# Power Amplifiers (1/2)


**ZHAO BO**

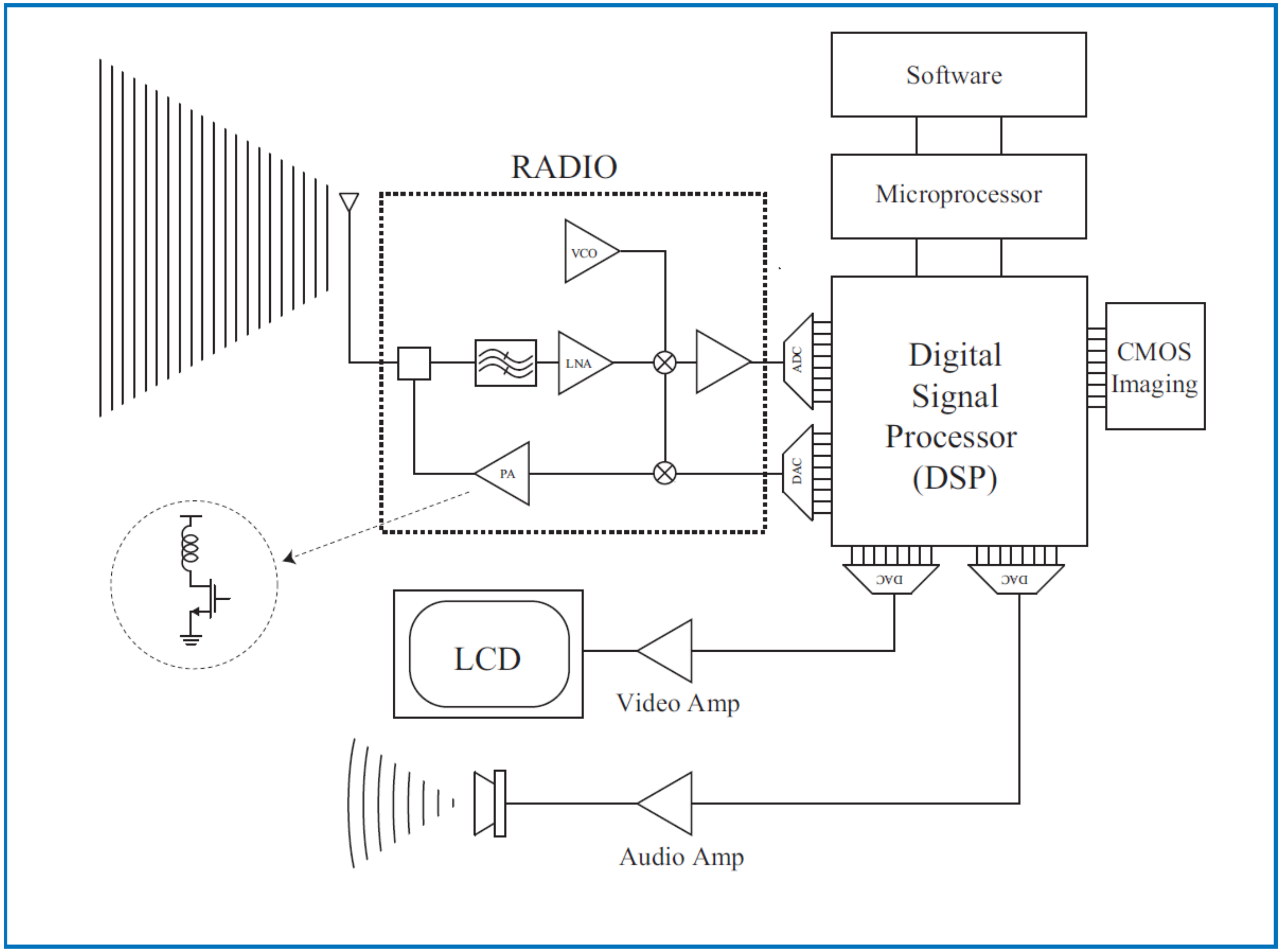
**Institute of VLSI Design**

**Zhejiang University**

**Email: zhaobo@zju.edu.cn**

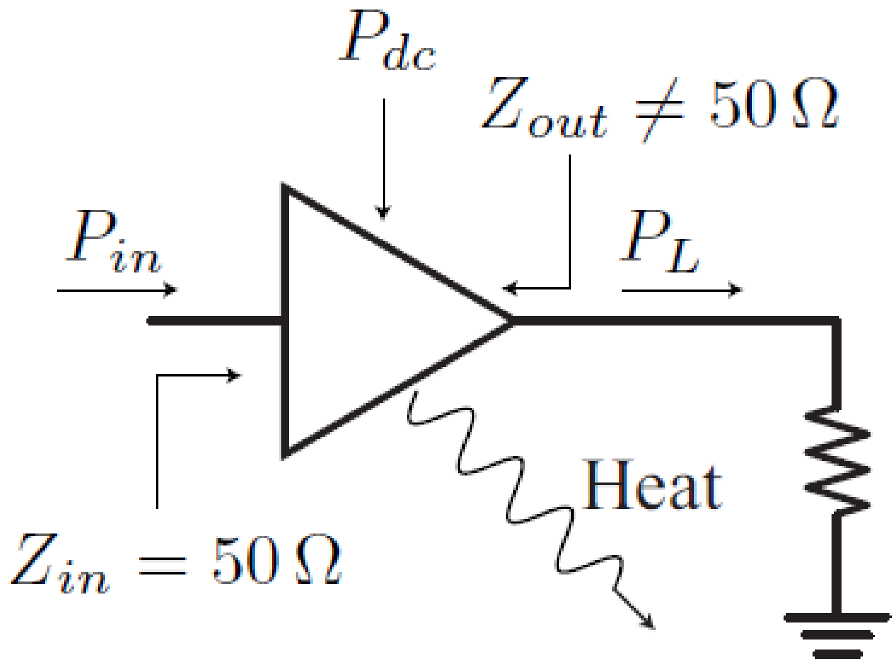
**Web： person.zju.edu.cn/zhaobo**

# A Cell Phone




*[Ali Niknejad, EE142 &EE242 of UC Berkeley]*

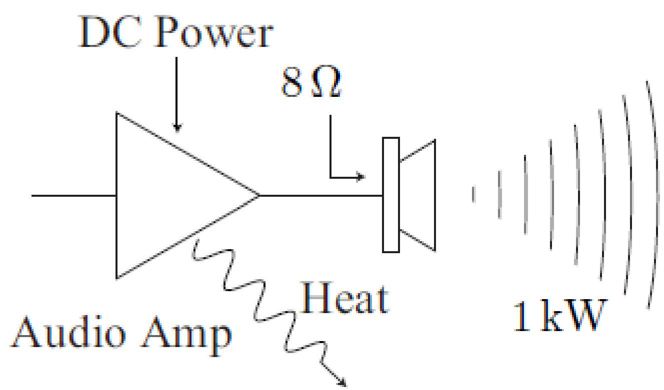
# Power Amplifier (PA)




- ❑**Powerful: PA delivers power to a given load with maximum efficiency**
- ❑**Linear: PA faithfully transfers the modulation from the input to the output**

***[Ali Niknejad, EE142&EE242 of UC Berkeley]***

# Audio PA Example




- Consider a PA that delivers 1kW of power into 8 speakers.
- Assuming a sinusoidal input, the peak voltage and current are

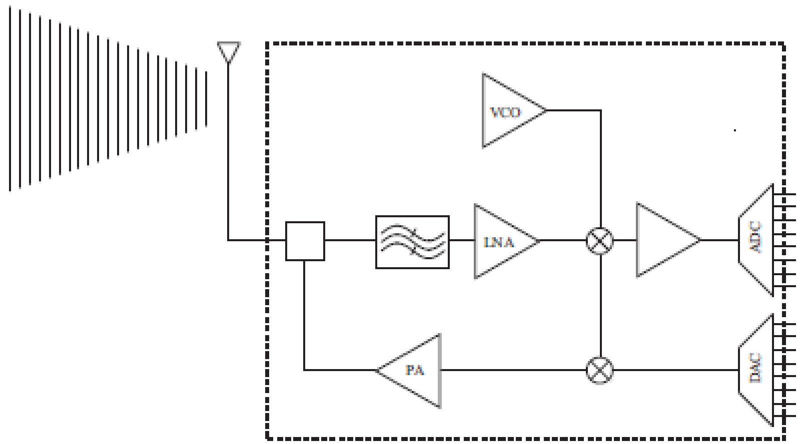
$$V = \sqrt{2RP} = \sqrt{2 \cdot 8 \cdot 1000} = 126\mathrm{V}$$

$$I = \frac{2P}{V} = 15.8\mathrm{A}$$

- Such large currents and voltages require special techniques and/or technology

*[Ali Niknejad, EE142&EE242 of UC Berkeley]*

# Mobile Phone Example




- Consider a typical mobile phone that delivers 1W in to a 50 antenna. Here we find that

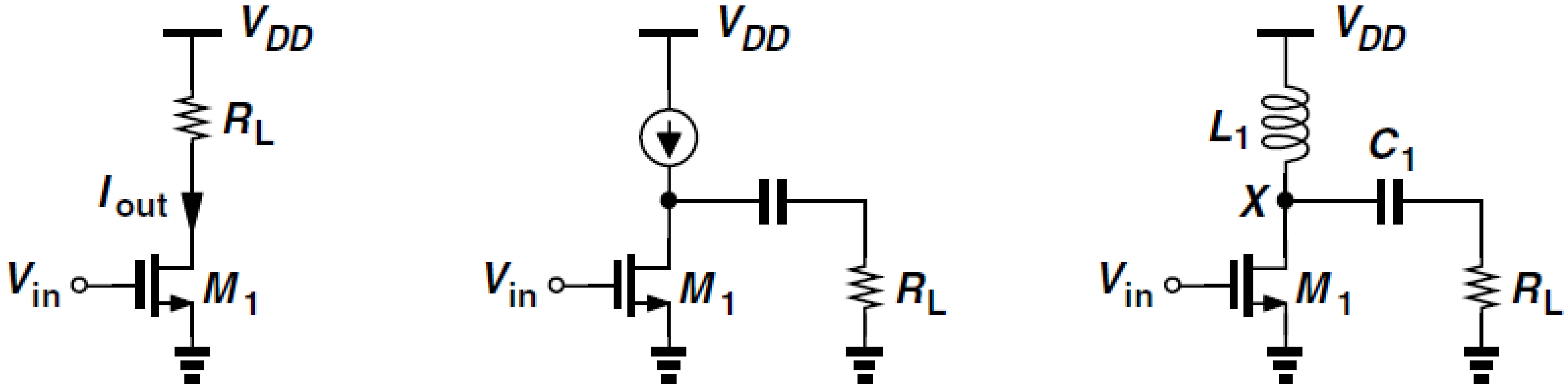
$$V_0 = \sqrt{2PR} = \sqrt{2 \cdot 50} = 10\mathrm{V}$$

$$I_0 = 2/10 = 0.2\mathrm{A}$$

- Most high-frequency Si transistors cannot handle 10V due to breakdown. Thus we need to transform the voltage down to a safe value

