Lecture 11

of

EEE307

Electronics for Communications

Department of Electrical & Electronic Engineering

Xi'an Jiaotong-Liverpool University (XJTLU)

Friday, 29th November 2019

- Large-signal Amplification
  - efficiency & linearity consideration
  - common-source configuration
- Classification of Power Amplifiers
  - classes A, B, AB, C – linear type
  - classes E & F – switching type

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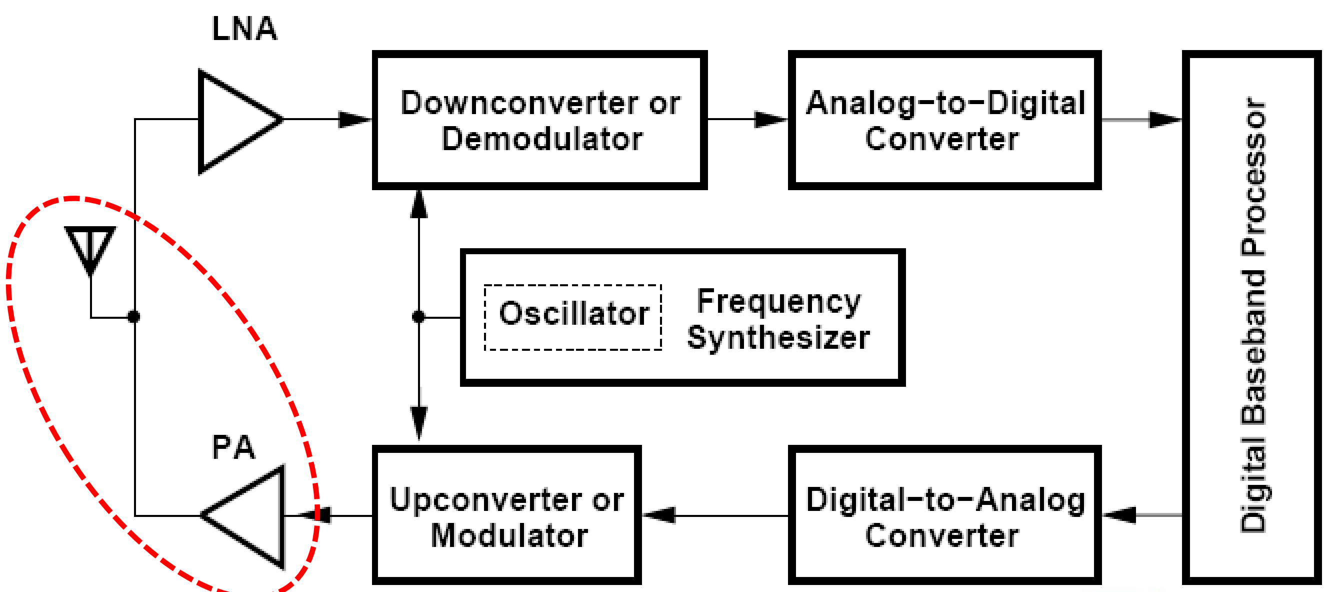
Wireless Transceiver

(antenna driven by transmitter)

- In using **radio waves** to transmit and receive information, the **transmitter** has to drive the **antenna** with a high power level so that the **electromagnetic** (EM) signal is strong enough to reach certain desirable distances.



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Radio Transmitter

(deliver RF power to antenna)

- In radio transmitters, the **power amplifier** (PA) is the key building block to deliver electrical power ***efficiently*** to the **antenna** for generating EM waves which carry the information.

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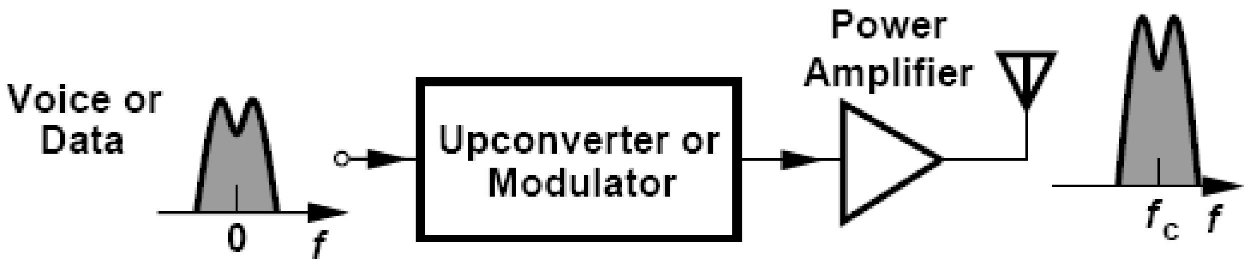

- While the RF PA is also a signal amplification circuit, its design and construction is not simply scaling up the small-signal amplifiers (e.g. LNA) to deliver higher output power.

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RF Power Amplifier

(power consumption & efficiency)

- To deliver high enough power (e.g. 1 W or 30 dBm) to the **antenna**, the RF PA consumes most power in a radio transceiver.
- High **power consumption** in RF PAs is unavailable and the key issue is **efficiency**.
- **Power efficiency** is particularly important for *portable* applications because we want to extend the battery life or reduce the battery weight.
- It would be a serious **thermal management** problem if the efficiency is low.
  - **power loss** $\Rightarrow$ **heat dissipation**.

RF Power Amplifier

(50% efficiency in maximum power transfer)

- With the importance of **efficiency** in RF PAs, the consideration of maximum power transfer (by ***conjugate* matching**) in small-signal amplifiers (e.g. LNA) is not quite applicable.
  - It is also unclear to define impedances in a large-signal, nonlinear system like RF PAs.
- Even with conjugate matching for maximum power transfer, the **efficiency** is only 50% at best.
  - 50% of the DC power supplied to the RF PA would dissipate as **heat** $\Rightarrow$ thermal management problems at the chip level or package level
  - possible heat sink requirement

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RF Power Amplifier

(other performance parameters & trade-off)

- Apart from **efficiency**, **linearity** and output power (as well as the power gain) are other important performance parameters in RF PAs.
  - In modern wireless communication systems, complex **modulation schemes** (with amplitude & phase modulations combined together) are employed to increase the data throughput. This places higher **linearity** requirement on RF PAs.
- The RF PA design typically involves the **trade-off** between **efficiency** and **linearity**.
  - It is **performance** and **cost** **trade-off**.
  - It is difficult to satisfy all requirements.

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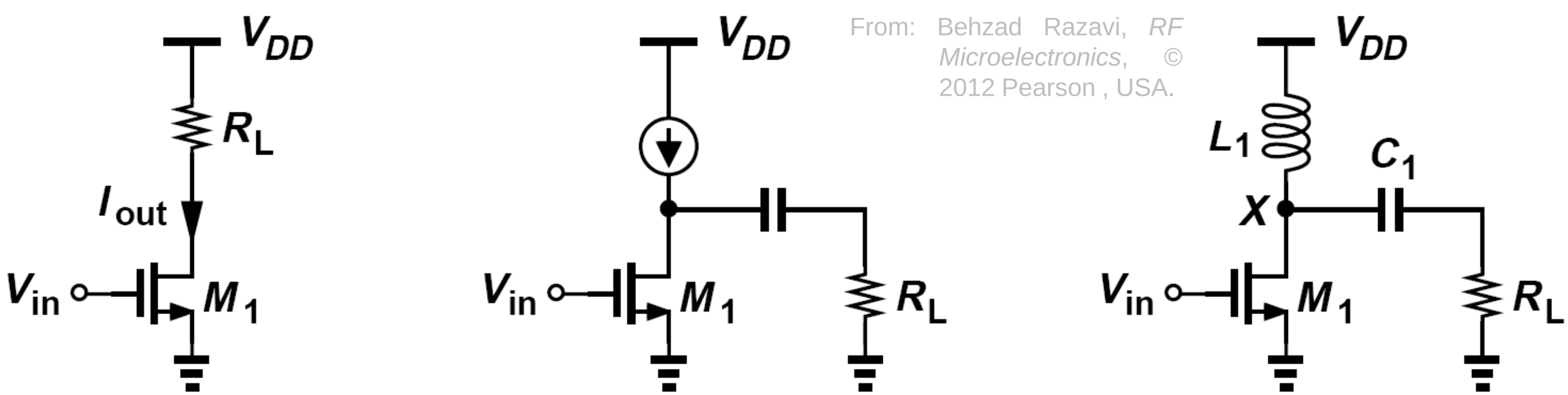
RF Power Amplifier

(common-source configuration)

- An RF PA can be realised in CMOS technology using the standard **common-source** (CS) configuration as in small-signal amplifiers (e.g. LNA).
  - One difference in RF PAs is the large current (e.g. 200 mA) flowing through the single transistor in the CS amplifier.



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  - The CS amplifier can have a resistive, current source or inductive load.

RF Power Amplifier

(common-emitter configuration)

- The use of the CS configuration in the RF PA is the same as that in the low-frequency PA design (e.g. audio amplifiers). The BJT counterpart is the common-emitter (CE) amplifier.

