ELECTRONIC CIRCUITS FOR COMMUNICATION

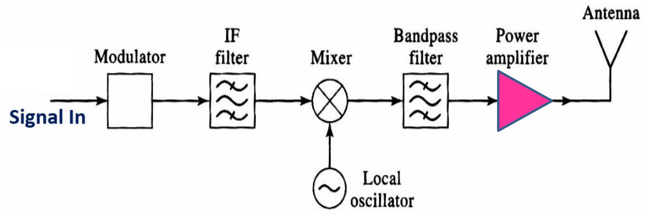
Chapter 6

RF Power Amplifiers

Textbook:

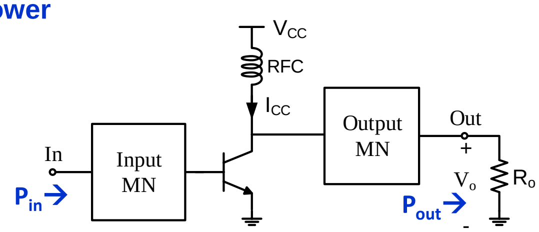
[1] B. Razavi, *RF Microelectronics*, Upper Saddle River, Prentice Hall, Second Edition, 2011

[2]



- Power amplifiers (PAs) are the critical components in the transmitter front-end and are used to amplify the transmitting signal to a required power level so that the signal can be detectable at the receiver.
- In order to provide a high power to the load, PAs typically work in the large signal conditions and consume a large DC power as well, making it the most power-hungry building block in RF transceivers.
- PAs are mainly characterized by **maximum output power, efficiency, power gain**, and **linearity (P1dB, IIP3)**.

Output Power



- The fundamental output power on the load R_o is calculated as

$$P_{out} = \frac{1}{2}\frac{V_o^2}{R_o}$$

- The maximum output power of the PAs depends on the DC power supply voltage V_{CC} and the optimum output impedance of the transistor.
- The output matching network is needed to match the load with the transistor's optimum output impedance for the maximum output power, or efficiency.

Efficiency

- There are **two types of efficiencies** used to characterize the PAs in term of the capability of converting the DC power to RF power.
- Drain/Collector efficiency, η, sometimes also called dc-to-RF efficiency, is used to measure how effectively the power from the DC supply is converted into the RF output power and is given by

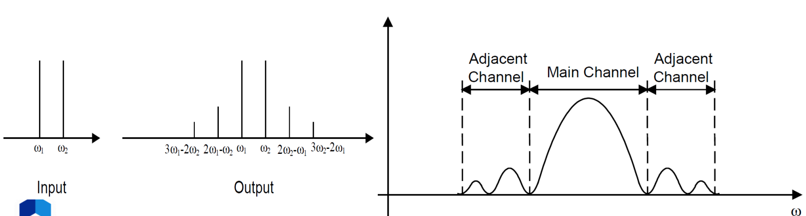
$$\eta = \frac{P_{out}}{P_{DC}} \quad \text{with} \quad P_{DC} = V_{CC} I_{CC}$$

- Power-added efficiency (PAE) is the efficiency of the PAs when the gain of the PA is taken into account. PAE is defined as

$$PAE = \frac{P_{out} - P_{in}}{P_{DC}} = \frac{P_{out} - P_{out}/G}{P_{DC}} = \eta\left(1 - \frac{1}{G}\right)$$

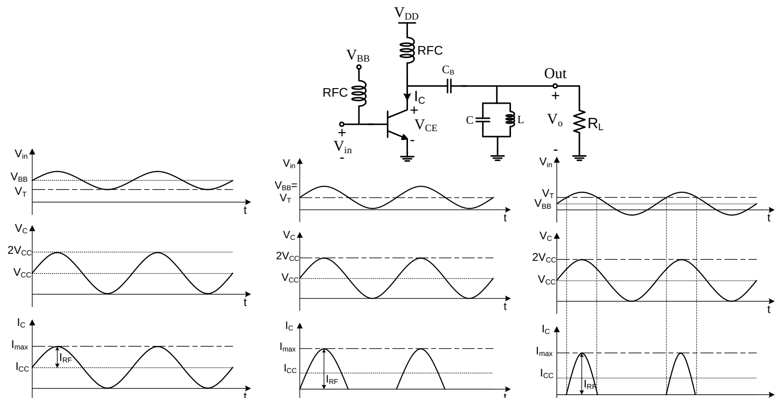
Linearity

- Linearity of the PAs is characterized by the 1-dB gain compression point, IIP3 and adjacent channel power ratio (ACPR).
- The 1-dB gain compression point indicates the power-handling capability of the PAs and is defined as the input/output power point where the nonlinearity of the PAs reduces the gain by 1 dB.
- Nonlinearity of the PAs causes the spectral regrowth or adjacent channel power problems for the modulated signal such as quadrature phase shift keying (QPSK), due to the high order inter-modulation (IMD).



Power Amplifier Classification

- Power amplifiers are traditionally categorized based on how they are bised, or collector/drain current waveform, under many classes: A, B, AB, C, D, E, F, S, ...



❑ Ideal Parallel-Tuned Circuit

- An ideal parallel-tuned circuit is a paralleled LC circuit that provides zero conductance (that is, infinite impedance) at the tuning frequency, f_0, and infinite conductance (zero impedance) for any other frequency.
- When connected in parallel to a load resistor, *R,* the ideal parallel-tuned circuit only allows a sinusoidal current (with frequency f_0) to flow through the load. Therefore, the voltage across the RLC parallel group is sinusoidal, while the total current (that is, the sum of the current through load and the current through the LC circuit) may have any waveform.
- A good approximation for the ideal parallel-tuned circuit is a circuit with a very high loaded *Q* (the higher the *Q,* the closer the approximation).
- Note that a high-Q parallel-tuned circuit uses small inductors and large capacitors, which may be a serious limitation in practical applications.

