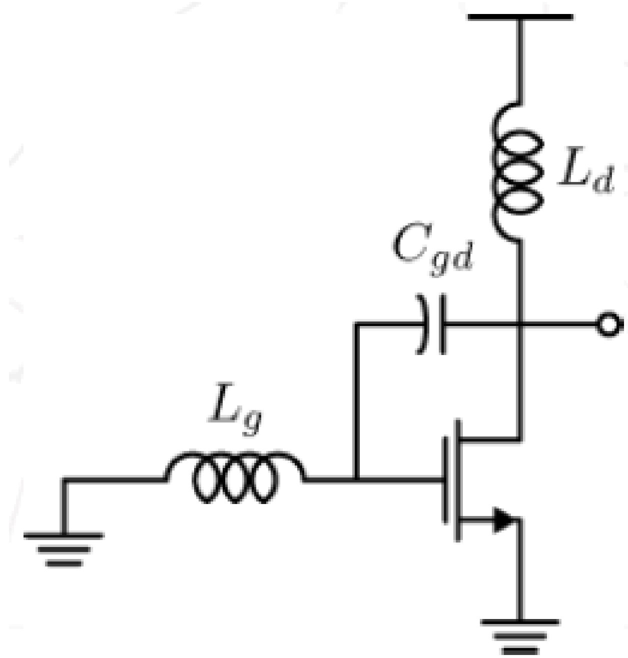




- To maximize the efficiency, the drain waveform is assumed to have a peak-to-peak swing of nearly $2V_{DD}$
- If V_{DD} is chosen equal to the nominal supply voltage of the process, the output transistor experiences breakdown or substantial stress
- Cascode transistors somewhat relaxes the breakdown or substantial stress

[B. Razavi, RF Microelectronics]

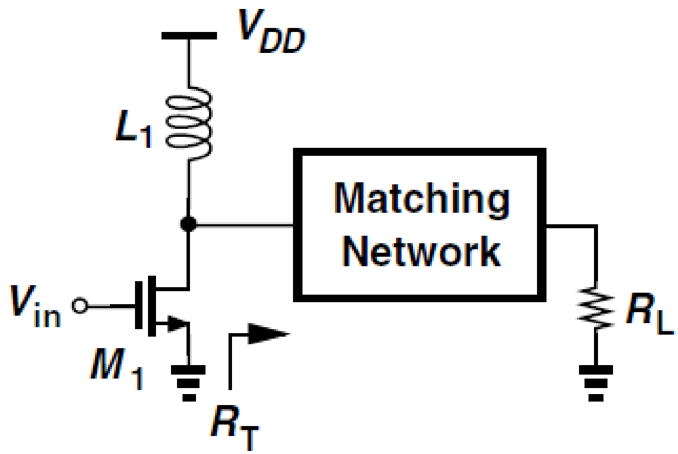
Parasitic Oscillator

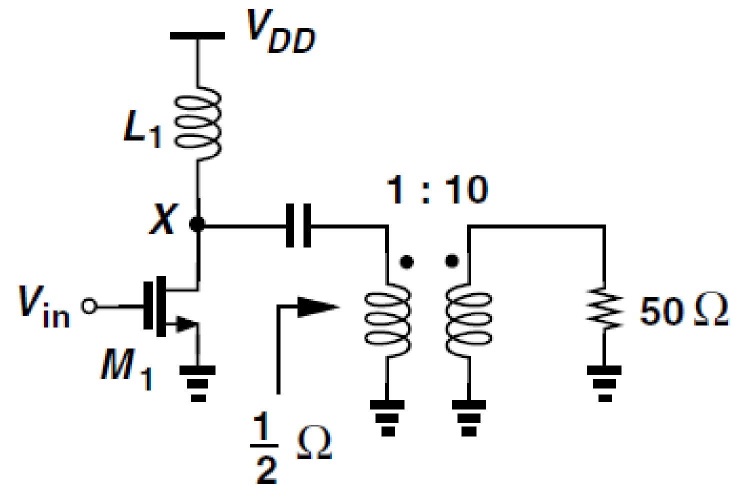


- ❑Due to the large device size, the parasitic gate-to-drain capacitance is substantial, providing a negative resistance
- ❑The gate inductance is usually utilized for biasing or to tune out the input cap

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Matching Networks



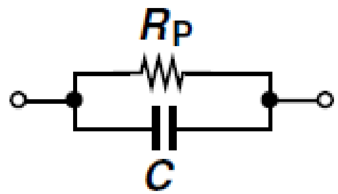


❑The network transfers the antenna resistance (usually 50Ohm) to an impedance which is preferred by the power amplifier

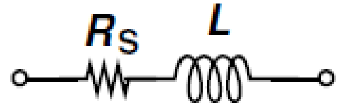
[B. Razavi, RF Microelectronics]

Q Factor

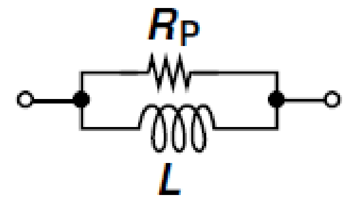
$$Q_S = \frac{\frac{1}{C\omega}}{R_S}$$



$$Q_P = \frac{R_P}{\frac{1}{C\omega}}$$

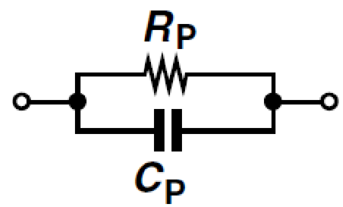


$$Q_S = \frac{L\omega}{R_S}$$



$$Q_P = \frac{R_P}{L\omega}$$

❑**Series to parallel conversion:**



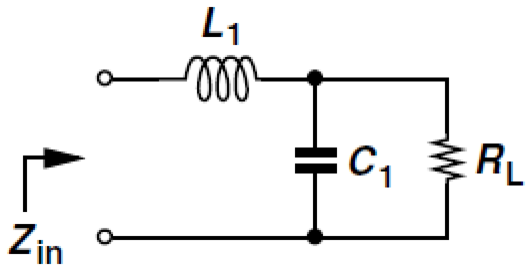
$$R_P = (Q_S^2 + 1)R_S \qquad C_P = \frac{Q_S^2}{Q_S^2 + 1}C_S$$

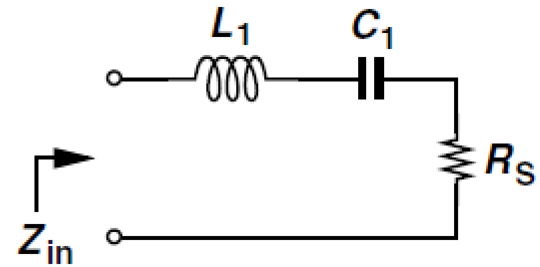
❑**So long as Q_S^2>>1**

$$R_P \approx Q_S^2 R_S \qquad C_P \approx C_S$$

[B. Razavi, RF Microelectronics]

Impedance Transformation

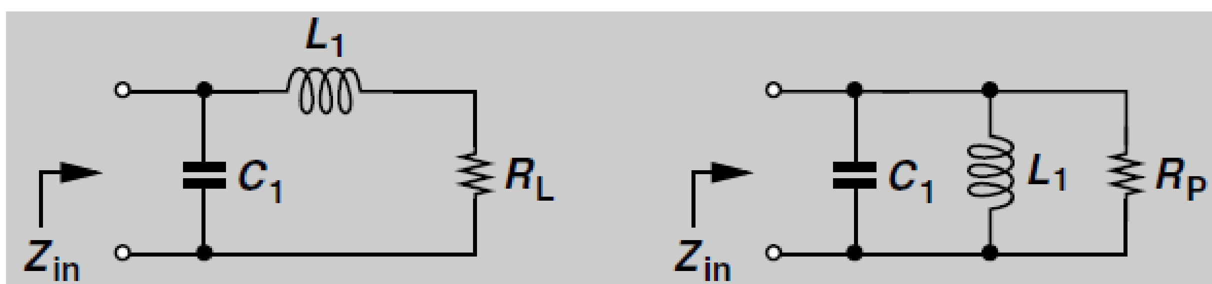




$$Z_{in}(j\omega) = \frac{R_L(1 - L_1C_1\omega^2) + jL_1\omega}{1 + jR_LC_1\omega}$$

$$Re\{Z_{in}\} = \frac{R_L}{1 + R_L^2C_1^2\omega^2} = \frac{R_L}{1 + Q_P^2}$$

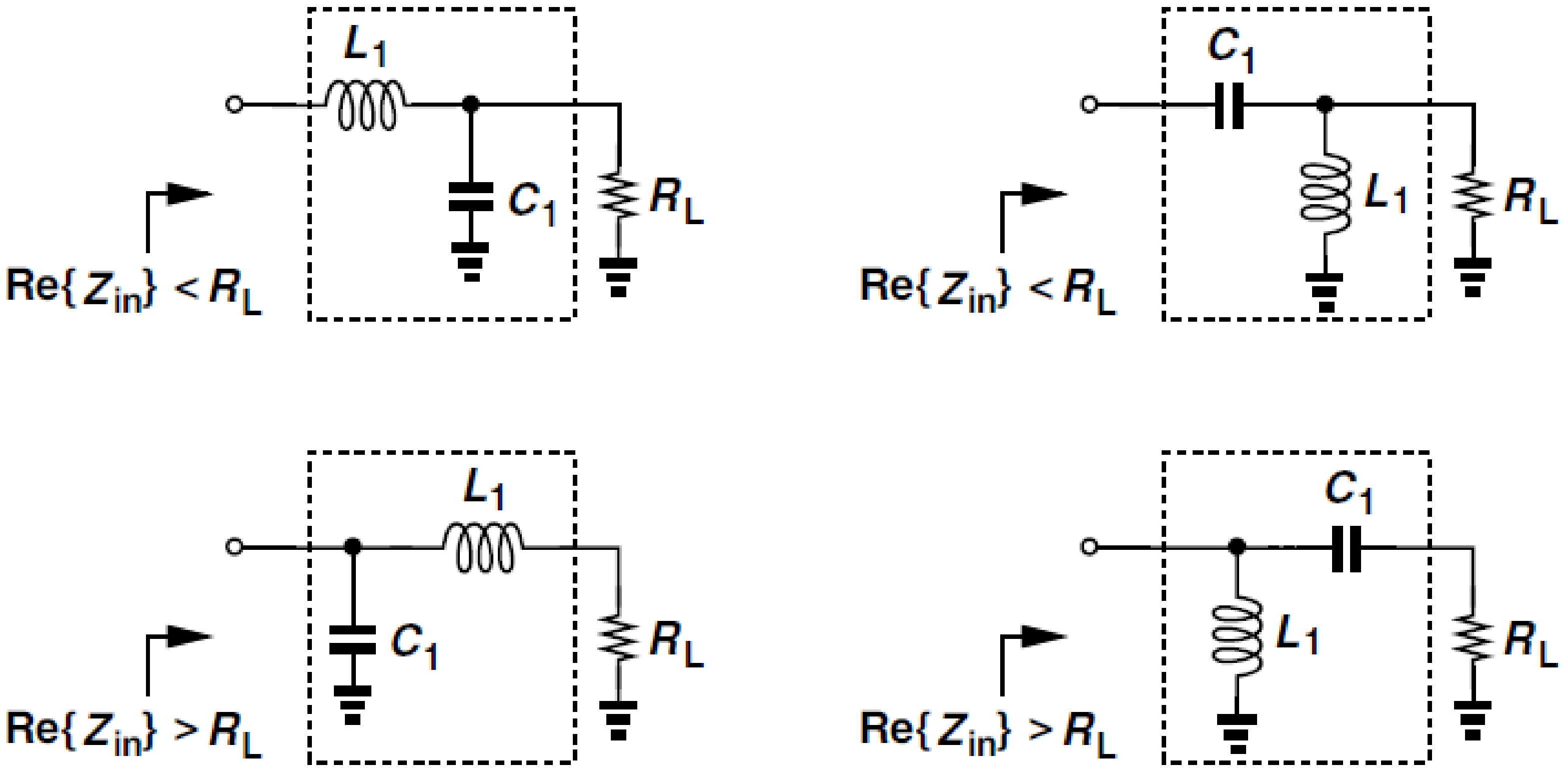
$$L_1 = \frac{R_L^2C_1}{1 + Q_P^2} = \frac{1}{C_1\omega^2}$$



$$R_P = Q_S^2R_L$$

[B. Razavi, RF Microelectronics]