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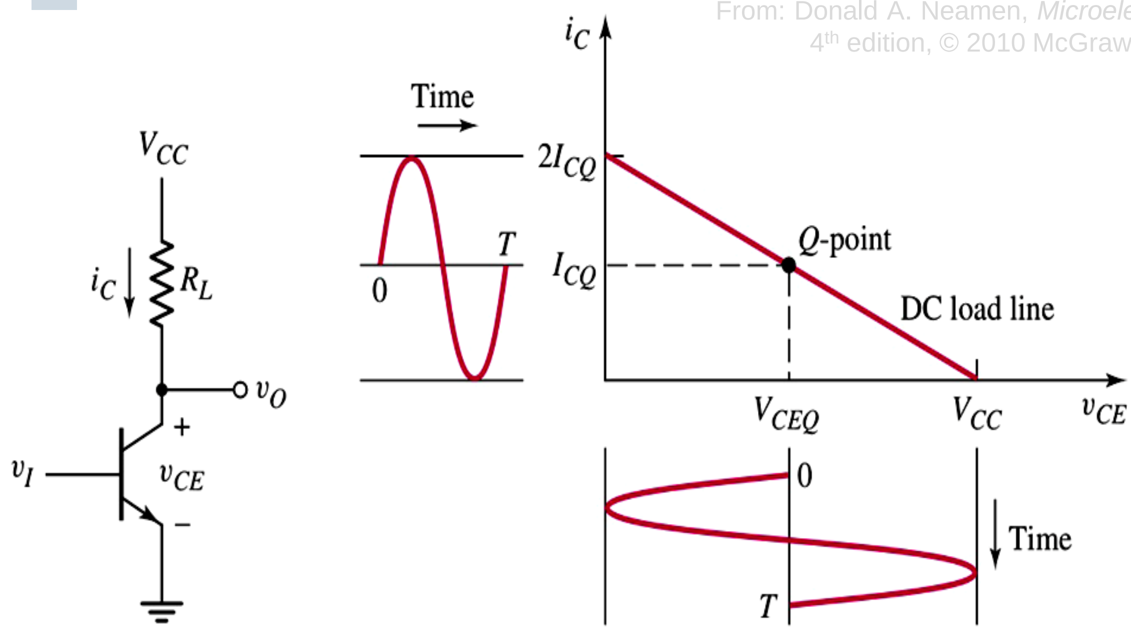
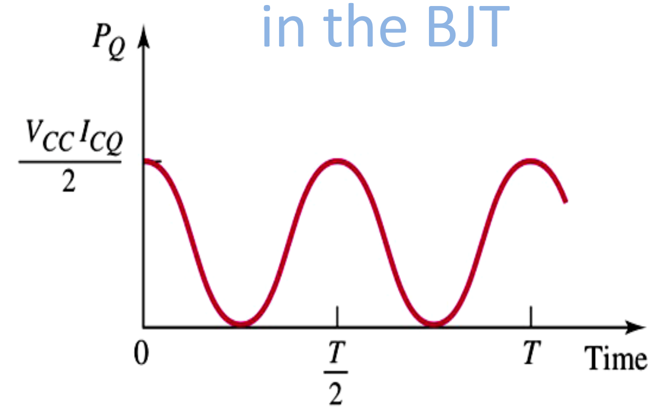


instantaneous power dissipation in the BJT



  - The CE amplifier shown here is in class-A operation.

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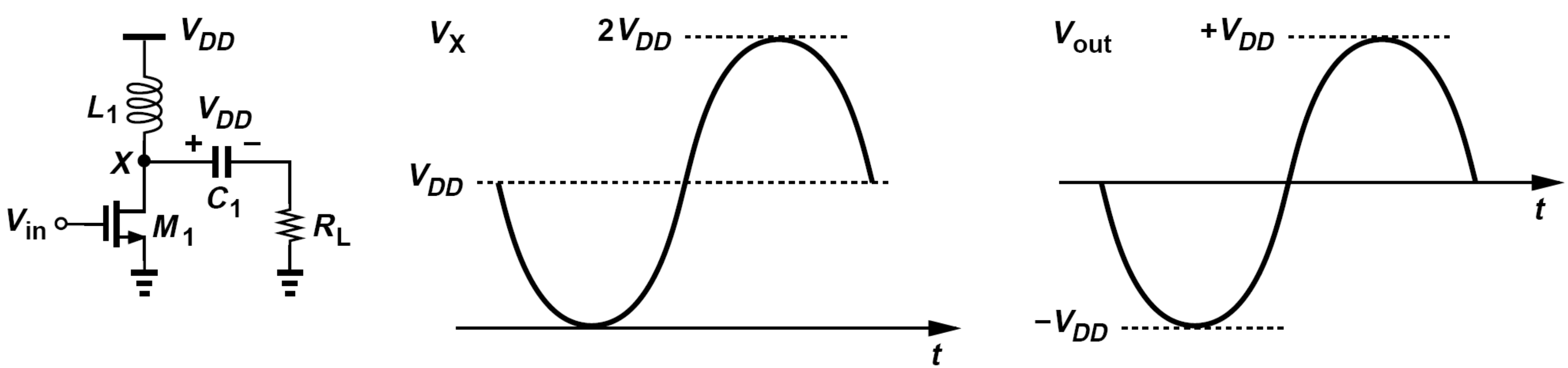
RF Power Amplifier

(inductive load & peak voltage)

- In the RF PA design with the common-source configuration, an **inductive load** is typically used.
  - With the inductive load, the instantaneous voltage at the drain terminal of the MOSFET can be as high as $|2V_{DD}|$ while the output swing is between -V_{DD} and +V_{DD}.

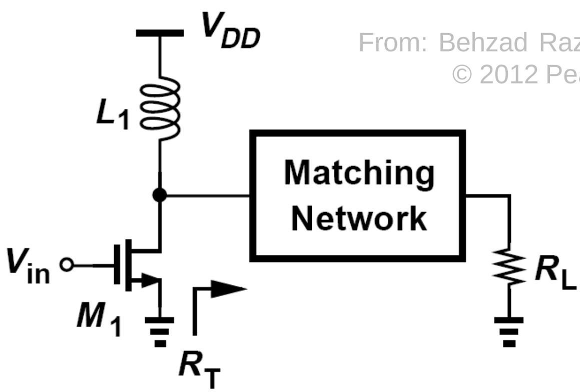


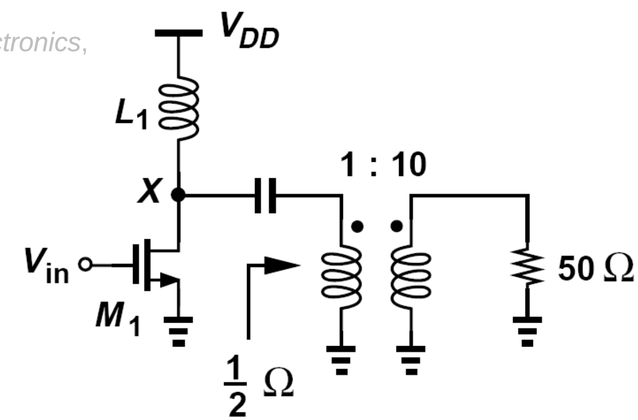
  - This implies the high breakdown voltage requirement of the MOSFET.

RF Power Amplifier

(inductive load & peak voltage)

- In order to reduce the peak voltage experienced by the transistor in the CS configuration, **matching network** is typically used between the RF PA and the antenna load.

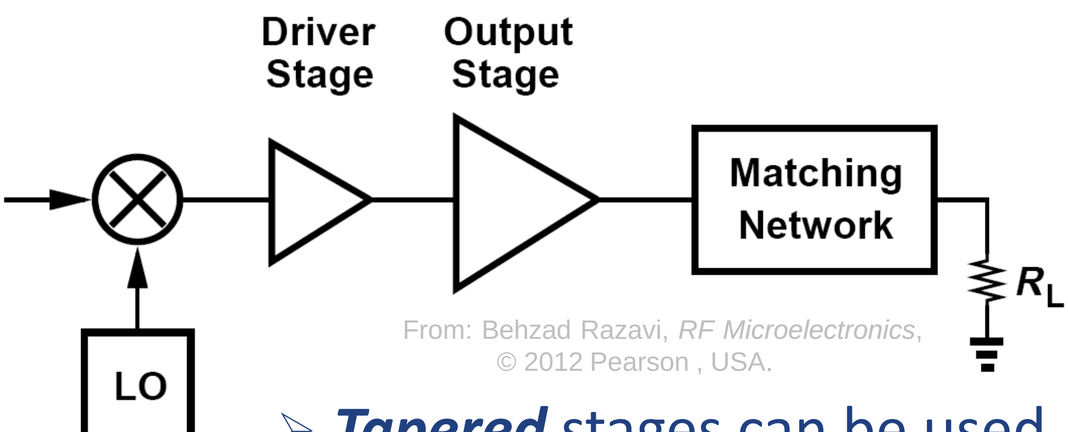




  - The **matching network** ***transforms*** the load resistance to a much lower value (e.g. 50 Ω to 0.5 Ω).
  - LC circuits and transformers can be used for the **impedance transformation**.

RF Power Amplifier
(high currents & tapered stages)

- With the **matching network** for **impedance transformation**, the peak-to-peak voltage swing experienced by the transistor in the RF PA can be lowered.
- To deliver the same power to antenna load with a reduced voltage swing, it means that the current flowing into the RF PA must be increased.



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- It needs a large size (W/L) for the MOSFET in the RF PA. Large size however causes large input capacitance.
- ***Tapered*** stages can be used.

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RF Power Amplifier

(efficiency definitions)

- Two common definitions of **efficiency** are used in quantifying the performance of RF PAs:
  - the **drain efficiency** (when the MOS transistors are used): $\eta = \dfrac{P_{out}}{P_{supp}}$
  - the **power added efficiency (PAE)**: $\eta_{\mathrm{PAE}} = \dfrac{P_{out} - P_{in}}{P_{supp}}$

    where $\boldsymbol{P}_{\text{out}}$ is the output power delivered to the load and $\boldsymbol{P}_{\text{supp}}$ is the DC power supplied to the RF PA.
- The **drain efficiency** η and **PAE** η_{PAE} will be very close if the RF PA has large enough power gain.