*[Ali Niknejad, EE142&EE242 of UC Berkeley]*

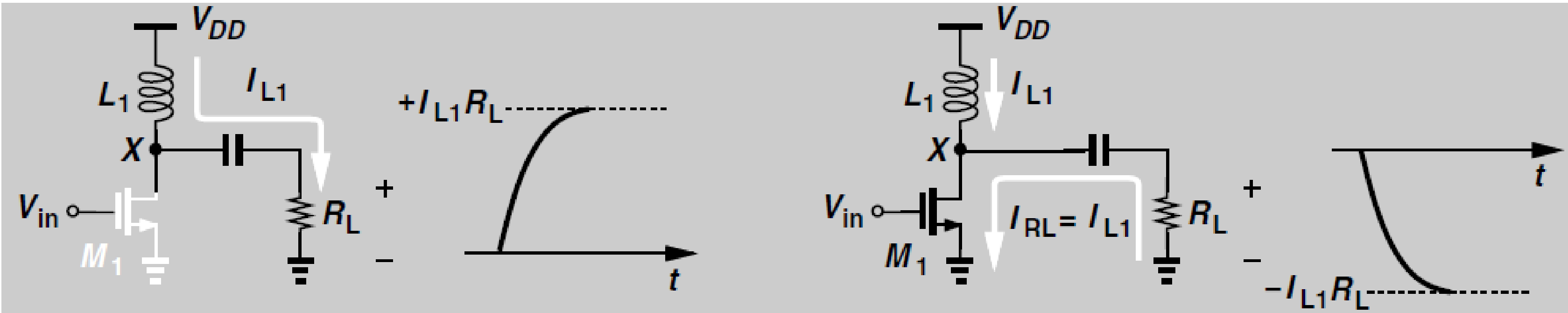
# CS Stages




- Without an inductor, the circuits require a supply voltage greater than 10V
- If the load is realized as an inductor, the drain AC voltage exceeds the supply $V_{DD}$, even reaching $2V_{DD}$ (or higher)
- While allowing a lower supply voltage, the inductive load does not relax the "stress" on the transistor

*[B. Razavi, RF Microelectronics]*

# CS Stages




❑A fundamental issue in PA design: The trade-off between the output power and the voltage swing experienced by the output transistor

❑The product of the breakdown voltage and $f_T$ of silicon devices is around 200 GHz · V

*[B. Razavi, RF Microelectronics]*

# PA Considerations

- PAs drive large voltages/currents into small load impedances. Thus matching networks are critical. Any loss in the matching network has a severe impact on the efficiency of the amplifier.

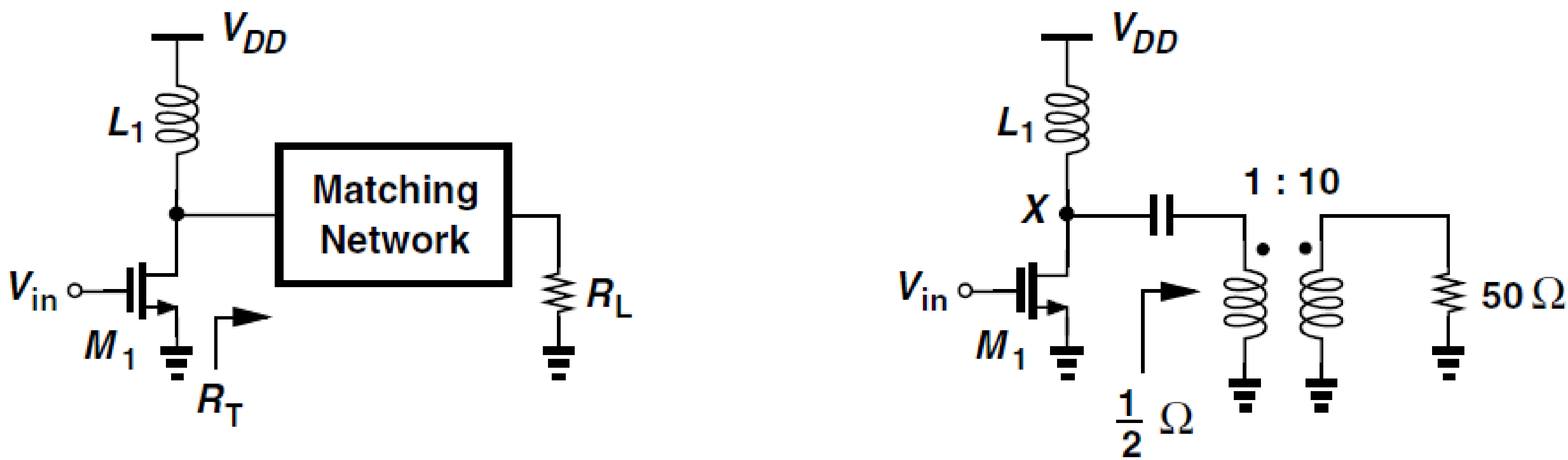
- Heat generation is high. We need to carefully provide heat sinks to keep the junction temperatures as low as possible.

- Due to the interface with the external "off-chip" world, packaging and board parasitics are very important.

- The spectral "leakage" and harmonic generation in a PA must be kept to the a minimum in order to minimize interference to other users.

*[Ali Niknejad, EE142&EE242 of UC Berkeley]*

# Impedance Transformation



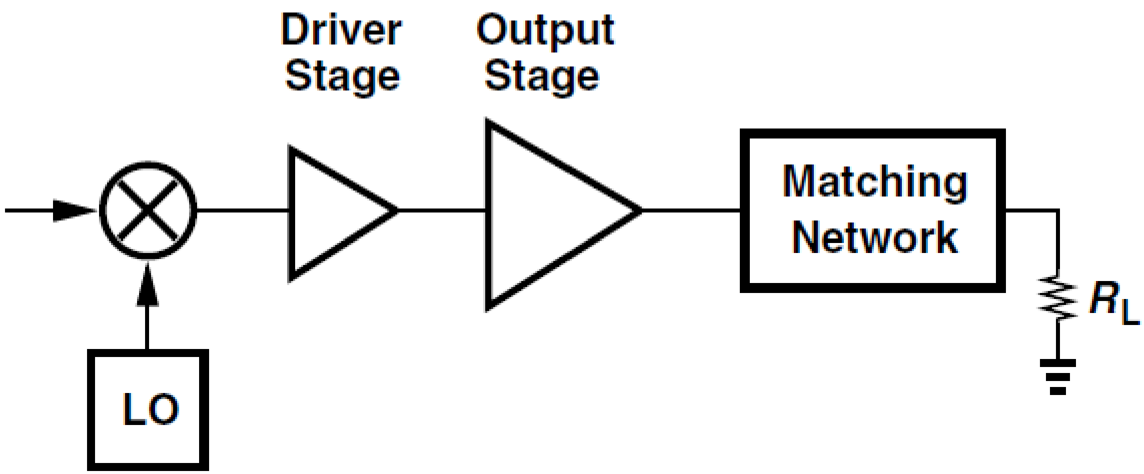

❑The network transfers the load resistance to a lower value ($R_T$) so that smaller voltage swings still deliver the required power

❑The need for transforming the voltage swings means that the current generated by the output transistor must be proportionally higher

*[B. Razavi, RF Microelectronics]*

# Effect of High Current

- ❑If the output transistor is chosen wide enough to carry a large current, then its input capacitance is very large, making the design of the preceding stage difficult




- ❑Tapered stages can be interposed between the upconversion mixers and the output stage
- ❑The multiple stages tend to limit TX output compression point
- ❑The driver also consumes high power

*[B. Razavi, RF Microelectronics]*

# Efficiency

- The Power Added Efficiency, or PAE, is a measure of how much power is added to a signal normalized by the DC power consumption

$$PAE = \eta = \frac{P_L - P_{in}}{P_{dc}}$$

- If the power gain is large

$$PAE = \frac{P_L(1 - G_p^{-1})}{P_{dc}} \approx \frac{P_L}{P_{dc}}$$

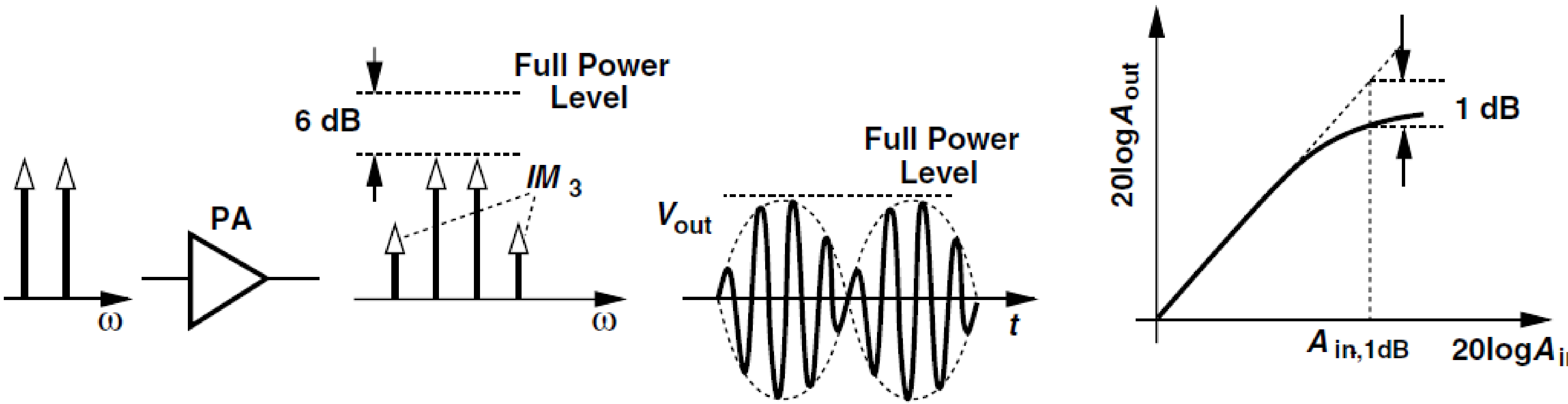
- The drain efficiency is defined as

$$\eta_{c|d} = \frac{P_L}{P_{dc}}$$

*[Ali Niknejad, EE142&EE242 of UC Berkeley]*

# Linearity

❑PA nonlinearity leads to: 1) high adjacent channel power as a result of spectral regrowth, and 2) amplitude compression

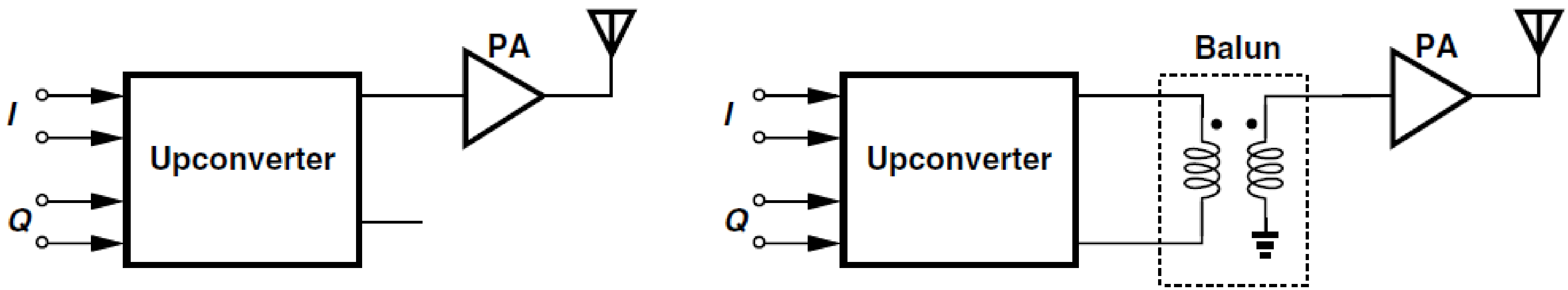



❑The amplitude of the tones is chosen such that each main component at the output is 6 dB below the full power level, thus producing the maximum desired output voltage swing when the two tones add in-phase

