EC 8353 ELECTRON DEVICES AND CIRCUITS

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UNIT-IV:MULTISTAGE AMPLIFIERS AND DIFEERENTIAL AMPLIFIERS

BIMOS cascade amplifier, Differential amplifier-Common Mode and Differential mode analysis-FET input stages-Single tuned Amplifiers-Gain and frequency response-Neuralization Methods, Power Amplifiers-Types(Qualitative Analysis)

BIMOS AMPLIFIERS

Objective

The objective of this presentation is:

1.) Show how two transistors are used to achieve amplifiers with improved performance

2.) Show the analysis of multiple transistor amplifiers using resistive loads

3.) Continue to build the amplifier concepts necessary to consider integrated circuit amplifiers

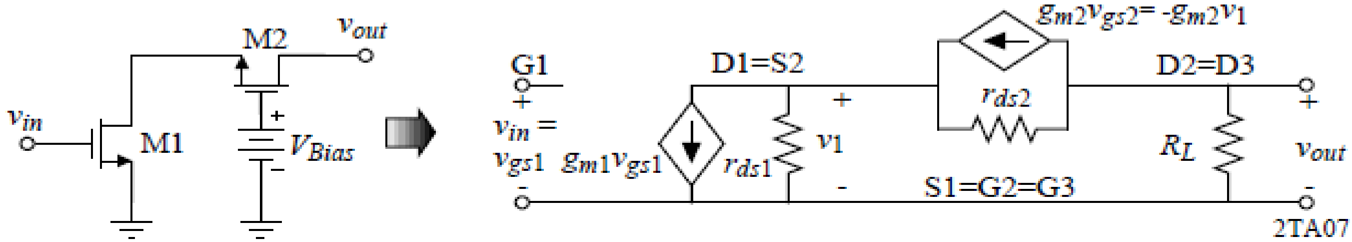
Outline

- BJT-MOS amplifiers
- Cascode amplifiers
- BJT CC-CE, CC-CC amplifiers
- Darlington transistor amplifer

CASCODE CONFIGURATION

MOS Cascode Amplifier

Circuit and small-signal model:



Small-signal performance (assuming a load resistance in the drain of R_L):

$$R_{in} = \infty$$

Using nodal analysis, we can write,

$$[g_{ds1} + g_{ds2} + g_{m2}]v_1 - g_{ds2}v_{\text{out}} = -g_{m1}v_{\text{in}}$$

$$-[g_{ds2} + g_{m2}]v_1 + (g_{ds2} + G_L)v_{\text{out}} = 0$$

Solving for v_{out}/v_{in} yields,

$$\frac{v_{out}}{v_{in}} = \frac{-g_{m1}(g_{ds2} + g_{m2})}{g_{ds1}g_{ds2} + g_{ds1}G_L + g_{ds2}G_L + G_L g_{m2}} \cong \frac{-g_{m1}}{G_L} = -g_{m1}R_L$$

Note that unlike the BJT cascode, the voltage gain, v_1/v_{in} is greater than -1.

$$\frac{v_1}{v_{in}} = -g_{m2}\left[r_{ds2}\middle|\middle|\left(\frac{r_{ds2}+R_L}{1+g_{m2}r_{ds2}}\right)\right] \approx -\frac{r_{ds2}+R_L}{r_{ds2}} = -\left(1+\frac{R_L}{r_{ds2}}\right)$$ (R_L must be less than r_{ds2} for the gain to be -1)

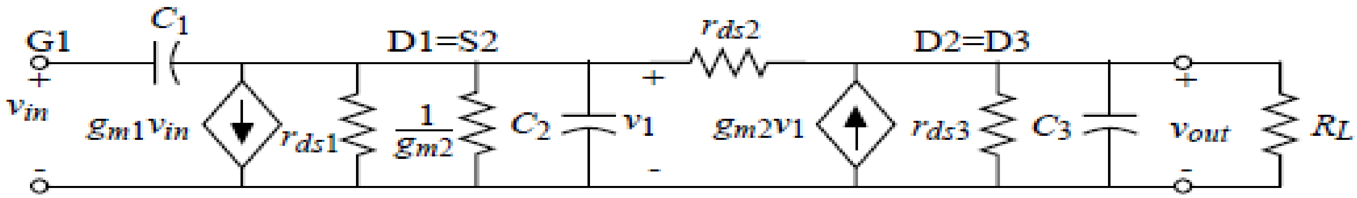
The small-signal output resistance is,

$$r_{out} = [r_{ds1} + r_{ds2} + g_{m2}r_{ds1}r_{ds2}] \,||\, R_L \cong R_L$$

CASCODE CONFIGURATION

MOS Cascode Amplifier Frequency Response

Small-signal model ($g_{m2}v_1$ has been rearranged and the substitution theorem applied):



where

$$C_1 = C_{gd1},\quad C_2 = C_{bd1} + C_{bs2} + C_{gs2} \quad \text{and} \quad C_3 = C_{bd2} + C_{bd3} + C_{gd2} + C_{gd3} + C_L$$

The nodal equations now become:

$$(g_{m2} + g_{ds1} + g_{ds2} + sC_1 + sC_2)v_1 - g_{ds2}v_{out} = -(g_{m1} - sC_1)v_{in}$$

and

$$-(g_{ds2} + g_{m2})v_1 + (g_{ds2} + g_{ds3} + G_L + sC_3)v_{out} = 0$$

Solving for $V_{out}(s)/V_{in}(s)$ gives,

$$\frac{V_{out}(s)}{V_{in}(s)} = \left(\frac{1}{1 + as + bs^2}\right)\left(\frac{-(g_{m1} - sC_1)(g_{ds2} + g_{m2})}{g_{ds1}g_{ds2} + (g_{ds3}+G_L)(g_{m2} + g_{ds1} + g_{ds2})}\right)$$

where

$$a = \frac{C_3(g_{ds1} + g_{ds2} + g_{m2}) + C_2(g_{ds2} + g_{ds3} + G_L) + C_1(g_{ds2} + g_{ds3})}{g_{ds1}g_{ds2} + (g_{ds3} + G_L)(g_{m2} + g_{ds1} + g_{ds2})}$$

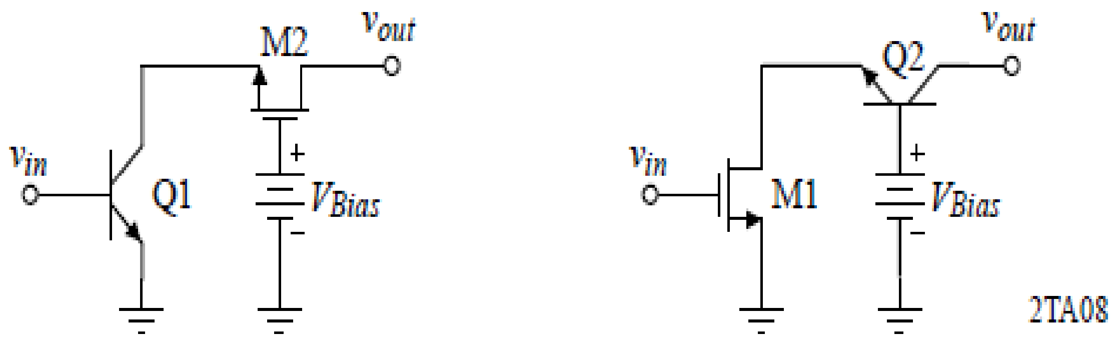
and

$$b = \frac{C_3(C_1 + C_2)}{g_{ds1}g_{ds2} + (g_{ds3}+G_L)(g_{m2} + g_{ds1} + g_{ds2})}$$

BICMOS CASCODE AMPLIFIER

<u>BiCMOS Cascode Amplifier</u>

Circuits:



Comparison:

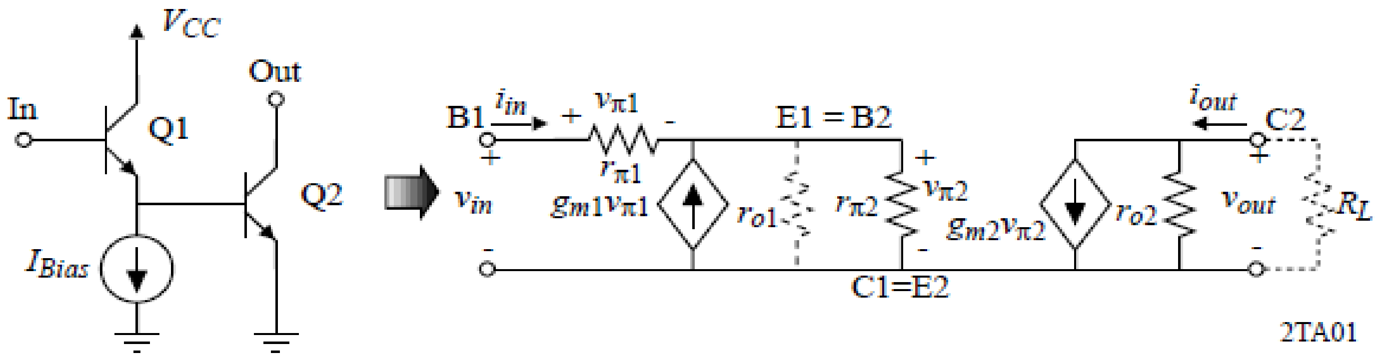
Larger voltage gain	Infinite input resistance
Smaller input resistance	Smaller voltage gain
Q1 voltage gain greater than -1V/V	M1 voltage gain less than -1V/V
High output resistance	High output resistance
Requires input current	Does not require input current

BJT CC-CE CONFIGURATION

BJT TWO TRANSISTOR AMPLIFIERS

The Common Collector-Common Emitter Configuration

Circuit:



Small-signal performance:

$$R_{in} = r_{\pi 1} + (1+\beta_{o1})r_{\pi 2}$$

$$R_{out} = r_{o2}$$

$$\frac{v_{out}}{v_{in}} = -\frac{g_{m2}(r_{o2}\|R_L)(1+\beta_{o1})r_{\pi 2}}{R_{in}} = -\frac{\beta_{o2}(r_{o2}\|R_L)(1+\beta_{o1})}{r_{\pi 1} + (1+\beta_{o1})r_{\pi 2}} \quad \rightarrow \quad -g_{m2}(r_{o2}\|R_L)$$

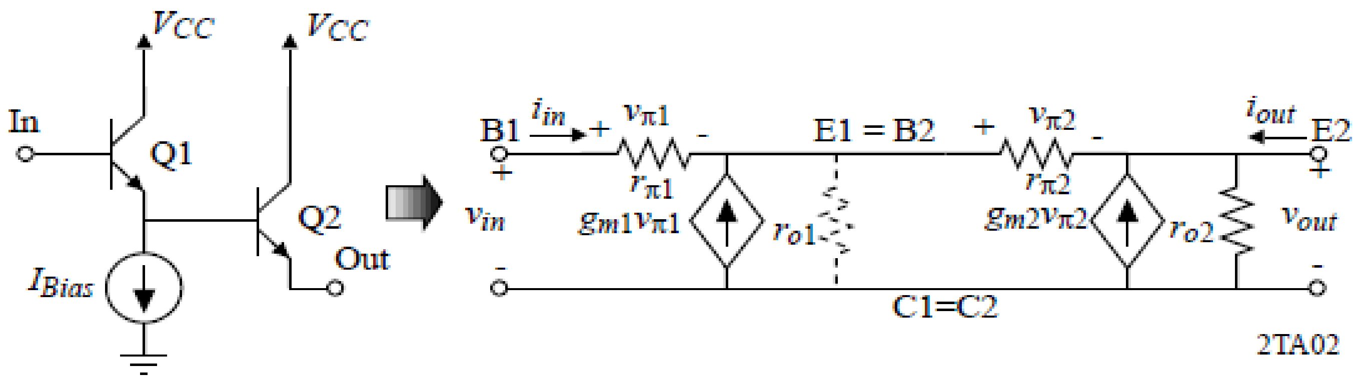
$$\frac{i_{out}}{i_{in}} = \frac{g_{m2}(1+\beta_{o1})r_{\pi 2}}{R_{in}} = \frac{\beta_{o2}(1+\beta_{o1})}{r_{\pi 1} + (1+\beta_{o1})r_{\pi 2}} \quad \rightarrow \quad \beta_{o2}(1+\beta_{o1})$$

Increased input resistance and current gain.