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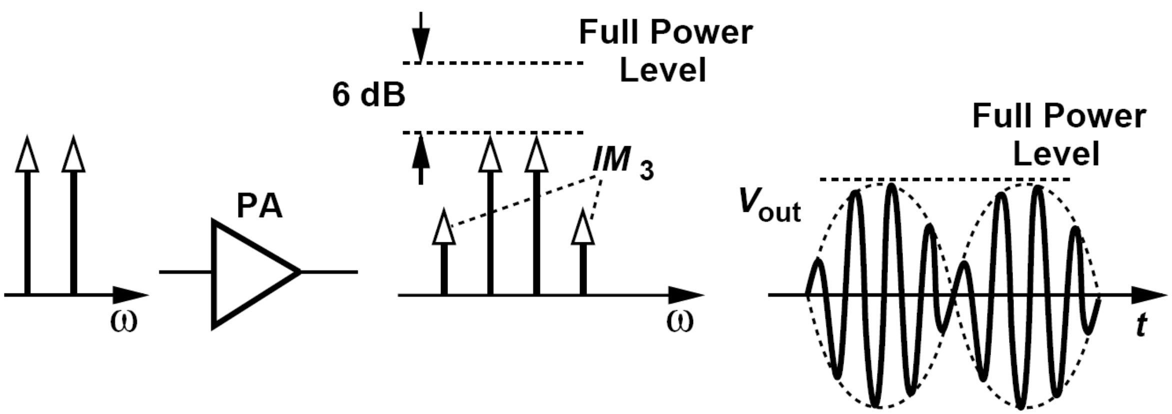
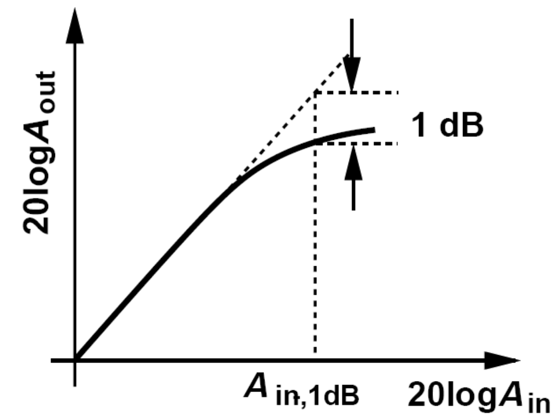
RF Power Amplifier

(linearity)

- To gauge the **linearity** performance, the RF PA characterisation begins with two generic tests of nonlinearity based on unmodulated tones: **intermodulation** and **compression**.





From: Behzad Razavi, *RF Microelectronics*,

  - The **3rd order intercept point (IP3)** and **1-dB compression point (P_{1dB})** are specified.

RF Power Amplifier

(differential upconverter output)

- As the **antenna** is typically *single-ended*, most stand-alone RF PAs are single-ended.
- To avoid wasting half of the transmitter signal gain with the ***differential*** output signal from the upconverter, a **balun** can be used between the upconverter and the ***single-ended*** RF PA.

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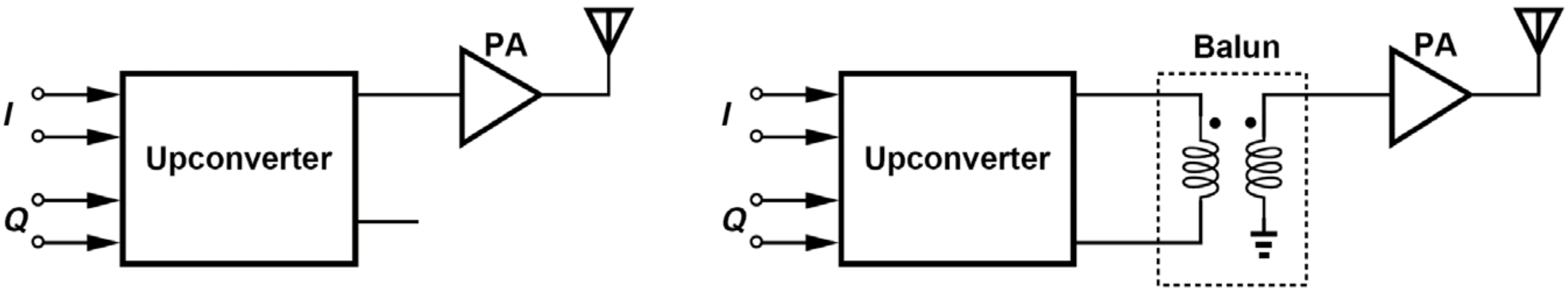

  - A **balun** is a transformer used to convert an *unbalanced* signal to a *balanced* one or vice versa.

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RF Power Amplifier

(differential RF PA)

- As the RF PA circuit typically use some inductors, large ***transient* currents** can be induced easily in high frequency operation.
- A ***differential*** realisation of RF PAs can ease significantly the adverse effects of the large ***transient* currents** compared with the ***single-ended*** RF PAs.

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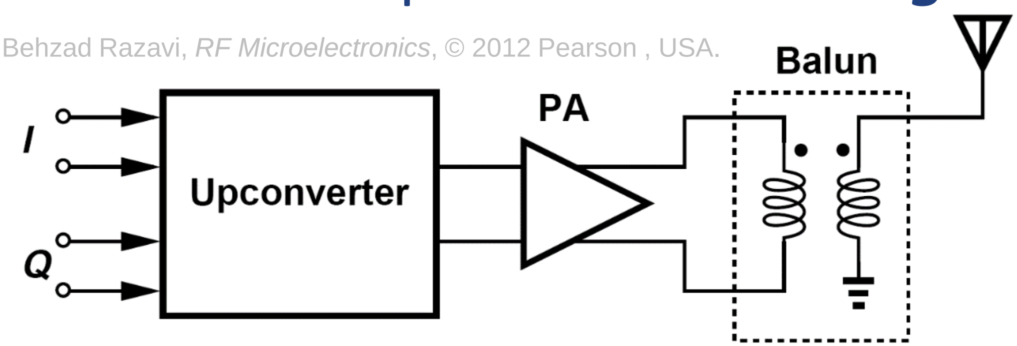
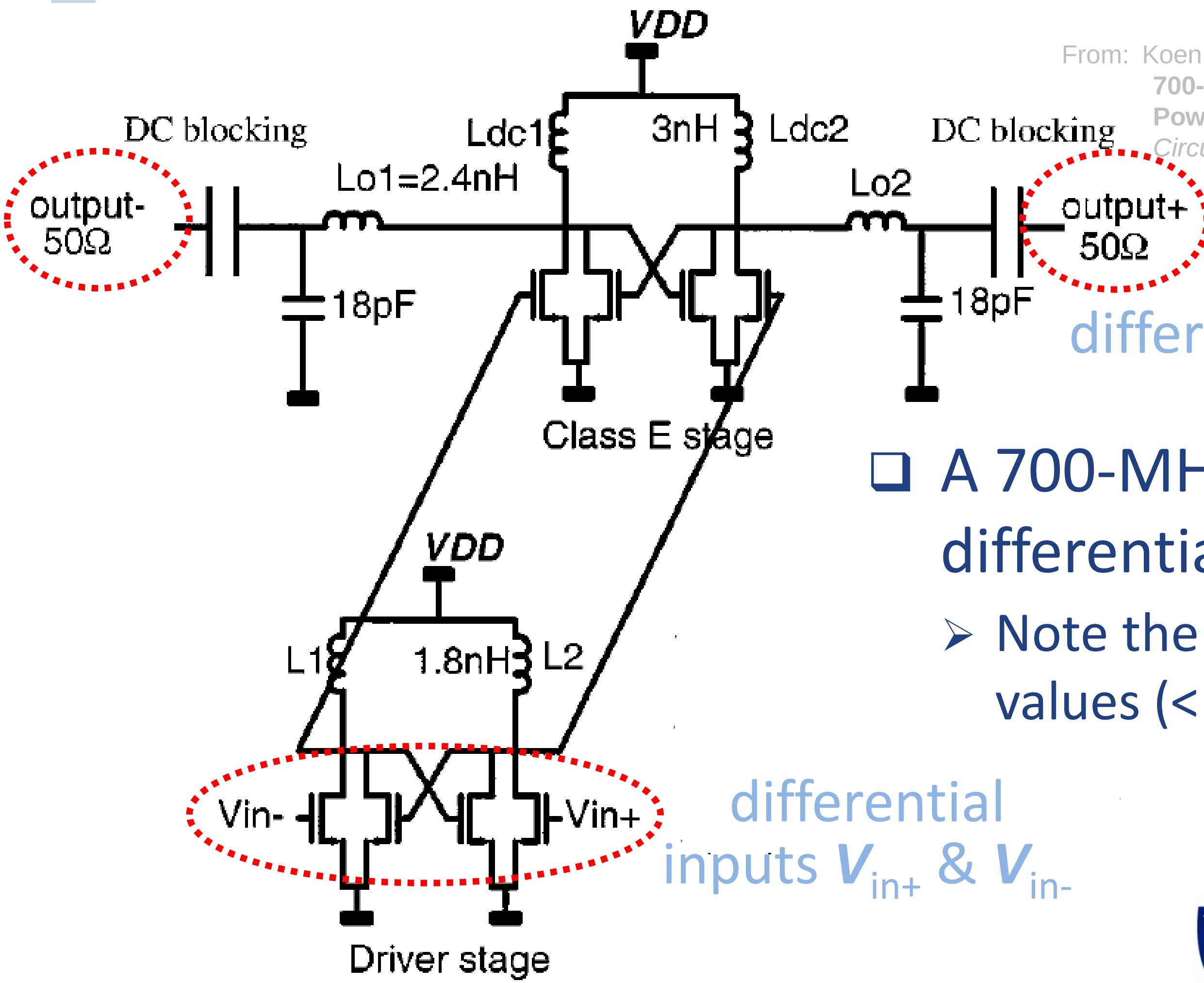


> With a ***differential*** RF PA, a **balun** is used to convert balanced signal to feed the single-ended antenna.