L Matching Networks



$$\frac{V_{out}}{V_{in}} = \sqrt{\frac{R_L}{Re\{Z_{in}\}}} \qquad \frac{I_{out}}{I_{in}} = \sqrt{\frac{Re\{Z_{in}\}}{R_L}}$$

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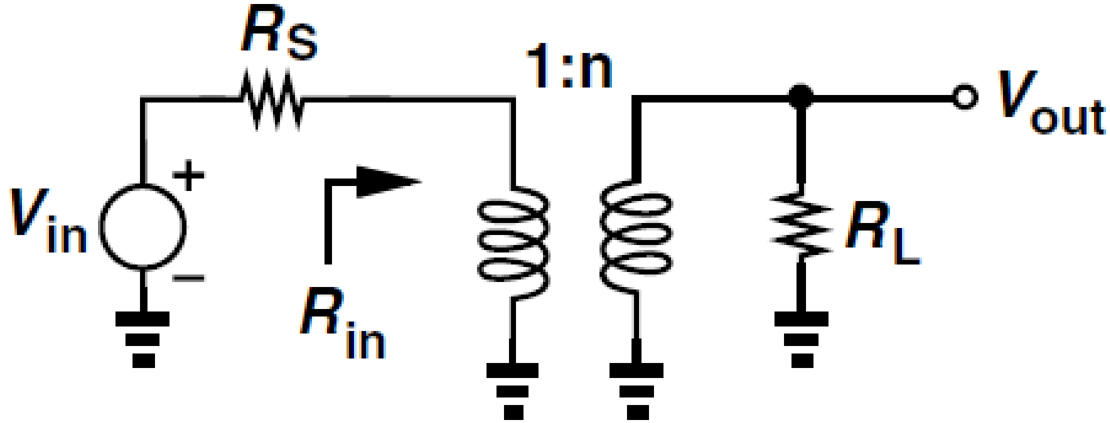
Transformer Matching

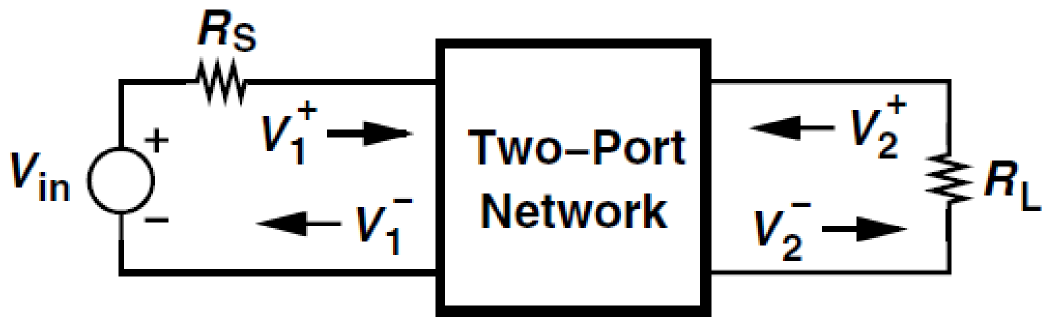


$$V_{in}^2/R_{in} = n^2 V_{in}^2/R_L$$

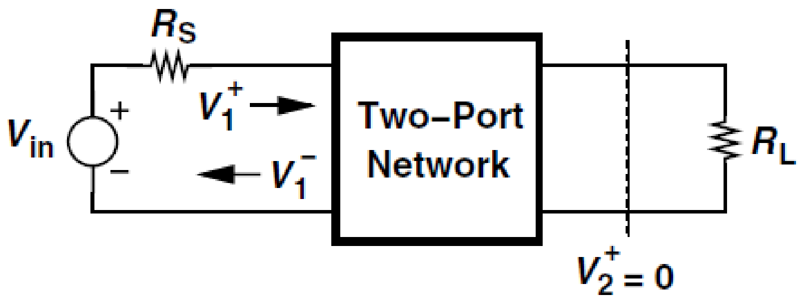
$$R_{in} = R_L/n^2$$

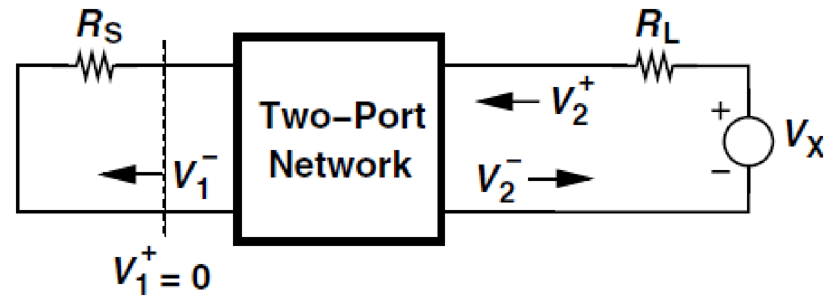
[B. Razavi, RF Microelectronics]

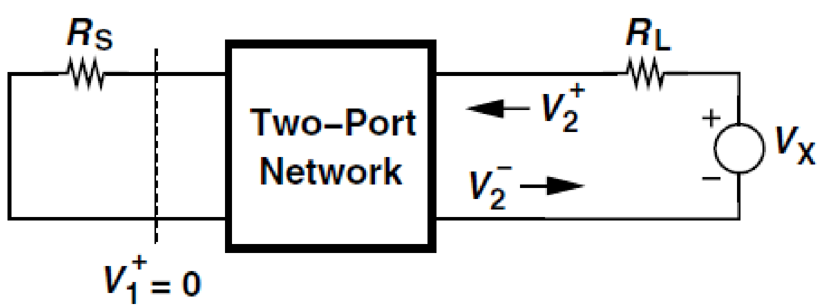
Scattering Parameters

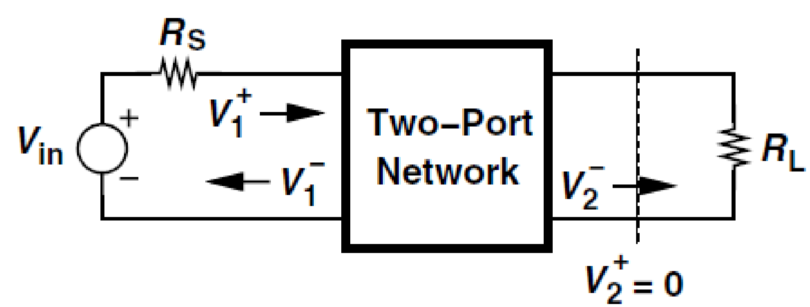


$$V_1^- = S_{11}V_1^+ + S_{12}V_2^+$$
$$V_2^- = S_{21}V_1^+ + S_{22}V_2^+$$









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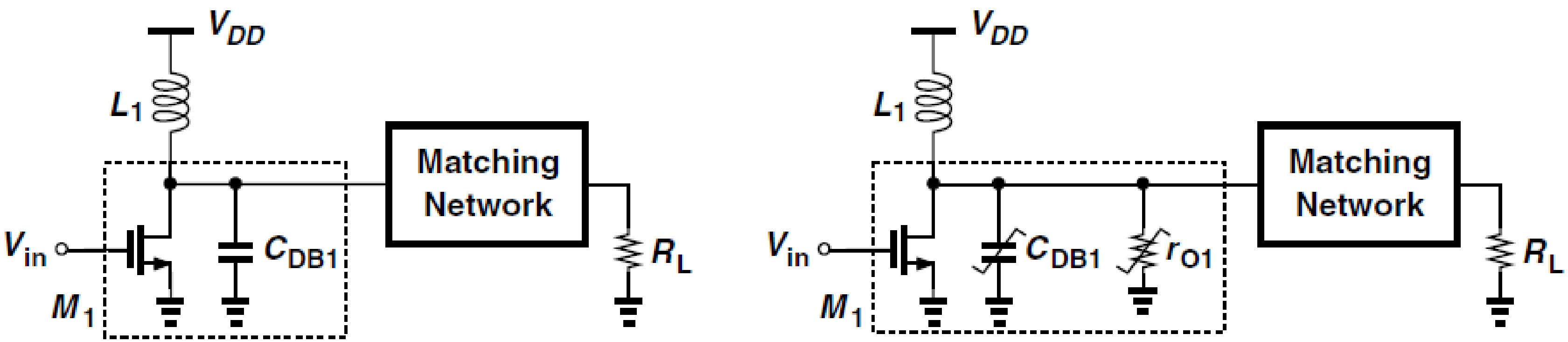
Large-Signal Matching



- The transistor exhibits an output resistance (r_{O1}) and parasitic capacitance (C_{DB2}), and both vary significantly with signal

- Thus, a nonlinear complex output impedance must be matched to a linear load

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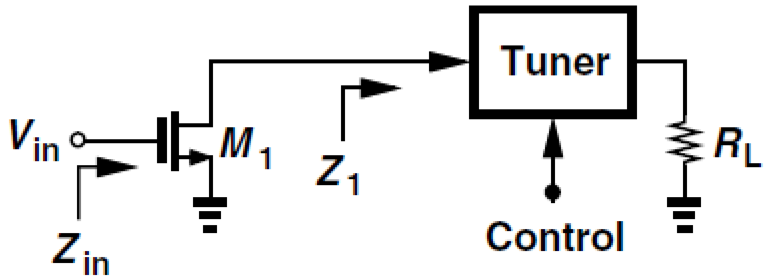
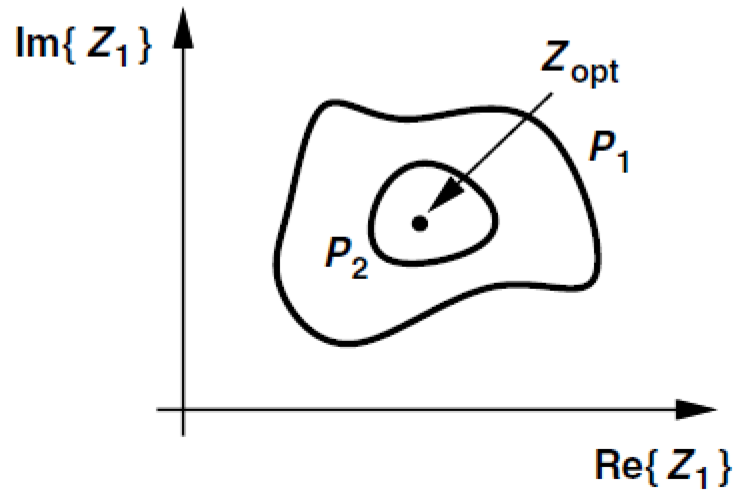
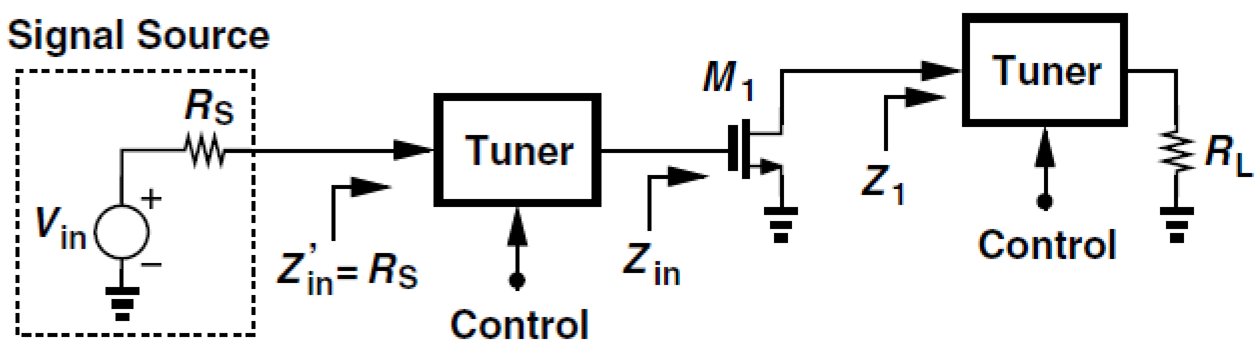
Load-Pull Measurement