❑ Ideal Series-Tuned Circuit

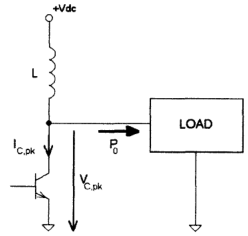
class A

class B

class C

❑ Power output capability:

- The power output capability, C_P, provides a means of comparing different types of power amplifiers or amplifier designs.

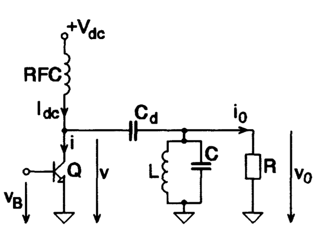


If P_0 is the RF output power, $I_{C,pk}$ is the peak collector current, $V_{C,pk}$ is the peak collector voltage, and *N* is the number of transistors in circuit, then the **power output capability** is given by

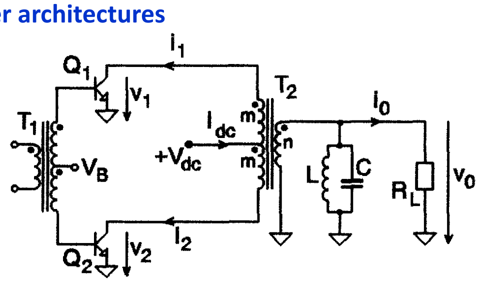
$$C_P = \frac{P_0}{N I_{C,pk} V_{C,pk}}$$

- Power transistors are the most expensive components in power amplifiers.
- Designers are constrained to use the lowest cost transistors. This means the devices have to be used as close as possible to their maximum voltage and current ratings.
- Therefore, the larger the power output capability of the circuit, the cheaper its practical implementation.

Class A, AB, B, or C amplifier architectures



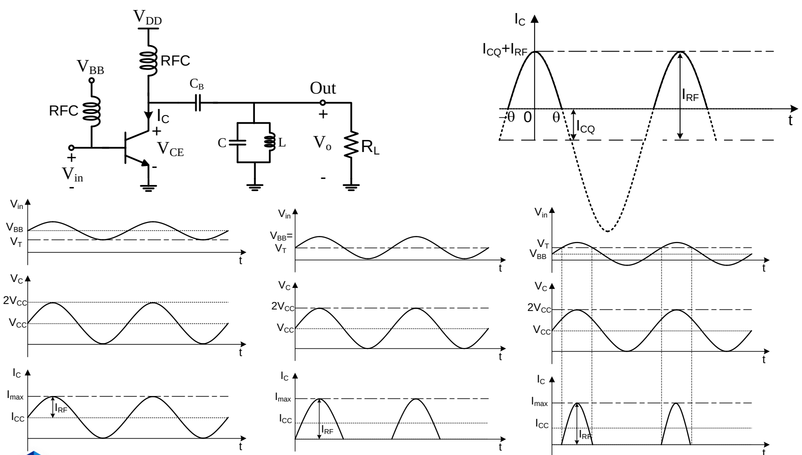
Single-ended Class A, AB, B, or C **PA**



Push-pull Class A, AB, B, or C PA

- They have the same basic collector circuit schematic.
- The circuits are all driven with sinusoidal (or approximately sinusoidal) waveforms.
- The active device behaves, at least for a certain portion of the RF cycle, as a controlled-current source

❑ The portion of the RF cycle the device spends in its active region (i.e., behaves as a controlled-current source) is the conduction angle and is denoted by $2\theta_C$.



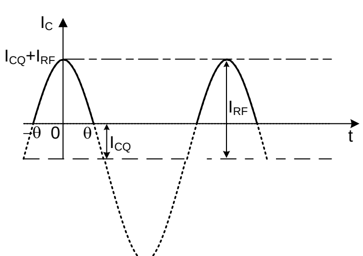
class A

class B

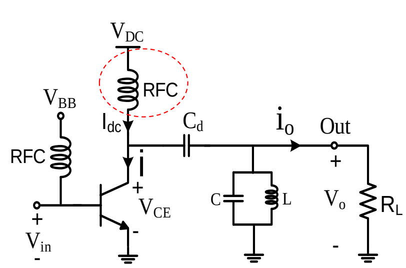
class C

❑ Based on the conduction angle, the amplifiers are generally classified as:

- Class A amplifiers, if $2\theta_C = 360°$. The active device is in its active region during the entire RF cycle.
- Class AB amplifiers, if $180° < 2\theta_C < 360°$.
- Class B amplifiers, if $2\theta_C = 180°$.
- Class C amplifiers, if $2\theta_C < 180°$. Note that, in saturated Class C amplifiers, the conduction angle includes the portion of the RF cycle when the active device is saturated.



- For Class A operation, the quiescent point (I_{dc}) must be selected to keep the transistor in its active region during the entire RF cycle, thus assuring a 360 degree conduction angle.
- The transistor works as a current source and conducts current 100% of time.
- LC tank can be omitted .