CC-CC CONFIGURATION

Common Collector-Common Collector

Circuit:



Small-signal performance ($I_{Bias} << I_{C2}$):

$$R_{in} = r_{\pi 1} + (1+\beta_{o1})[r_{\pi 2}+(1+\beta_{o21})(r_{o2}\|R_L)] \approx (1+\beta_{o1})(1+\beta_{o21})(r_{o2}\|R_L)$$

$$R_{out} = \frac{\frac{R_S+r_{\pi 1}}{1+\beta_{o1}} + r_{\pi 2}}{1+\beta_{o2}} = \frac{R_S+r_{\pi 1}+r_{\pi 2}(1+\beta_{o1})}{(1+\beta_{o1})\,(1+\beta_{o2})} \approx \frac{1}{g_{m2}}$$

$$\frac{v_{out}}{v_{in}} \approx 1$$

$$\frac{i_{out}}{i_{in}} = (1+\beta_{o2})(1+\beta_{o1})$$

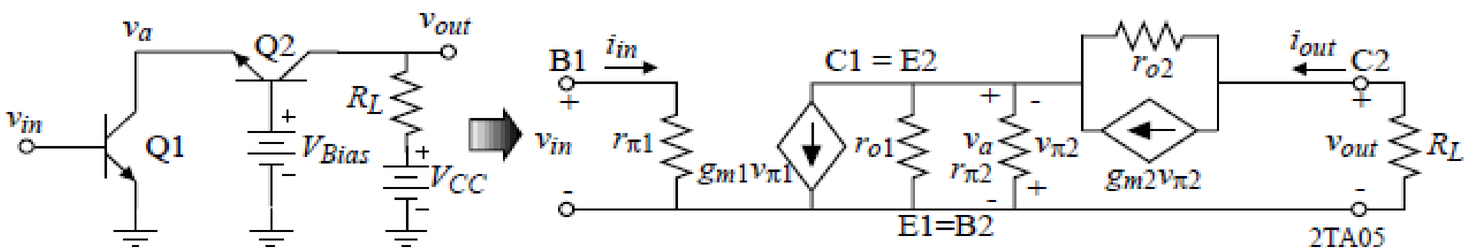
Very high input resistance and very low output resistance.

BJT CASCODE AMPLIFIER

CASCODE CONFIGURATION

BJT Cascode Amplifer

Circuit and small-signal model:



If $\beta_1 \approx \beta_2$ and r_o can be neglected, then:

$$R_{in} = r_{\pi 1}$$

$$R_{out} \approx \beta_2 r_{o2}$$

$$\frac{v_{out}}{v_{in}} = \left(\frac{v_{out}}{v_a}\right)\left(\frac{v_a}{v_{in}}\right) = (g_{m2}R_L)\left(\frac{r_{\pi 2}}{1+\beta_{o2}} \cdot \frac{-\beta_{o1}}{r_{\pi 1}}\right) \approx (g_{m2}R_L)\ (-1) = -\ g_{m2}R_L$$

$$\frac{i_{out}}{i_{in}} = \alpha_2\beta_1$$

The advantage of the cascode is that the gain of Q1 is -1 and therefore the Miller capacitor, C_μ, is not translated to the base-emitter as a large capacitor.

DIFFERENTIAL AMPLIFIER

Differential amplifiers are pervasive in analog electronics

- Low frequency amplifiers
- High frequency amplifiers
- Operational amplifiers – the first stage is a differential amplifier
- Analog modulators
- Logic gates

Advantages

- Large input resistance
- High gain
- Differential input
- Good bias stability
- Excellent device parameter tracking in IC implementation

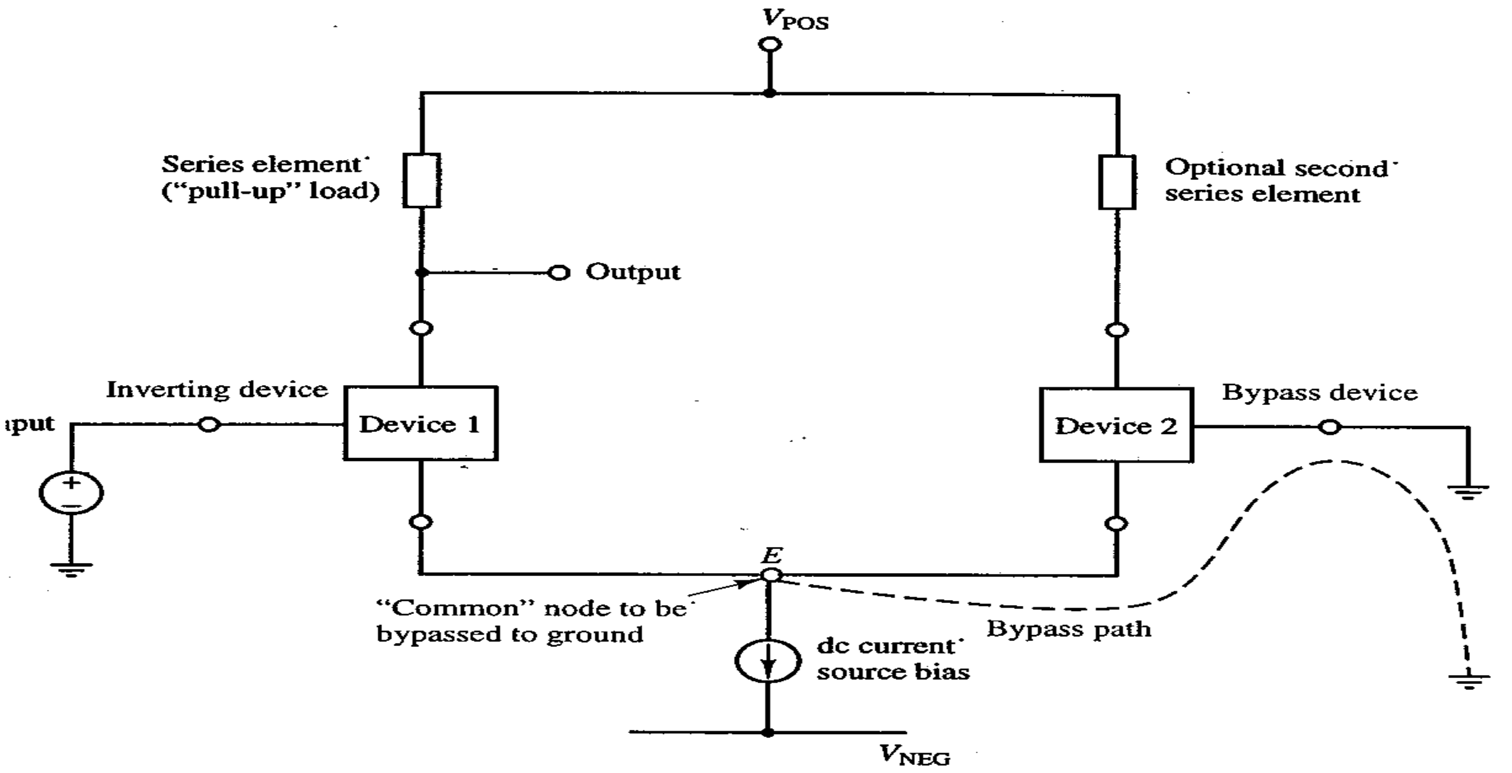
DIFFERENTIAL AMPLIFIER TOPOLOGY

In contrast to the single device common-emitter (common-source) amplifier with negative feedback bias resistor of the previous slide, the differential circuit shown at left provides a better bypass scheme.

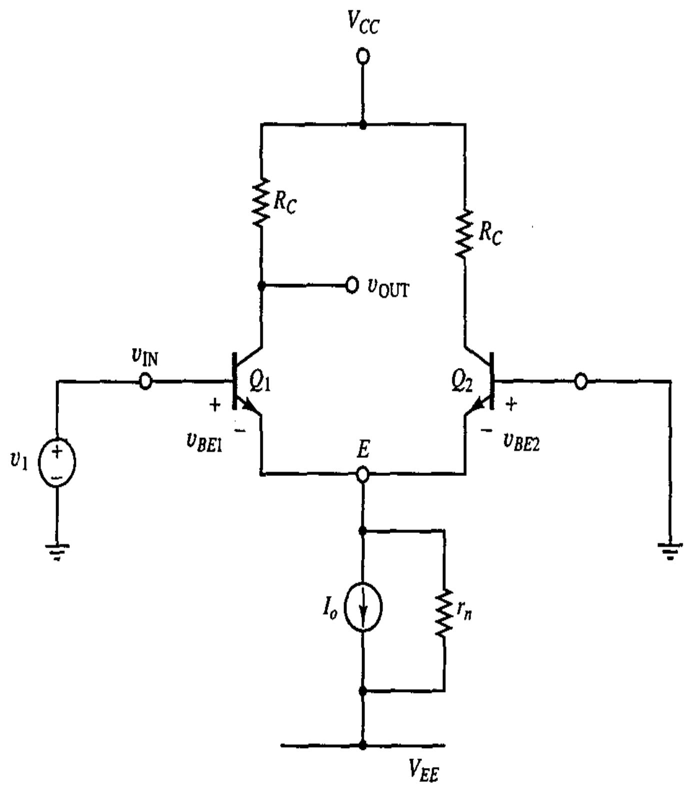
Device 2 provides bypass for active device 1,Bias provided by dc current source

Device 2 can also be used for input, allowing a differential input

Load devices might be resistors or they might be current sources (current mirrors)

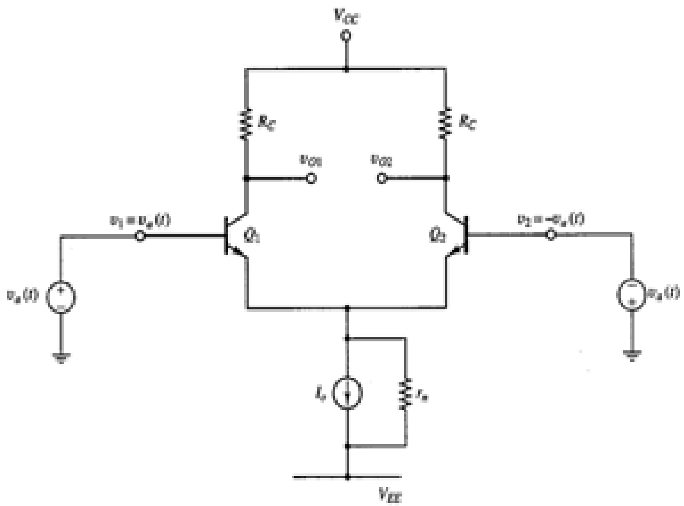


BJT DIFFERENTIAL AMPLIFIER



- Q1 & Q2 are matched (identical) NPN transistors
- Rc is the load resistor
  - Placed on both sides for symmetry, but could be used to obtain differential outputs
- I_o is the bias current
  - Usually built out of NPN transistor and current mirror network
  - r_n is the equivalent Norton output resistance of the current source transistor
- Input signal is switching around ground
- $V_{ref} = 0$ for this particular design
  - Both sides are DC-biased at ground on the base of Q1 and Q2
- v_{BE} is the forward base-emitter voltage across the junctions of the active devices
- Since Q1 and Q2 are assumed matched, Io splits evenly to both sides
  - $I_{C1} = I_{C2} = I_o/2$

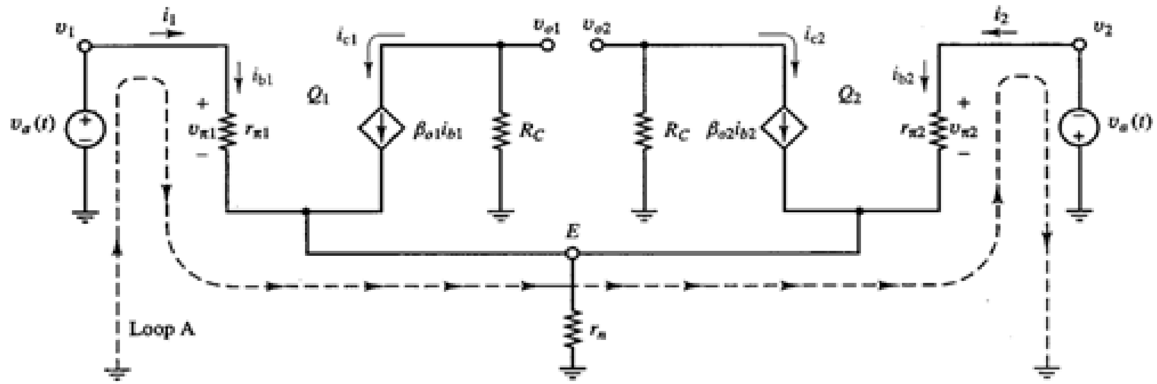
SMALL SIGNAL EQUIVALENT CIRCUIT



- At left is a bipolar differential amplifier schematic having two inputs that are differential in nature, i.e. equal in magnitude but opposite in phase
  - The differential input $v_1 - v_2 = v_a(t) - (-v_a(t)) = 2v_a(t)$
  - The common mode input $= [v_a + (-v_a)]/2 = 0$
- A small-signal model for the diff amp is shown below, where the Tx output collector resistance r_o is assumed to be >> R_C (in parallel) and is neglected
- We can derive the small-signal gain due to the differential input by applying KVL to loop A

  $$v_a(t) - (-v_a(t)) = 2v_a(t) = i_{b1}r_{\pi 1} - i_{b2}r_{\pi 2} = 2i_{b1}r_\pi$$