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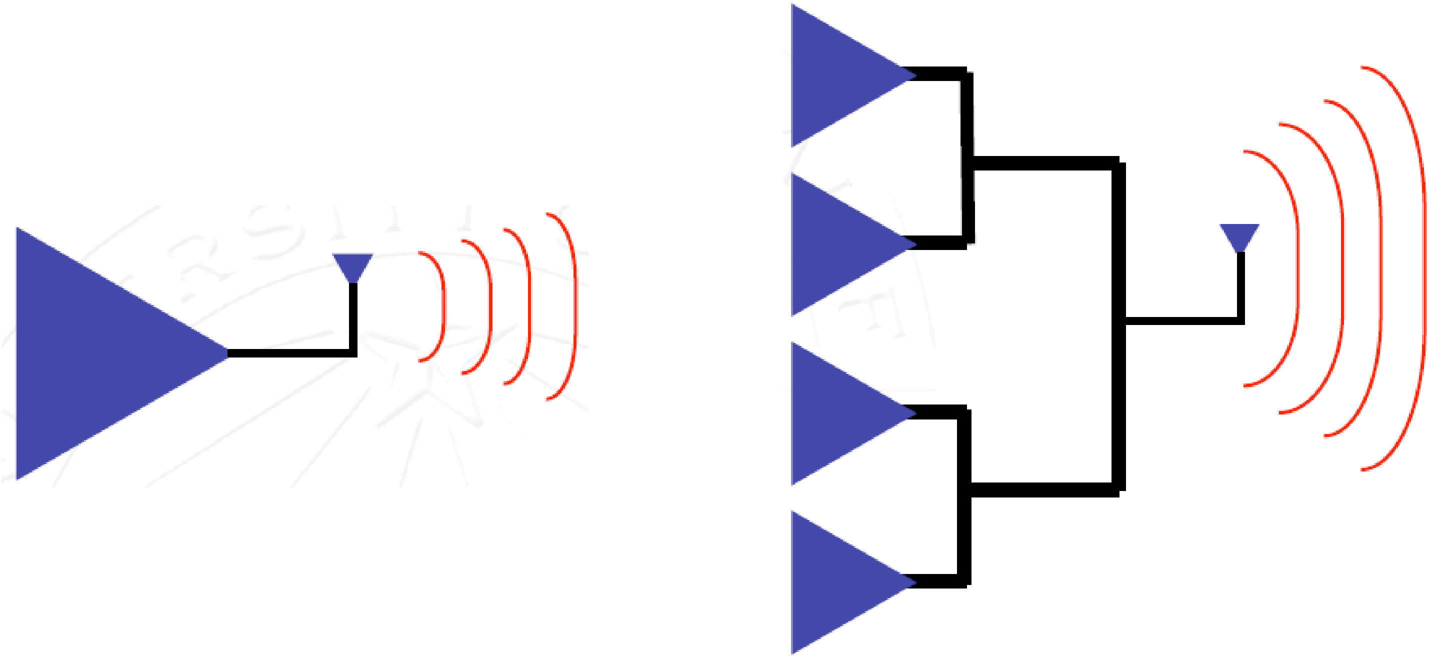
Peak Output Power

- The peak output power determines the range for two-way communications
- The peak power is often specified at the 1-dB compression point
- Need about ~1W for cellular handsets (~1 km distance)
- Need about ~100mW for W-LAN (100 m)
- Need about ~10mW for W-PAN (Bluetooth) (1-10 m)
- Need about ~1mW for UWB and sensor networks
- In practice, the average power transmitted may be much lower than the peak output power due to power control (slow time scale) or various modulations (fast time scale)

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Power Combining



- ❑Power combining can be performed to emit a big power

- ❑The pressure on each PA can be alleviated

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Source of Nonlinearity

- PAs exhibit nonlinear distortion in amplitude and phase
- For a modulated signal, both sources of distortion are significant

- The dominant sources are AM-to-AM and AM-to-PM
- Amplitude distortion: AM-to-AM conversion
- Phase distortion: AM-to-PM conversion

- For input: $x(t)=A(t)\cos(\omega t+\varphi(t))$, the corresponding output:

$y(t)=g[A(t)]\cos(\omega t+\varphi(t)+\psi(A(t)))$

- AM-to-AM conversion dominated by g_m non-linearity
- AM-to-PM conversion dominated by non-linear capacitors

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Modulation Schemes

System	Bandwidth (MHz)	Modulation	Duplex	TX Duty Cycle	Peak-Average Power Ratio (dB)	Peak-Minimum Power Ratio (dB)	Antenna Power (dBm)	Power Control Range (dB)
1G (AMPS)	0.03	FM	full	100%	0	0	28	25
ANSI-136	0.03	p/4-DQPSK	half	33%	3.5	19	28	35
GSM	0.20	GMSK	half	13%	0	0	33	30
GPRS	0.20	GMSK	half	13–50%	0	0	33	30
EDGE	0.20	3p/8-8PSK	half	13–50%	3.2	17	27	30
UMTS	3.84	HPSK	full	100%	3.5–7	infinite	24	80
IS-95B	1.23	OQPSK	full	100%	5.5–12	26—infinite	24	73
cdma2000	1.23	HPSK	full	100%	4–9	infinite	24	80
Bluetooth	1.0	GFSK	half	variable	0	0	20	—
802.11b	11.0	QPSK	half	variable	3	infinite	20	—
802.11a/g	18.0	OFDM	half	variable	6–17	infinite	20	—

- ❑PA designs for constant modulation schemes are much easier (GSM, AMPS)
- ❑OFDM PAs are very hard !

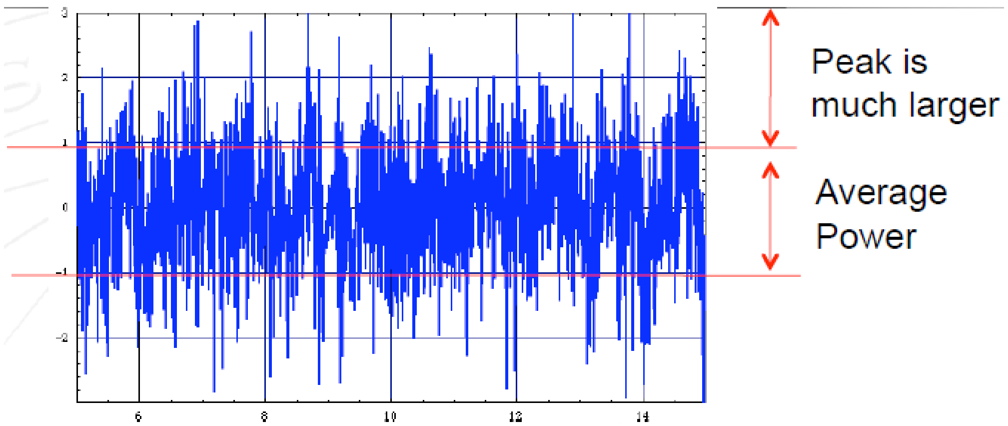
[Ali Niknejad, EE142&EE242 of UC Berkeley]

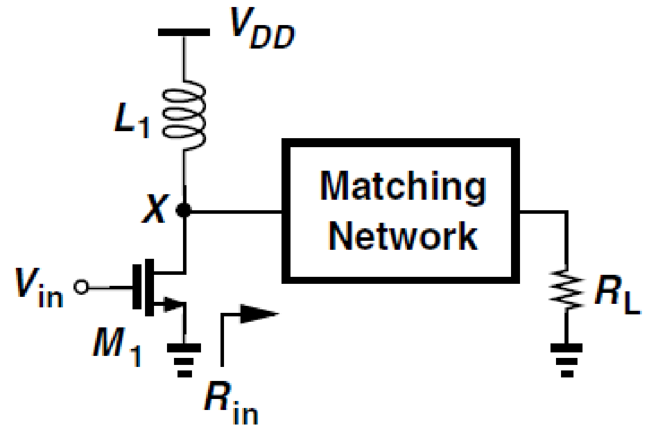
Power Linearization

- Power backoff
- Forward linearization
- Feedback
- Predistortion
- Envelop Feedback
- Polar Modulation
- Outphasing
- Doherty PA

[B. Razavi, RF Microelectronics]

Power Backoff



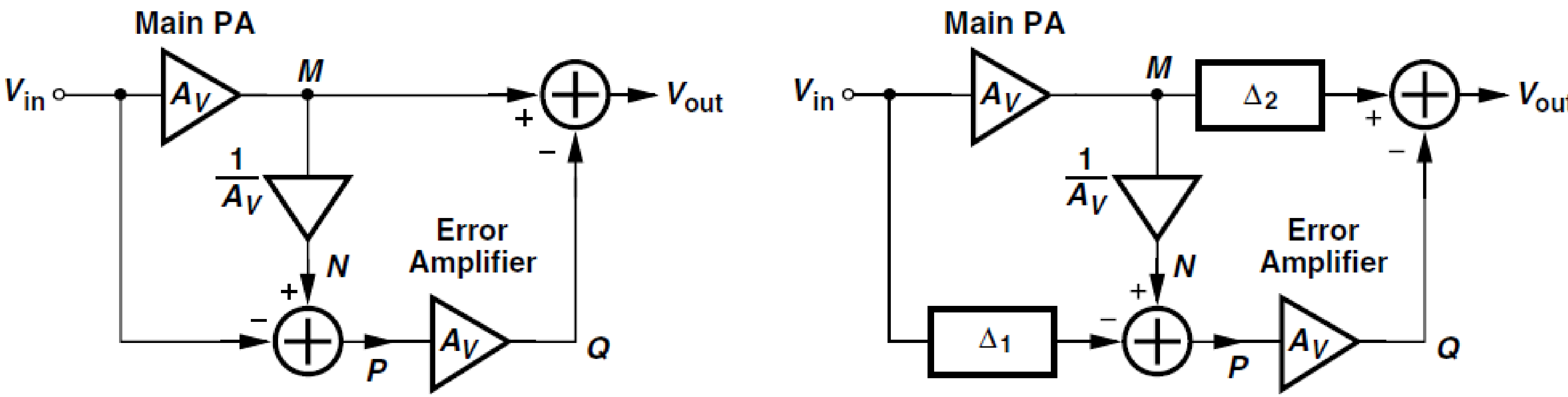


- ❑An OFDM 802.11g system needs 20 dBm at antenna and has a power-to-average ratio of about 17 dB. That means to transmit 20 dBm average power, the PA should be capable of transmitting 37 dBm !!!
- ❑In applications requiring a linear PA due to PAR (Peak-to-Average Rate), we must back-off from the peak power point to avoid clipping the waveform, but compromising the efficiency

[Ali Niknejad, EE142&EE242 of UC Berkeley]

PA Forward Linearization

- A nonlinear PA generates an output voltage waveform that can be viewed as the sum of a linear replica of the desired signal and an "error" signal

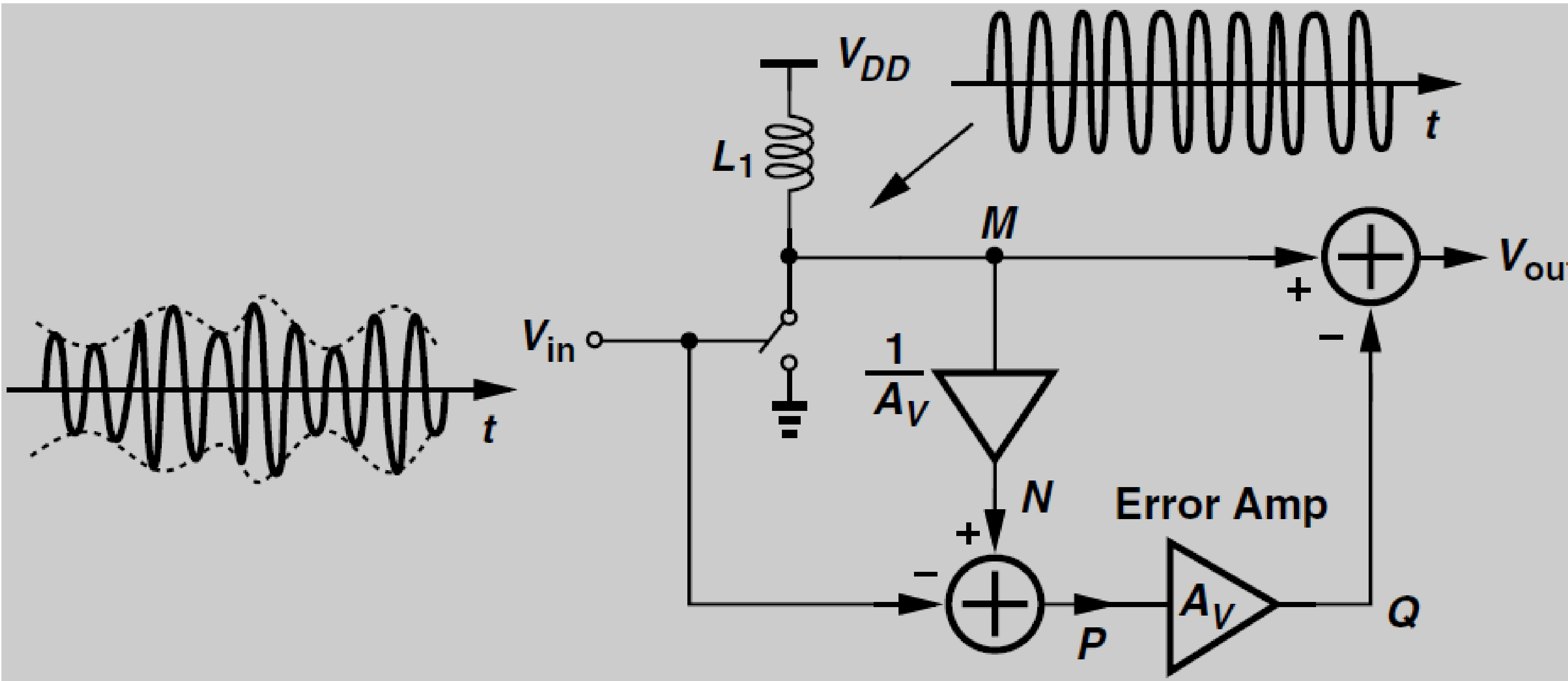


- $V_M = A_V V_{in} + V_D$, where V_D represents the distortion content

- The delay cells Δ_1 and Δ_2 are inserted to compensate the delays of $1/A_V$ and A_V