❑ DC Analysis:

$I = I_{dc}$

$V_{CE} = V_{DC}$

❑ AC Analysis:

$I = I_{dc} - i_0$

$i_o = I_o \sin\theta$

$v_o = V_o \sin\theta$

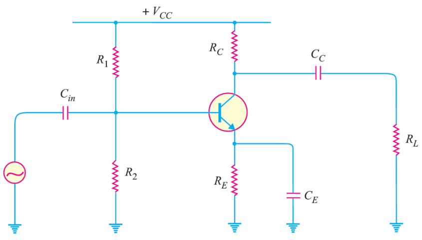
$v_{CE} = V_{DC} + V_o \sin\theta$

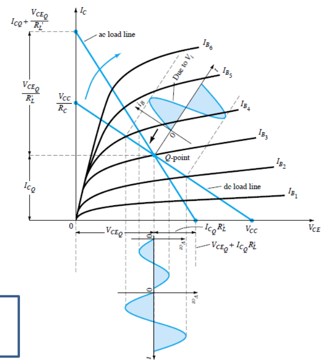
$\theta = \omega t = 2\pi f t$ is the angular time

Reviews – AC and DC Load Line

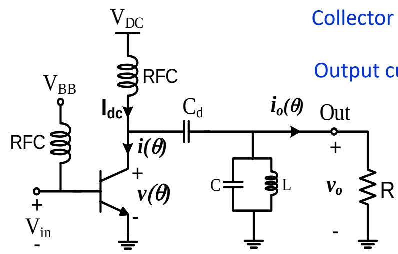
❖ ***DC Load Line:*** $I_{CQ} = f(V_{CE}) = \frac{V_{CC}}{R_C + R_E/\alpha} - \frac{V_{CE}}{R_C + R_E/\alpha} \approx \frac{V_{CC}}{R_C + R_E} - \frac{V_{CE}}{R_C + R_E}$

❖ ***AC Load Line:*** $i_C = f(v_{CE}) = I_{CQ} + i_c = I_{CQ} - \frac{v_{ce}}{R_C \parallel R_L} = I_{CQ} + \frac{V_{CEQ}}{R_C \parallel R_L} - \frac{v_{CE}}{R_C \parallel R_L}$





❖ ***Max-Swing Condition:*** $I_{CQ} = \frac{V_{CC}}{R_{ac} + R_{DC}}$



Collector current: $i(\theta) = I_{dc} - I_0 \sin\theta$

Output current: $i_0(\theta) = I_{dc} - i(\theta) = I_0 \sin\theta$

Output voltage:

$v(\theta) = V_{dc} + V_0 \sin\theta = V_{dc} + RI_0 \sin\theta$

DC Load Line: $R_{DC}=0$

AC Load Line: $R_{AC} = R_L$

➢ The transistor remains in the active region if the following conditions are satisfied

$$I_0 \le I_{dc} \qquad V_0 \le V_{dc}$$

➢ Max-Swing Condition: $I_{dc} = \frac{V_{CC}}{R}$

$I_{0,max} = I_{dc} = V_{cc}/R$
$V_{0,max} = V_{CC}$

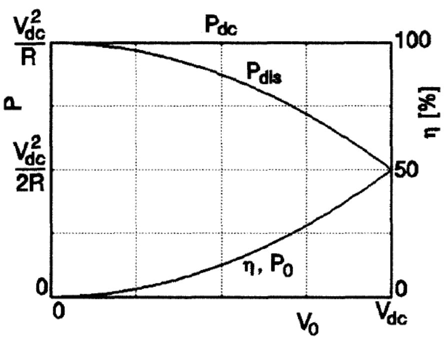
Output power:

$$P_0 = \frac{I_0^2}{2} R = \frac{V_0^2}{2R}$$

$$P_{0,max} = \frac{V_{dc}^2}{2R}$$

DC power: $P_{dc} = V_{dc} I_{dc} = \frac{V_{dc}^2}{R}$

Efficiency: $\eta = \frac{P_0}{P_{dc}} = \frac{1}{2}\frac{V_0^2}{V_{dc}^2} \le \eta_{max} = \frac{1}{2} = 50\,\%$



$P_{dis} = P_{dc} - P_o$

$I_{C,max} = 2\frac{V_{dc}}{R} = 2I_{dc}$
$V_{CE,max} = 2V_{dc}$

The power output capability of the Class A amplifier is therefore

$$C_P = \frac{P_{0,max}}{(2V_{dc})(2I_{dc})} = \frac{1}{8} = 0.125$$

Some observations and practical considerations

1. The resonant LC circuit is not necessarily required here. The Class A amplifier can use a resistive load and operate over a wide frequency range. However, the nonlinearity of the active device cannot be avoided at high signal levels and the output signal would be distorted. Thus, the load often includes tuned circuits, or band- or low-pass filters, to filter out the collector current harmonics.

2. The basic circuit and the operation of the Class A RF PAs are quite similar to those of the small-signal Class A amplifier. There is no dividing line between small-signal and Class A PAs.

3. The push-pull circuit may be used to combine the output powers provided by two identical transistors (Class A operated). This cancels most of the even harmonic currents. The drawbacks are related to the circuit complications: transformers are usually bulky, expensive, and introduce additional losses. The power output capability of the push-pull Class A amplifier is 1/8, the same value as in the single-ended Class A amplifier.

4. The Class A amplifier presents a linear transfer characteristic and a high power gain (20 to 30 dB, even at high frequencies). However, because of their low efficiency level, Class A amplifiers are most often used as low-level drivers for more efficient PAs.