*[B. Razavi, RF Microelectronics]*

# Single Ended and Differential

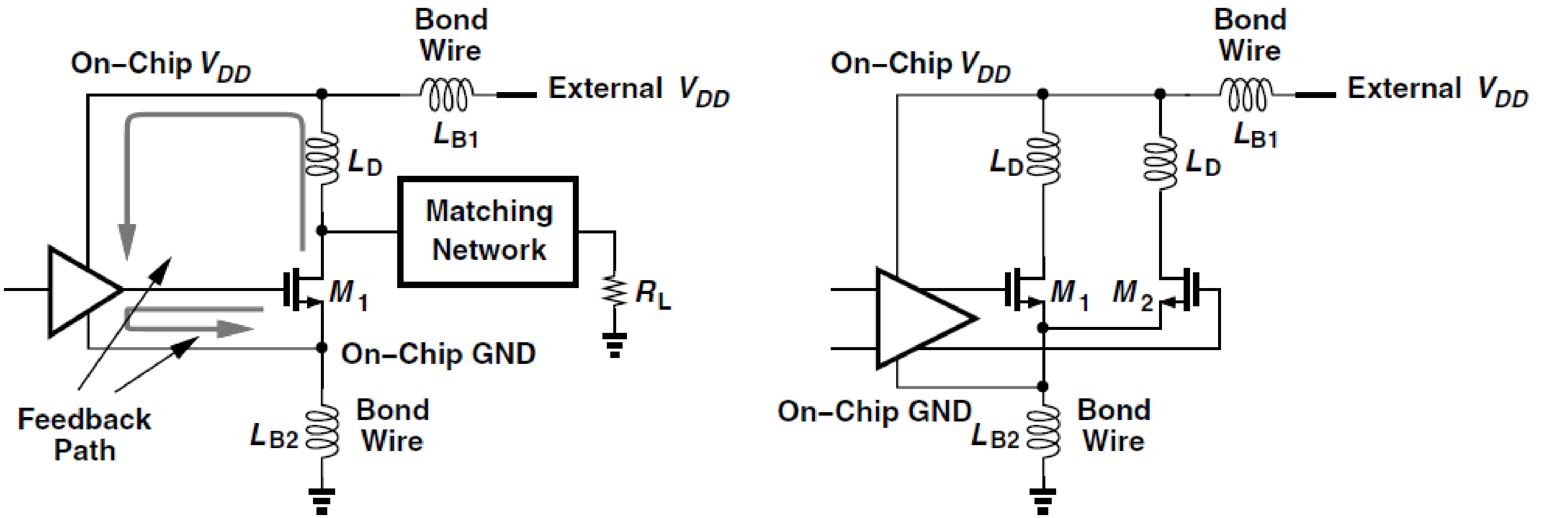
- The antenna is typically single-ended, and single-ended RF circuits are much simpler to test
- Single-ended transmitter “waste” half of the voltage gain because they sense only one output of the upconverter




- A balun can be interposed between upconverter and PA
- But the balun introduces its own loss, especially if it is integrated on the chip

*[B. Razavi, RF Microelectronics]*

# Bond Wires



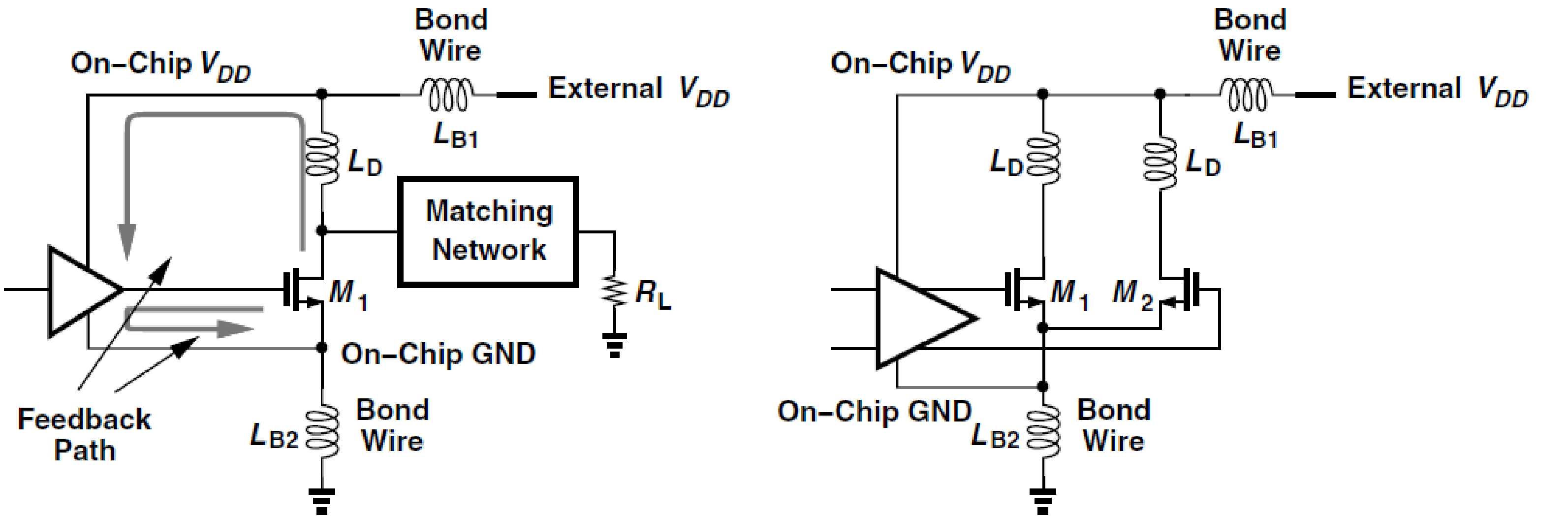

❑Single-ended PAs stems from very large transient currents that they pull from the supply to the ground

❑The resonance or impedance transformation is altered, and allows signal to travel back through the supply line

❑The ground bond wire inductance degenerates the output stage and introduces feedback

*[B. Razavi, RF Microelectronics]*

# Differential PA

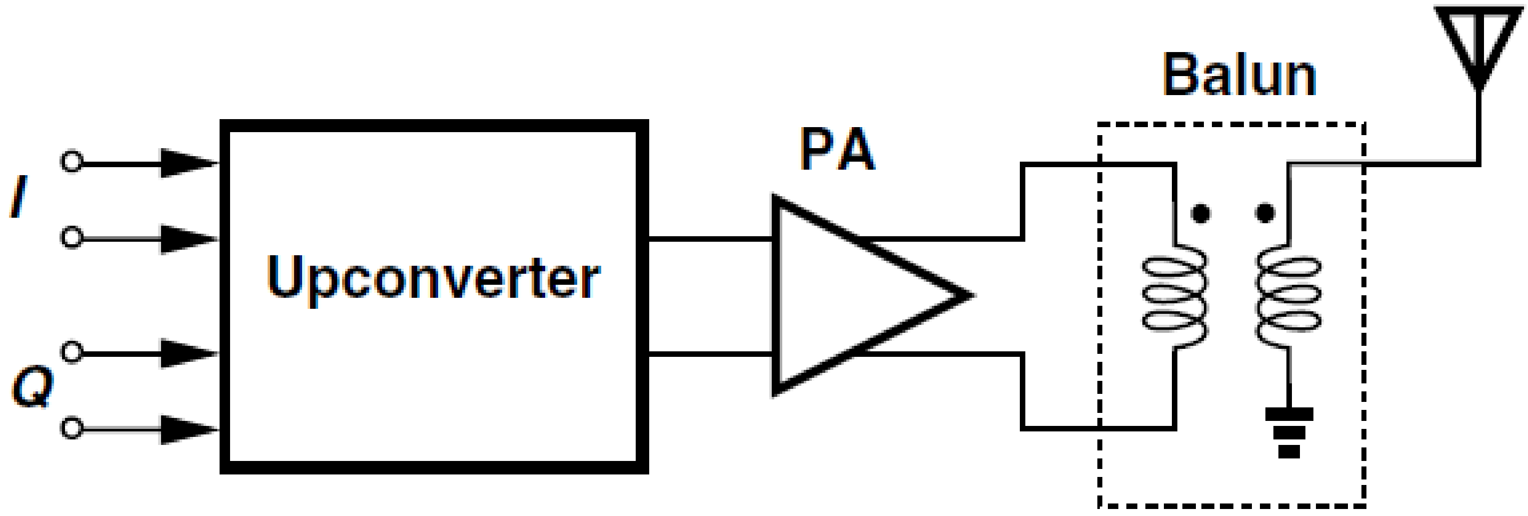



❑A differential PA draws much smaller transient currents from supply and ground lines, exhibiting less sensitivity to the bond-wire inductors and creating less feedback

❑The degeneration issue is also relaxed considerably

*[B. Razavi, RF Microelectronics]*

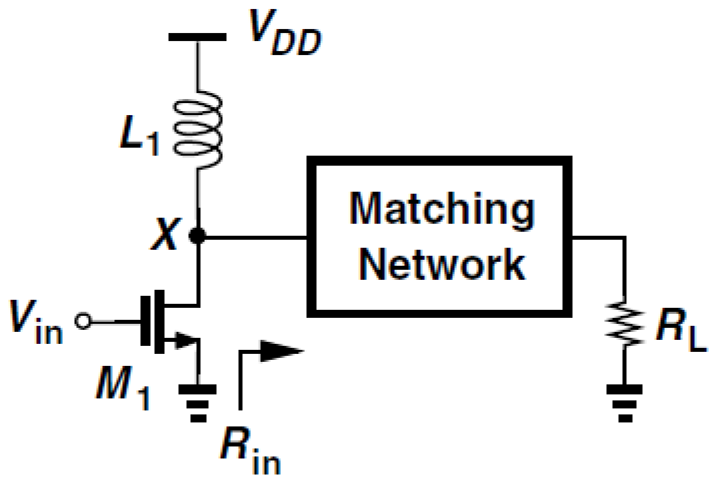
# Differential PA

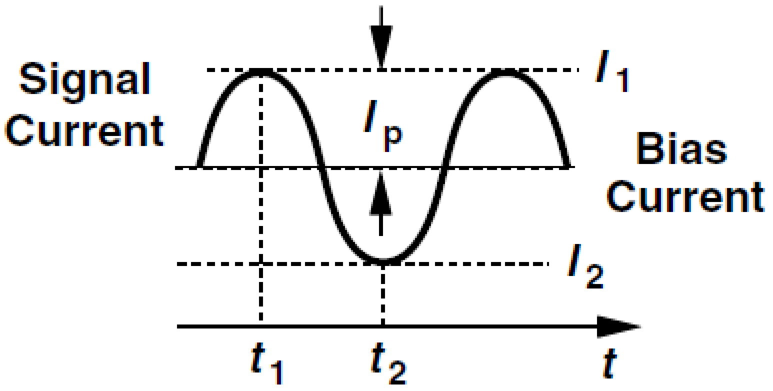



- The use of a differential PA ameliorates both the voltage gain and package parasitic issues
- The PA must still drive a single-ended antenna in most cases, so a balun must be inserted between PA and antenna
- Differential PA can also reduce LO pulling by propagating symmetrically toward the LO