[B. Razavi, RF Microelectronics]

PA Forward Linearization

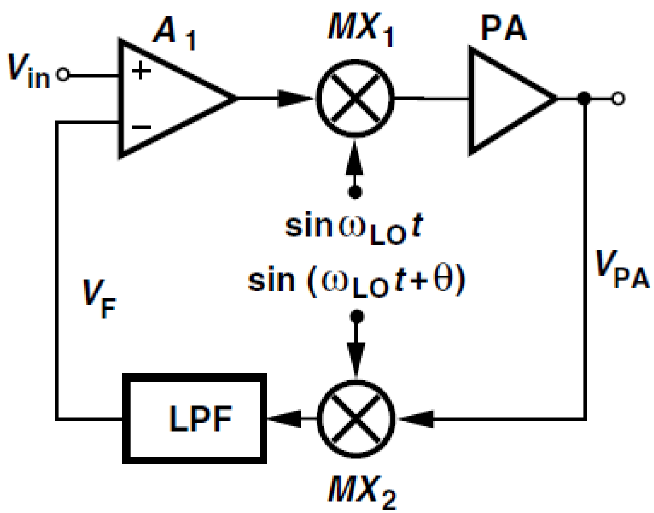


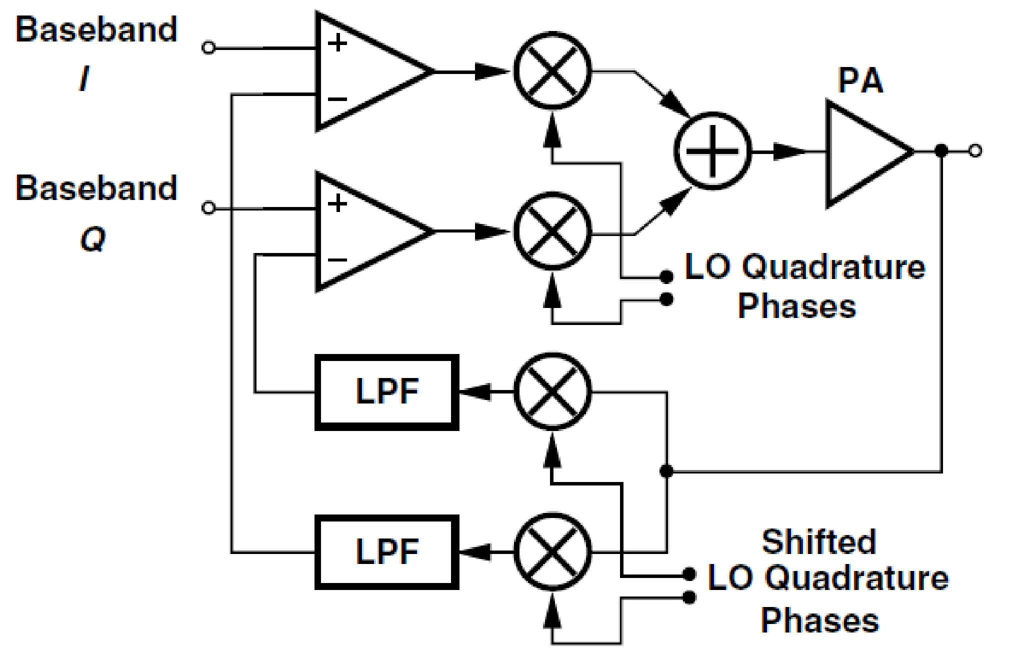
❑A nonlinear transistor acts a switch, and then the PA removes the envelope of the signal, retaining only the phase/frequency modulation part

[B. Razavi, RF Microelectronics]

Cartesion Feedback

❑A mixer can help to convert the signals into low frequency, and then the phase shift is easier to compensate





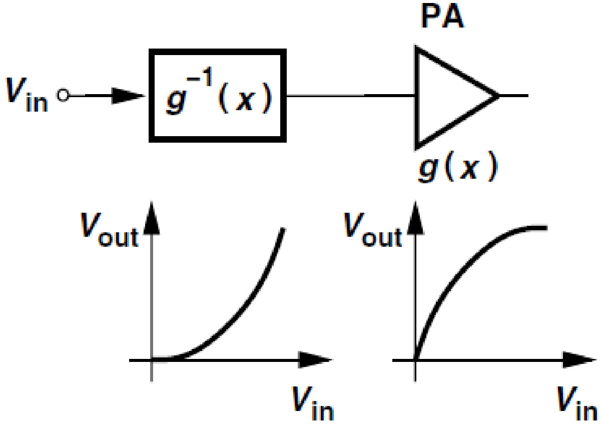
❑The loop attempts to make V_{PA} an accurate replica of V_{in}, enhancing the linearity

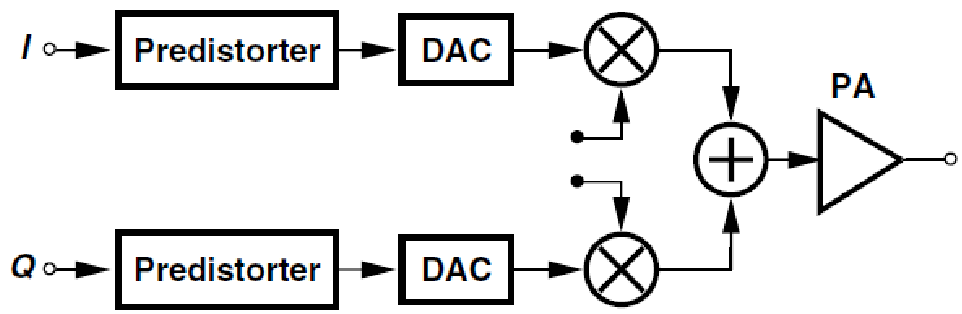
❑The phase θ is added so as to ensure stability

[B. Razavi, RF Microelectronics]

Predistortion

- If the PA expressed as y=g(x), predistortion subjects the input to a characteristic $y=g^{-1}(x)$, resembling an ideal linearity



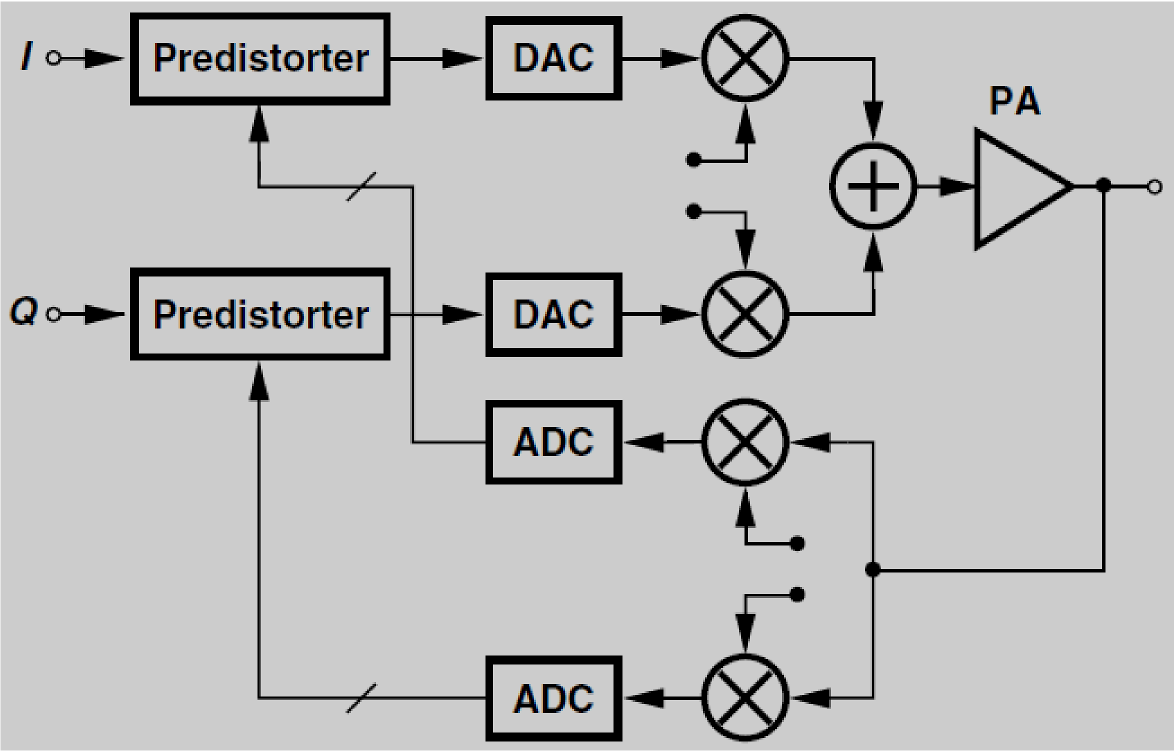


- There will be mismatch between predistorter and PA, where the PA transfer curve is affected by PVT variations and different antennas
- Predistortion can also be realized in the digital domain to allow a more accurate cancellation

[B. Razavi, RF Microelectronics]

Predistortion with Feedback

- The performance of predistortion can be improved if the predistorter is continuously informed of the PA nonlinearity

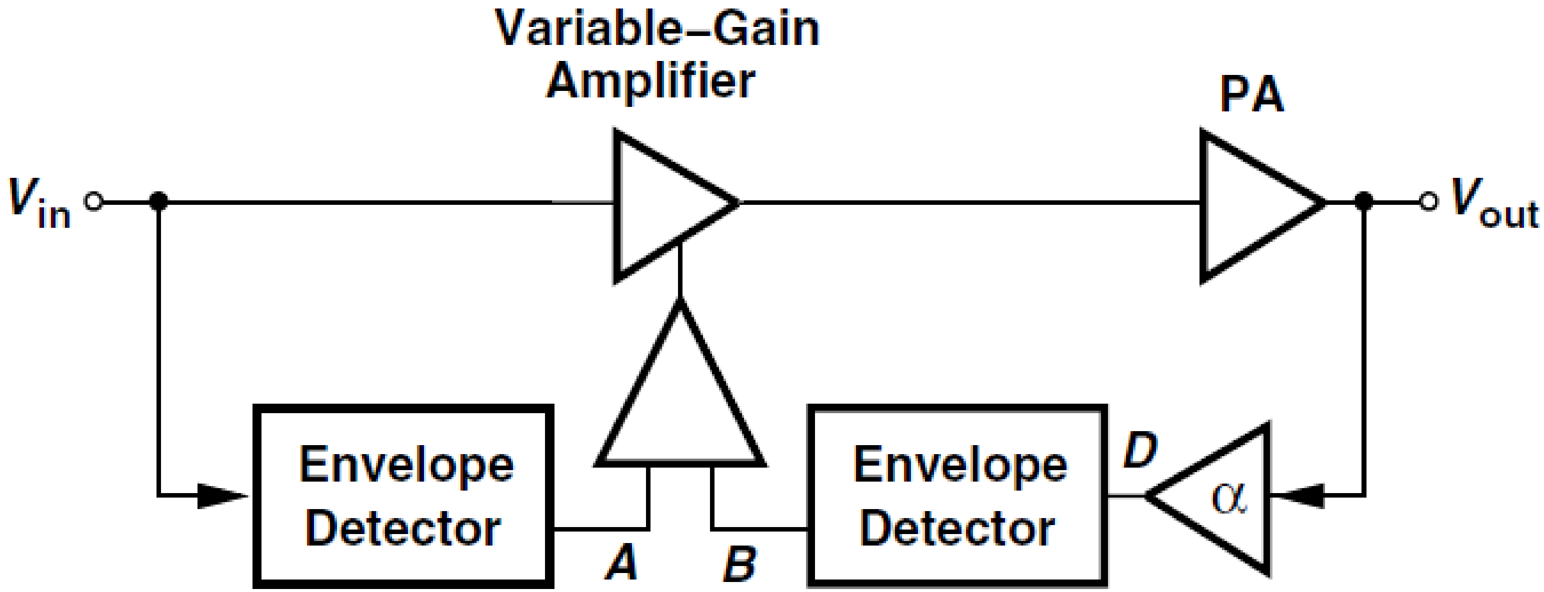


- The feedback signal produced by the low-frequency ADCs "adjusts" the predistortion