Some observations and practical considerations

➢ RF BJTs have a high saturation voltage *Vsat* = 1. . . 3 V This is an RF saturation voltage and its value is significantly higher than the DC or low-frequency value provided in the data sheets. The effect of the saturation voltage can be taken into account by

$$I_0 \le I_{dc} \qquad V_0 \le V_{dc} - V_{sat}$$

Then:

$$P_{0,max} = \frac{(V_{dc} - V_{sat})^2}{2R}$$

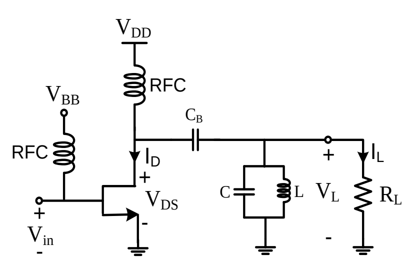
$$I_{dc} = \frac{V_{dc} - V_{sat}}{R} \qquad P_{dc} = \frac{V_{dc}(V_{dc} - V_{sat})}{R}$$

$$\eta_{max} = \frac{1}{2}\left(1 - \frac{V_{sat}}{V_{dc}}\right) < \frac{1}{2} \qquad C_P = \frac{1}{4}\frac{V_{dc} - V_{sat}}{2V_{dc} - V_{sat}} < \frac{1}{8}$$

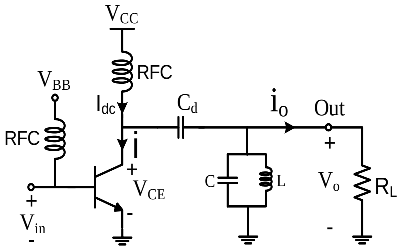
<u>Example:</u>

A class-A CMOS power amplifier (PA) is designed to deliver a maximum RF power of 2 W to the load 50Ω-R_L using a DC power supply voltage of 3 V.

a. Is the given schematic appropriate ?. If no, what is your modification ?
b. Calculate the DC current and the efficiency of the PA in max output power condition.
c. Find the maximum values of current and voltage that the transistor has to withstand.
d. The input power of the PA is adjusted so that the PA provides 1 W at the output. Find the efficiency of the PA in this condition.
e. What is the efficiency if V_{sat} = 0.5 V.



- For Class B operation, the quiescent point (I_{dc}) must be selected to keep the transistor in its active region during the one-haft RF cycle, thus assuring a 180 degree conduction angle.
- The transistor works as a current source and conducts current 50% of time.
- LC tank and Matching network is needed



DC Analysis:

$V_{BB} = V_{BEQ}$

$I = I_{dc} = 0$

$V_{CE} = V_{DC}$

AC Analysis:

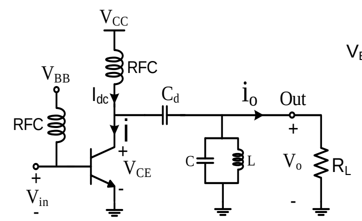
$i = I_M \text{Sin}\omega t \quad (\text{Sin } \omega t > 0)$

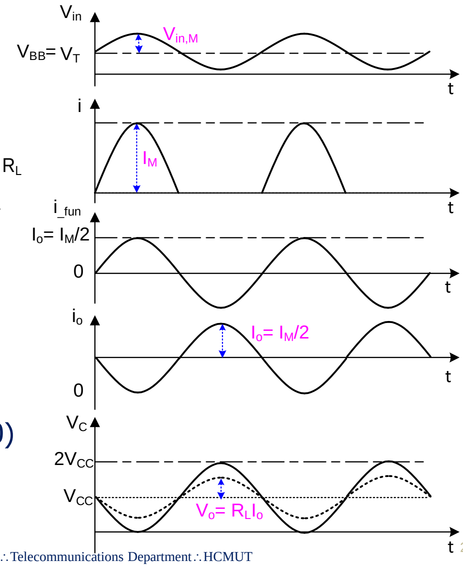
$i_o = I_o \sin(\omega t + \pi)$

$v_{CE} = V_{DC} + R_L i_o$

What is the function of LC tank ?

- The harmonics will be filtered out by LC tank.





DC Analysis:

$V_{BB} = V_{BEQ}$

$I = I_{dc,Q} = 0$

$V_{CE,Q} = V_{CC}$

AC Analysis:

$i = I_M \text{Sin}\omega t \quad (\text{Sin } \omega t > 0)$

$i_o = I_o \sin(\omega t + \pi)$

$v_{CE} = V_{DC} + V_o \sin(\omega t + \pi)$

$V_o = R_L I_o$

- The average collector current is calculated as

$$I_{DC} = \frac{1}{T}\int_0^T I_M \text{Sin}\,\omega_0 t\, dt = \frac{I_M}{\pi}$$

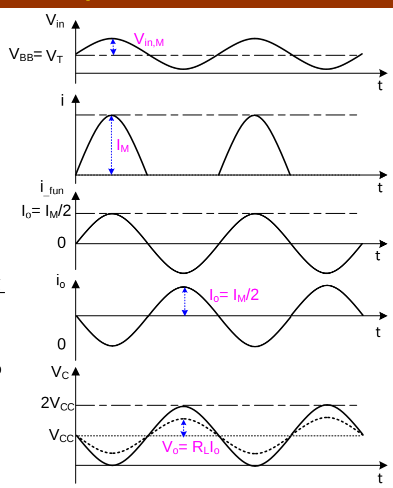
- The fundamental component of collector current is calculated as

$$I_o = \frac{1}{T}\int_0^T I_M \text{Sin}(\omega_0 t)\, \text{Sin}(\omega_0 t)\, dt = \frac{I_M}{2}$$

- Maximum voltage on the load V_o can not be larger than Vcc

$$V_o = R_L I_o = \frac{I_M}{2} R_L \le V_{cc}$$

$$\boxed{I_{M,max} = 2\frac{V_{cc}}{R_L}} \quad \boxed{I_{o,max} = \frac{V_{cc}}{R_L}}$$



$$\boxed{V_{CE,max} = 2V_{cc} \quad I_{C,max} = 2\frac{V_{cc}}{R_L}}$$

- Output power is calculated as

$$P_o = \frac{1}{2}\frac{V_o^2}{R_L} = \frac{1}{2}R_L I_o^2 \quad \rightarrow \quad P_{o,max} = \frac{1}{2}\frac{V_{cc}^2}{R_L}$$