*[B. Razavi, RF Microelectronics]*

# Class-A PA

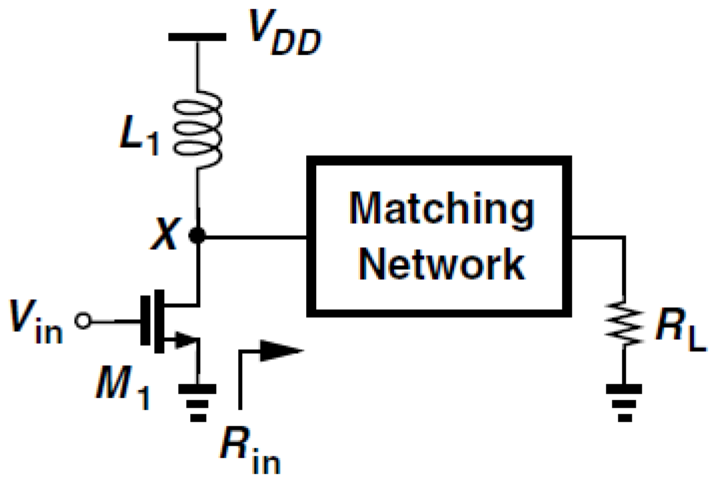


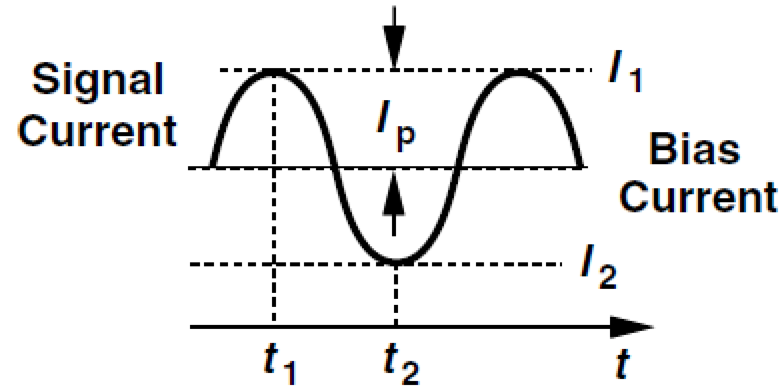




- ❑Class-A PAs are defined as circuits in which the transistor(s) remain on and operate linearly across the full input and output range
- ❑The transistor bias current is chosen higher than the peak signal current
- ❑The input voltage should be small to ensure the linearity

*[B. Razavi, RF Microelectronics]*

# Efficiency of Class-A PA




- **To reach maximum efficiency, we allow $V_X$ to reach $2V_{DD}$ and nearly zero. Thus, the power delivered to the load**

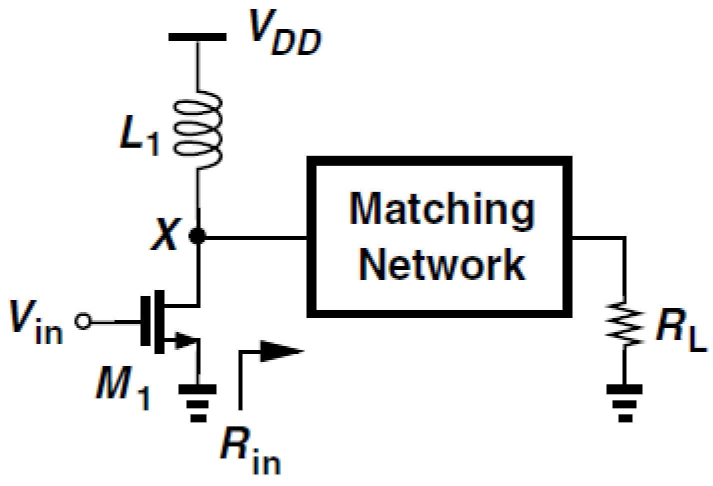
$$(2V_{DD}/2)^2/(2R_{in}) = V_{DD}^2/(2R_{in})$$

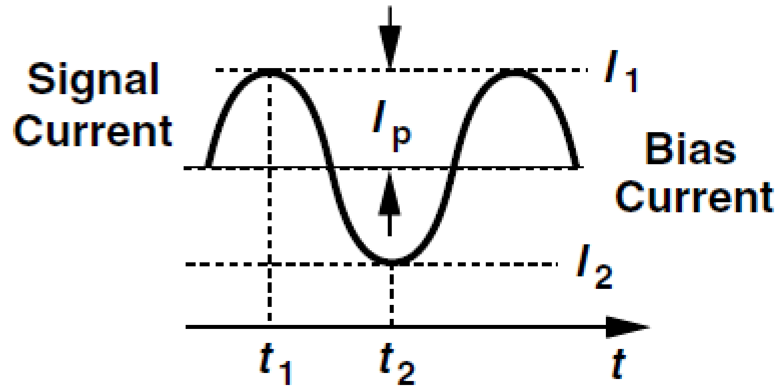
- **The DC power is consumed by the constant current of $V_{DD}/R_{in}$ from the supply voltage, so** $\eta = \dfrac{V_{DD}^2/(2R_{in})}{V_{DD}^2/R_{in}} = 50\%$

- **The other 50% of the supply power is dissipated by transistor**

*[B. Razavi, RF Microelectronics]*

# Efficiency of Class-A PA




❑**The assumptions lead to an efficiency of 50% in class-A PA:**

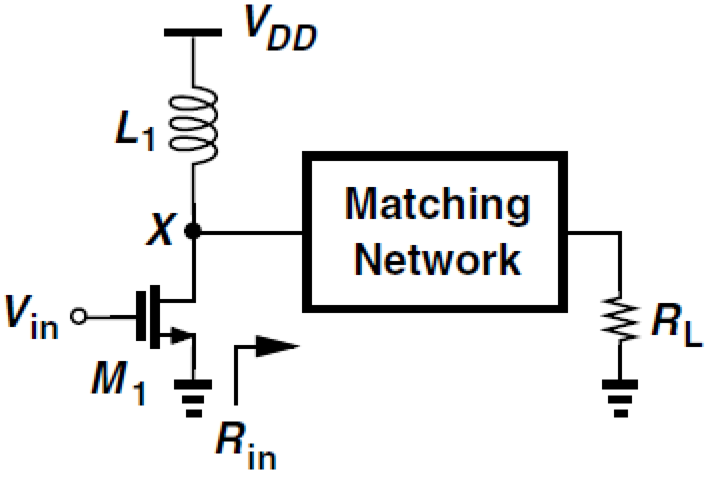
➢ **The drain peak-to-peak voltage swing is equal to twice the supply voltage with no reliability or breakdown issues**

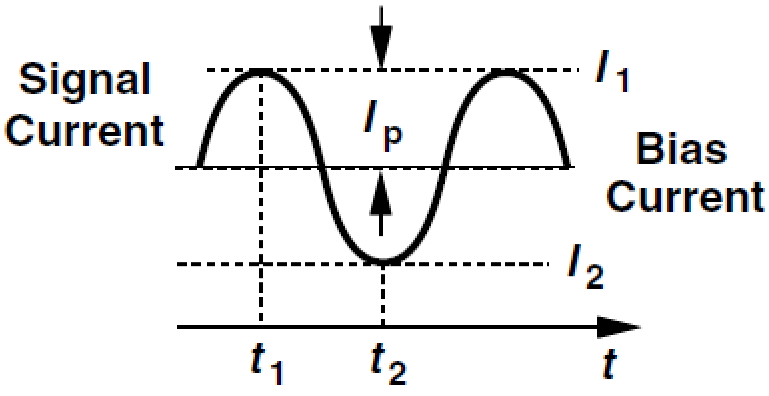
➢ **The transistor barely turns off (tolerable nonlinearity)**

➢ **The matching network is lossless**

*[B. Razavi, RF Microelectronics]*

# Conduction Angle

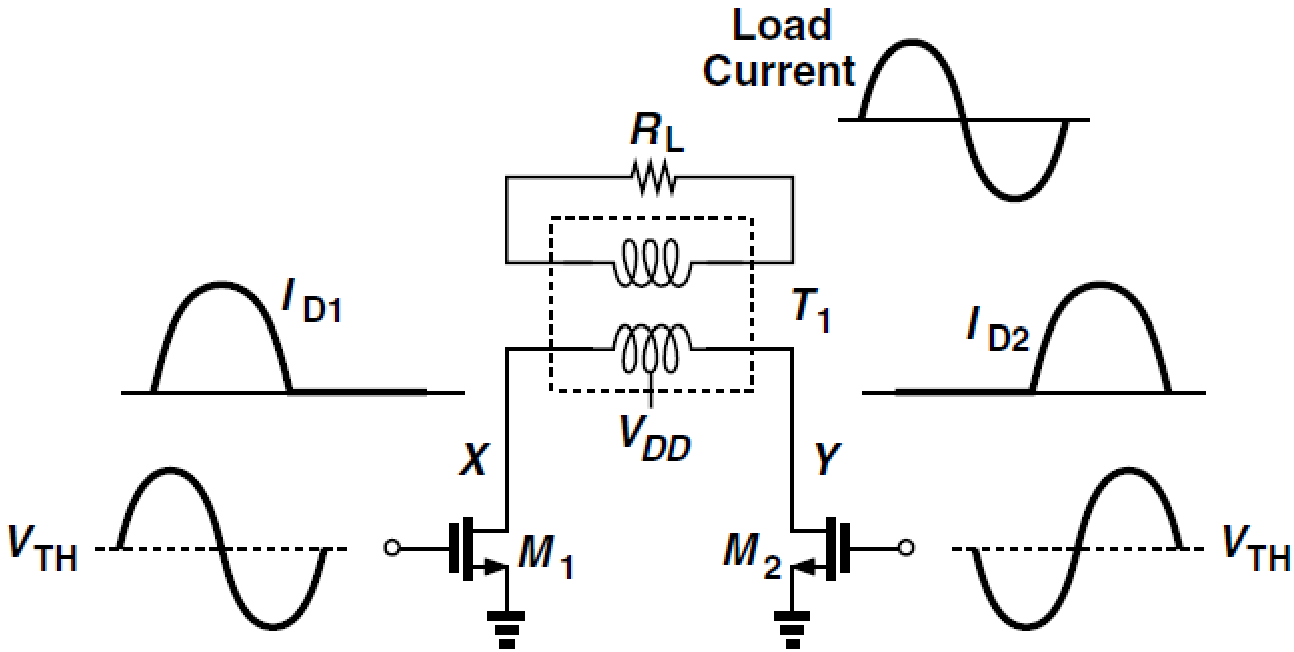



- ❑The conduction angle is defined as the percentage of the signal period during which the transistor(s) remain on multiplied by 360°
- ❑In class-A stages, the conduction angle is 360° because the output transistor is always on