[B. Razavi, RF Microelectronics]

Envelop Feedback

❑In order to reduce envelope nonlinearity of PAs, it is possible to apply negative feedback only to the envelope of the signal

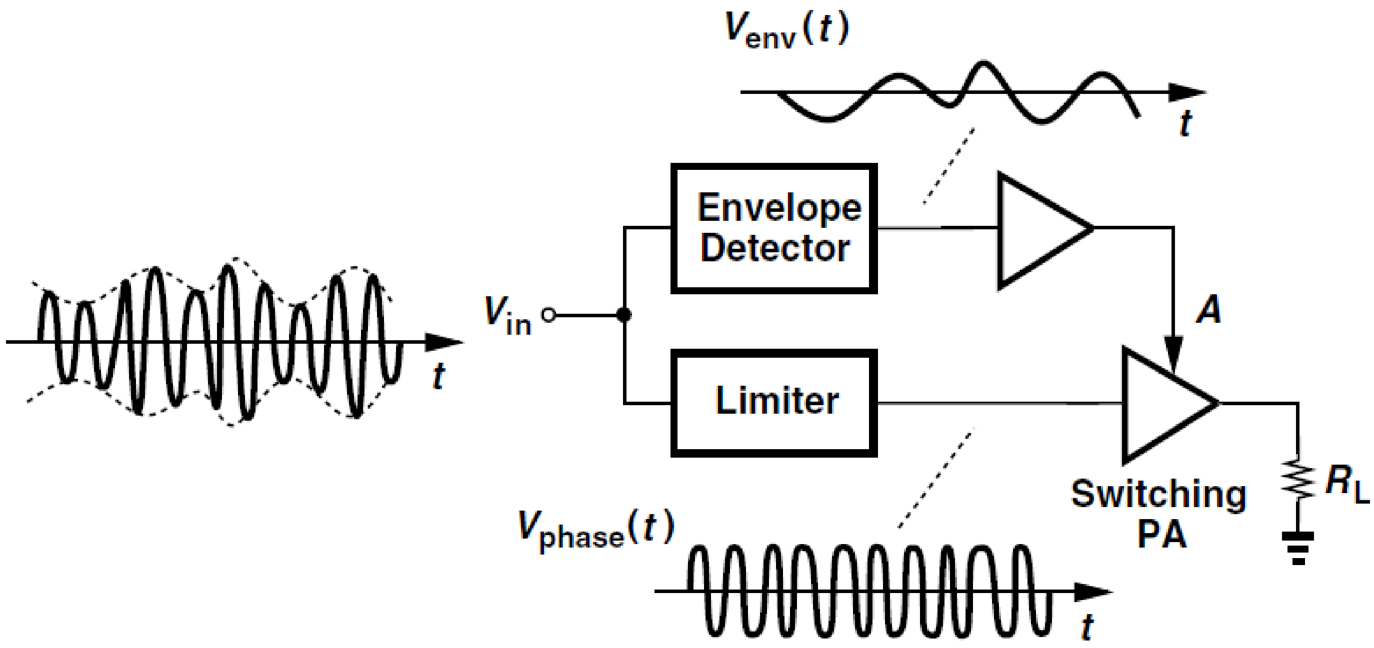


❑With a high loop gain, the signals at A and B are nearly identical, thus forcing V_{out} to track V_{in} with a gain factor of 1/α

[B. Razavi, RF Microelectronics]

Polar Modulation

❑We can decompose $V_{in}(t)$ into an envelope signal and a phase signal, amplify each separately and combine them



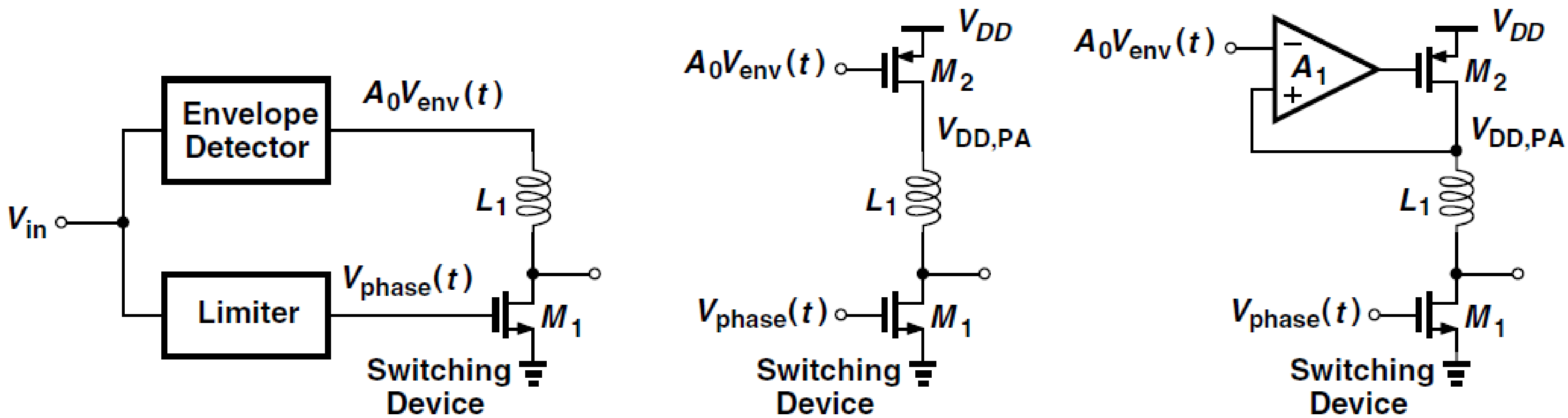
❑A switching PA can be used to improve the efficiency

❑The linearity is guaranteed by the envelop detector

[B. Razavi, RF Microelectronics]

Polar Modulation Realization

- The envelope signal directly can drive the supply of PA



- In this "open-loop" control, $V_{DD,PA}$ is a function of various device parameters
- The "closed-loop" control introduce a high gain of amplifier A_1 so that $V_{DD,PA} \approx A_0V_{env}(t)$

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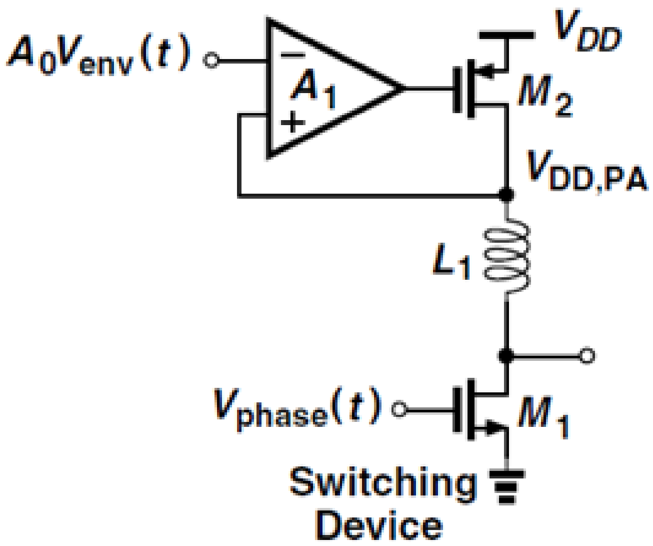
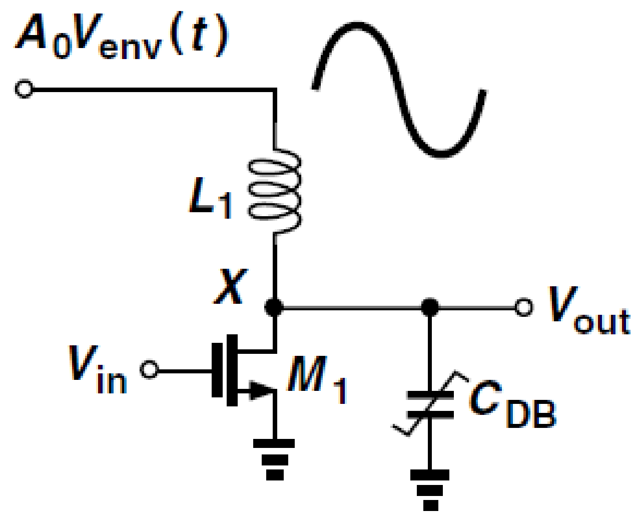
AM-PM Conversion

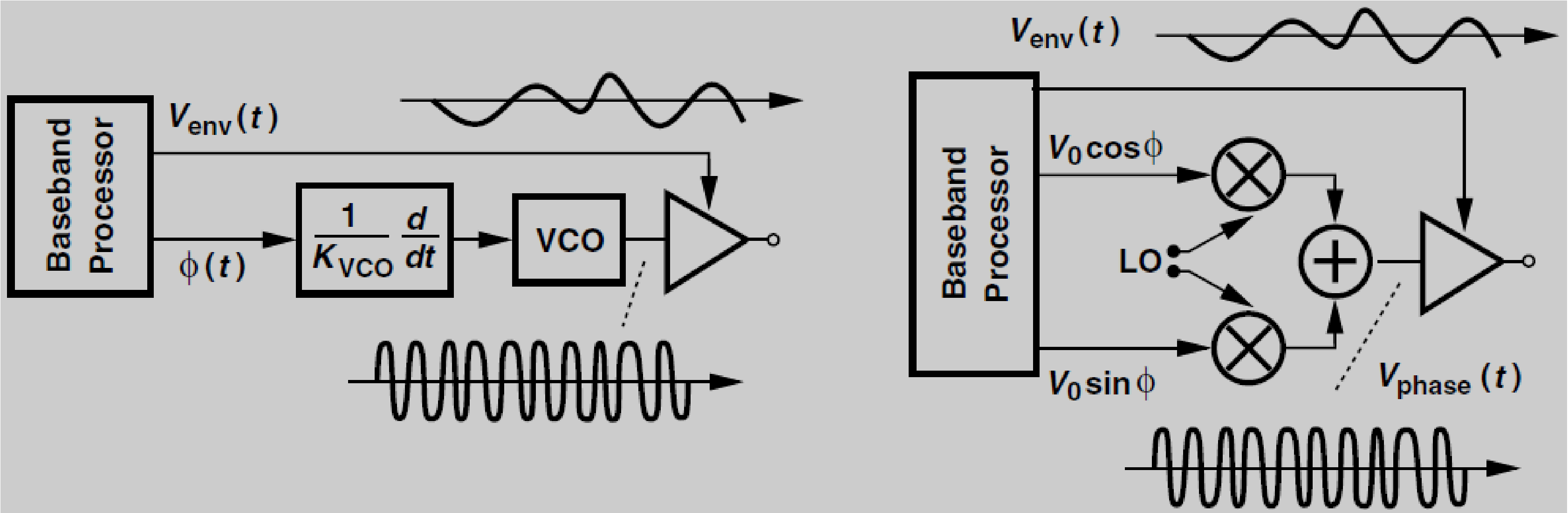




- ❑As $V_{DD,PA}$ swings up and down to track $A_0V_{env}(t)$, the parasitic capacitance C_{DB} varies, so the phase signal is corrupted by the envelope signal