- DC power:

$$P_{DC} = V_{CC} I_{DC} = V_{CC}\frac{I_M}{\pi} = V_{CC}\frac{2I_0}{\pi} \quad \rightarrow \quad P_{DC,Max} = \frac{2}{\pi}\frac{V_{CC}^2}{R_L}$$

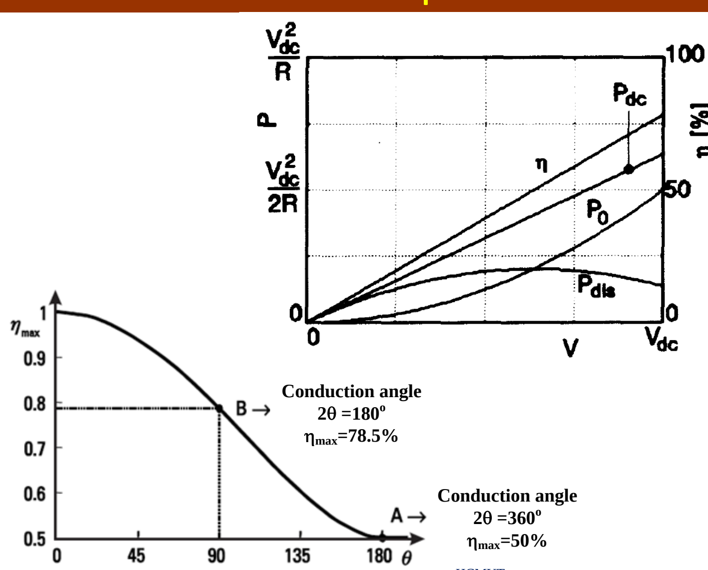
- Efficiency:

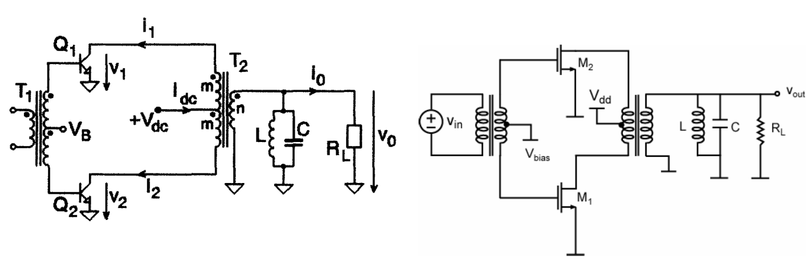
$$\eta = \frac{P_o}{P_{DC}} \qquad \eta_{max} = \frac{P_{o,max}}{P_{DC,max}} = \frac{\pi}{4} = 78.5\%$$

- Transistor dissipated power:

$$P_{Dis} = P_{DC} - P_o \quad \rightarrow \quad P_{Dis,max} = \frac{2}{\pi^2}\frac{V_{cc}^2}{R_L}$$

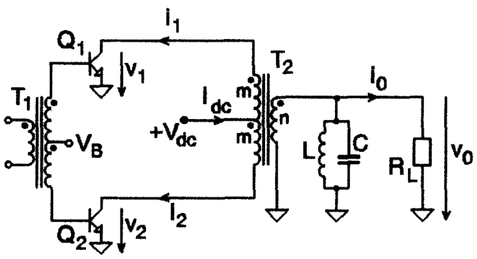
$$\boxed{C_P = \frac{P_{o,max}}{V_{CE,max} I_{C,max}} = \frac{1}{8}}$$

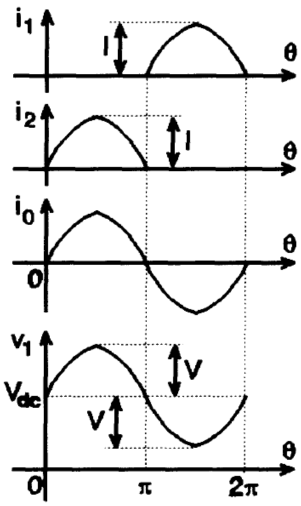




- **Depending on V_{bias} and V_{in} push-pull amplifier can be operated as Class A, B, AB, C, or D amplifier.**
- **Theoretically a Class B push-pull amplifier has low distortion comparable to class A because either half will be conducting at any time.**
- **Real Class B is not possible because devices do not have abrupt turn-on characteristic–most are Class AB.**

3. Class B Power Amplifier - *Push-Pull Amplifier*





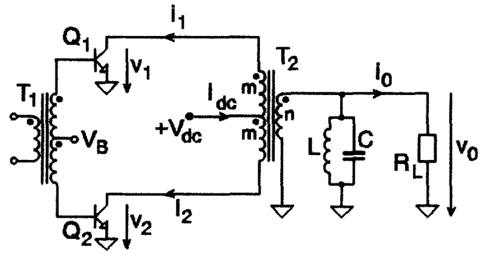
- In each half cycle, a half-sinusoidal current of peak value I is carried through one-half of the primary winding of T2.
- The secondary current is sinusoidal

$$i_0(\theta) = I_0 \sin\theta = \frac{m}{n} I \sin\theta$$

and determines a sinusoidal output voltage

$$v_0(\theta) = V_0 \sin\theta = \frac{m}{n} I R_L \sin\theta$$

3. Class B Power Amplifier - *Push-Pull Amplifier*



- The voltages across the two transistors are given by

$$v_1(\theta) = V_{dc} + V\sin\theta = V_{dc} + \frac{m}{n} V_0 \sin\theta = V_{dc} + \frac{m^2}{n^2} I R_L \sin\theta$$
$$= V_{dc} + RI\sin\theta$$
$$v_2(\theta) = V_{dc} - V\sin\theta = V_{dc} - RI\sin\theta$$