RF Power Amplifier

(differential implementation)



From: Koen L. R. Mertens and Michiel S. J. Steyaert, "**A 700-MHz 1-W Fully Differential CMOS Class-E Power Amplifier**," *IEEE Journal of Solid-state Circuits*, vol. 37, no. 2, February 2002 (pp. 137-141).

differential outputs

- A 700-MHz 1-W CMOS differential power amplifier
  - Note the typical inductance values (< 5 nH) for the RF PA.

differential inputs V_{in+} & V_{in-}

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Classification of Power Amplifiers

(different classes & design trade-off)

- Despite the apparent simple circuit construction, power amplifiers are traditionally categorised in quite a number of classes: A, B, AB, C, D, E, F etc.
  - The varying classes of RF PAs indicate the difficulty in the design **trade-off** to *optimise* the performance, especially **efficiency** and **linearity**.
- RF PAs of class A, B, AB and C have almost the same schematic circuit (e.g. CS or CE configuration) in terms of the power amplification transistor.
  - They are distinguished primarily by the bias condition of the transistor.

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Classification of Power Amplifiers

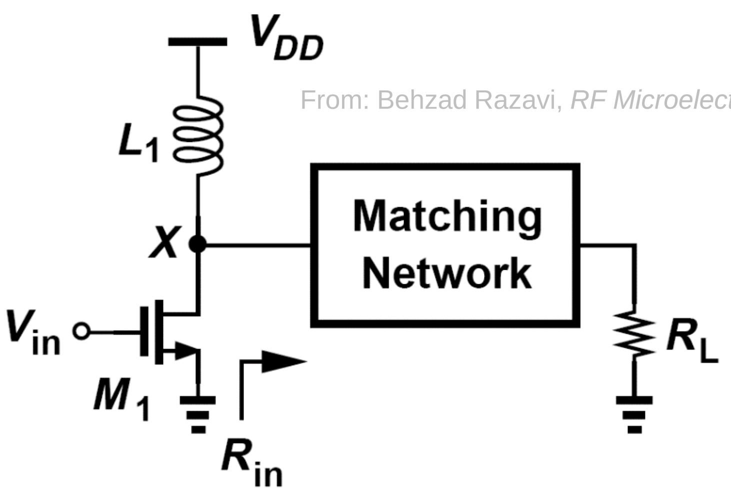
(linear & switching RF PAs)

- RF PAs of class A, B, AB and C share an attribute that both the input and output **waveforms** are presumably **sinusoidal**.
  - They generally display better **linearity** in the signal amplification.
  - The power amplification transistors work as a voltage-controlled current source.
- RF PAs of class D, E and F are of the switching type that improves the **efficiency**.
  - The transistor works as a switch.
  - The waveforms are not sinusoidal.

Class A Power Amplifiers

(linear power amplifier)

- In the common-source (or common-emitter in the BJT case) configuration, a <u>class A</u> power amplifier has the transistor always on and operating ***linearly*** across the full input and output range.



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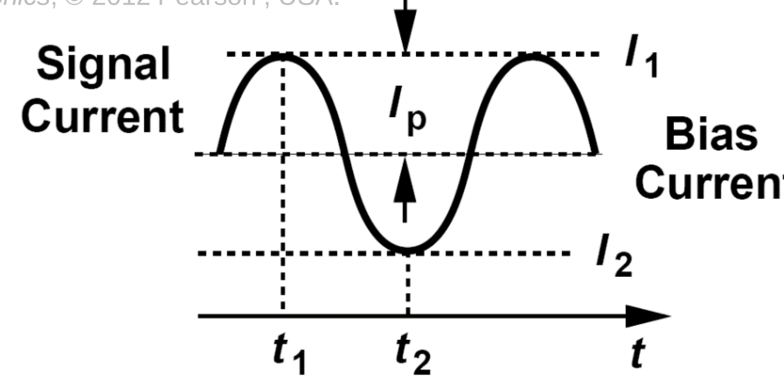

$$\eta = \frac{V_{DD}^2 / (2R_{in})}{V_{DD}^2 / R_{in}} = 50\%$$

Class B Power Amplifiers

(on half of the cycle)

- In a class B power amplifier, the power amplification transistors are on only during half of the cycle of the sinusoidal signal.
  - Two transistors can be employed as parallel stages and each transistor conducts only half of the cycle.

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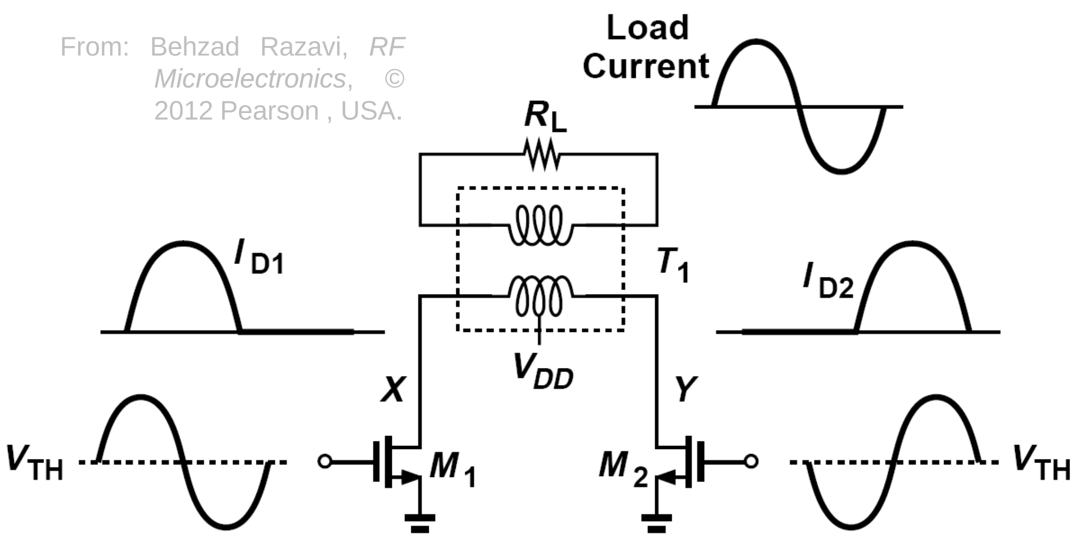

- Class B power amplifiers have better efficiency than class A.
- $\eta_B = \pi/4 \approx 79\%$.

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Class B Power Amplifiers

(use of complementary transistors)

- A class B power amplifier can also be implemented using a pair of ***complementary*** transistors (e.g. npn & pnp BJTs, nMOSFET & pMOSFET).

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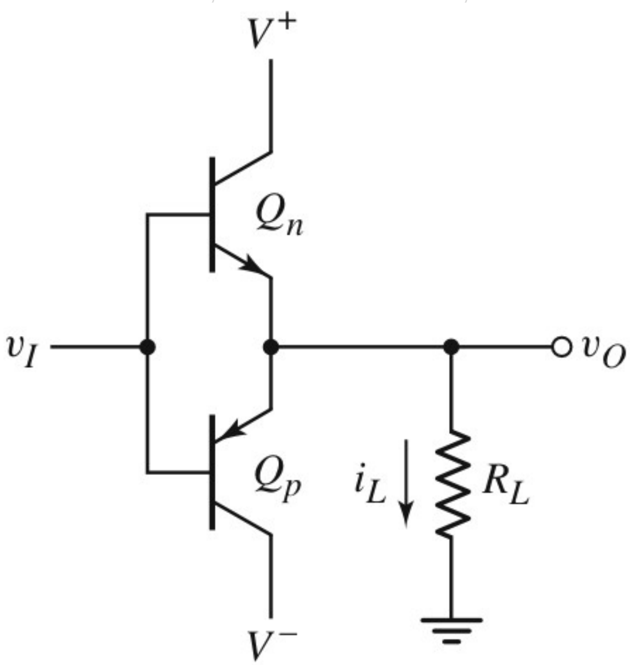

- This configuration is called a ***complementary* push-pull output stage** as used in audio amplifiers.
  - BJT $\boldsymbol{Q_n}$ conducts during the positive half of the input cycle while $\boldsymbol{Q_p}$ conducts during the negative half-cycle.

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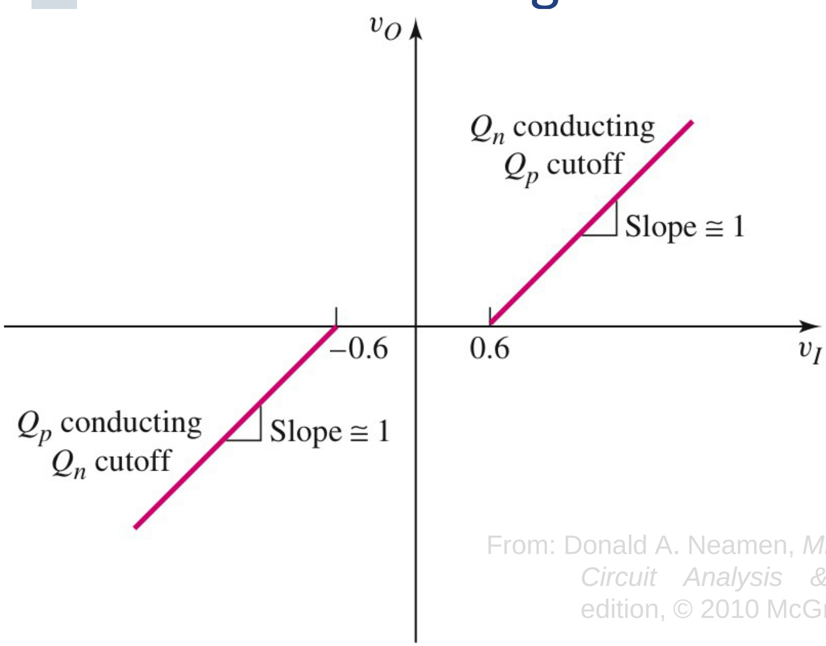
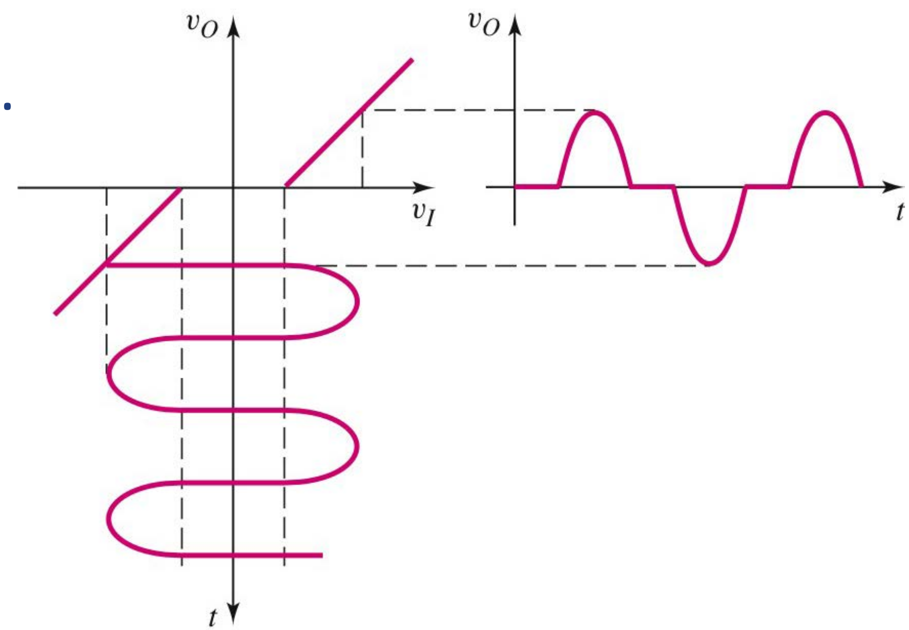
Push-Pull Output Stage