*[B. Razavi, RF Microelectronics]*

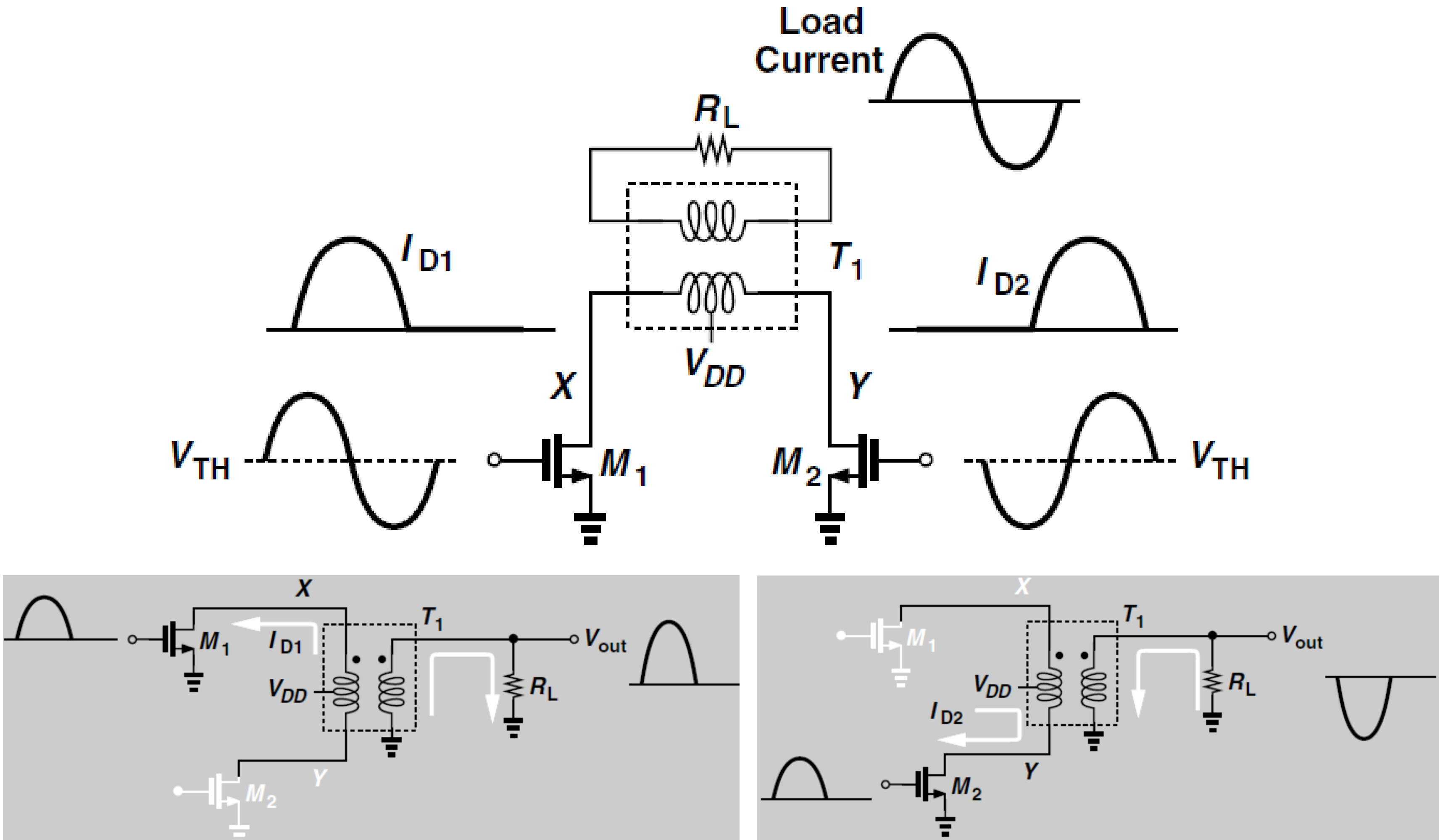
# Class-B PA




- The drain currents of $M_1$ and $M_2$ are combined by a transformer
- Each transistor turns off for half of period (i.e., the conduction angle is $180^o$)

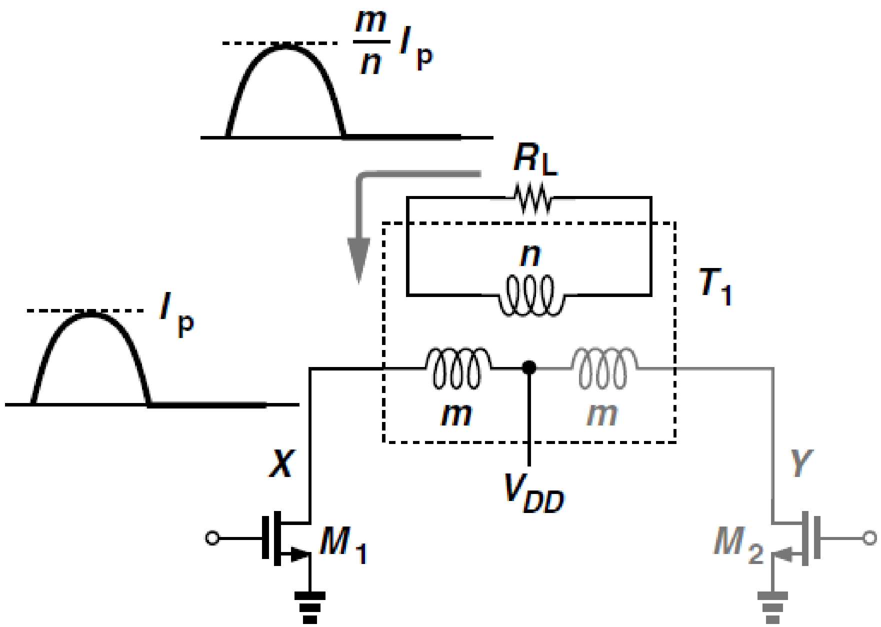
*[B. Razavi, RF Microelectronics]*

# Current Combine




[B. Razavi, RF Microelectronics]

# Efficiency of Class-B PA




❑Since two current waveforms are drawn from $V_{DD}$ in each period, the average power provided by $V_{DD}$ is equal to

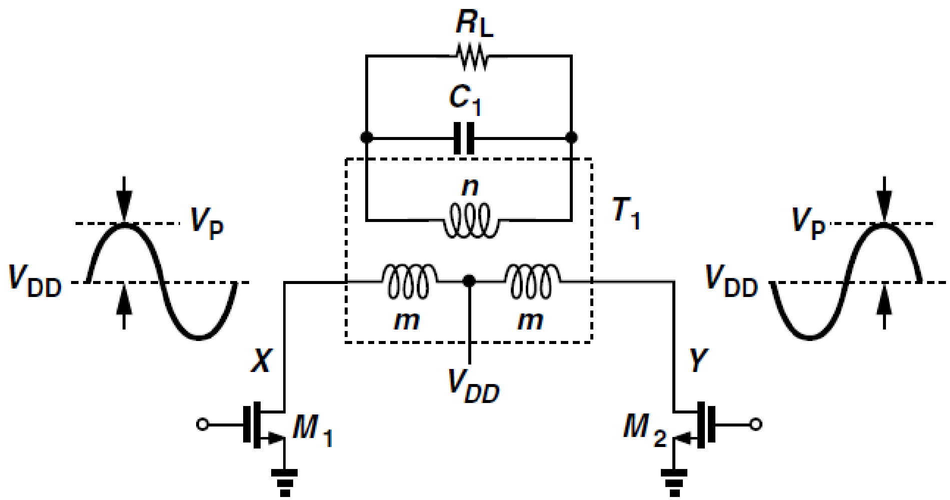
$$P_{supp} = 2\frac{I_p}{\pi}V_{DD}$$

❑The transistor current $I_{D1}=I_p\sin\omega_0 t$ produces a similar current in the load $I_L=(m/n)I_p\sin\omega_0 t$, producing an average power:

$$P_{out} = \left(\frac{m}{n}\right)^2 \frac{R_L I_p^2}{2} \qquad \eta = \frac{\pi}{4V_{DD}}\left(\frac{m}{n}\right)^2 I_p R_L$$

[B. Razavi, RF Microelectronics]

# Efficiency of Class-B PA




❑In the presence of a resonant load, the primary transformer senses a voltage given by

$$V_{XY} = 2V_p \sin \omega_0 t$$

❑Experiencing a ratio of n/(2m) outputs a voltage:

$$V_{out}(t) = \left(\frac{n}{2m}\right) 2V_p \sin \omega_0 t \;= \frac{m}{n} I_p R_L \sin \omega_0 t \qquad V_p = \frac{m^2}{n^2} I_p R_L$$

❑We choose $V_p$=$V_{DD}$ to maximize the efficiency: $\eta = \dfrac{\pi}{4} \approx 79\%$

❑In recent RF design literature, class B operation often refers to half of the circuits, which still has a maximum efficiency of π/4

*[B. Razavi, RF Microelectronics]*

# Class-AB PA

- The term “class AB” is sometimes used to refer to a single-ended PA whose conduction angle falls between 180º and 360º, i.e., in which the output transistor turns off for less than half of a period

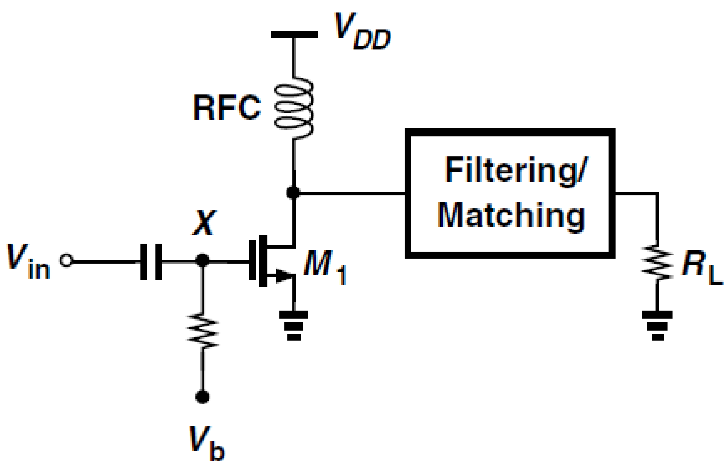
- From another perspective, a class-AB PA is less linear than a class A stage and more linear than a class B stage

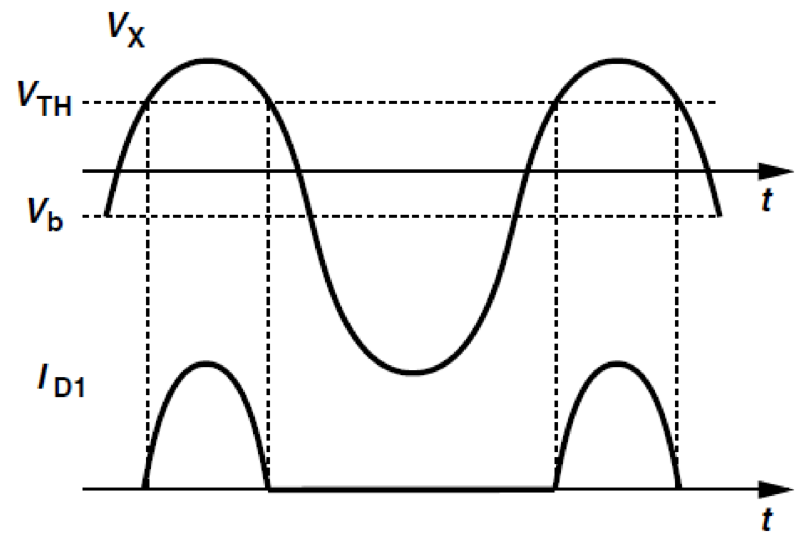
- Class-AB PA is usually accomplished by reducing the input voltage swing and hence backing off from the 1-dB compression point

*[B. Razavi, RF Microelectronics]*

# Class-C PA

- ❑Class A and B stages indicates that a smaller conduction angle yields a higher efficiency
- ❑In class C stages, this angle is reduced further (and the circuit becomes more nonlinear)