Where $R = \left(\frac{m}{n}\right)^2 R_L$ is the resistance seen across one-half of the primary winding with the other half open

- The two transistors do not saturate if $V < V_{dc}$

3. Class B Power Amplifier - *Push-Pull Amplifier*

- The two transistors do not saturate if $V < V_{dc}$
- The output power $P_0 = \frac{V_0^2}{2R_L} = \frac{V^2}{2R}$ $\quad P_{0,max} = \frac{V_{dc}^2}{2R}$ for $V = V_{dc}$
- The DC-input current is found as

$$I_{dc} = \frac{1}{2\pi}\int_0^{2\pi} i_{dc}(\theta)\,d\theta = \frac{2}{\pi} I = \frac{2}{\pi}\frac{V}{R}$$

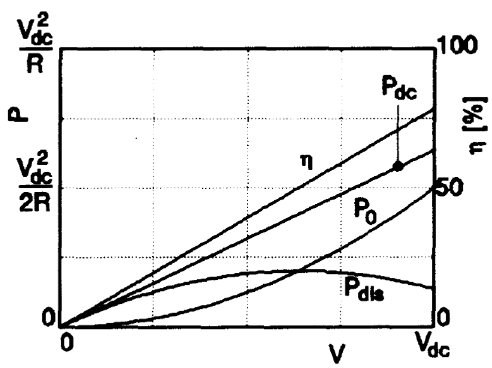
Where $i_{dc}(\theta) = i_1(\theta) + i_2(\theta) = I|\sin\theta|$

- The DC input power and the collector efficiency are

$$P_{dc} = V_{dc} I_{dc} = \frac{2}{\pi}\frac{V_{dc}}{R} V$$

$$\eta = \frac{P_0}{P_{dc}} = \frac{\pi}{4}\frac{V}{V_{dc}} \le \eta_{max} = \frac{\pi}{4} \approx 78.5\%$$

3. Class B Power Amplifier - *Push-Pull Amplifier*



$$P_{dis,max} = \frac{2}{\pi^2}\frac{V_{dc}^2}{R} = \frac{4}{\pi^2} P_{0,max} \approx 0.4053 P_{0,max}$$

$$C_P = \frac{P_{0,max}}{2(2V_{dc})I} = \frac{1}{8} = 0.125$$

3. Class B Power Amplifier - *Push-Pull Amplifier*

- The effects of V_{sat} on the performance of push-pull Class B amplifiers are determined using a procedure similar to that used for Class A amplifiers.

$$P_0 = \frac{V^2}{2R} \qquad P_{0,max} = \frac{(V_{dc} - V_{sat})^2}{2R} \qquad P_{dc} = \frac{2}{\pi}\frac{V_{dc}}{R} V$$

$$\eta = \frac{\pi}{4}\frac{V}{V_{dc}} \le \eta_{max} = \frac{\pi}{4}\left(1 - \frac{V_{sat}}{V_{dc}}\right) < \frac{\pi}{4} \qquad C_P = \frac{1}{4}\frac{V_{dc} - V_{sat}}{2V_{dc} - V_{sat}} < \frac{1}{8}$$

EXAMPLE 2.4

Design a push-pull Class B amplifier that delivers $P_0 = 8$ W to a 50-ohm load. The DC-supply voltage is $V_{dc} = 12$ V. Assume that the transistors used in this circuit have $V_{sat} = 2$ V. To avoid saturation, the collector voltage swing must be kept below $V_{dc} - V_{sat} = 10$ V. According to Equation 2.32

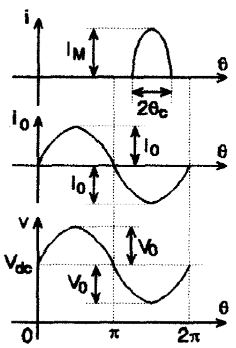
$$P_0 \le P_{0,max} = \frac{(V_{dc} - V_{sat})^2}{2R} \qquad R \le \frac{(V_{dc} - V_{sat})^2}{2P_0} = 6.25\,\Omega \qquad 2.33$$

4. Class C Power Amplifier

- Many applications that do not require linear amplification of the input signal as obtained in Class A, push-pull Class B, or AB amplifiers.
- Examples of such applications are the amplification of CW or FM signals or amplifiers for AM signals using collector amplitude modulation.
- Class C amplifiers have an important advantage because their collector efficiency is higher than that obtained in Class A, B, or AB amplifiers.
- The major disadvantages, with respect to the previously discussed amplification classes, are a higher harmonic content of the output that may require additional filtering and a lower power gain.

4. Class C Power Amplifier

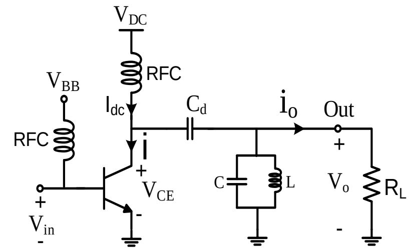
- **Conductance angle**: The portion of the RF cycle the device spends in its active region is the **conduction angle** and is denoted by $2\vartheta_C$. Based on the conduction angle, the amplifiers are generally classified as:



- **Class A amplifiers**, if $2\vartheta_C$ = 360°. The active device is in its active region during the entire RF cycle.
- **Class AB amplifiers**, if 180° < $2\vartheta_C$ < 360°.
- **Class B amplifiers**, if $2\vartheta_C$ = 180°.
- **Class C amplifiers**, if $2\vartheta_C$ < 180°.