(crossover distortion)

- In the simple ***complementary*** **push-pull output stage**, the voltage transfer characteristics have a range of input voltage around 0 V where both transistors are cut-off and the output voltage is zero.
  - It causes signal distortion.





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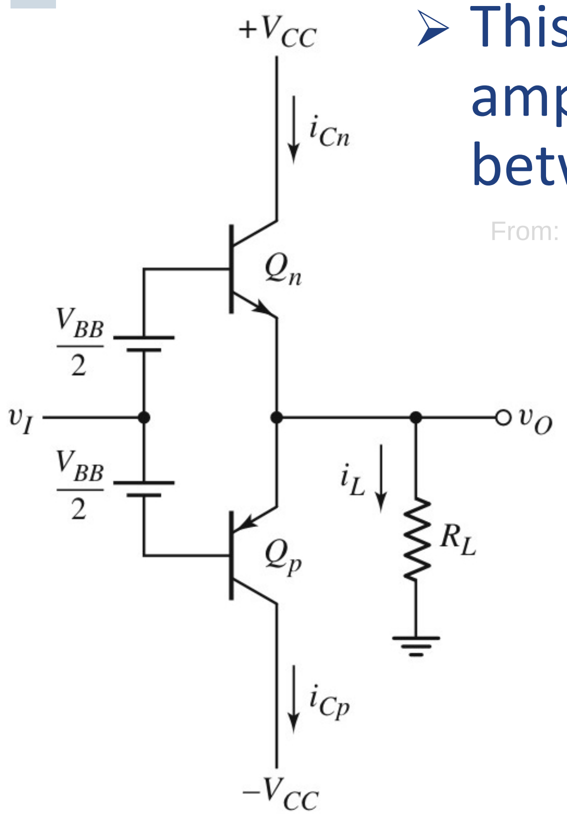
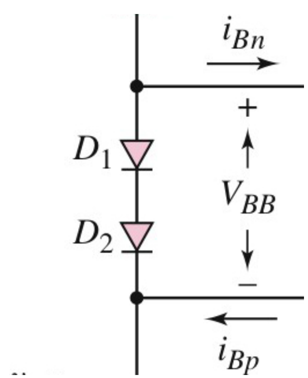
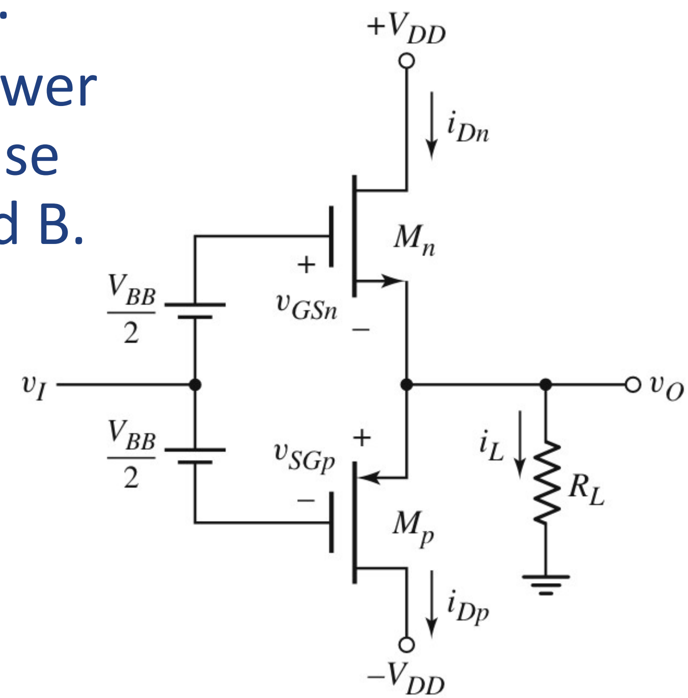
Class AB Power Amplifiers

(crossover distortion elimination)

- Crossover distortion in the ***complementary*** **push-pull output stage** can be avoided by applying a small bias voltage on each output transistor.
  - This is the class AB power amplifier, a compromise between classes A and B.







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Classification of Power Amplifiers

(conduction angle less than 180° or π)

- In the classification of power amplifiers, it is helpful to distinguish the classes by the **conduction angle**.
  - It is defined as the percentage of the signal period during which the output transistors conduct current multiplied by 360° (or 2π).
- The conduction angle is 360° (or 2π) for class A power amplifiers, 180° (or π) for class B, and slightly more than 180° (or π) for class AB.

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Class C Power Amplifiers

(conduction angle less than)

- It can be seen in classes A and B power amplifiers that a smaller **conduction angle** gives higher **efficiency**.
- In class C power amplifiers, the output transistor is biased to conduct in less than half of the cycle.

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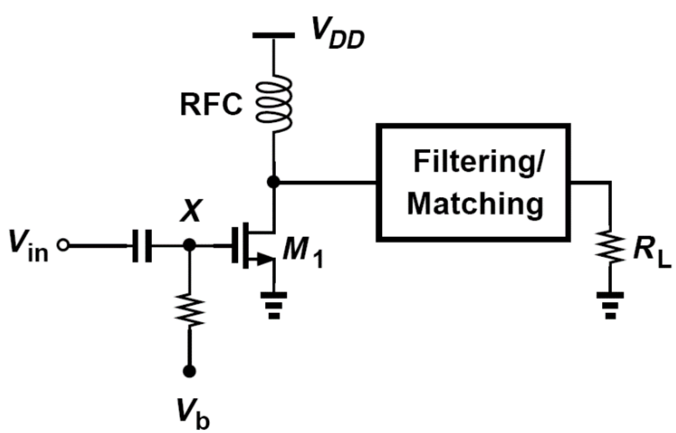

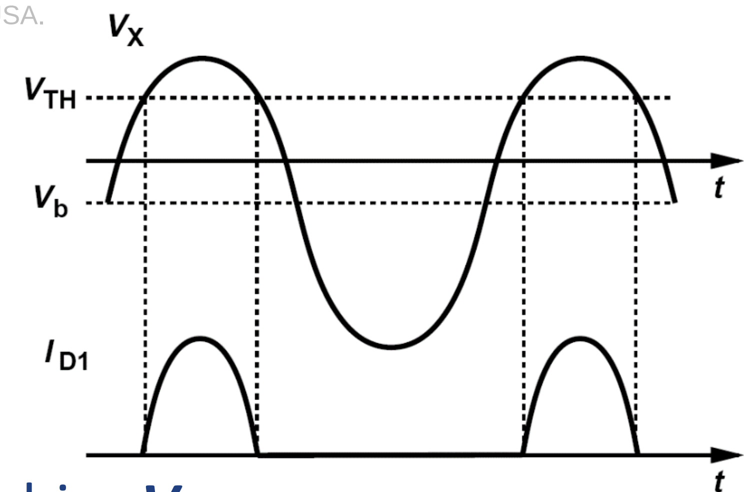

  - In the CS configuration, the bias $\boldsymbol{V_b}$ makes $\boldsymbol{V_X}$ above $\boldsymbol{V_{TH}}$ of the MOSFET for only a fraction of the cycle.

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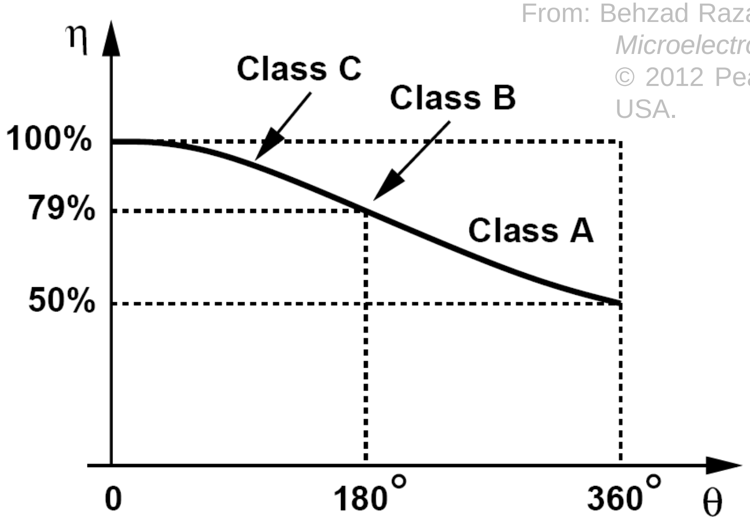
Power Amplifiers

(efficiency & conduction angle)

- As the transistor conducts current for a smaller fraction of the period, class C power amplifiers have higher **efficiency** than that of classes A and B.
  - However, the **linearity** and **output power** become worse.