  - since $i_{b1} = -i_{b2}$ and $r_{\pi 1} = r_{\pi 2}$
  - Or, $i_{b1} = v_a(t)/r_\pi$ and $i_{b2} = -\ v_a(t)/r_\pi$

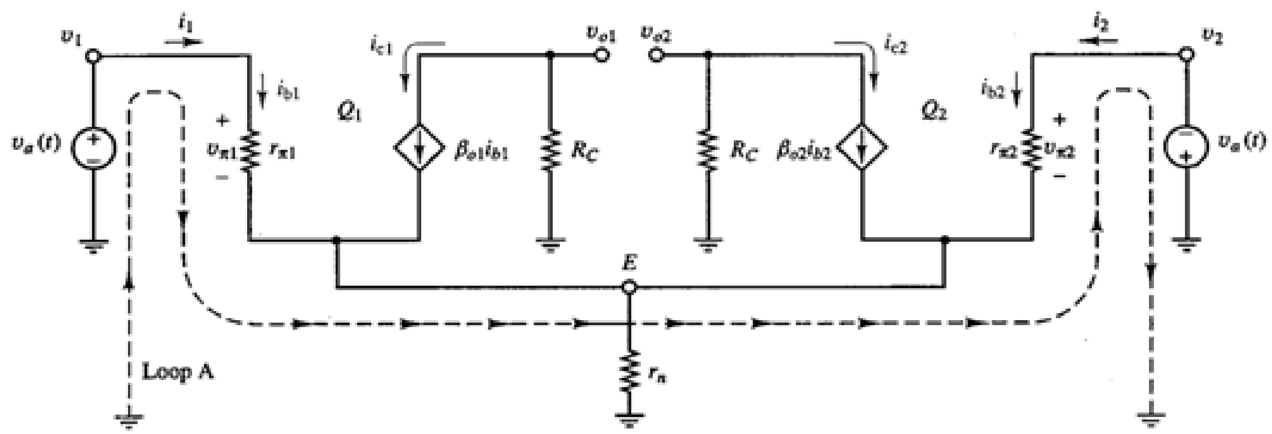


BJT DIFFERENTAIL AMPLIFIER

- Solving for the output voltages we can obtain
  - $v_{o1} = -i_{c1}R_C = -\beta_o i_{b1}R_C = -(\beta_o/r_\pi)v_a(t)R_C$ and $v_{02} = +(\beta_o/r_\pi)v_a(t)R_C$
- We can now find the gain with differential-mode input and single-ended output or with differential-mode input and differential output

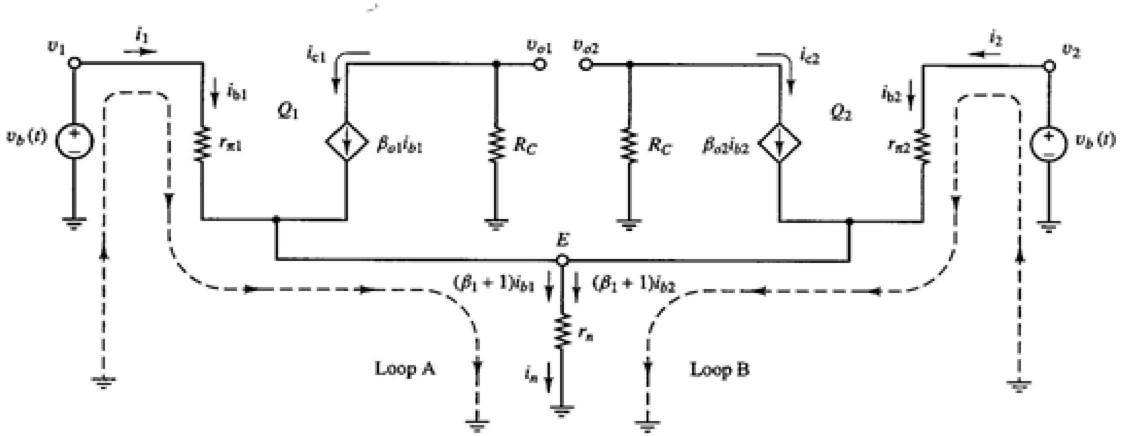
  $\mathbf{A_{dm\text{-}se1} = v_{01}/v_{idm} = -g_m R_C/2}$ and $\mathbf{A_{dm\text{-}se2} = +\,g_m R_C/2}$

  $\mathbf{A_{dm\text{-}diff} = (v_{01} - v_{02})/\ v_{idm} = -\ g_m R_C}$
- Since corresponding currents on the left and right side of the differential small-signal model are always equal and opposite, implying that no current ever flows throw r_n
  - Node E acts as a "**virtual ground**"
- If the output resistances of Q1 and Q2 are low enough to require keeping them in the analysis, we simply replace R_C with the parallel combination of $R_C||r_o$ for transistor Q1 and Q2



Small-Signal Model of BJT Diff Amp with CM Inputs

- The figure below is the small-signal model for the diff amp with common-mode inputs
  - $v1 = v2 = v_b(t)$ and $v_{icm} = ½ (v1 + v2) = v_b(t)$
- The common-mode currents from both inputs flow through rn as shown by the two loops
  - $i_n = 2(\beta_o + 1)\, i_{b1} = 2\,(\beta_o + 1)\, i_{b2}$
  - and therefore, $v_b = i_b r_\pi + 2(\beta_o + 1) i_b r_n$ or $i_b = v_b/[r_\pi + 2(\beta_o + 1) r_n]$
- The collector voltages can be found as
  - $v_{01} = v_{02} = -\, \beta_o R_C v_b/[r_\pi + 2(\beta_o + 1) r_n] = \sim -\, g_m R_C v_b/\, [1 + 2 g_m r_n]$
- The common-mode gain with single-ended output is given by
  - $A_{cm\text{-}se1} = A_{cm\text{-}se2} = v_{o1}/v_{icm} = v_{o2}/v_{icm} = -\, \mathbf{g_m R_C/[1 + 2 g_m r_n]} = \sim \mathbf{-R_C/2r_n}$
- The common-mode gain with differential output is $A_{cm\text{-}diff} = (v_{o1} - v_{o2})/v_{icm} = 0$



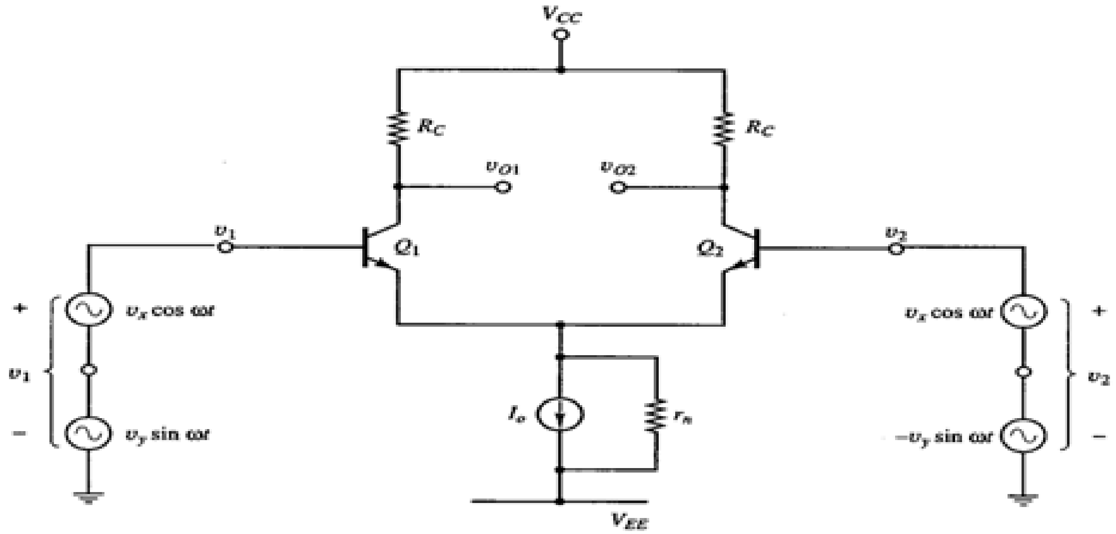
BJT Diff Amp Circuit with Both Diff & CM Inputs

- The example below illustrates the principle of superposition in dealing with both differential mode and common mode inputs to a diff amp
  - $v_1 = v_x \cos \omega_1 t + v_y \sin \omega_2 t$ and $v_2 = v_x \cos \omega_1 t - v_y \sin \omega_2 t$
- Using the definitions of differential mode and common mode inputs, respectively,

  $v_{idm} = v1 - v2 = 2v_y \sin \omega_2 t$ and $v_{icm} = (v1 + v2)/2 = v_x \cos \omega_1 t$,
  - we can obtain

    $$\mathbf{v_{o1} = A_{dm\text{-}sel}\ v_{idm} + A_{cm\text{-}sel}\ v_{icm}}$$

    $$\mathbf{= -\ \beta_o R_C\ [(v_y/\ r_\pi)\ \sin \omega_2 t + (v_x/\{r_\pi + 2\ (\beta_o + 1)\ r_n\})\ \cos \omega_1 t]}$$
  - The expression for v_{02} is similar except that the first term (differential mode) has a minus sign
  - Note that the common mode output is reduced by the factor $(\beta_o + 1)$ in the denominator



Common-Mode Rejection Ratio

- In a differential amplifier we typically want to amplify the differential input while, at the same time, rejecting the common-mode input signal
- A figure of merit ***Common Mode Rejection Ratio*** is defined as

$$\mathbf{CMRR = |A_{dm}|/|A_{cm}|}$$

  - where A_{dm} is the differential mode gain and A_{cm} is the common mode gain
- For a bipolar diff amp with differential output, the CMRR is found to be

$$CMRR = |A_{dm\text{-}diff}|/|A_{cm\text{-}diff}| = |-g_m R_C| \;/\; 0 = \textbf{infinity}$$

- In the case of the bipolar diff amp with single-ended output, CMRR is given by

$$CMRR = |A_{dm\text{-}se}|/|A_{cm\text{-}se}| = |\tfrac{1}{2} g_m R_C| \;/\; |\beta_o R_C/[r_\pi + 2(\beta_o + 1)r_n]|$$

$$= [r_\pi + 2(\beta_o + 1)r_n]/2r_\pi = \sim \beta_o r_n/r_\pi = g_m r_n = I_C r_n/\eta V_T$$

$$= \mathbf{I_o r_n/2\eta V_T}$$

  - since $\beta_o = g_m r_\pi$ and V_T is defined as kT/q
- CMRR is often expressed in decibels, in which case the definition becomes
  - $CMRR = 20 \log (|A_{dm}|/|A_{cm}|)$

TUNED AMPLIFIERS

Amplifiers which amplify a specific frequency or narrow band of frequencies are called **tuned amplifiers.**

Tuned amplifiers are mostly used for the amplification of high or radio frequencies.

It offers a very high impedance at *resonant frequency* and very small impedance at all other frequencies.

Advantages of Tuned Amplifiers

1. Small power loss.
2. High selectivity
3. Smaller collector supply voltage
4. Used in RF amplifiers, Communication receivers, Radar , Television ,IF amplifiers
5. Harmonic distortion is very small

Classification

Tuned Amplifiers

- Small Signal
  - To amplify low RF signals
  - Power output is low
  - Operated in class A
    - Single tuned
    - Double tuned
    - Staggered tuned
- Large Signal
  - To amplify large RF signals
  - Power output is more
  - Operated in class B, class C or class AB modes.
  - Pushpull configuration used to further reduce harmonic distortion.