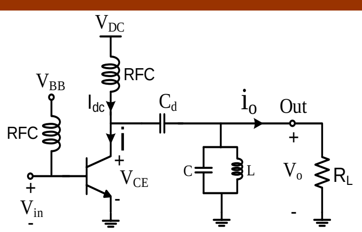
4. Class C Power Amplifier

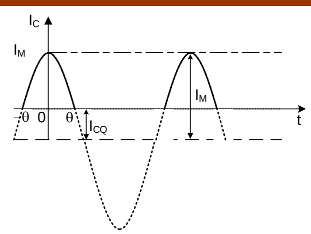
- **Basic circuit of single-ended class A, AB, B, or C amplifier**:



- This is a single-ended circuit, and the transistor operates in the common emitter (CE) configuration (common-base configurations are also possible).
- Variations among practical circuits operating in **different classes may occur in the base-bias or drive circuits**.
- The collector circuit includes an RF choke (RFC) that provides a DC input current, I_{dc}, a DC blocking capacitor, C_d (short-circuit at the operating frequency and its harmonics), the load resistor, R, and a parallel resonant LC circuit tuned to the operating frequency ω_0.

4. Class C Power Amplifier



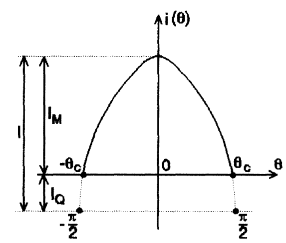


- The DC component of the collector current $i(\theta)$ flows through the RFC and then through the DC-power supply.
- The variable component of $i(\theta)$ flows through DC-blocking capacitor C_d and through the parallel RLC tuned circuit.
- The tuned circuit provides a zero impedance path to ground for the harmonic currents contained in $i(\theta)$ and only the **fundamental component** of $i(\theta)$ flows through the load resistance.
- As a result, the **output voltage** is a **sinusoidal waveform**.
- This requires the use of a parallel resonant circuit (or an equivalent band- or low-pass filter).

4. Class C Power Amplifier

- The collector current is a periodical waveform described by

$$i(\theta)=\begin{cases}\dfrac{I_M(\cos\theta-\cos\theta_c)}{1-\cos\theta_c} & -\theta_c+2k\pi\le\theta\le\theta_c+2k\pi \quad k\in Z\\ 0 \quad \text{otherwise}\end{cases}$$



- Its Fourier analysis results:

$$i(\theta)=I_M\sum_{n=0}^{\infty}\alpha_n(\theta_c)\cos n\theta$$

where:

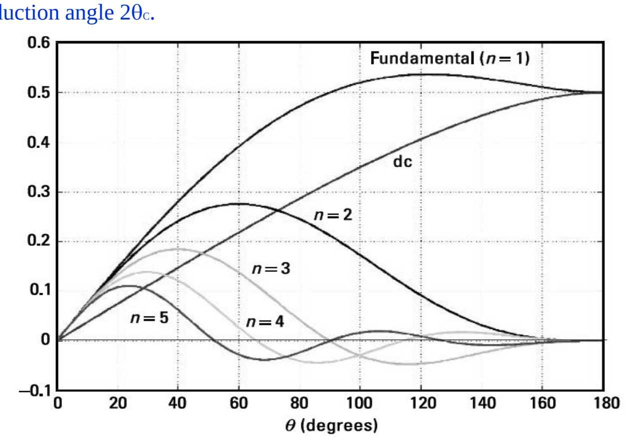
$$\alpha_0(\theta_c)=\frac{\sin\theta_c-\theta_c\cos\theta_c}{\pi(1-\cos\theta_c)} \qquad \alpha_1(\theta_c)=\frac{\theta_c-\sin\theta_c\cos\theta_c}{\pi(1-\cos\theta_c)}$$

$$\alpha_n(\theta_c)=\frac{\dfrac{\sin(n-1)\theta_c}{n-1}-\dfrac{\sin(n+1)\theta_c}{n+1}}{n\pi(1-\cos\theta_c)} \qquad n=2,3,\ldots$$

- The collector current harmonics as a function of the conduction angle.

4. Class C Power Amplifier

- These equations are valid for any $0 < 2\theta_c < 360°$; that is, for all Class A, AB, B, and C PAs. The variation of the Fourier coefficients $\alpha_0, \alpha_1, \alpha_2$ and α_3 (giving the DC component, the fundamental, and the second and third harmonic, respectively), with the conduction angle $2\theta_c$.



Fourier series coefficients α_n versus the conduction angle

4. Class C Power Amplifier

Due to the ideal tuned circuit, the output current (flowing through the load resistance R) is sinusoidal and its amplitude is given by

$$I_0=I_M\alpha_1(\theta_c)$$

As a result, the output voltage is also sinusoidal, with the amplitude $V_0 = RI_0$. The collector voltage is

$$v(\theta)=V_{dc}+V_0\cos\theta=V_{dc}+RI_M\alpha_1(\theta_c)\cos\theta$$

The DC input power P_{dc} and the collector efficiency η are

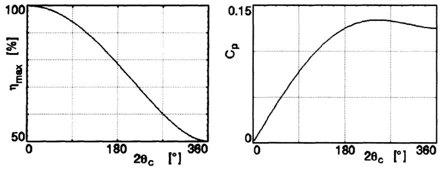
$$P_{dc}=V_{dc}I_{dc}=V_{dc}I_M\alpha_0(\theta_c)$$

$$\eta=\frac{P_0}{P_{dc}}=\frac{V_0^2}{2RV_{dc}I_M\alpha_0(\theta_c)}=\frac{V_0}{V_{dc}}\frac{\alpha_1(\theta_c)}{2\alpha_0(\theta_c)}=$$

$$=\frac{V_0}{V_{dc}}\frac{\theta_c-\sin\theta_c\cos\theta_c}{2(\sin\theta_c-\theta_c\cos\theta_c)}$$