[B. Razavi, RF Microelectronics]

Polar Modulation Realization



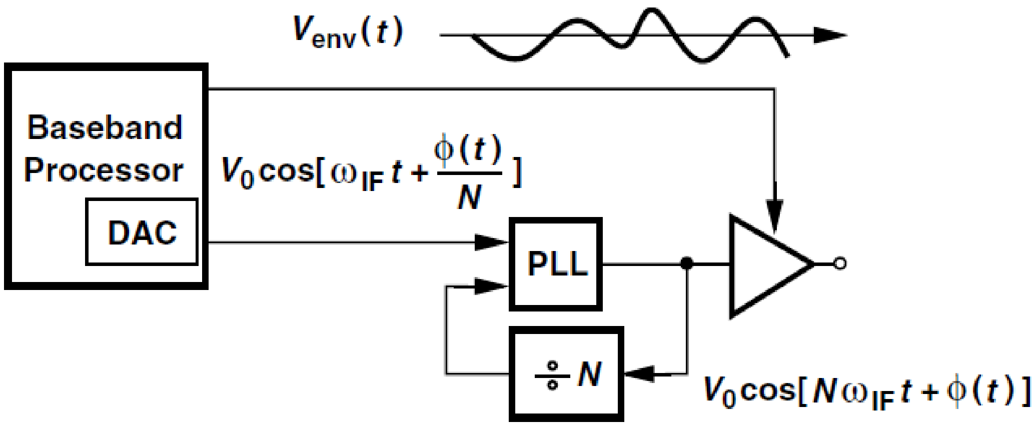
❑We can applying the phase information to the control line of a VCO, where the integration performed by the VCO requires that φ(t) be first differentiated

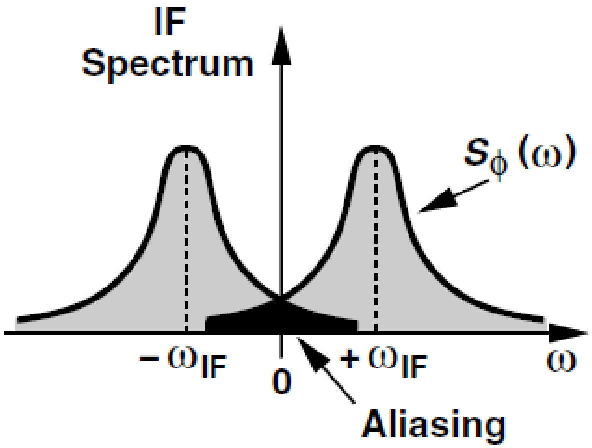
❑Consider a quadrature modulator:

$$V_{phase}(t) = V_0 \cos\omega_0 t \cos\phi - V_0 \sin\omega_0 t \sin\phi$$

[Behzad Razavi, RF Microelectronics]

PLL Based Polar Modulation

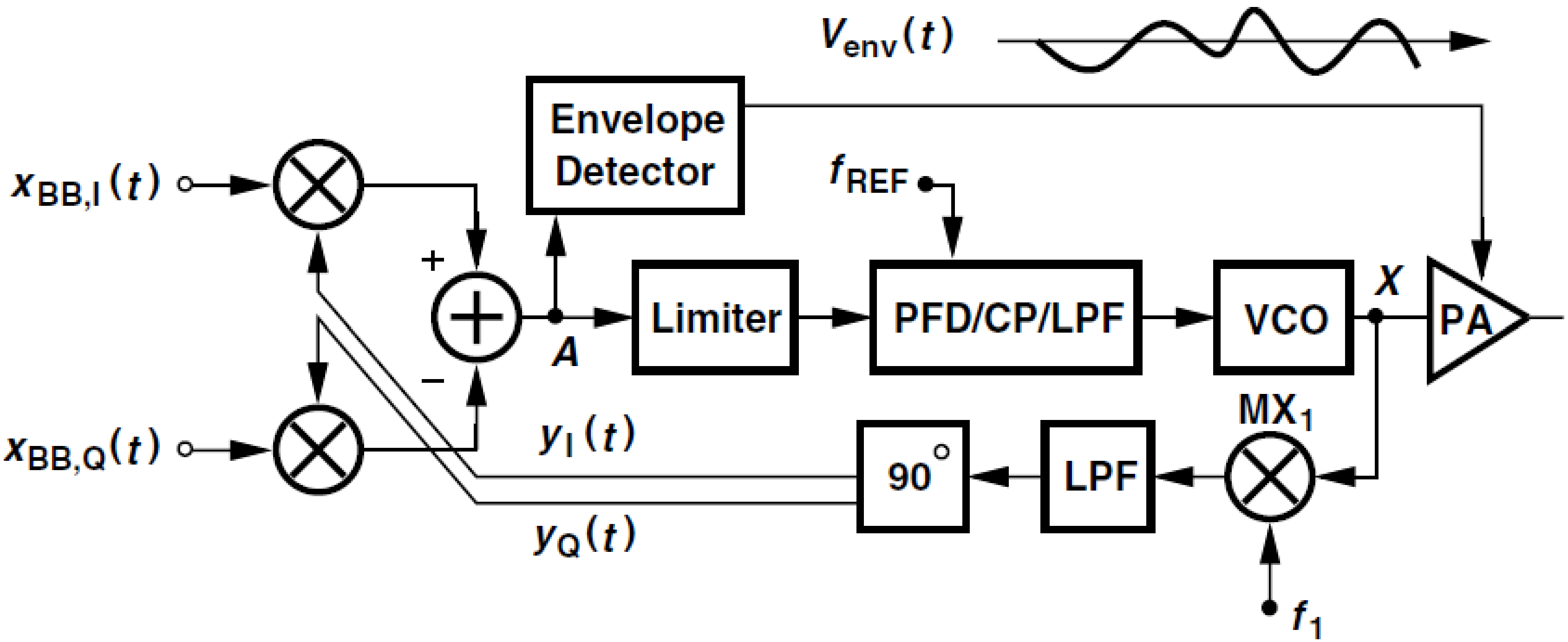




- ❑The DAC output frequency ω_{IF} must be low enough to avoid imposing severe speed power trade-offs on the baseband DAC
- ❑The DAC output frequency must be high enough to avoid aliasing

[Behzad Razavi, RF Microelectronics]

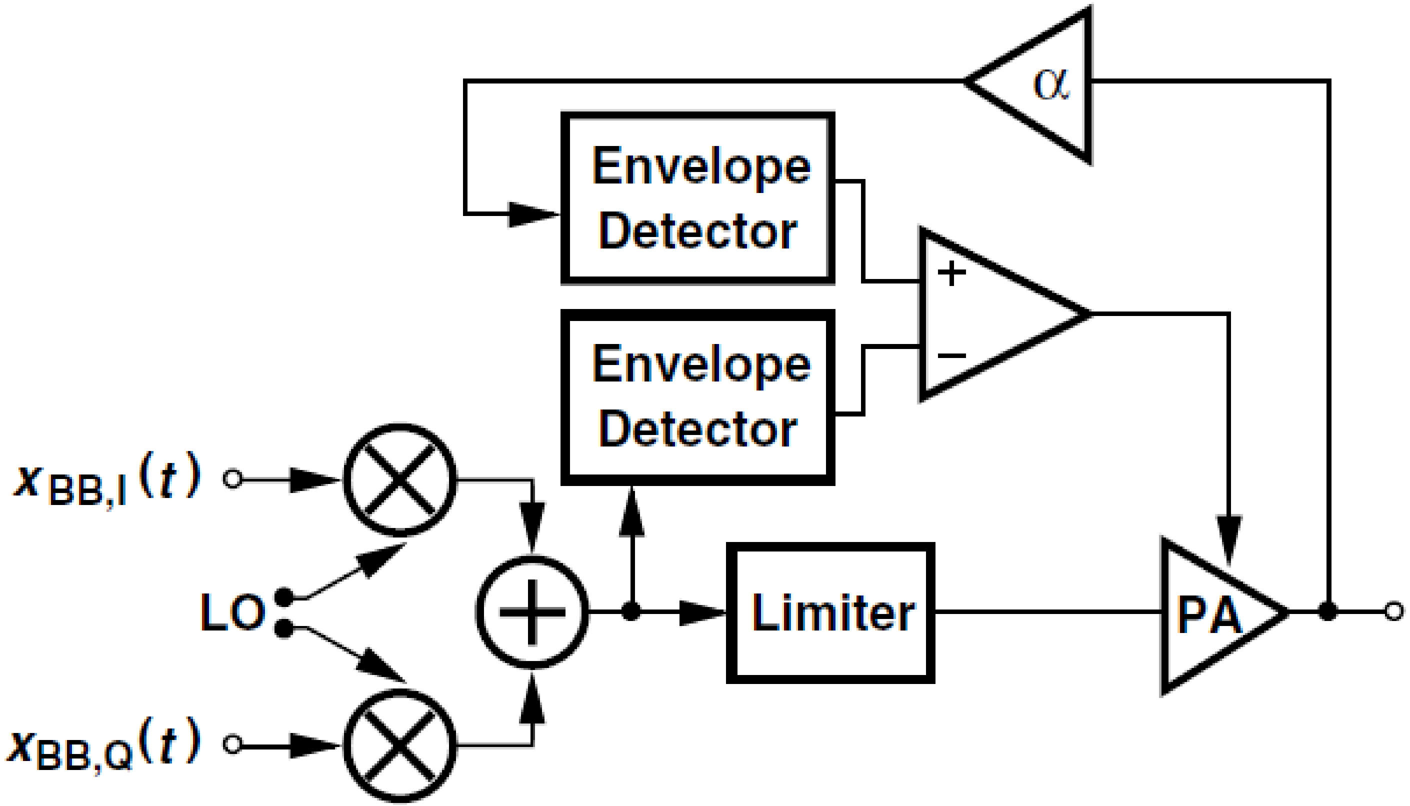
PLL Based Polar Modulation



❑Quadrature upconversion is performed to a certain IF, extract the envelope component, and apply it to the PA

[Behzad Razavi, RF Microelectronics]

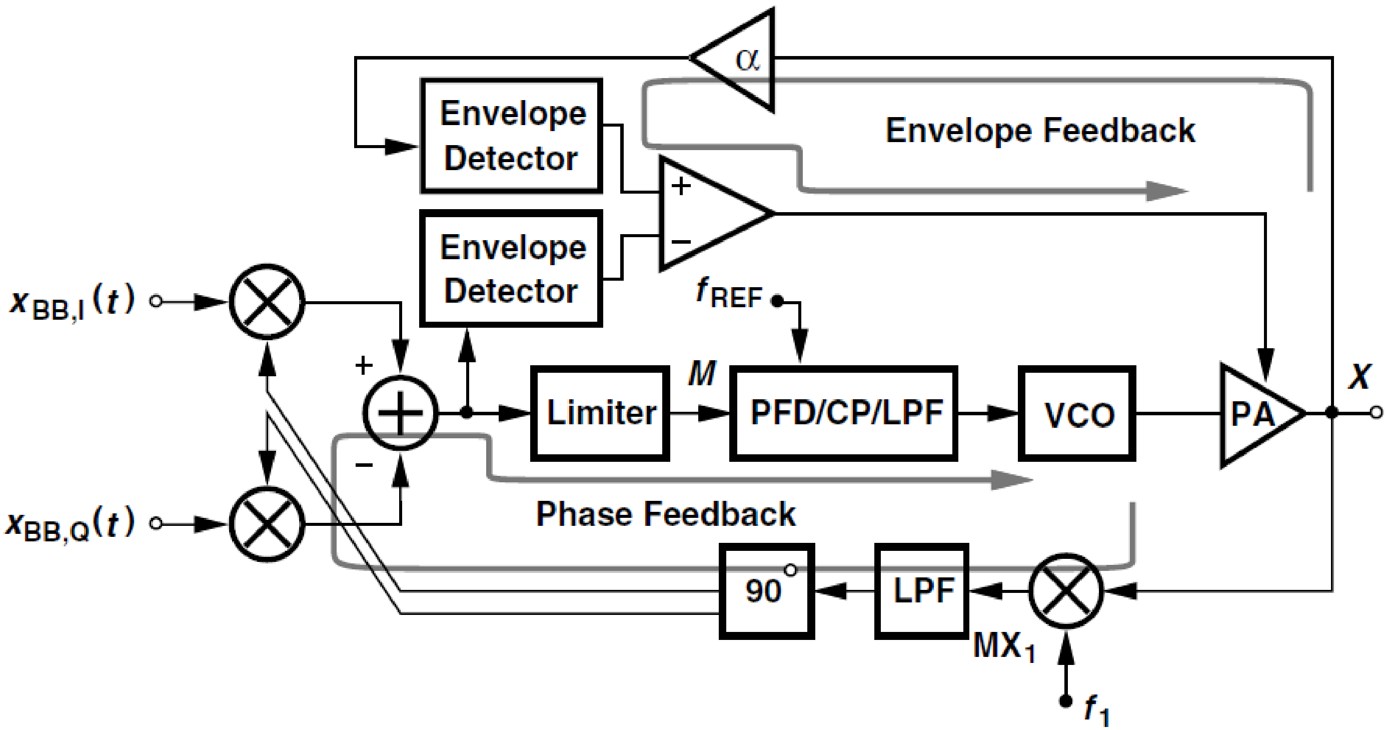
Envelop Feedback



❑The feedback loop thus forces a faithful (scaled) replica of the IF envelope at the PA output