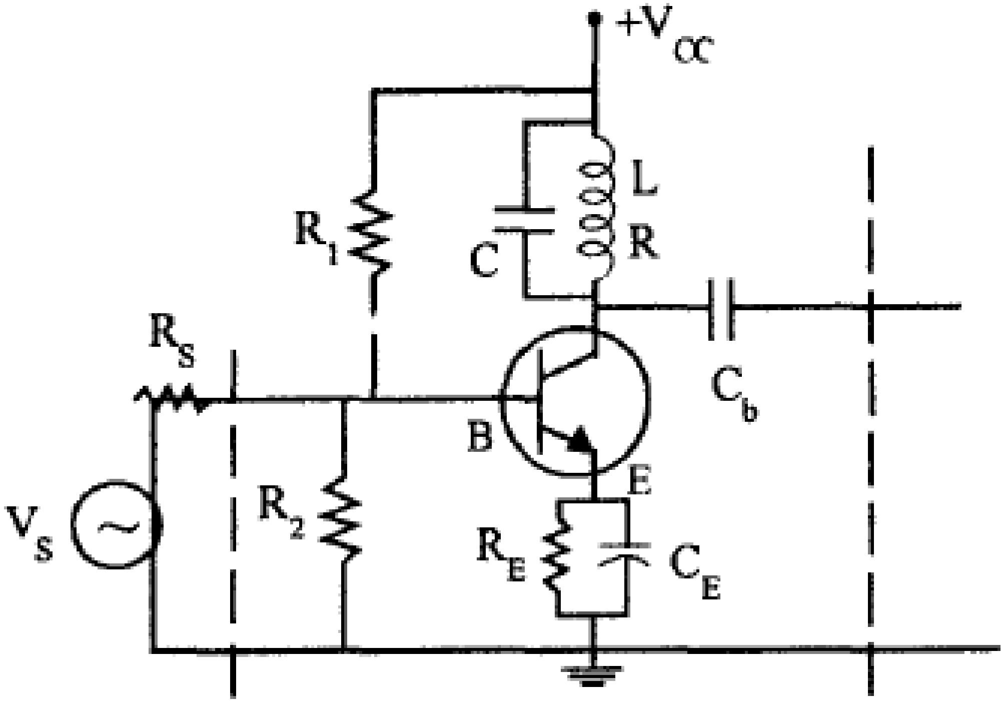
SINGLE TUNED AMPLIFIER

•Uses one parallel tuned circuit as the load IZI in each stage and all these tuned circuits in different stages are tuned to the same frequency. To get large Av or Ap, multistage amplifiers are used. But each stage is tuned to the same frequency, one tuned circuit in one stage.

Single tuned amplifiers are further classified as :

- Capacitive coupled
- Transformer coupled or inductive coupled

Single Tuned Capacitive Coupled Amplifier



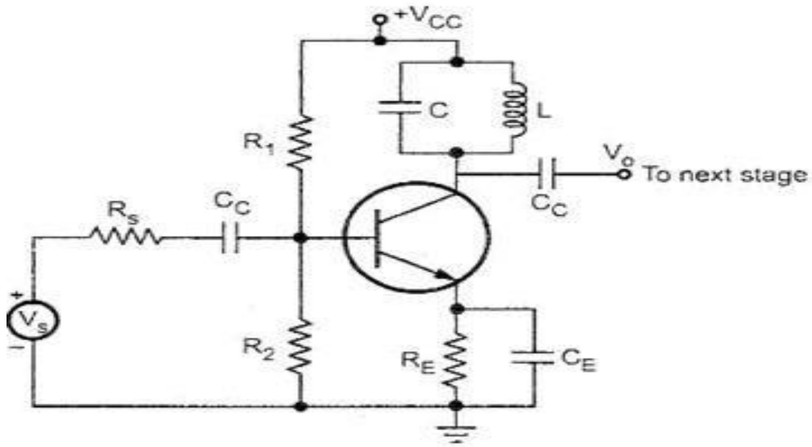


Fig. 3.13 Single tuned capacitive coupled transistor amplifier

Single tuned multistage amplifier circuit uses one parallel tuned circuit as a load in each stage with tuned circuits in all stages tuned to the same frequency. Fig. 3.13 shows a typical single tuned amplifier in CE configuration.

As shown in Fig. 3.13 tuned circuit formed by L and C acts as collector load and resonates at frequency of operation. Resistors R_1, R_2 and R_E along with capacitor C_E provides self bias for the circuit.

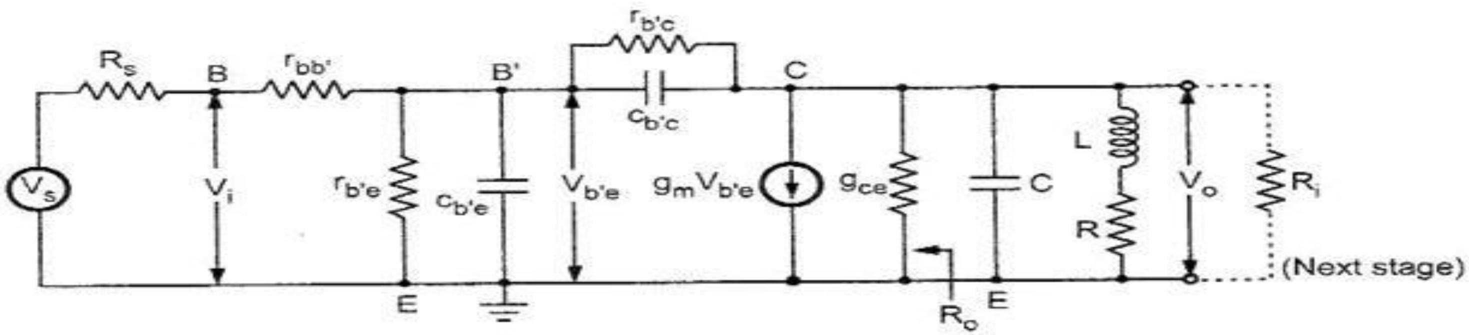


Fig. 3.14 Equivalent circuit of single tuned amplifier

The Fig. 3.14 shows the equivalent circuit for single tuned amplifier using hybrid π parameters.

As shown in the Fig. 3.14, R_i is the input resistance of the next stage and R_o is the output resistance of the current generator $g_m V_{b'e}$. The reactances of the bypass capacitor C_E and the coupling capacitors C_C are negligibly small at the operating frequency and hence these elements are neglected in the equivalent circuit shown in the Fig. 3.14.

The equivalent circuit shown in Fig. 3.14 can be simplified by applying Miller's theorem. Fig. 3.15 shows the simplified equivalent circuit for single tuned amplifier.

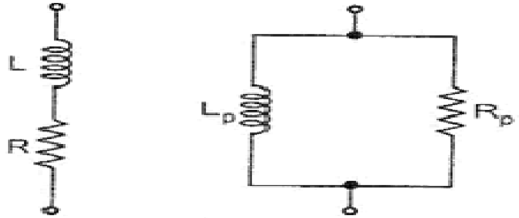


Fig. 3.16

The series RL circuit is represented by its equivalent parallel circuit. The conditions for equivalence are most easily established by equating the admittances of the two circuits shown in Fig. 3.16.

Admittance of the series combination of RL is given as,

$$Y = \frac{1}{R + j\omega L}$$

Multiplying numerator and denominator by $R - j\omega L$ we get,

$$Y = \frac{R - j\omega L}{R^2 + \omega^2 L^2} = \frac{R}{R^2 + \omega^2 L^2} - \frac{j\omega L}{R^2 + \omega^2 L^2}$$

$$= \frac{R}{R^2 + \omega^2 L^2} - \frac{j\omega^2 L}{\omega(R^2 + \omega^2 L^2)}$$

$$= \frac{1}{R_p} + \frac{1}{j\omega L_p}$$

where $$R_p = \frac{R^2 + \omega^2 L^2}{R} \quad \text{... (4)}$$

and $$L_p = \frac{R^2 + \omega^2 L^2}{\omega^2 L} \quad \text{... (5)}$$

Centre frequency

The centre frequency or resonant frequency is given as,

$$f_r = \frac{1}{2\pi\sqrt{L_p C_{eq}}} \quad \text{...(6)}$$

where $$L_p = \frac{R^2 + \omega^2 L^2}{\omega^2 L}$$

and $$C_{eq} = C_{b'c}\left(\frac{A-1}{A}\right) + C \quad \text{...(7)}$$

$$= C_o + C$$

Therefc where ω_r is the centre frequency or resonant frequency. ...nd the tuned circuit capacitance.

Quality factor Q

The quality factor Q of the coil at resonance is given by,

$$Q_r = \frac{\omega_r L}{R} \quad \text{...(8)}$$

From equation (4) we have,

$$R_p = \frac{R^2 + \omega^2 L^2}{R} = R + \frac{\omega^2 L^2}{R}$$

As $\frac{\omega^2 L^2}{R} >> 1$, $R_p = \frac{\omega^2 L^2}{R}$ ...(9)

From equation (5) we have,

$$L_p = \frac{R^2 + \omega^2 L^2}{\omega^2 L} = \frac{R^2}{\omega^2 L} + L$$

$$\approx L \qquad \because \omega L >> R \qquad \text{... (10)}$$

From equation (9), we can express R_p at resonance as,

$$R_p = \frac{\omega_r^2 L^2}{R}$$

$$= \omega_r Q_r L \qquad \because Q_r = \frac{\omega_r L}{R} \qquad \text{... (11)}$$

Therefore, Q_r can be expressed interms of R_p as,

$$Q_r = \frac{R_p}{\omega_r L} \qquad \text{...(12)}$$

The effective quality factor including load can be calculated looking at the simplified equivalent output circuit for single tuned amplifier.