The maximum theoretical collector efficiency (obtained for $V_0 = V_{dc}$) varies with the conduction angle as

$$\eta_{max} = \frac{\theta_c - \sin\theta_c \cos\theta_c}{2(\sin\theta_c - \theta_c \cos\theta_c)}$$



If $V_0 = V_{dc}$, the peak collector voltage is $v_{max} = 2\,V_{dc}$ and the peak collector current is given by

$$i_{max} = i_M = \frac{V_{dc}}{R\alpha_1(\theta_c)}$$

The output power P_0 and the power output capability C_P are

$$P_0 = \frac{V_0^2}{2R} = \frac{V_{dc}^2}{2R} \qquad C_P = \frac{P_0}{v_{max} i_{max}} = \frac{\alpha_1(\theta_c)}{4}$$

Comments:

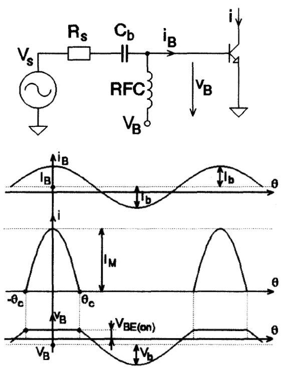
a. The **collector efficiency** is higher in Class C amplifiers than in Class A, AB, or B amplifiers, and it increases as the conduction angle decreases. If $\vartheta_C \to 0$, then $\eta \to 100\%$.

b. The **power output capability** of Class C amplifiers is lower than 0.125 (as obtained in Class A or B circuits) and decreases as the conduction angle decreases.

c. As a result, the **choice of conduction angle** would be a tradeoff among **collector efficiency**, **peak value of the collector current**, and **power gain**.

Class	η_{max}	$\frac{P_0}{V_{dc}^2/R}$	$\frac{v_{max}}{V_{dc}}$	$\frac{i_{max}}{I_{dc}}$	C_P
A	50%	0.5	2	2	0.125
B	78.5%	0.5	2	π	0.125
C	$\frac{\alpha_1(\theta_c)}{2\alpha_0(\theta_c)}$	0.5	2	$\frac{1}{\alpha_0(\theta_c)}$	$\frac{\alpha_1(\theta_c)}{4}$

- **DC bias**: The conduction angle in a Class C amplifier is controlled by a DC-bias voltage V_B applied to the base, and an amplitude V_b of the signal across the base-emitter junction.

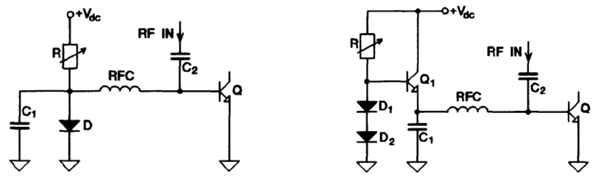


For $-\theta_c < \theta < \theta_c$, the transistor is in its active region. Consequently, the voltage across its base-emitter junction is $V_{BE(on)} \approx 0.7$ and

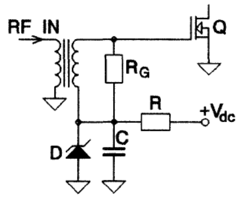
$$V_{BE(on)} = v_B(\theta_c) = V_B + V_b \cos\theta_c$$

This equation allows calculation of the required bias voltage, V_B, in the base circuit.

Simple bias circuits for BJTs



Simple bias circuits for MOSFETs



EXAMPLE 2.6

Design a Class C amplifier that delivers $P_0 = 8$ W to a 50-ohm load with 85-percent efficiency. The DC-power supply is $V_{dc} = 12$ V; the saturation voltage and/or resistance are ignored. For maximum collector efficiency, $V_0 = V_{dc}$. The equivalent load resistance of the amplifier must be $R = 9\,\Omega$ (a matching circuit is required to transform the load resistance of 50 ohms into $R = 9\,\Omega$). According to Figure 2-11, a collector efficiency $\eta_{max} = 85\%$ requires $2\theta_c \approx 147°$. The collector current fundamental is $I_0 = V_{dc}/R = 1.33$ A and, according to Equation 2.41, the peak collector current is $I_M = 2.97$ A. The DC input power is $P_{dc} = P_0/\eta = 9.41$ W. Thus, $I_{dc} = P_{dc}/V_{dc} = 0.78$ A. The peak collector voltage is $v_{max} = V_{dc} = 24$ V. The power output capability, $C_P = 0.112$, is given by Equation 2.48 or can be obtained from the values above.

- **Practical considerations:** The effects of V_{sat} on the performance of Class C amplifiers are determined as

$$P_{0,max} = \frac{(V_{dc} - V_{sat})^2}{2R} \qquad \eta_{max} = \left(1 - \frac{V_{sat}}{V_{dc}}\right)\frac{\theta_c - \sin\theta_c \cos\theta_c}{2(\sin\theta_c - \theta_c \cos\theta_c)}$$

$$C_P = \frac{\alpha_1(\theta_c)}{2}\,\frac{V_{dc} - V_{sat}}{2V_{dc} - V_{sat}}$$