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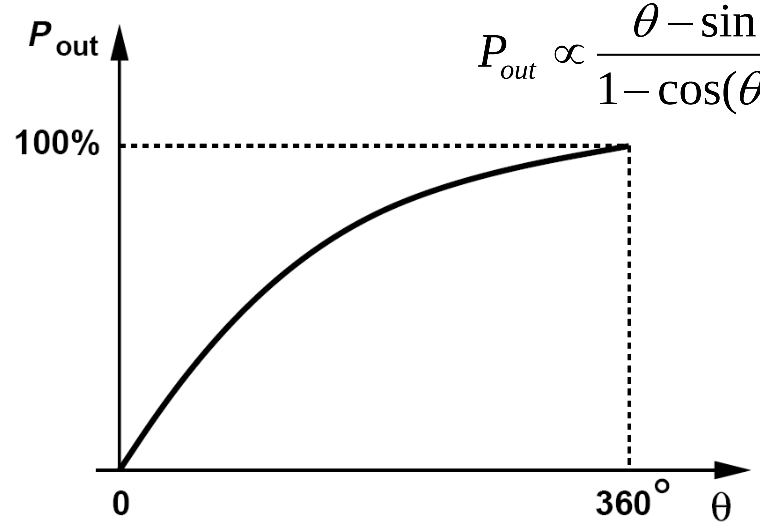
$$\eta = \frac{1}{4}\frac{\theta - \sin\theta}{\sin(\theta/2) - (\theta/2)\cos(\theta/2)}$$



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

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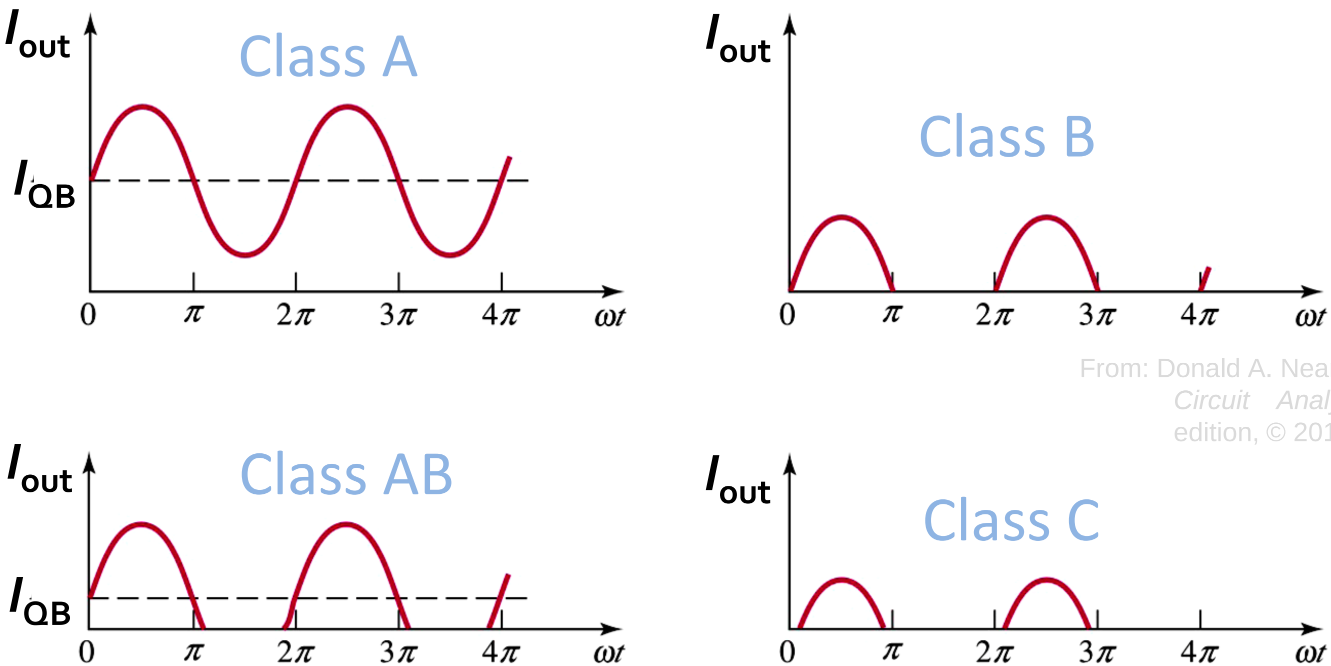
Classes A, B, AB & C

(same type but different conduction angle)

- Power amplifiers of classes A, B, AB and C are of the same type with the difference in the quiescent biasing for the transistors to conduct in different fraction of the period.



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Classes A, B, AB & C RF PAs

(sinusoidal waveform & power dissipation)

- **Sinusoidal signals** are assumed at the input and output in classes A, B, AB and C **radio-frequency power amplifiers**.
- If the current and/or voltage waveforms at the drain (or collector) are non-sinusoidal, the output transistors' power dissipation can be minimised.
  - The non-sinusoidal waveforms can minimise the time during which the output transistors conduct current while sustaining a large voltage.
  - The power amplifier efficiency can then be raised by reducing power consumption of the output transistors.
  - **Power = V(*t*) × I(*t*)**, where V(*t*) & I(*t*) are the output voltage and current of the transistor and may have different phases.

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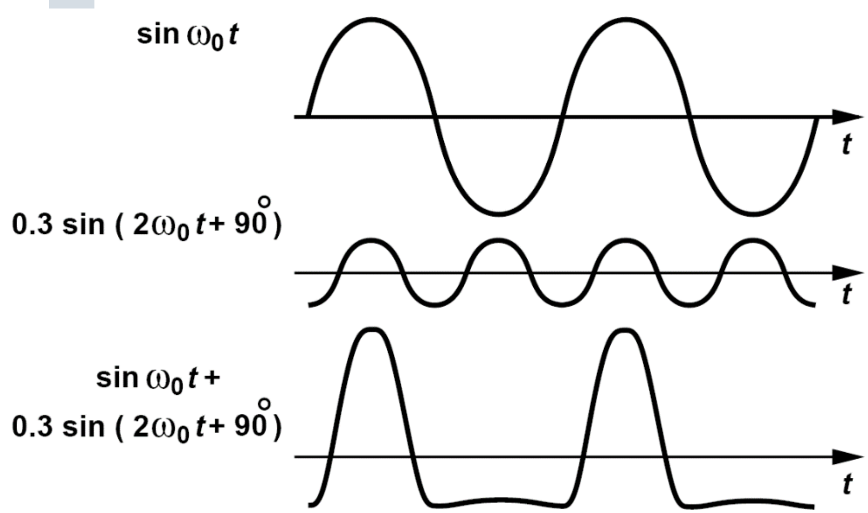
Non-Sinusoidal Waveforms

(harmonics arising from nonlinearity)

- With the **large-signal amplification**, the output transistor's current can swing by a large amount. As a result, there can always be some degree of **nonlinearity**.
- There can be second and/or third **harmonics** (<u>at the drain</u>) arising from large current signals.



- The ***higher* harmonics** can be enhanced to make the waveform non-sinusoidal, reducing the **overlap time** between the voltage across and current flowing in the transistor.

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High-Efficiency Class A RF PA

(with harmonic enhancement)

- The waveform at the drain (or collector in the BJT case) of the output transistor can be shaped by the output **matching network**.

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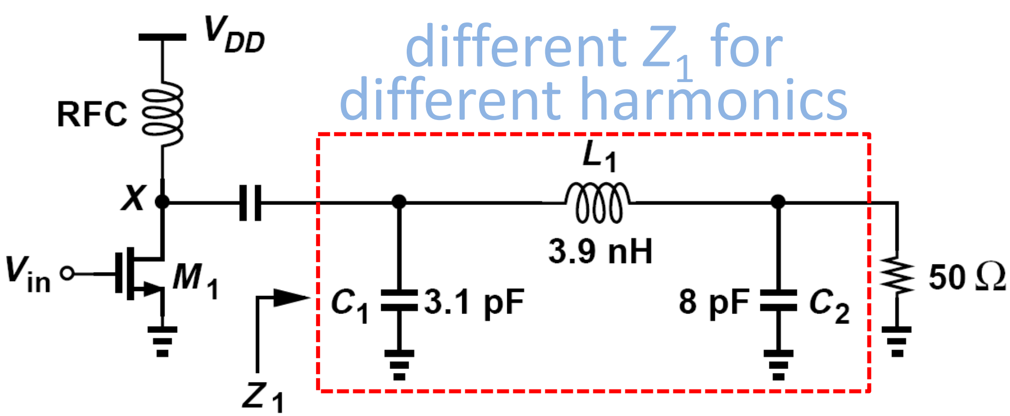
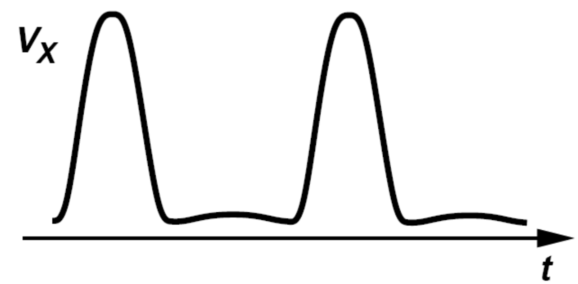
- The **matching network** can be designed such that its input impedance Z_1 is low at the fundamental and high at the second harmonic.