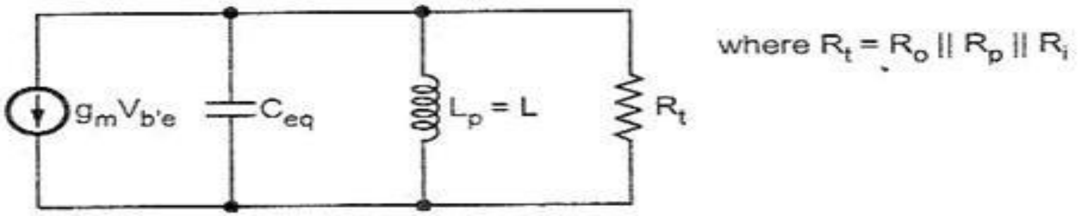


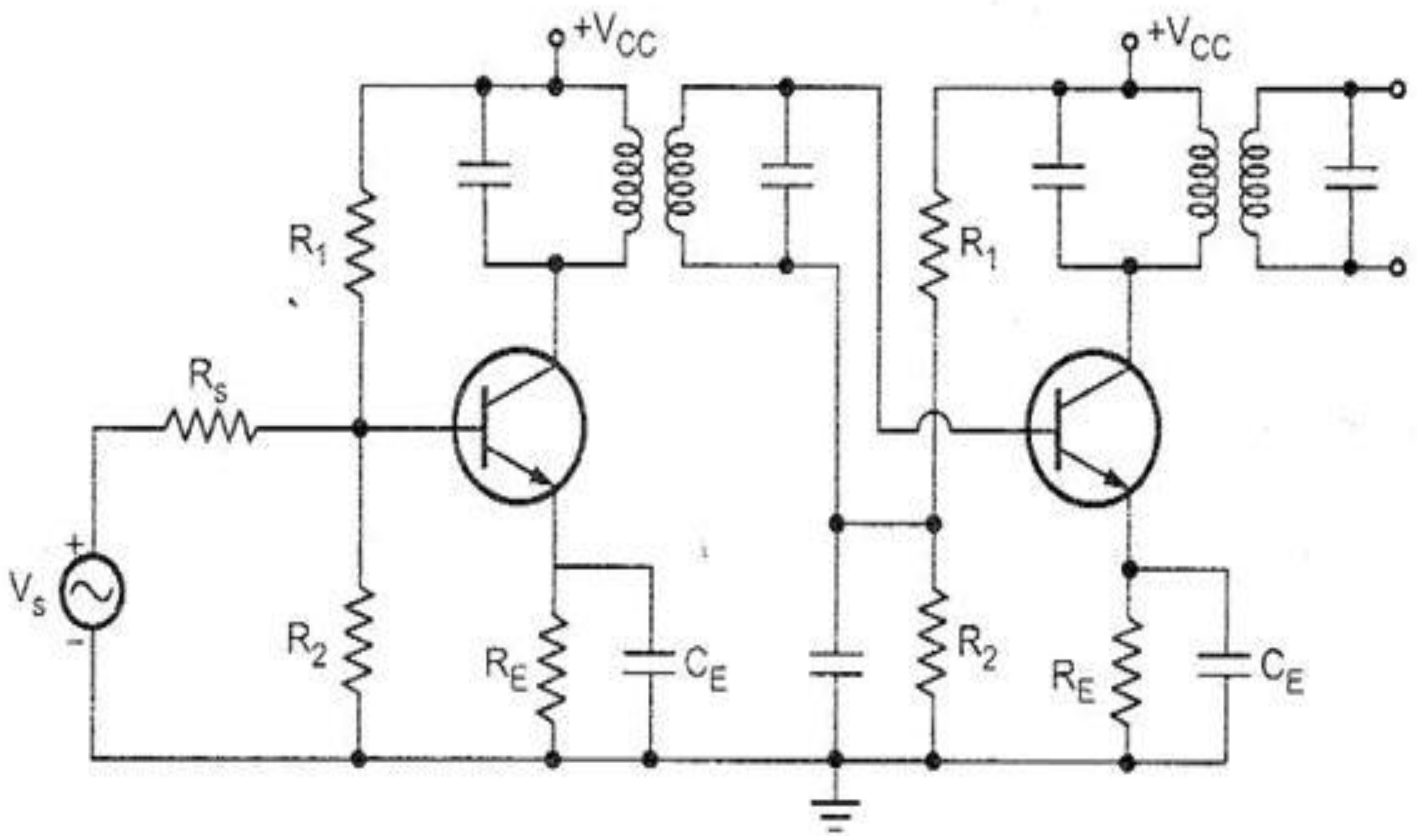
Fig. 3.17 Simplified output circuit for single tuned amplifier

$$\text{Effective quality factor } Q_{eff} = \frac{\text{Susceptance of inductance L or capacitance C}}{\text{Conductance of shunt resistance } R_t}$$

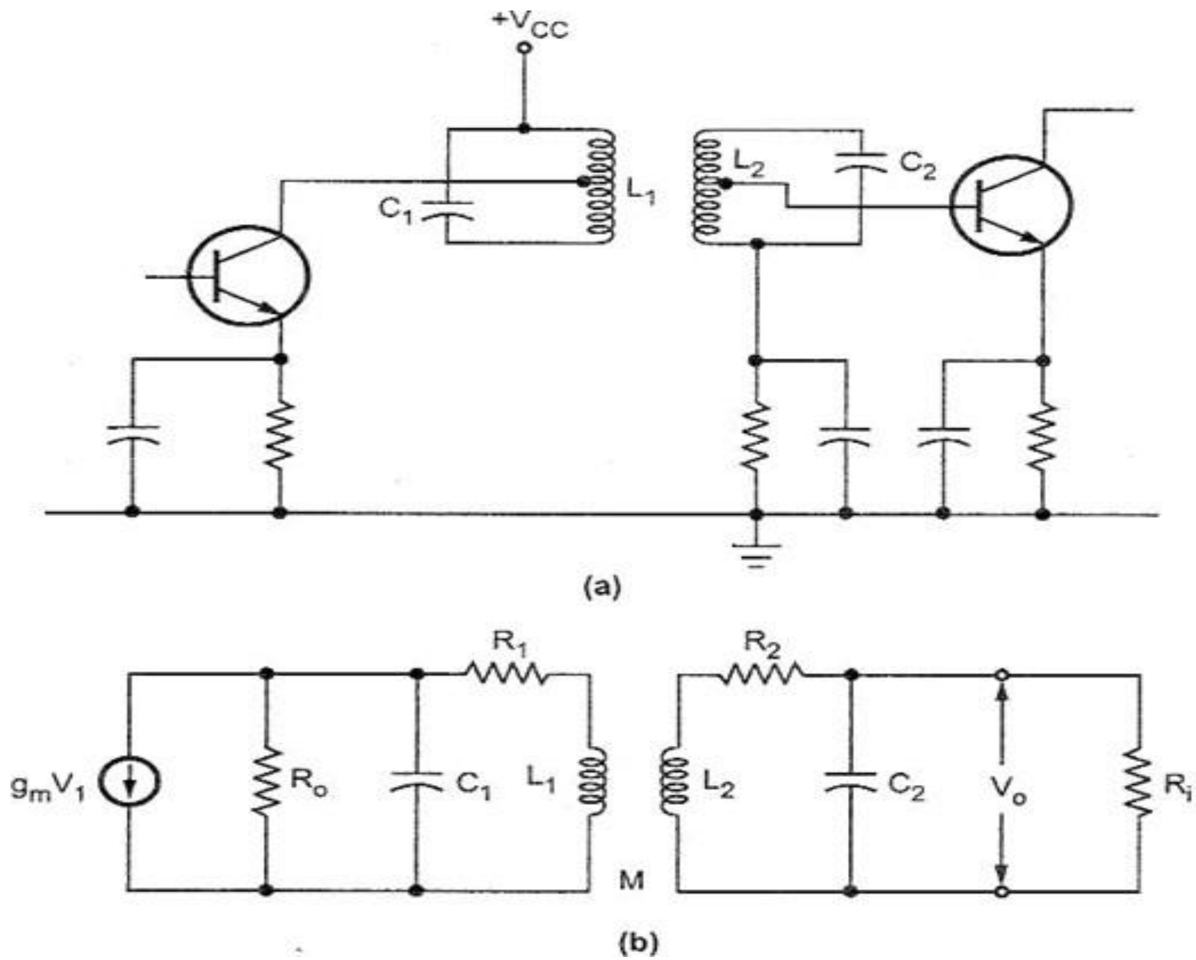
$$= \frac{R_t}{\omega_r L} \text{ or } \omega_r C_{eq} R_t \qquad \text{... (13)}$$

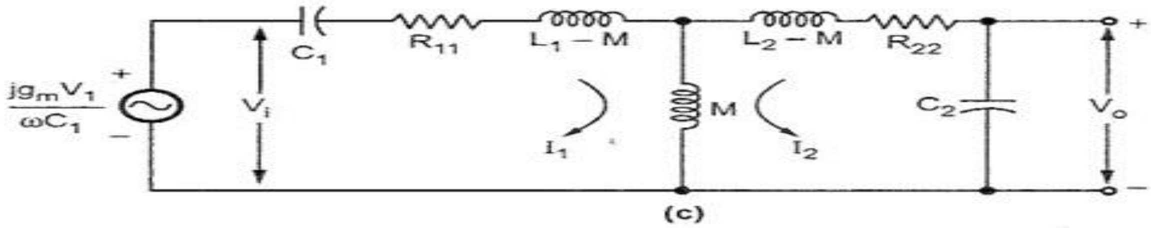
DOUBLE TUNED AMPLIFIER:

The below figure shows double tuned RF amplifier in CE configuration. Here, voltage developed across tuned circuit is coupled inductively to another tuned circuit. Both tuned circuits are tuned to the same frequency.



Analysis of double tuned circuits:





(c)

Fig. 3.19 Equivalent circuits for double tuned amplifier

Therefore we can write,

$$R_{11} = \frac{\omega_o^2 L_1^2}{R_o} + R_1$$

$$R_{12} = \frac{\omega_o^2 L_2^2}{R_i} + R_2$$

In the simplified circuit the current source is replaced by voltage source, which is now in series with C_1. It also shows the effect of mutual inductance on primary and secondary sides.

We know that, $Q = \frac{\omega_r L}{R}$

Therefore, the Q factors of the individual tank circuits are

$$Q_1 = \frac{\omega_r L_1}{R_{11}} \text{ and } Q_2 = \frac{\omega_r L_2}{R_{22}} \quad \ldots(1)$$

Usually, the Q factors for both circuits are kept same. Therefore, $Q_1 = Q_2 = Q$ and the resonant frequency $\omega_r^2 = 1/L_1 C_1 = 1/L_2C_2$.

Looking at Fig. 3.19 (c), the output voltage can be given as,

$$V_o = -\frac{j}{\omega_r C_2} I_2 \quad \ldots(2)$$

To calculate V_o/V_1 it is necessary to represent I_2 interms of V_1. For this we have to find the transfer admittance Y_T. Let us consider the circuit shown in Fig. 3.20. For this circuit, the transfer admittance can be given as,

$$= \left[\frac{g_m \, \omega_r \sqrt{L_1 \, L_2} \, kQ^2}{4\,Q\delta - j\,(1 + k^2Q^2 - 4\,Q^2\,\delta^2)} \right] \quad \ldots (4)$$

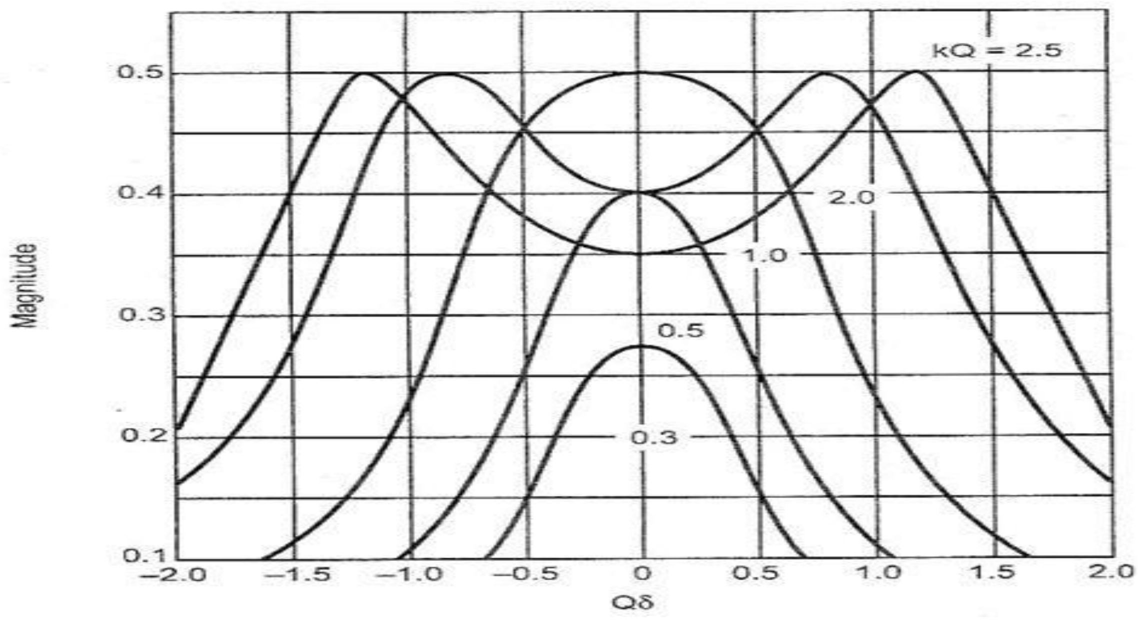
Taking the magnitude of equation (4) we have,

$$|A_v| = g_m \, \omega_r \sqrt{L_1 \, L_2} \, Q \frac{kQ}{\sqrt{1 + k^2Q^2 - 4\,Q^2\,\delta^2 + 16\,Q^2\,\delta^2}} \quad \ldots (5)$$

The Fig. 3.21 shows the universal response curve for double tuned amplifier plotted with kQ as a parameter.

The frequency deviation δ at which the gain peaks occur can be found by maximizing equation (4), i.e.

$$4Q\delta - j\,(1 + k^2Q^2 - 4Q^2\delta^2) = 0 \quad \ldots (6)$$



At $k^2Q^2 = 1$, i.e. $k = \frac{1}{Q}$, $f_1 = f_2 = f_r$. This condition is known as **critical coupling**. For values of $k < 1/Q$, the peak gain is less than maximum gain and the coupling is poor.

At $k > 1/Q$, the circuit is overcoupled and the response shows the double peak. Such double peak response is useful when more bandwidth is required.