[Behzad Razavi, RF Microelectronics]

Phase & Envelop Feedback



- ❑If PA introduces AM-to-PM conversion, the PLL still guarantees that the phase at X tracks the baseband phase modulation
- ❑The two feedback loops can interact and cause instability, requiring careful choice of their bandwidths

[Behzad Razavi, RF Microelectronics]

Outphasing

- If the signal to be emitted is constant-envelop, a nonlinear PA can be adopted to maximize the efficiency (such as Class-E)
- If the signal to be emitted is variable-envelop, a linear PA is required to keep the information on the envelop, while linear PA usually results in low efficiency (such as Class-A)
- A variable-envelop signal can be expressed by:

$$V_{in}(t) = V_{env}(t)\cos[\omega_0 t + \phi(t)] = V_1(t) + V_2(t)$$

$$V_1(t) = \frac{V_0}{2}\sin[\omega_0 t + \phi(t) + \theta(t)]$$

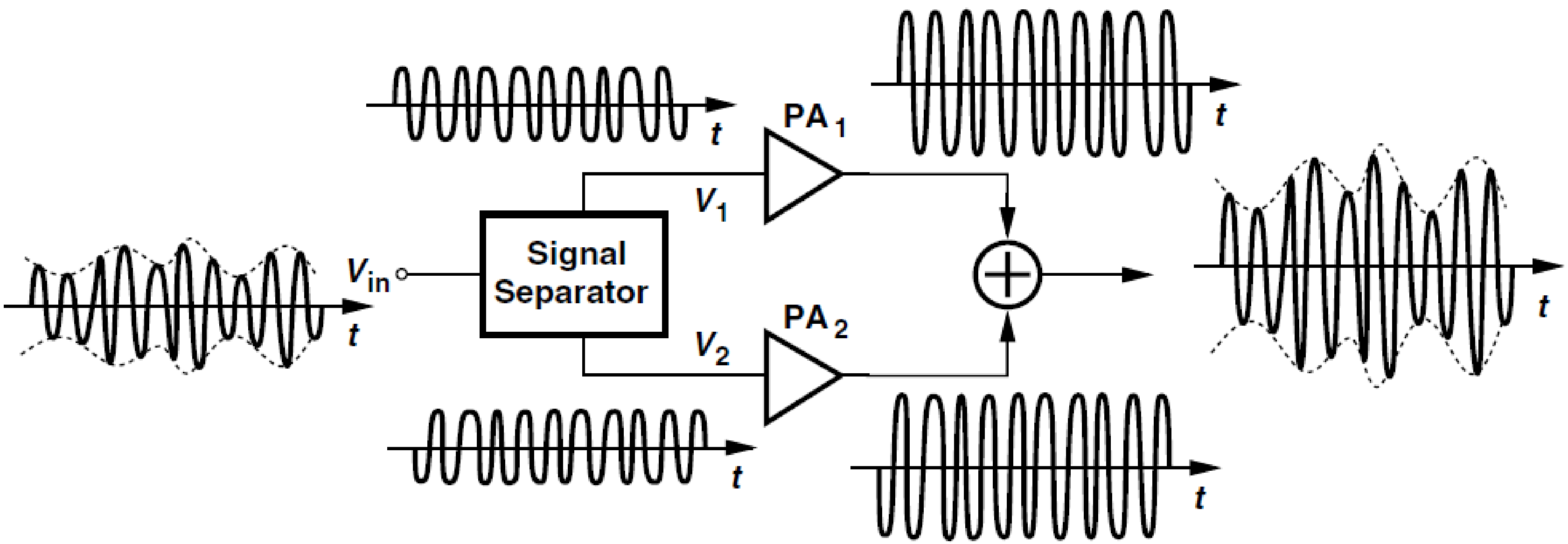
$$V_2(t) = -\frac{V_0}{2}\sin[\omega_0 t + \phi(t) - \theta(t)]$$

$$\theta(t) = \sin^{-1}\frac{V_{env}(t)}{V_0}$$

[Behzad Razavi, RF Microelectronics]

Outphasing

- It is possible to avoid envelope variations in a PA by decomposing a variable-envelope signal into two constant-envelope waveforms, which is called "outphasing"



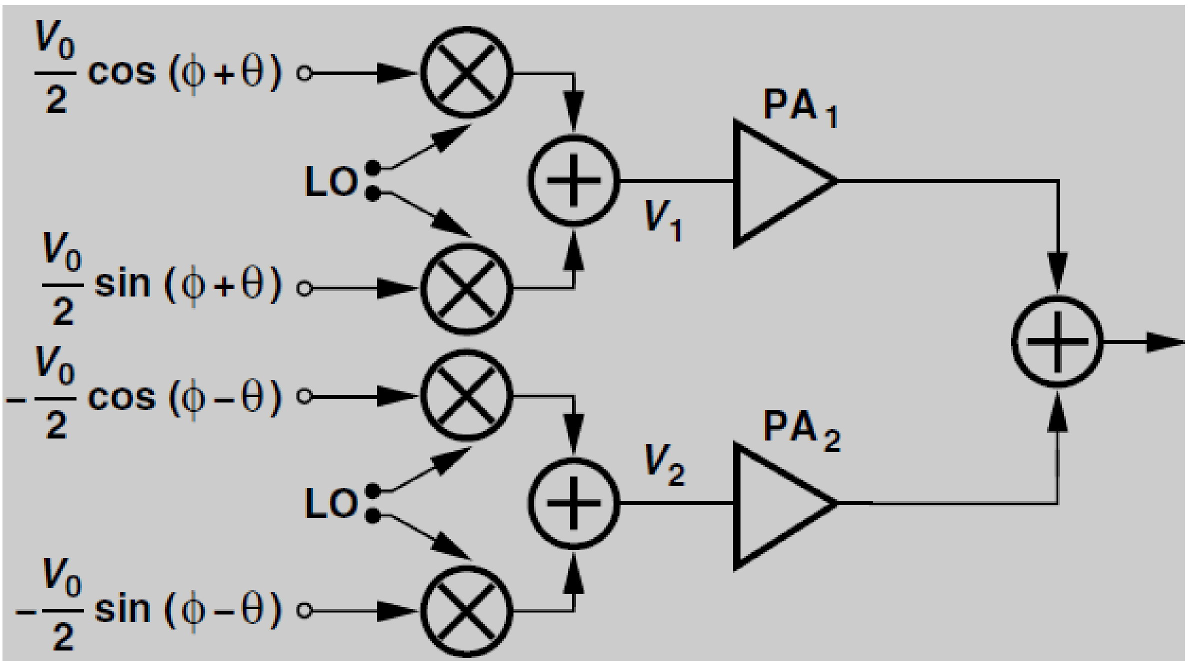
[Behzad Razavi, RF Microelectronics]

An Outphasing Transmitter

$$V_{in}(t) = V_{env}(t)\cos[\omega_0 t + \phi(t)] = V_1(t) + V_2(t)$$

$$V_1(t) = \frac{V_0}{2}\cos[\phi(t)+\theta(t)]\sin\omega_0 t + \frac{V_0}{2}\sin[\phi(t)+\theta(t)]\cos\omega_0 t$$

$$V_2(t) = -\frac{V_0}{2}\cos[\phi(t)-\theta(t)]\sin\omega_0 t - \frac{V_0}{2}\sin[\phi(t)-\theta(t)]\cos\omega_0 t$$



[Behzad Razavi, RF Microelectronics]

Outphasing: Advantages and Issues

- ❑A critical advantage of outphasing is that it does not require supply modulation, saving the efficiency and headroom lost in the envelope buffer necessary in polar modulation

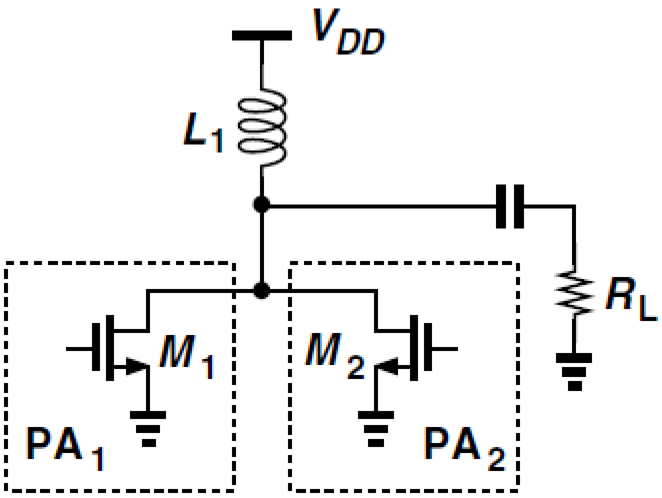
- ❑The summation of the outputs in the outphasing technique entails power loss (as in the feedforward topology)
- ❑The gain and phase mismatches between the two paths in result in signal distortion at the output
- ❑The signal traveling through one PA may affect that through the other, resulting in spectral regrowth and even corruption
- ❑As the amplitude modulation is changed into phase modulation, the two signal paths occupy a large bandwidth

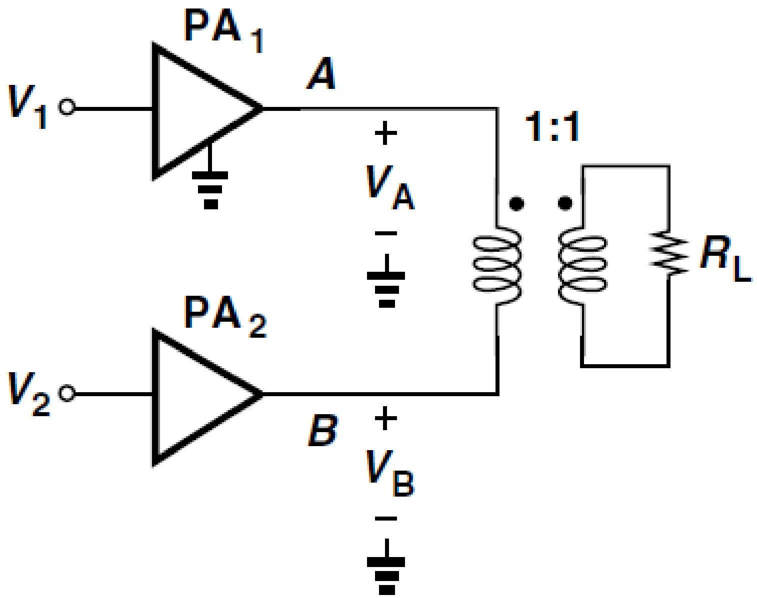
[Behzad Razavi, RF Microelectronics]

Combining Circuits

❑Two transistors of PAs can share the same load to sum the output currents

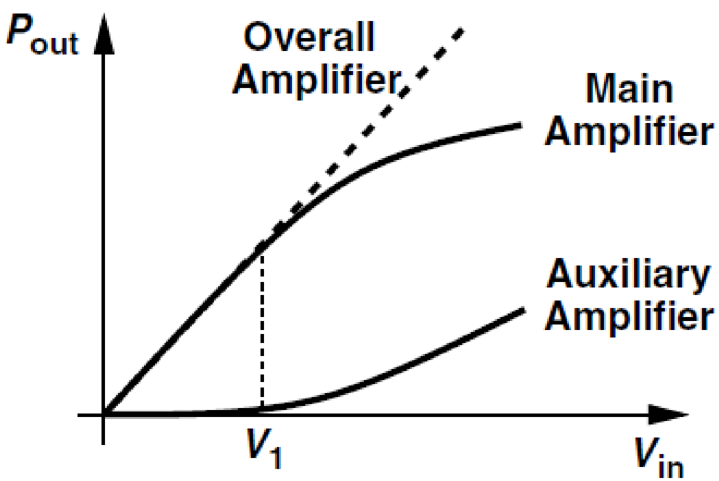
❑A transformer can be adopted to sum the outputs and drives the load resistance