different Z_1 for different harmonics



V_X at the ***drain*** like a square wave

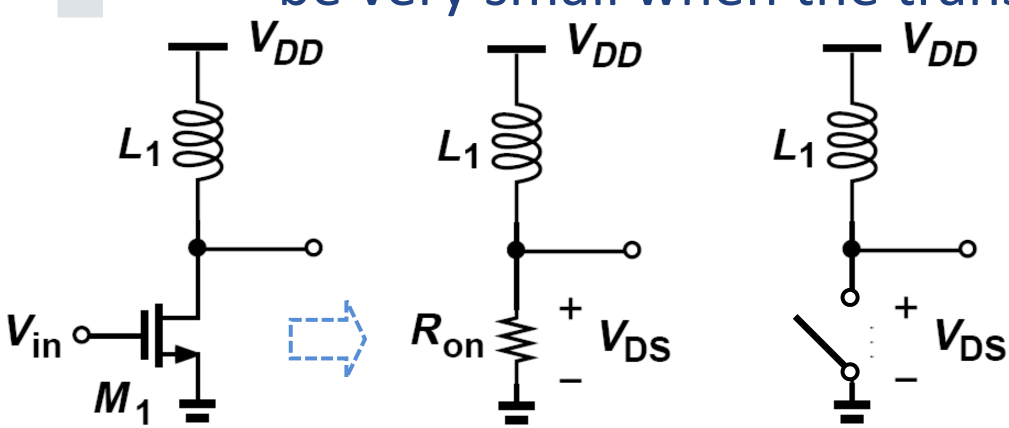


  - In the signal delivered to the load, the harmonic content is not raised.

Class E RF Power Amplifier

(transistor as a switch)

- To further improve the efficiency of RF power amplifiers, the output transistor can be used as a **switch**, instead of a voltage-controlled current source (in classes A, B, AB and C PAs).
  - Ideally, the output transistor turns on and off ***abruptly***.
  - To serve as a good **switch**, the on-resistance R_{on} should be very small when the transistor is turned on.



  - When it is off, it should be like open-circuit and hence no current flows through it.

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Class E RF Power Amplifier

(switching RF PA)

- Such a circuit configuration using the transistor's **switching action** for power amplification is the class E power amplifier and it is called a "***switching* power amplifier**".
  - It is a type of ***nonlinear* amplifiers** that achieve efficiency approaching 100% while delivering full power to the antenna.
  - The perfect efficiency is based on the reasoning that an *ideal* **switch** dissipates no power: there is either zero voltage across it or zero current through it.
  - The ***switching* amplifier** version of the **push-pull output stage** is the class D PA.

Class E RF Power Amplifier
(switching RF PA)

- Such a "***switching* power amplifier**" topology achieves a high **efficiency** if:

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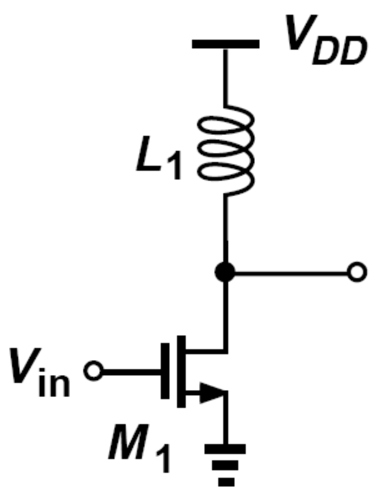

1. the output transistor M_1 sustains a small voltage V_{DS} when it carries current;
2. M_1 carries a small current when it sustains a finite voltage;
3. the transition times between the on- and off-states are minimised.

   - It is like minimising power dissipation in the CMOS inverter.

- The input signal V_{in} for ***switching*** the transistor should approximate a rectangular waveform.

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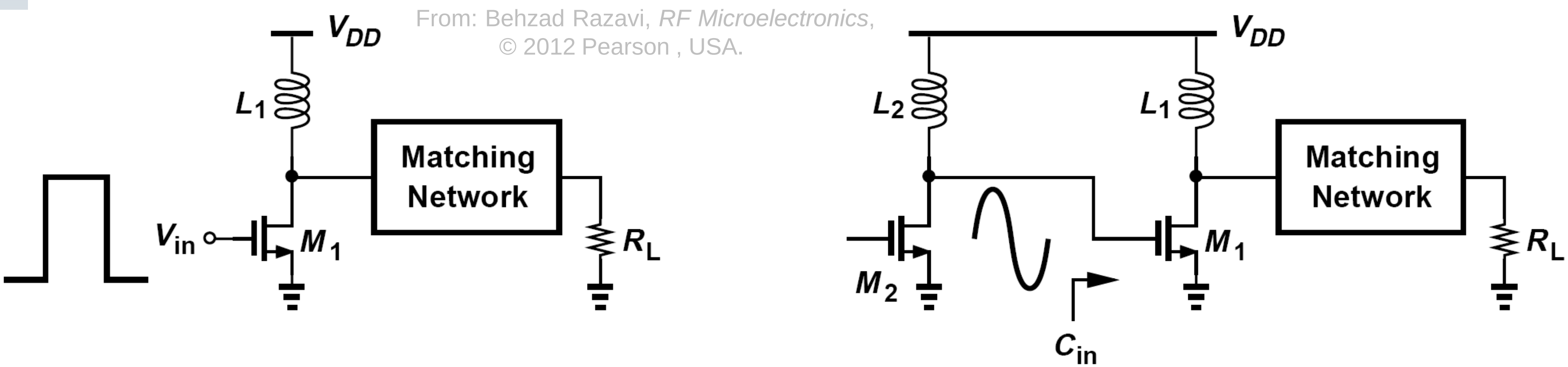
Class E RF Power Amplifier

(switching RF PA)

- While the gate of the output MOSFET must be ***switched*** as *abruptly* as possible to *maximise* the **efficiency**, its typically large transistor size (W/L) in RF PA makes resonance necessary at the input.
  - This inevitably gives rise a nearly sinusoidal waveform.

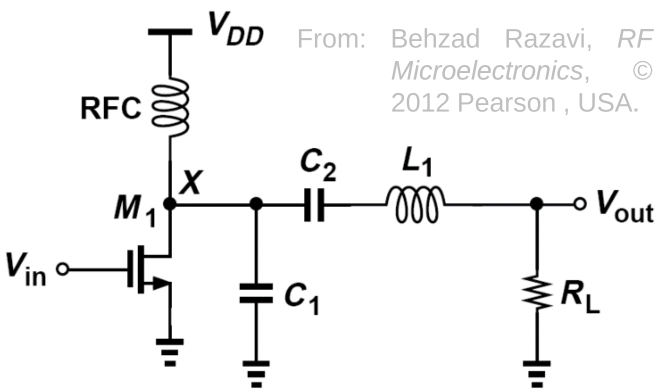


  - As a result, the ***switching* transistor** is driven by a *gradual* waveform.

Class E RF Power Amplifier

(finite input & output transition)

- ❑ The operation of <u>class E</u> power amplifiers in reality never has the perfect **rectangular waveform** to ***switch*** on and off the transistor ***abruptly***.
- ❑ The finite input and output transition times in class E amplifiers can be handled by proper load design.



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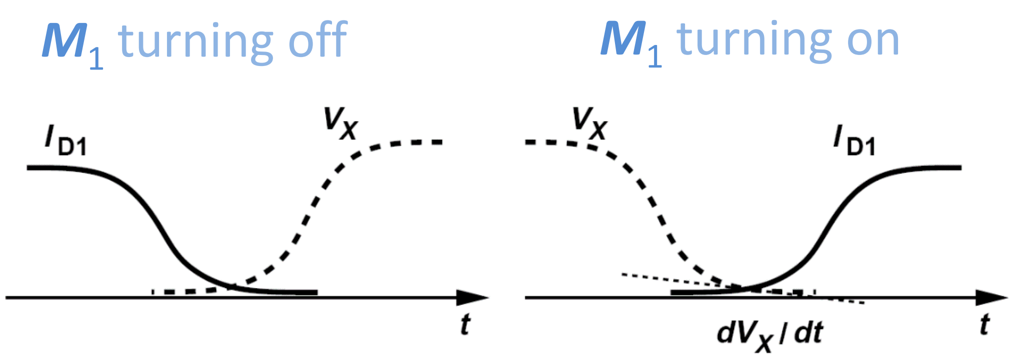
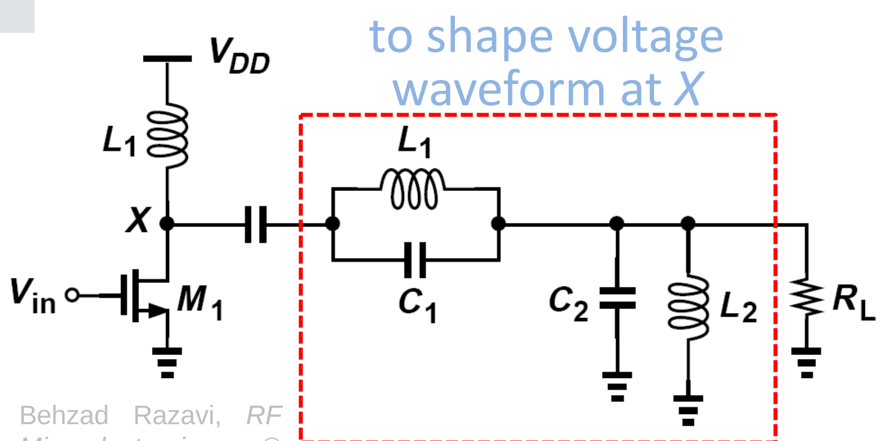


  - ➢ The passive output network is designed such that I_{D1} drops to zero when V_X rises and vice versa.