The gain magnitude at peak is given as,

$$|A_p| = \frac{g_m \omega_o \sqrt{L_1 L_2}\, kQ}{2} \qquad \dots (8)$$

And gain at the dip at $\delta = 0$ is given as,

$$|A_d| = |A_p| \frac{2\,kQ}{1 + k^2Q^2} \qquad \dots (9)$$

The ratio of peak gain and dip gain is denoted as γ and it represents the magnitude of the ripple in the gain curve.

$$\gamma = \left|\frac{A_p}{A_d}\right| = \frac{1 + k^2Q^2}{2\,kQ} \qquad \dots (10)$$

$$\gamma = \left|\frac{A_p}{A_d}\right| = \frac{1 + k^2Q^2}{2\,kQ} \qquad \dots (10)$$

Using quadratic simplification and choosing positive sign we get,

$$kQ = \gamma + \sqrt{\gamma^2 - 1} \qquad \dots (11)$$

The bandwidth between the frequencies at which the gain is $|A_d|$ is the useful bandwidth of the double tuned amplifier. It is given as,

$$BW = 2\,\delta' = \sqrt{2}\,(f_2 - f_1) \qquad \dots (12)$$

At 3 dB bandwidth,

$$\gamma = \sqrt{2}$$

$$\therefore \quad kQ = \gamma + \sqrt{\gamma^2 + 1} = \sqrt{2} + \sqrt{\sqrt{2}^2 + 1} = 2.414$$

$$\therefore \quad 3\text{ dB BW} = 2\,\delta' = \sqrt{2}\,(f_2 - f_1)$$

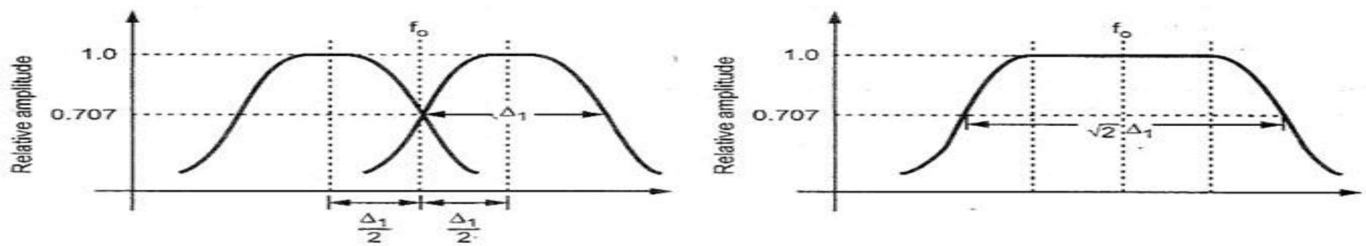
$$= \sqrt{2}\left[f_r\left(1 + \frac{1}{2Q}\sqrt{k^2Q^2 - 1}\right) - f_r\left(1 - \frac{1}{2Q}\sqrt{k^2Q^2 - 1}\right)\right]$$

$$= \sqrt{2}\left[\left(\frac{f_r}{Q}\sqrt{k^2Q^2 - 1}\right)\right]$$

$$= \sqrt{2}\left[\frac{f_r}{Q}\sqrt{(2.414)^2 - 1}\right] = \frac{3.1\, f_r}{Q}$$

STAGGER TUNED AMPLIFIER:

The double tuned amplifier gives greater 3dB bandwidth having steeper sides and flat top. But alignment of double tuned amplifier is difficult. To overcome this problem two single tuned cascaded amplifiers having certain bandwidth are taken and their resonant frequencies are so adjusted that they are separated by an amount equal to the bandwidth of each stage. Since resonant frequencies are displaced or staggered, they are known as stagger tuned amplifiers.
The advantage of stagger tuned amplifier is to have a better flat, wideband characteristics in contrast with a very sharp, rejective, narrow band characteristics of synchronously tuned circuits (tuned to same resonant frequencies).



(a) Response of individual stages
(b) Overall response of staggered pair
Fig. 3.23

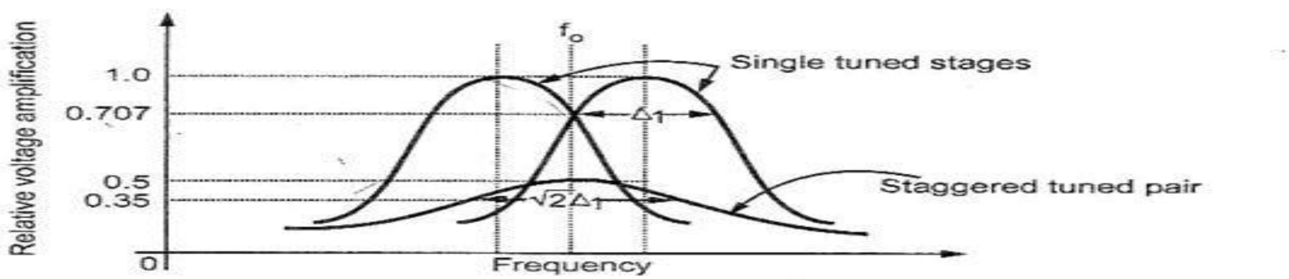


Fig. 3.24 Response of individually tuned and staggered tuned pair

Analysis

L 2.35

From equation (14) of section 3.4 we can write the gain of the single tuned amplifier as,

$$\frac{A_v}{A_v \text{ (at resonance)}} = \frac{1}{1+2jQ_{eff}\,\delta}$$

$$= \frac{1}{1+jX}, \text{ where } X = 2\,Q_{eff}\,\delta$$

Since in stagger tuned amplifiers the two single tuned cascaded amplifiers with separate resonant frequencies are used, we can assume that the one stage is tuned to the frequency $f_r + \delta$ and other stage is tuned to the frequency $f_r - \delta$. Therefore we have,

$$f_{r1} = f_r + \delta$$

and

$$f_{r2} = f_r - \delta$$

According to these tuned frequencies the selectivity functions can be given as,

$$\frac{A_v}{A_v \text{ (at resonance)}_1} = \frac{1}{1+j(X+1)} \text{ and}$$

$$\frac{A_v}{A_v \text{ (at resonance)}_2} = \frac{1}{1+j(X-1)}.$$

The overall gain of these two stages is the product of individual gains of the two stages.

Power Amplifiers

BASICS ….

- In mathematical terms, if the input signal is denoted as **S**, the output of a *perfect* amplifier is **X*S**, where X is a *constant* (a fixed number). The "*" symbol means
  ”multiplied by".

- No amplifier does exactly the ideal .

Contd..

- **But many do a very good job if they are operated within their advertised power ratings .**

- **Output signal of *all* amplifiers contain additional (unwanted) components that are not present in the input signal; these additional characteristics may be lumped together and are generally known as *distortion*.**

CONTD….

- Power amplifiers get the necessary energy for amplification of input signals from the AC wall outlet to which they are plugged into.

- If you had a *perfect* amplifier, all of the energy the amplifier took from the AC outlet would be converted to useful output (to the speakers)

Contd ….

- Power is not really something that can be "amplified". *Voltage* and *current* can be amplified.

- The term "power amplifier" although technically incorrect has become understood to mean an amplifier that is intended to drive a load (such as a speaker, a motor, etc).

Functional blocks of an amplifier

- All power amplifiers have:

1. A Power supply
2. An input stage
3. An output stage

1.Power Supply

- The primary purpose of a power supply in a power amplifier is to take the 120 V AC power from the outlet and convert it to a DC voltage.

- The very best of amplifiers have two totally independent power supplies, one for each channel (they do share a common AC power cord though).

2. Input Stage

- The general purpose of the input stage of a power amplifier (sometimes called the "front end") is to receive and prepare the input signals for "amplification" by the output stage.

- Two types:

  1.Balanced Input

  2.Single Ended Input

2. Input Stage

- **Balanced inputs** are much preferred over **single ended inputs** when interconnection cables are long and/or subject to noisy electrical environments because they provide very good *noise rejection*.

- The input stage also contains things like input level controls.

3.Output Stage

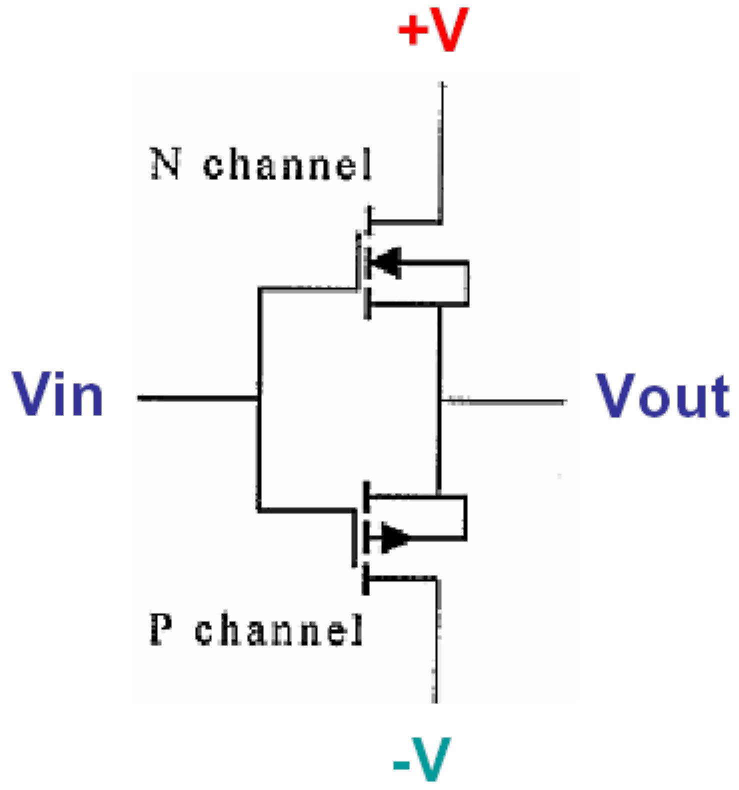
- The portion which actually converts the weak input signal into a much more powerful "replica" which is capable of driving high power to a speaker.
- This portion of the amplifier typically uses a number of "power transistors" (or MOSFETs) and is also responsible for generating the most **heat** in the unit.
- The output stage of an amplifier interfaces to the speakers.

Amplifier Classes

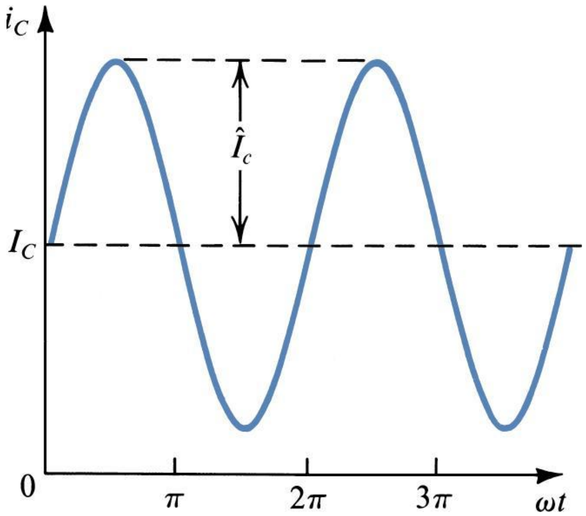
- The **Class** of an amplifier refers to the design of the circuitry within the amp.