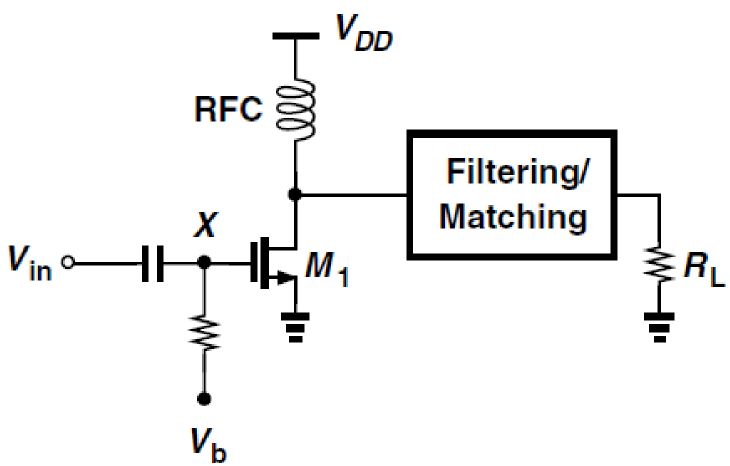


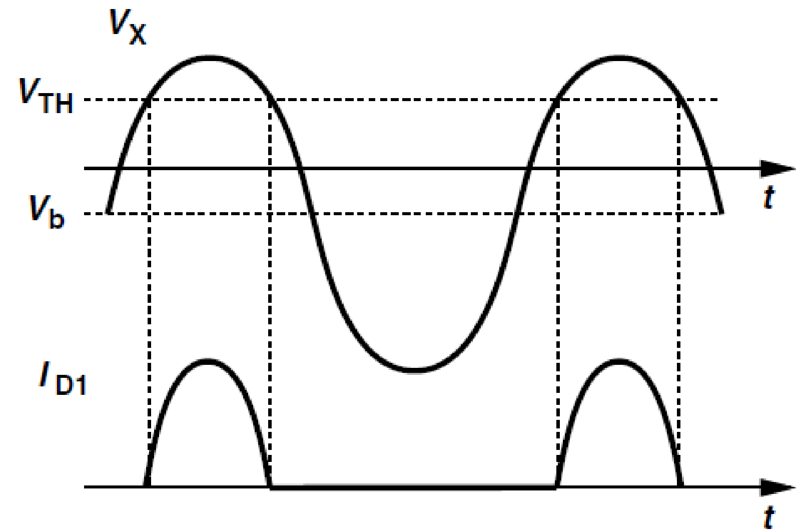




- ❑To avoid large harmonic levels at the antenna, the input/output matching network must provide some filtering

*[B. Razavi, RF Microelectronics]*

# Class-C PA

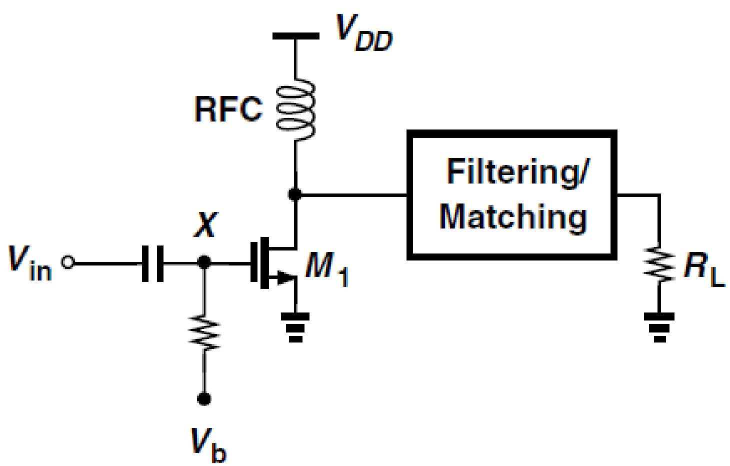


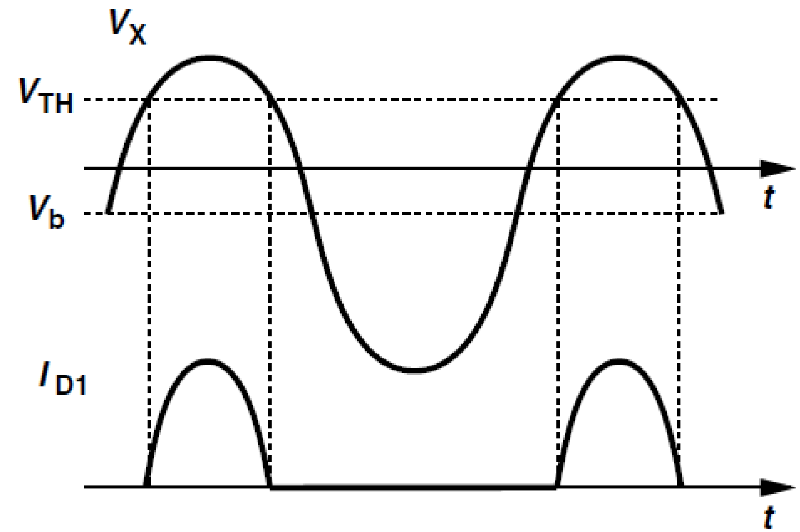




- **The distinction between class C and one-transistor class B stages is in the conduction angle θ**
- **As θ decreases, the transistor is on for a smaller fraction of the period, thus dissipating less power, and meanwhile the PA outputs less power**

***[B. Razavi, RF Microelectronics]***

# Efficiency of Class-C PA




- If the drain current of $M_1$ is assumed to be the peak section of a sinusoid and the drain voltage is a sinusoid having a peak amplitude of $V_{DD}$, then the efficiency can be obtained as

$$\eta = \frac{1}{4} \frac{\theta - \sin\theta}{\sin(\theta/2) - (\theta/2)\cos(\theta/2)}$$

- This relation suggests an efficiency of 100% as θ approaches zero

*[B. Razavi, RF Microelectronics]*

# Efficiency of Class-C PA

- The maximum efficiency of class-C PA is 100%, while the actual power delivered to the load:

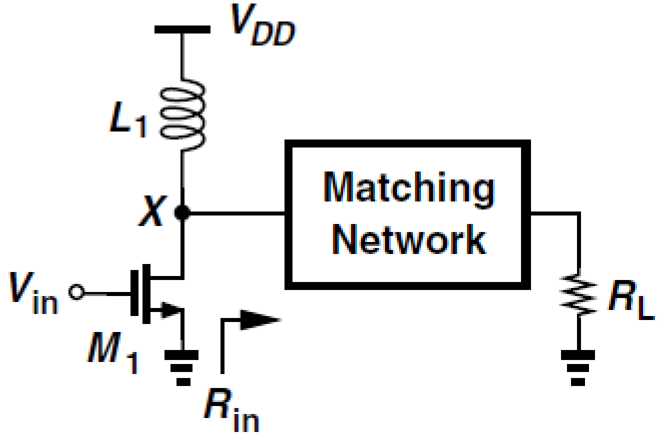
$$P_{out} \propto \frac{\theta - \sin\theta}{1 - \cos(\theta/2)}$$

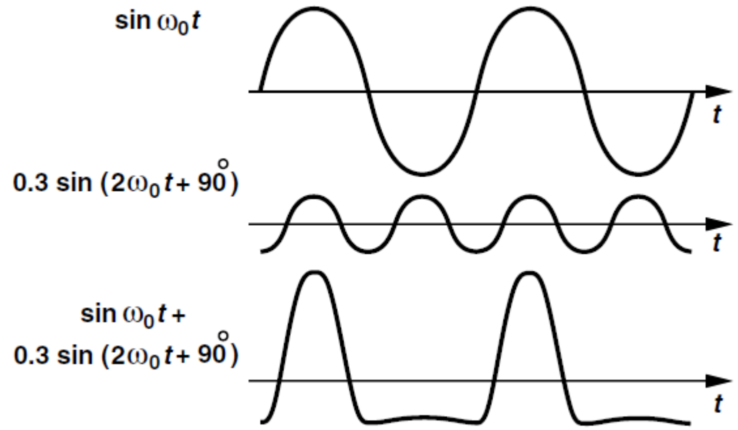
- The output power falls to zero as θ approaches zero
- In other words, a class-C PA provides a high efficiency only if it delivers a fraction of the peak output power
- The small conduction angle dictates that the output transistor be very wide so as to deliver a high current for a short amount of time

*[B. Razavi, RF Microelectronics]*

# Harmonic Enhanced Class-A

- If we minimize the time during which the transistor carries a large current and sustains a large voltage, we can reduce the power consumed by the transistor and raise the efficiency

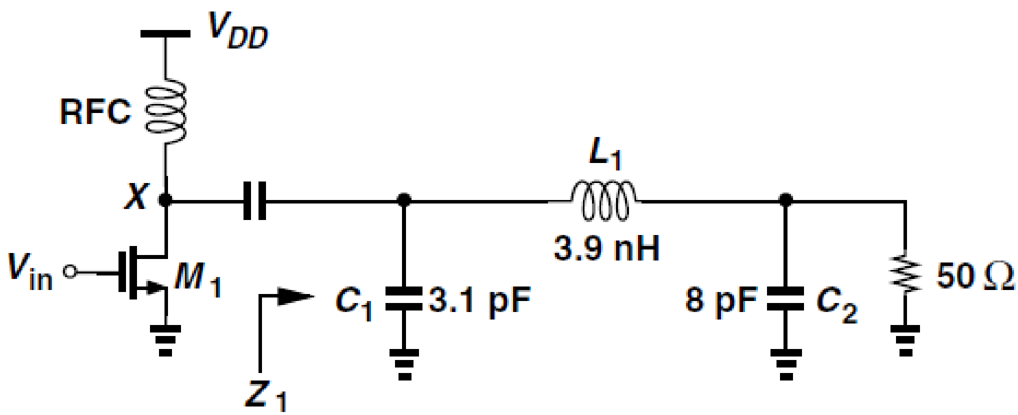


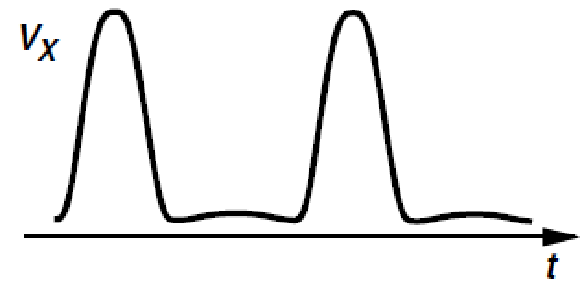




- The input impedance of matching network is low at the fundamental and high at the second harmonic
- The overlap time between the voltage across and the current flowing in the output transistor is reduced

*[B. Razavi, RF Microelectronics]*

# Harmonic Enhanced Class-A



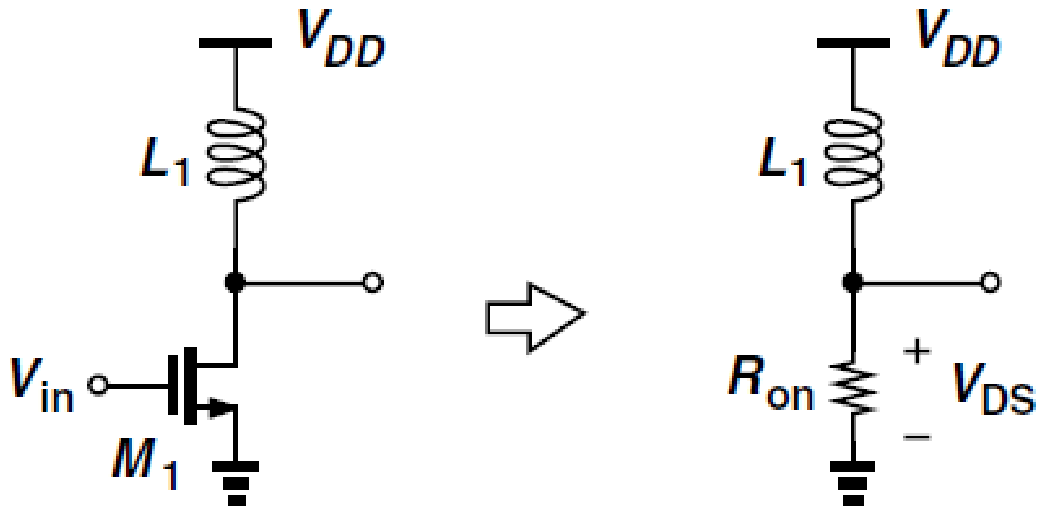




- The technique realizes different impedances for different harmonics to make the drain voltage approach a square wave
- A matching network transforms the 50Ohm load to $Z_1$=9Ohm at f=850MHz and $Z_2$=330Ohm at 2f=1.7GHz
- The second harmonic is enhanced by a factor of 37, and then the PA achieves 73% efficiency