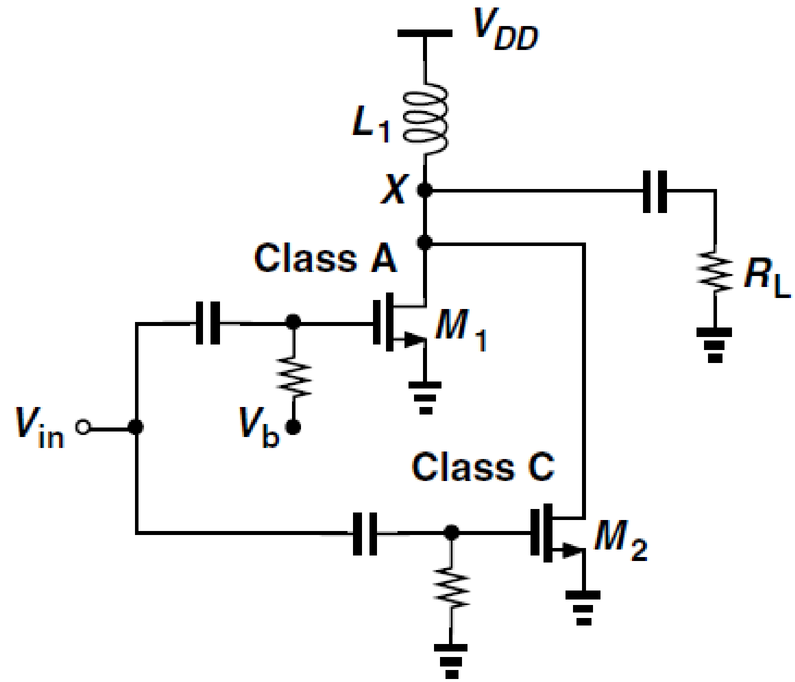




[Behzad Razavi, RF Microelectronics]

Doherty PA

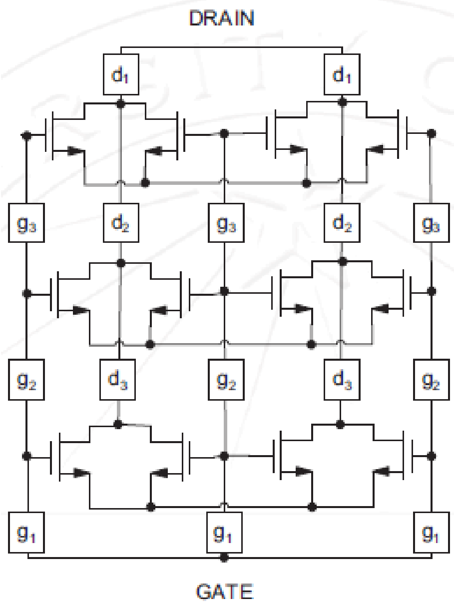


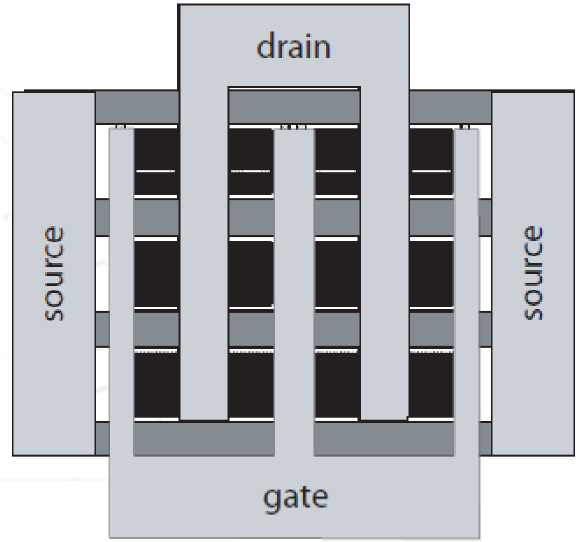


- If an auxiliary transistor is introduced that provides gain only when the main transistor begins to compress, then the overall gain can remain relatively constant for higher input and output levels.

[Behzad Razavi, RF Microelectronics]

Power Transistor

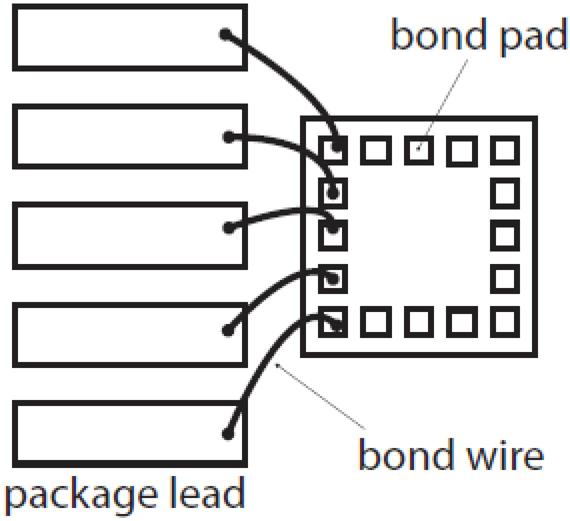


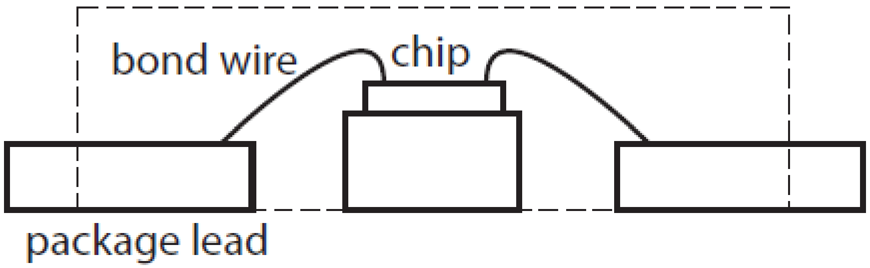


- ❑Power transistors are typically very large (millimeter size) and the layout is broken into sub-cells, where the gate/drain lines are delay equalized
- ❑The layout metals introduce significant resistance and capacitance, which needs to be carefully modeled

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Package Parasitics

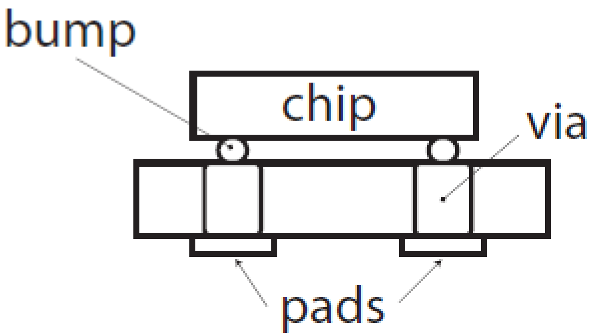


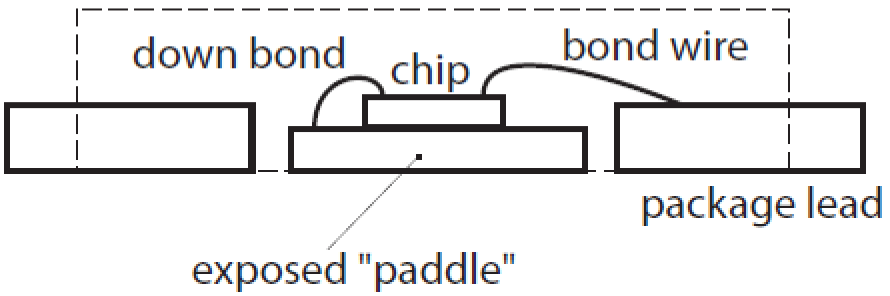


- ❑In a normal wire-bonding package, long bond wires are required to make the connections, leading to large inductance
- ❑The model of the package/chip should include the pads, the bond wires, as well as the package leads

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Advanced Packaging

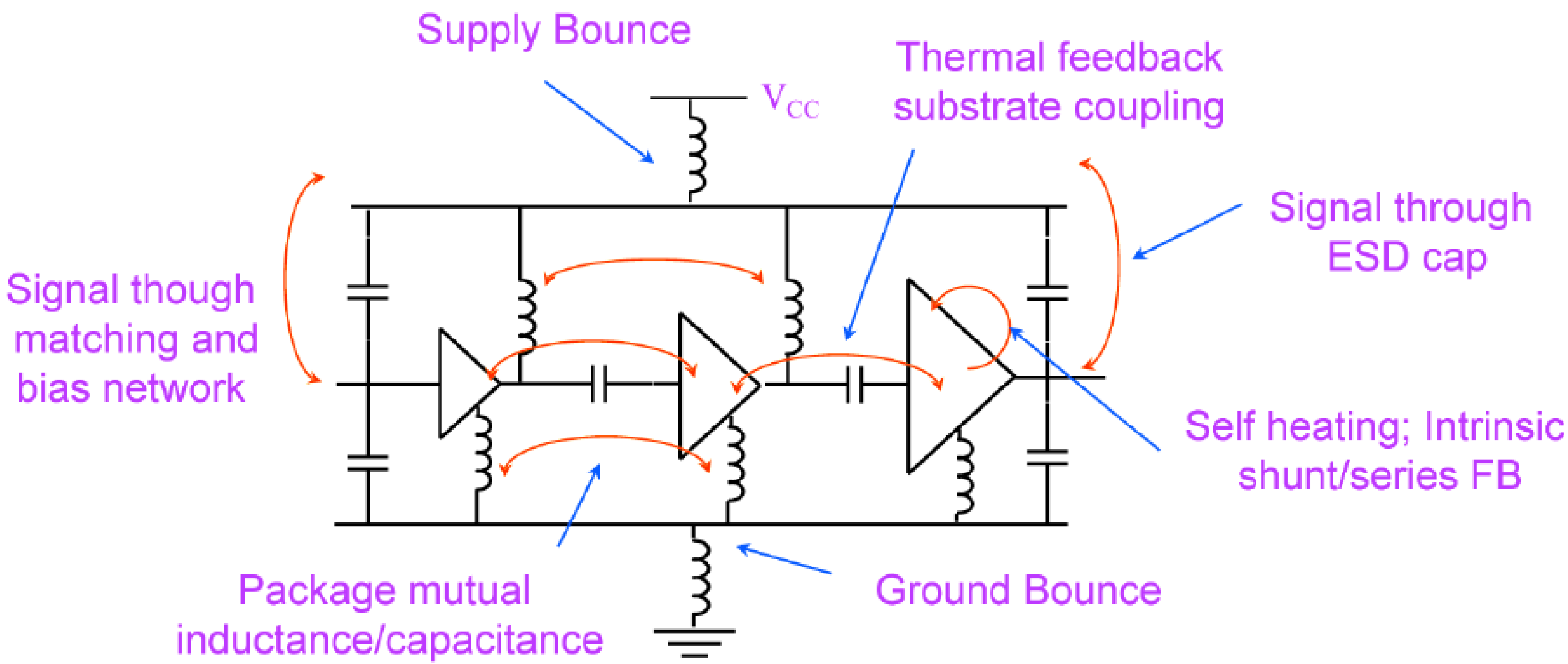




- ❑In flip-chip technology, the chip is flipped and “bumped” onto a board directly. This results in small inductance connections
- ❑In an exposed “paddle” package, there is a ground plane inside the package. We use conductive glue to mount the chip onto the package. Short down-bonds then create low inductance ground connections
- ❑In the extreme case, we can use several down-bonds in parallel surrounding the chip in addition to thinning the die

[Ali Niknejad, EE142&EE242 of UC Berkeley]

Parasitic Coupling



❑Package: ESD, bias, pins, bond wires

❑Substrate: Devices (passive and active), thermal

❑Maximum safe power gain ~ 30 dB

[Ali Niknejad, EE142&EE242 of UC Berkeley]