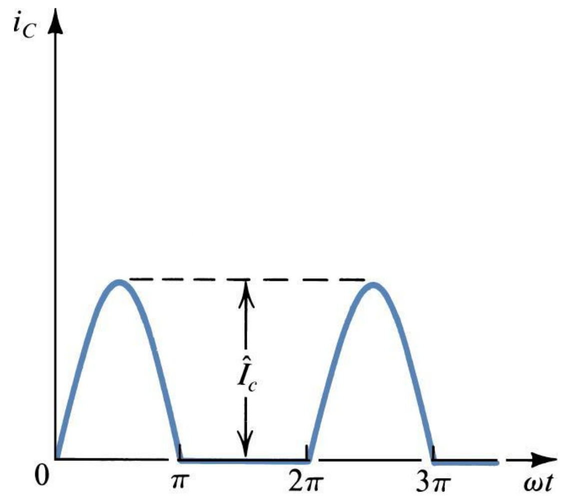
- For audio amplifiers, the **Class of amp refers to the output stage of the amp.**

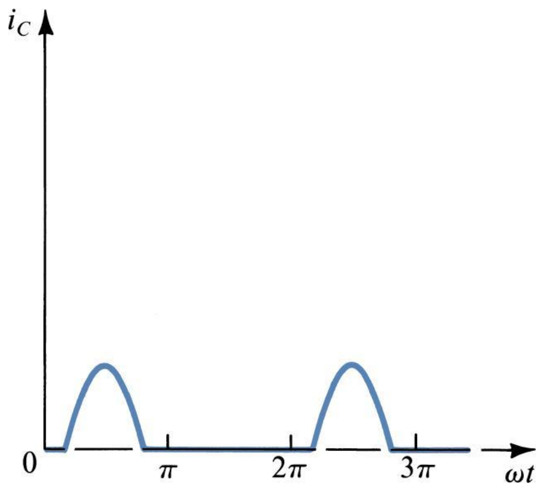
Basic Power Amplifier Output Stage
(Source-Follower MOSFET Configuration)

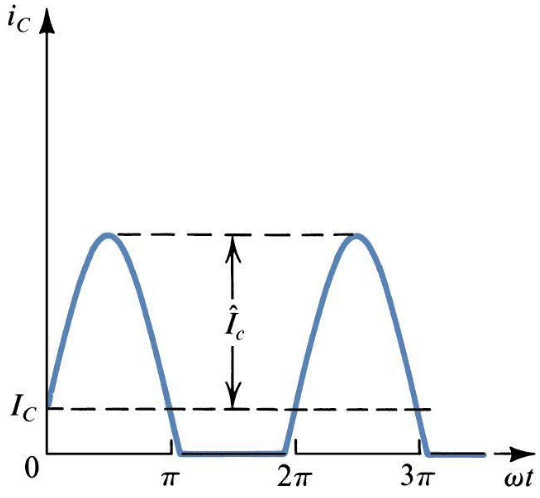


CLASSES









Collector current waveforms for transistors operating in (a) class A, (b) class B, (c) class AB, and (d) class C amplifier stages.

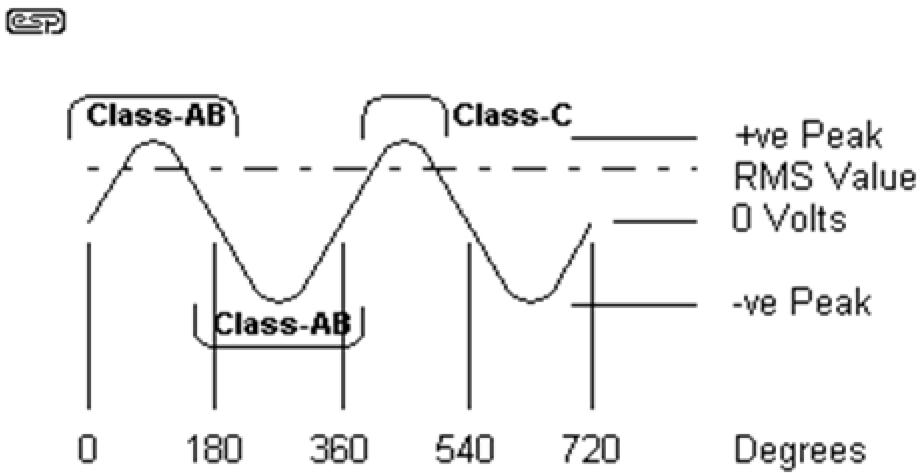


Figure 1 - The Sinewave Cycle

- Class-A: Output device(s) conduct through 360 degrees of input cycle (never switch off) - A single output device is possible. The device conducts for the entire waveform in Figure 1
- Class-B: Output devices conduct for 180 degrees (1/2 of input cycle) - for audio, two output devices in "push-pull" must be used (see Class-AB)
- Class-AB: Halfway (or partway) between the above two examples (181 to 200 degrees typical) - also requires push-pull operation for audio. The conduction for each output device is shown in Figure 1.

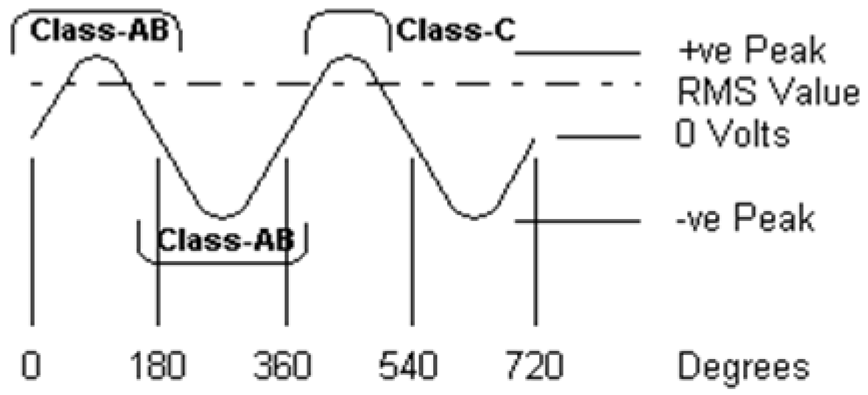


Figure 1 - The Sinewave Cycle

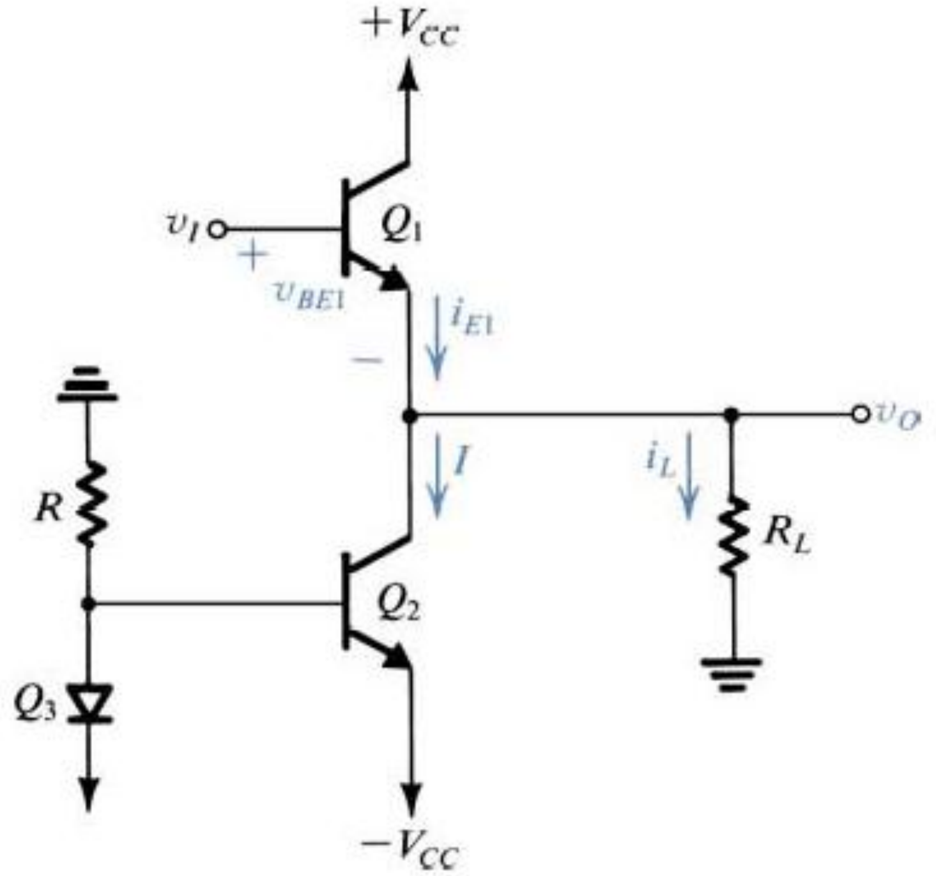
- Class-C: Output device(s) conduct for less than 180 degrees (100 to 150 degrees typical) - Radio Frequencies only - cannot be used for audio! This is the sound heard when one of the output devices goes open circuit in an audio amp! See Figure 1, showing the time the output device conducts

Power Amplifier Classes – “A”

- Class “A”
  - key ingredient of class A operation is that output device is always on
  - single-ended design with only one type polarity output device
  - the most inefficient of all power amplifier designs, averaging only around 20% (large, heavy, and run very hot)
  - are inherently the most linear, with the least amount of distortion

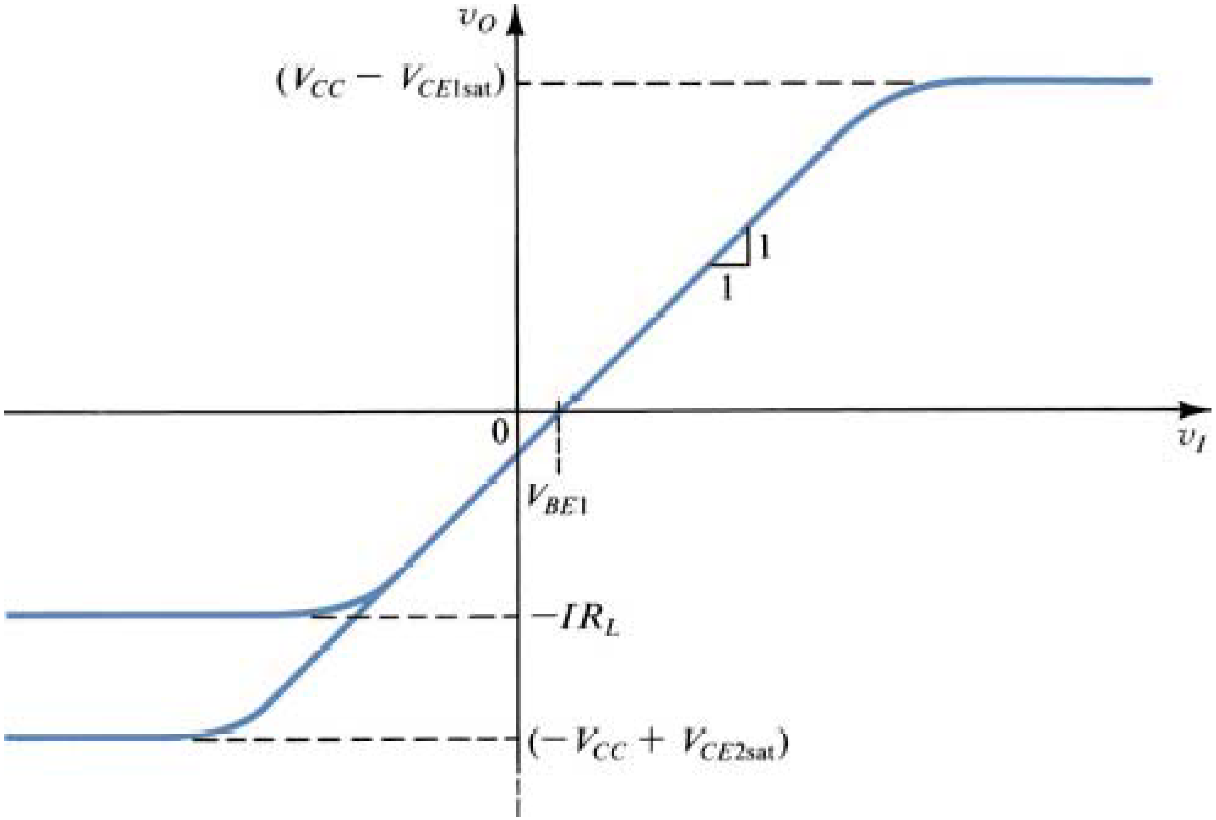
Class A Output Stage

- Class A output stage is a simple linear current amplifier.
- It is also very inefficient, typical maximum efficiency between 10 and 20 %.
- Only suitable for low power applications.
- High power requires much better efficiency.