*[B. Razavi, RF Microelectronics]*

# Class-E PA

- Class-E PAs are nonlinear amplifiers that achieve efficiencies approaching 100% while delivering full power

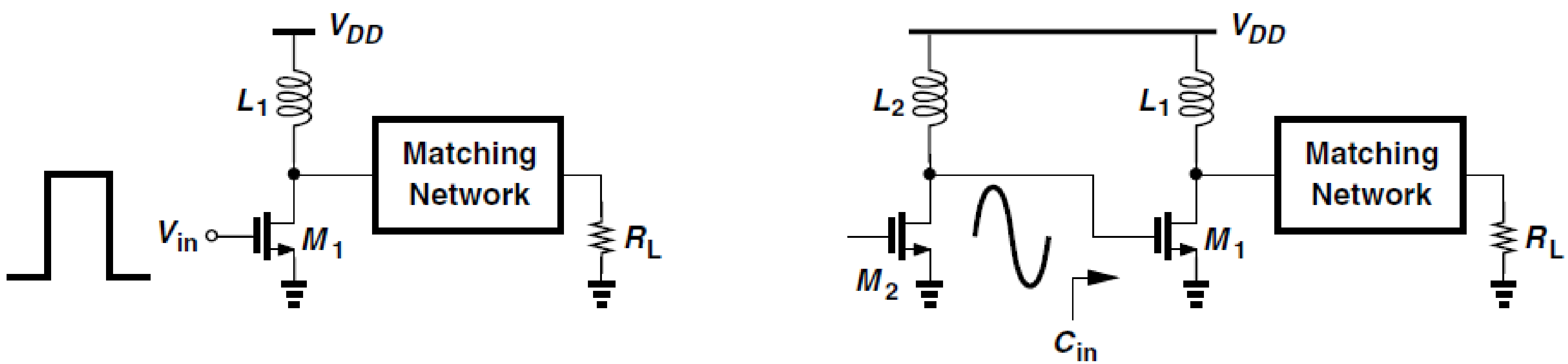



- If the transistor operates as a switch, rather than a voltage dependent current source, ideally turning on and off abruptly, resulting in a class-E PA (switching PA)

*[B. Razavi, RF Microelectronics]*

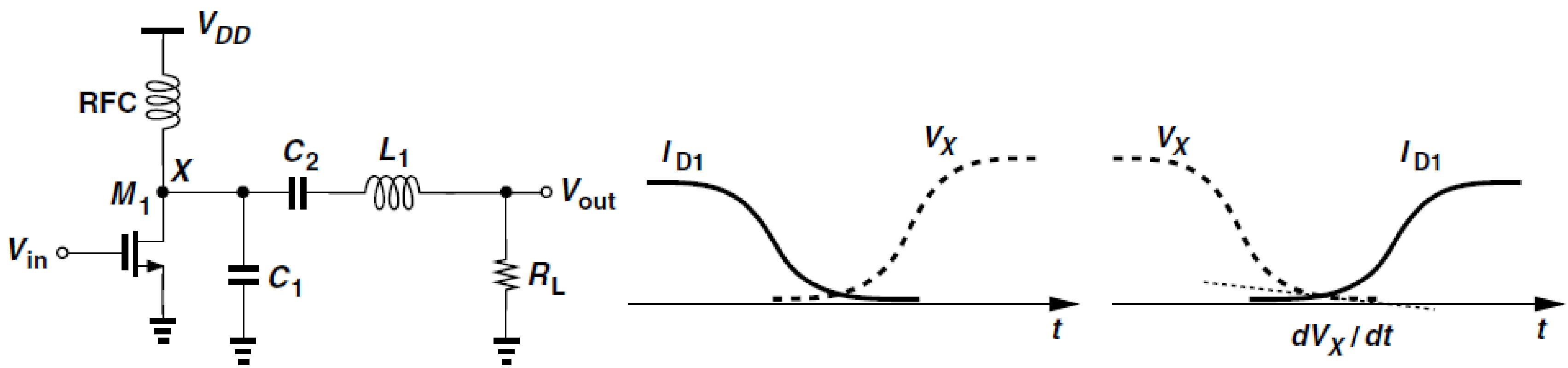
# Class-E PA

- A serious dilemma in class-E PA design is that the gate of transistor must be switched as abruptly as possible so as to maximize the efficiency
- But the input of transistor is usually a sinusoid waveform from previous stages




[B. Razavi, RF Microelectronics]

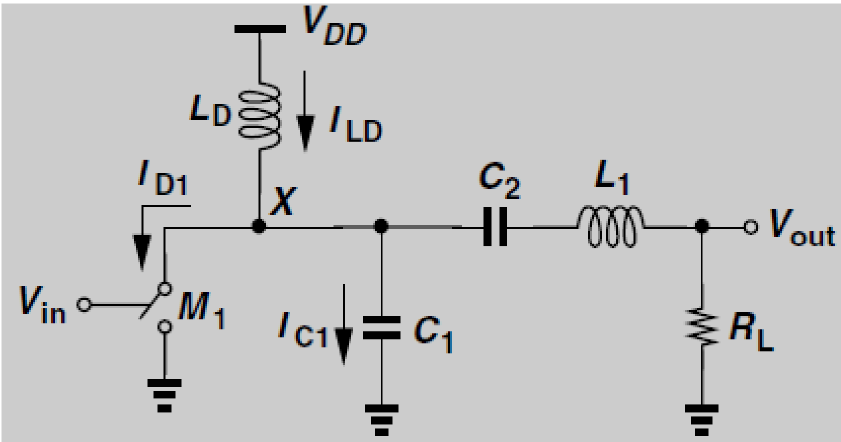
# Class-E PA

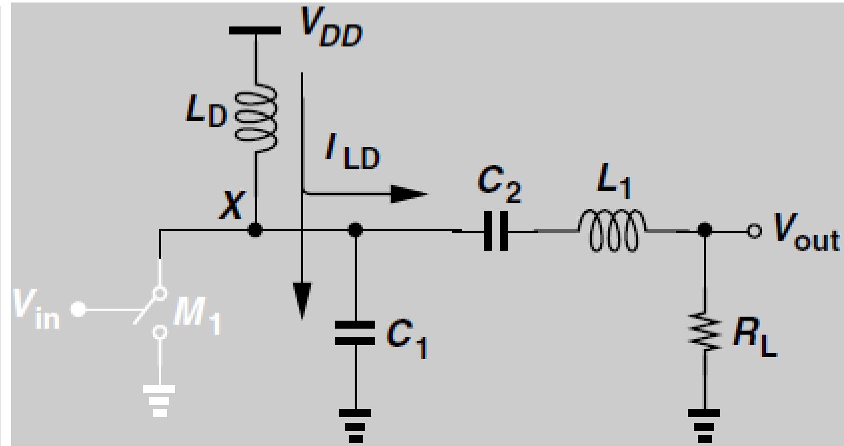



- ❑As the switch turns off, $V_X$ remains low long enough for the current to drop to zero (guaranteed by $C_1$)
- ❑$V_X$ reaches zero just before the switch turns on, ensuring that the voltage and current of transistor do not overlap
- ❑In the vicinity of the turn-on point, $dV_X/dt$ is also near zero to lower the sensitivity to violations

*[B. Razavi, RF Microelectronics]*

# Class-E PA

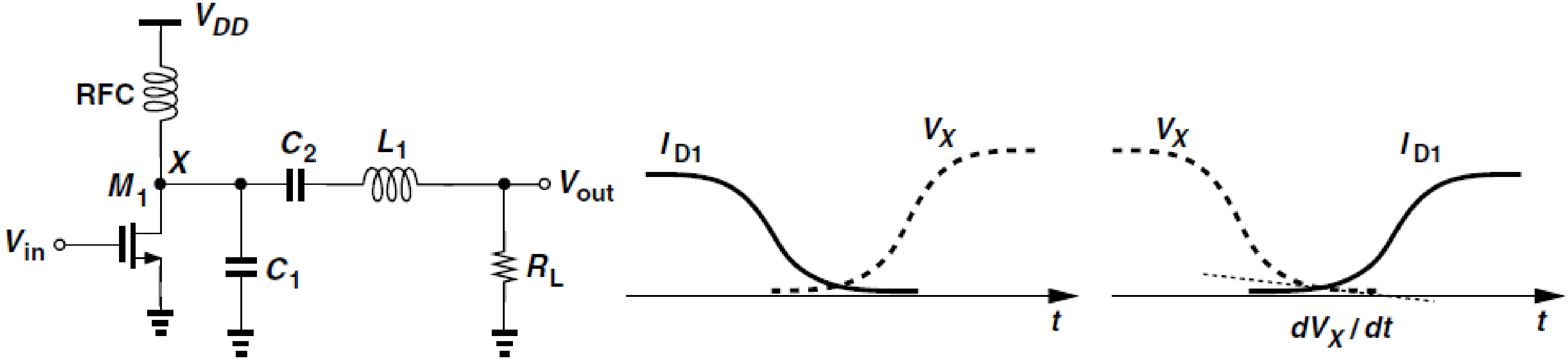



- ❑One half cycle is dedicated to charging $L_D$ at a small voltage $V_X$
- ❑When $M_1$ turns off, the inductor current begins to flow through $C_1$, and $V_X$ start to go up
- ❑The matching network attenuates higher harmonics of $V_X$, yielding a nearly sinusoidal output

*[B. Razavi, RF Microelectronics]*

# Class-E PA

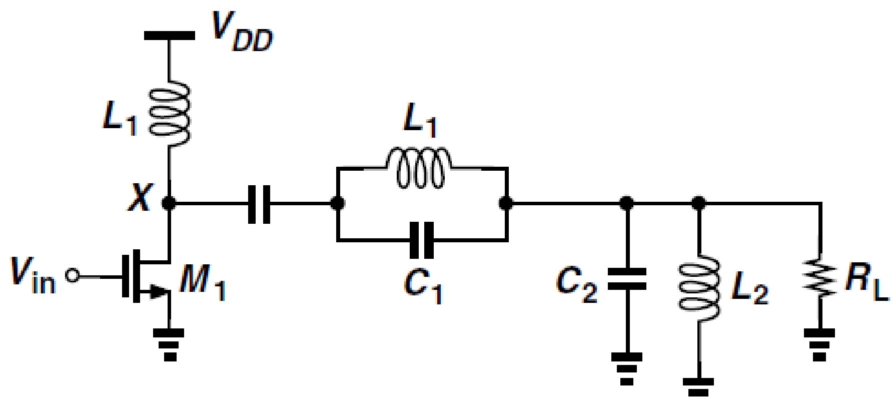


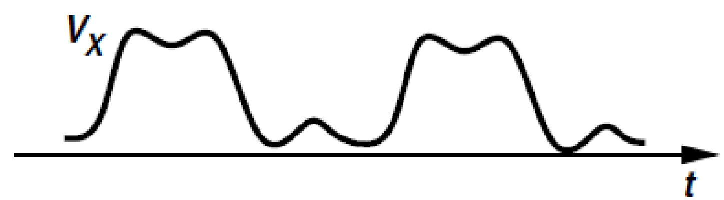

- Class-E PA is quite nonlinear and exhibit a trade-off between efficiency and output harmonic content
- Class-E PA sustains a large peak voltage in the off state, raising serious device reliability or breakdown issues