Class F RF Power Amplifier

(overcome issues of class E PA)

- The class E power amplifier has quite poor **power handling capability** as it results in a large peak current and voltage.
- Besides, the large drain current can degrade the **efficiency** as the transistor used as a **switch** has a non-zero on-resistance $\boldsymbol{R}_{\mathrm{on}}$.
- The **harmonic enhancement** technique for high-efficiency class A power amplifiers can be used in class E amplifiers.



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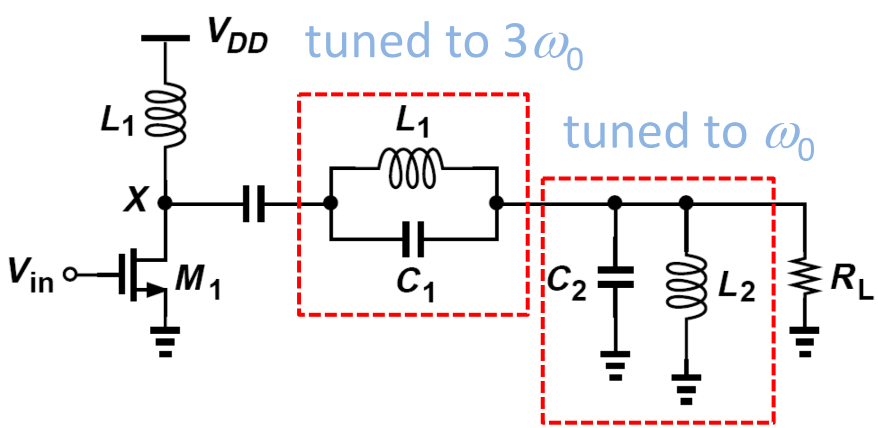
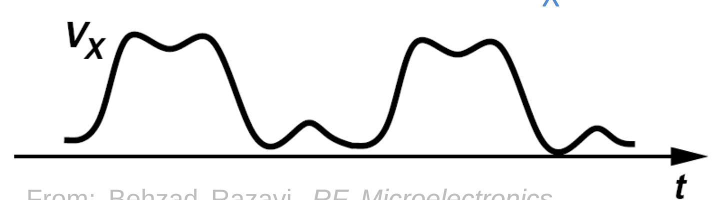
- The output **matching network** can be used to ***shape*** the waveform at the drain. This is the <u>class F</u> PA.

Class F RF Power Amplifier

(harmonic enhancement)

- In the generic **switching stage**, the passive output network can be designed (with LC tanks) to provide a high termination impedance for the second or third harmonics. The **voltage waveform** across the transistor as a **switch** then exhibits *sharper* edges than a sinusoid $\Rightarrow$ square wave.





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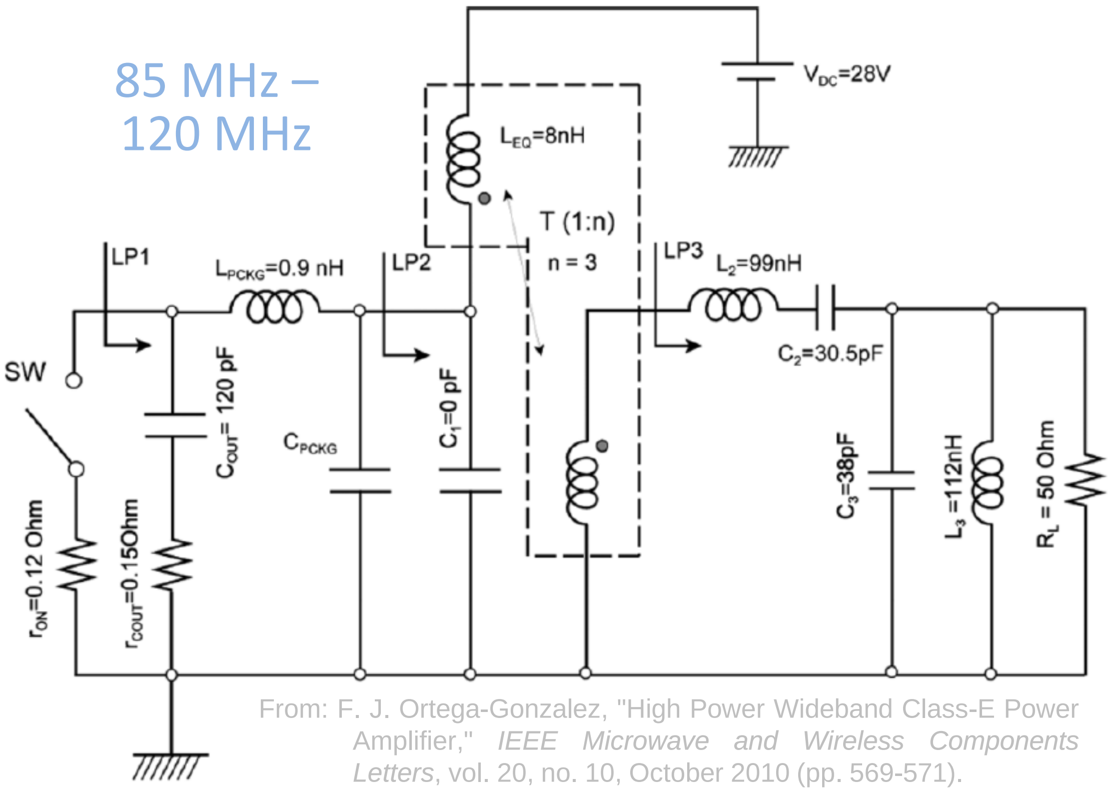
  - This reduces the power loss in the ***switching*** transistor.
  - Note the impedance is still seen from X as R_L at the fundamental frequency ω_0.

Wideband RF Power Amplifier

(passive output network)

85 MHz – 120 MHz



From: F. J. Ortega-Gonzalez, "High Power Wideband Class-E Power Amplifier," *IEEE Microwave and Wireless Components Letters*, vol. 20, no. 10, October 2010 (pp. 569-571).

- ➢ Do you know where the output transistor is?
- ➢ What type is the RF power amplifier?

- ❑ It can be seen about the importance of passive **matching network** in RF power amplifier design.
- ❑ In fact, passive **LC circuits** can be used for making an RF power amplifier for **wideband** amplification.

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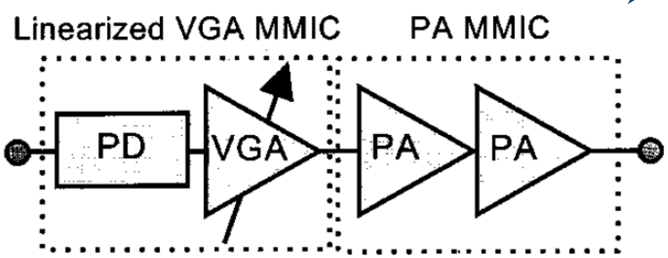
RF PA with Variable Gain

(pre-stage circuit driving output transistors)

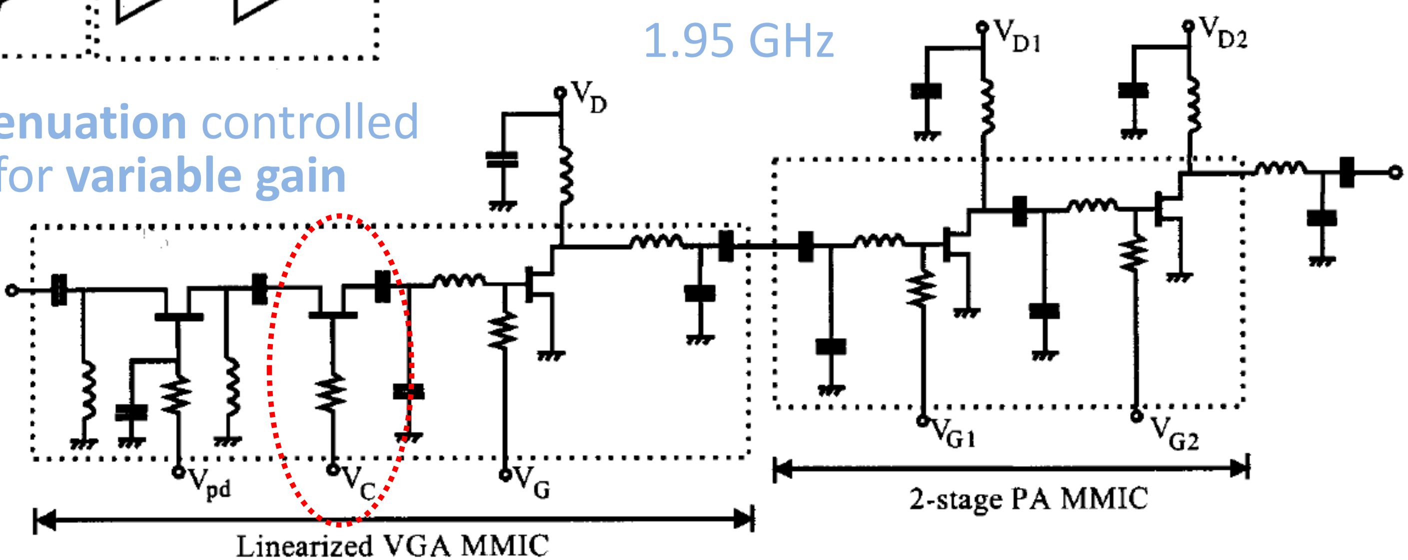
- RF power amplifiers can also be made with **variable gain**.
  - To avoid degrading the **efficiency**, the **variable gain** feature is introduced in the pre-stage circuit.



1.95 GHz

signal **attenuation** controlled by $\boldsymbol{V_C}$ for **variable gain**

From:



From: Gary Hau, Takeshi B. Nishimura, and Naotaka Iwata, "High Efficiency, Wide Dynamic Range Variable Gain and Power Amplifier MMICs for Wide-Band CDMA Handsets," *IEEE Microwave and Wireless Components Letters*, vol. 11, no. 1, January 2001 (pp. 13-15).