*[B. Razavi, RF Microelectronics]*

# Class-F PA

❑If the load network provides a high termination impedance at the second or third harmonics, the voltage waveform across the switch exhibits sharper edges than a sinusoid, thereby reducing the power loss in the transistor

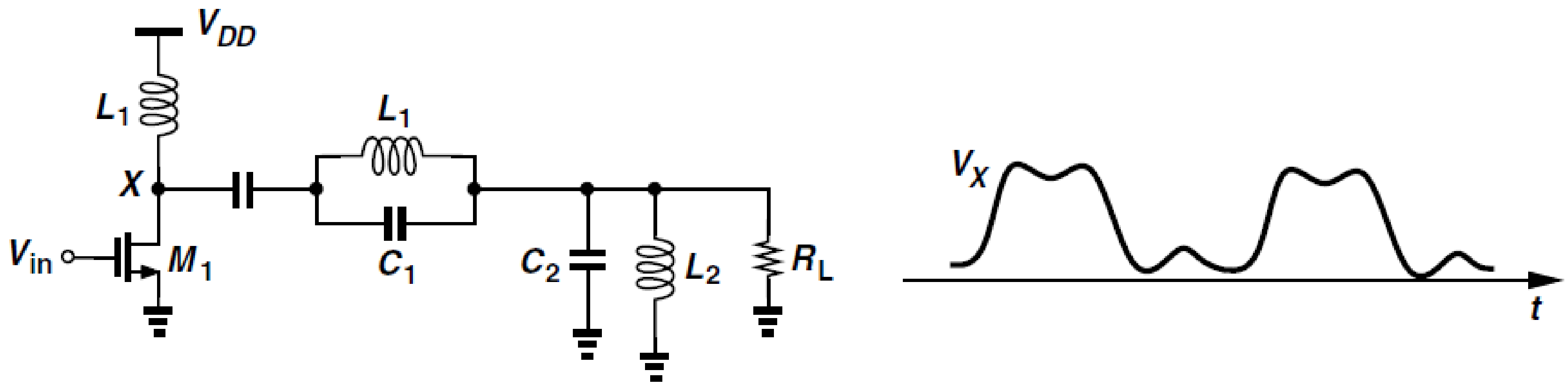



❑The tank consisting of $L_1$ and $C_1$ resonates at three times the input frequency, and then $V_X$ approaches a rectangular waveform with the addition of the third harmonic

*[B. Razavi, RF Microelectronics]*

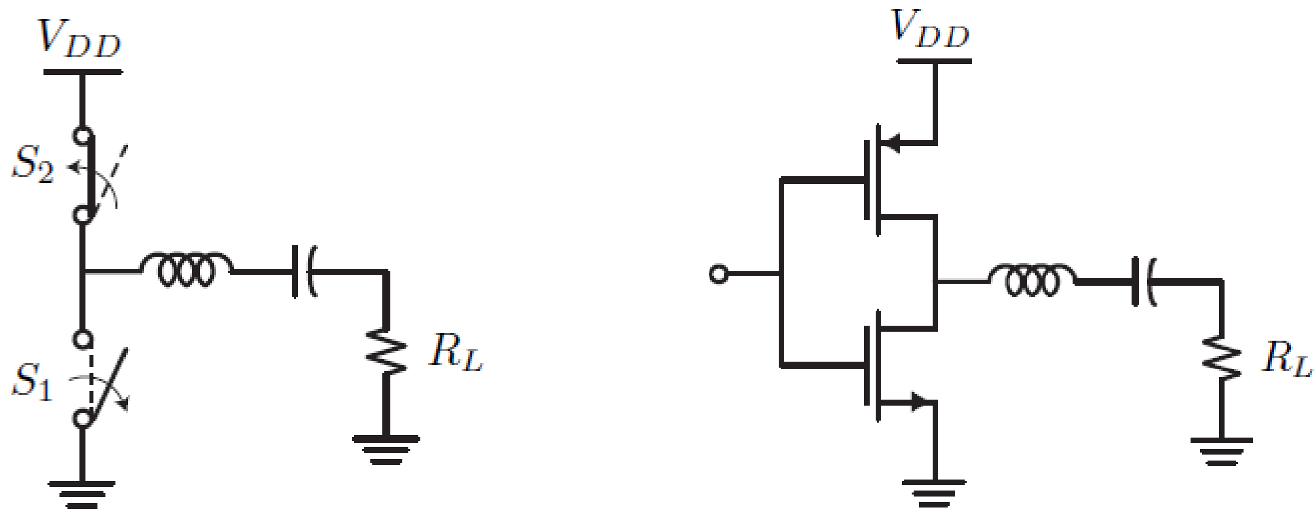
# Class-F PA




- If the drain current of the transistor is assumed to be a half-wave rectified sinusoid, it can be proved that the peak efficiency of class F amplifiers is equal to 88% for third harmonic peaking

*[B. Razavi, RF Microelectronics]*

# Class-D PA




- If give up linearity, then we can create some intrinsically efficient amplifiers using switches. An ideal switch does not dissipate any power since either the voltage or current is zero
- MOS transistors make particularly good switches. The input voltage should be large enough
- A series LCR filter only allows the first harmonic of voltage to flow into the load

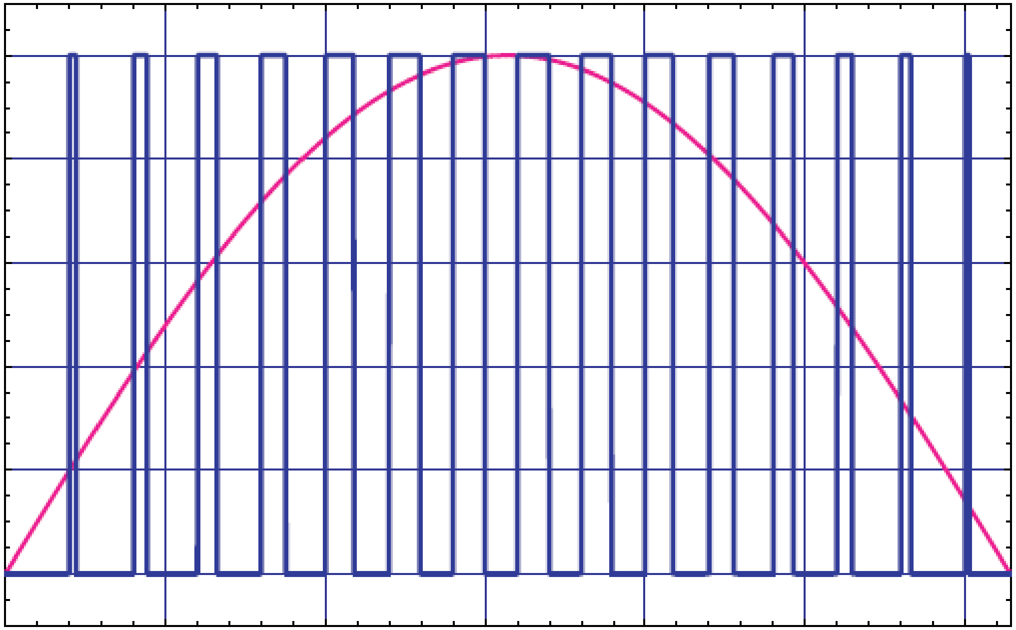
*[Ali Niknejad, EE142 &EE242 of UC Berkeley]*

# Efficiency of Class-D PA

- We can see that the efficiency has to be 100% for an ideal switch. That's because there is no where for the DC power to flow except to the load
- The real efficiency is lowered by the switch-on resistance
- We can make our switches bigger to minimize the resistance, but this in turn increases the parasitic capacitance
- There are two forms of loss associated with the parasitic capacitance, the capacitor charging losses $CV^2f$ and the parasitic substrate losses
- The power required to drive the switches also increases proportional to $C_{gs}$ since we have to burn $CV^2f$ power to drive the inverter

*[Ali Niknejad, EE142 &EE242 of UC Berkeley]*

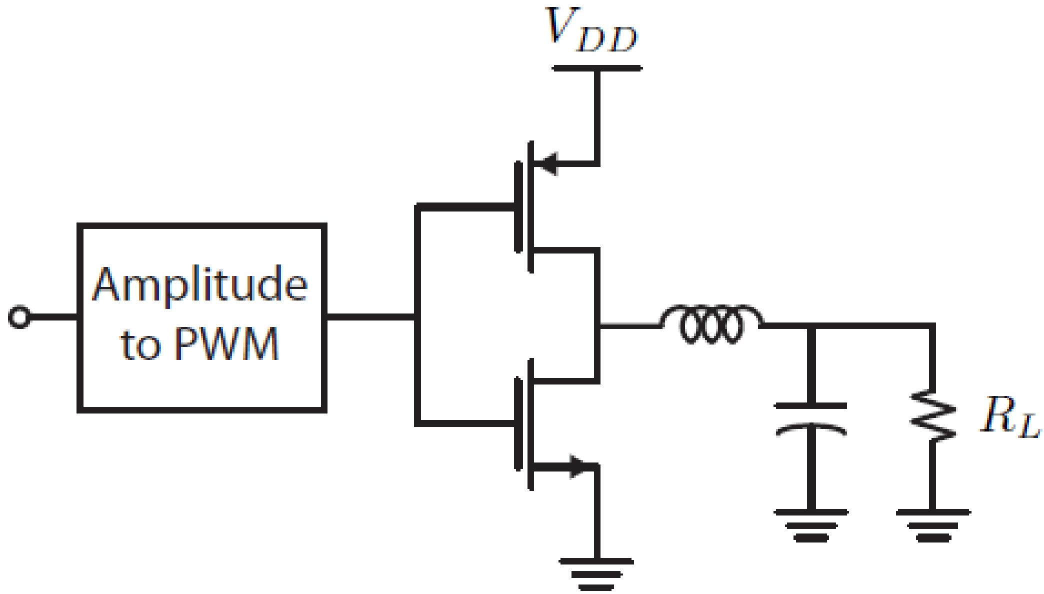
# Class-S PA



- ❑If the switching rate is much higher than the fundamental, then amplitude modulation can be converted to pulse-width modulation
- ❑A low-pass filter at the output faithfully recreates the envelope of the signal

*[Ali Niknejad, EE142 &EE242 of UC Berkeley]*

# Class-S PA




❑Class S amplifiers are commonly used at low frequencies (audio) since the transistors can be switched at a much higher frequency than the fundamental

❑This allows efficiencies approaching 100% with good linearity

*[Ali Niknejad, EE142 &EE242 of UC Berkeley]*

# Efficiency Summary

| Typology | Efficiency |
|---|---|
| Class A | 50% |
| Harmonic Enhanced Class A | ~73% |
| Class B | 79% |
| Class AB | 50%-79% |
| Class C | ~100% |
| Class E | ~100% |
| Class F | ~88% |
| Class D | ~100% |
| Class S | ~100% |