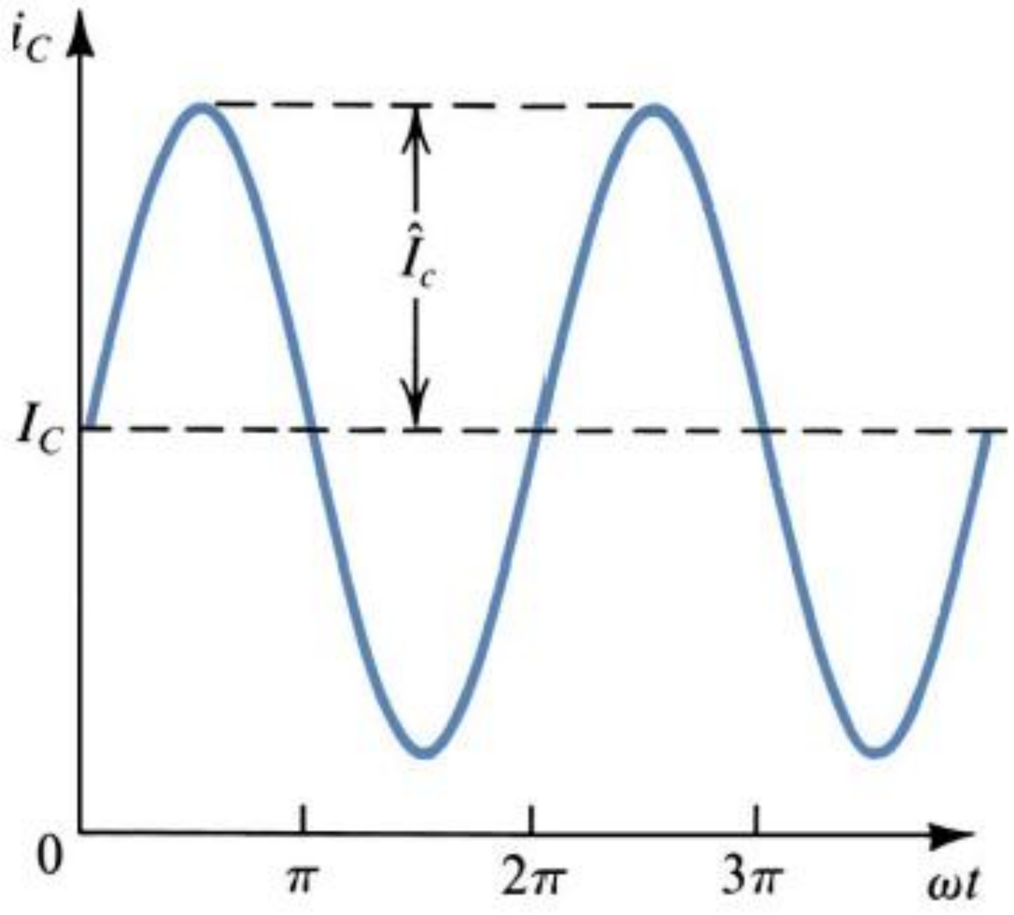


An emitter follower (Q_1) biased with a constant current I supplied by transistor Q_2.

Transfer Characteristics

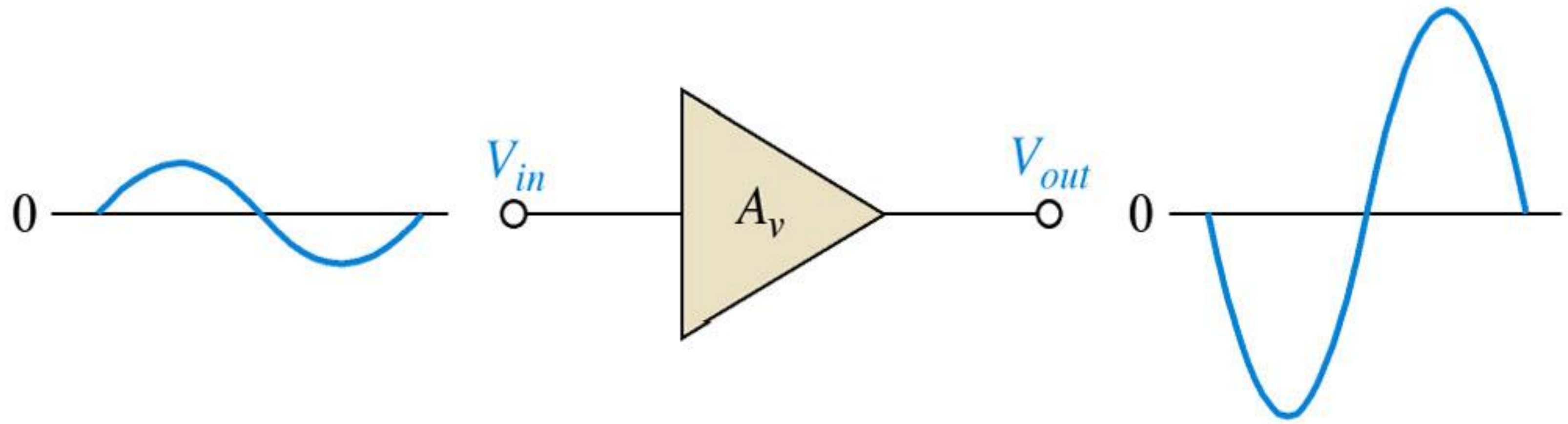


Transfer characteristic of the emitter follower. This linear characteristic is obtained by neglecting the change in v_{BE1} with i_L. The maximum positive output is determined by the saturation of Q_1. In the negative direction, the limit of the linear region is determined either by Q_1 turning off or by Q_2 saturating, depending on the values of I and R_L.

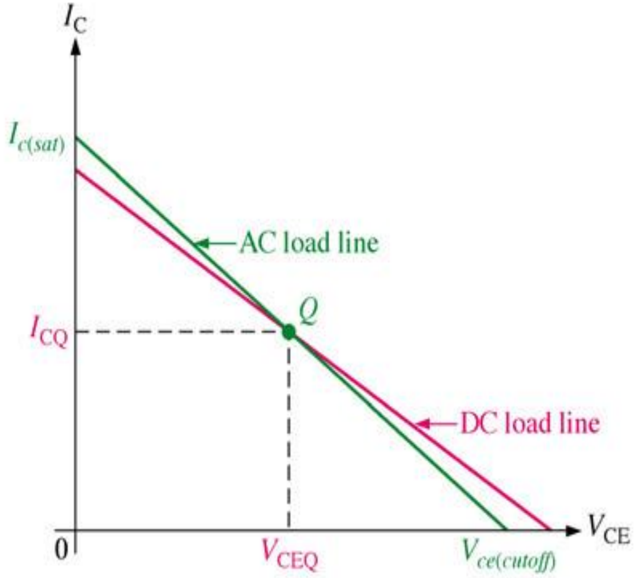


Collector current waveforms for transistors operating in class A amplifier stage

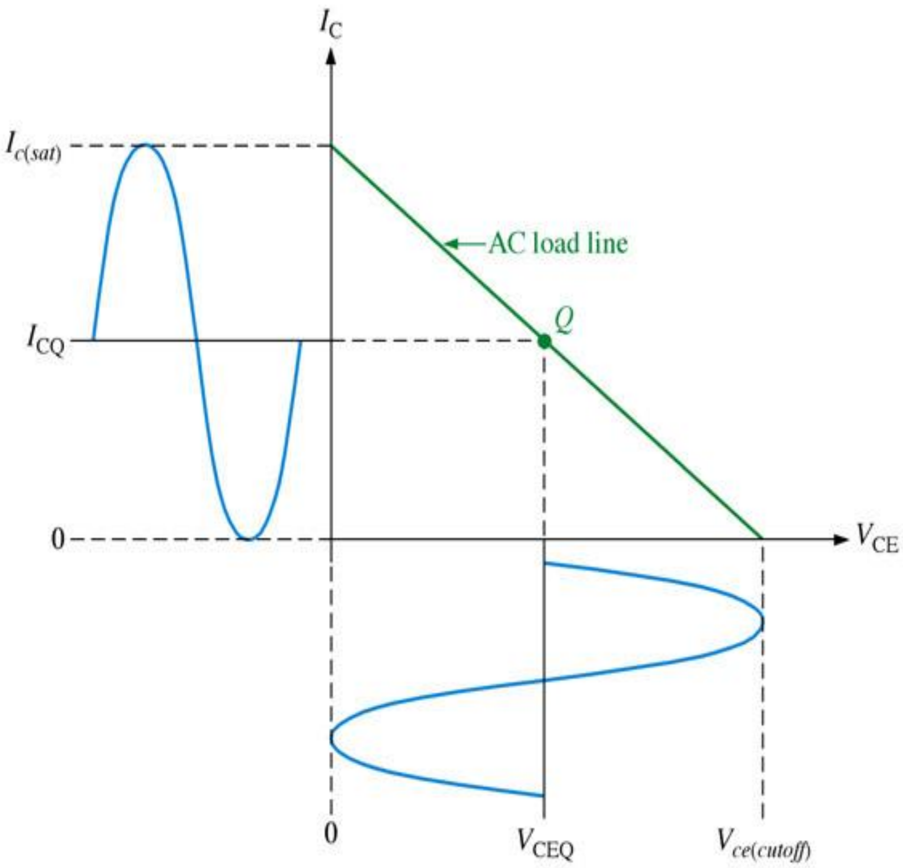
BASIC CLASS A AMPLIFIER OPERATION. OUTPUT IS SHOWN 180 DEGREE OUT OF PHASE WITH THE INPUT (INVERTED).



Maximum class A output occurs when the Q-point is centered on the ac load line.

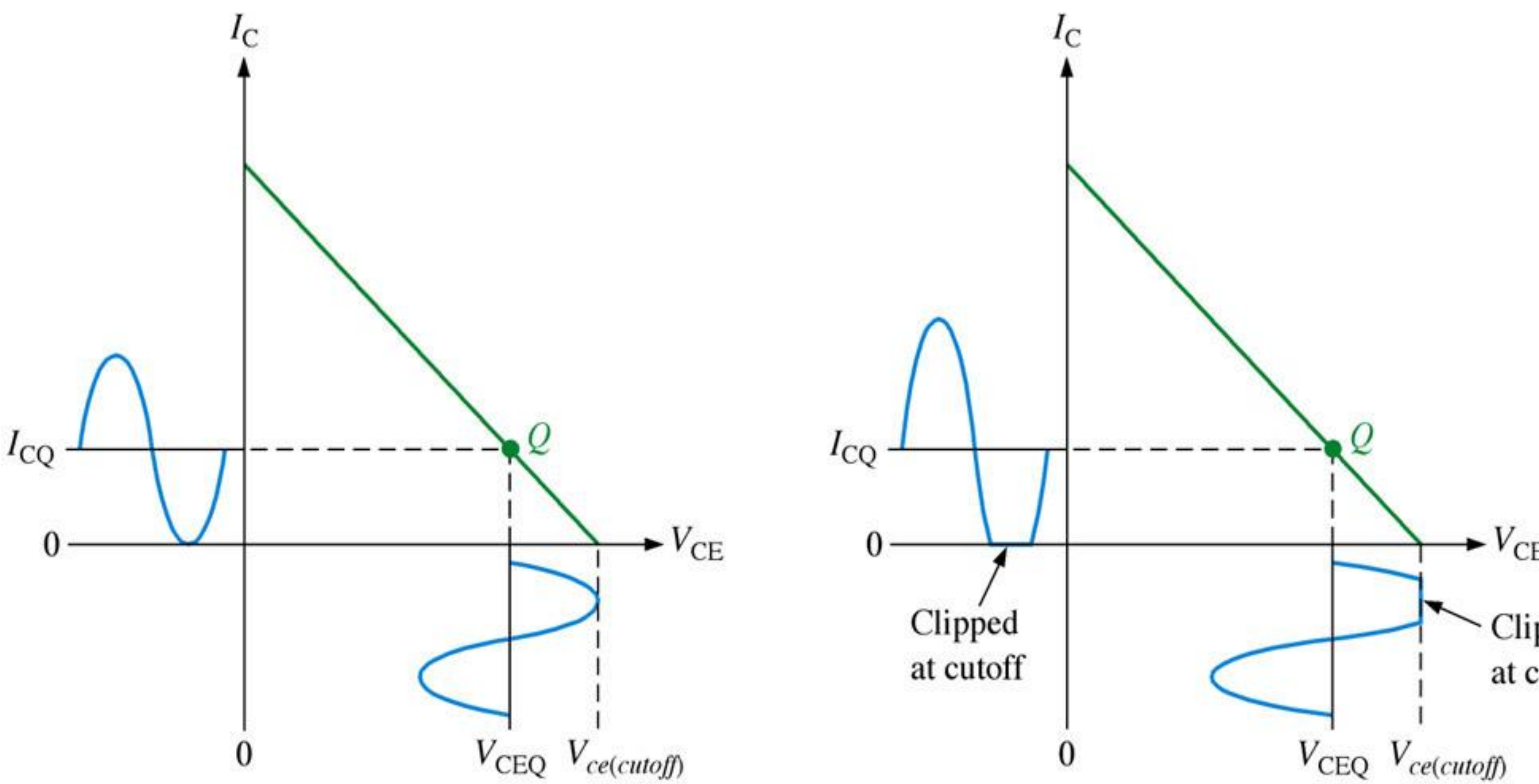


(a)



(b)

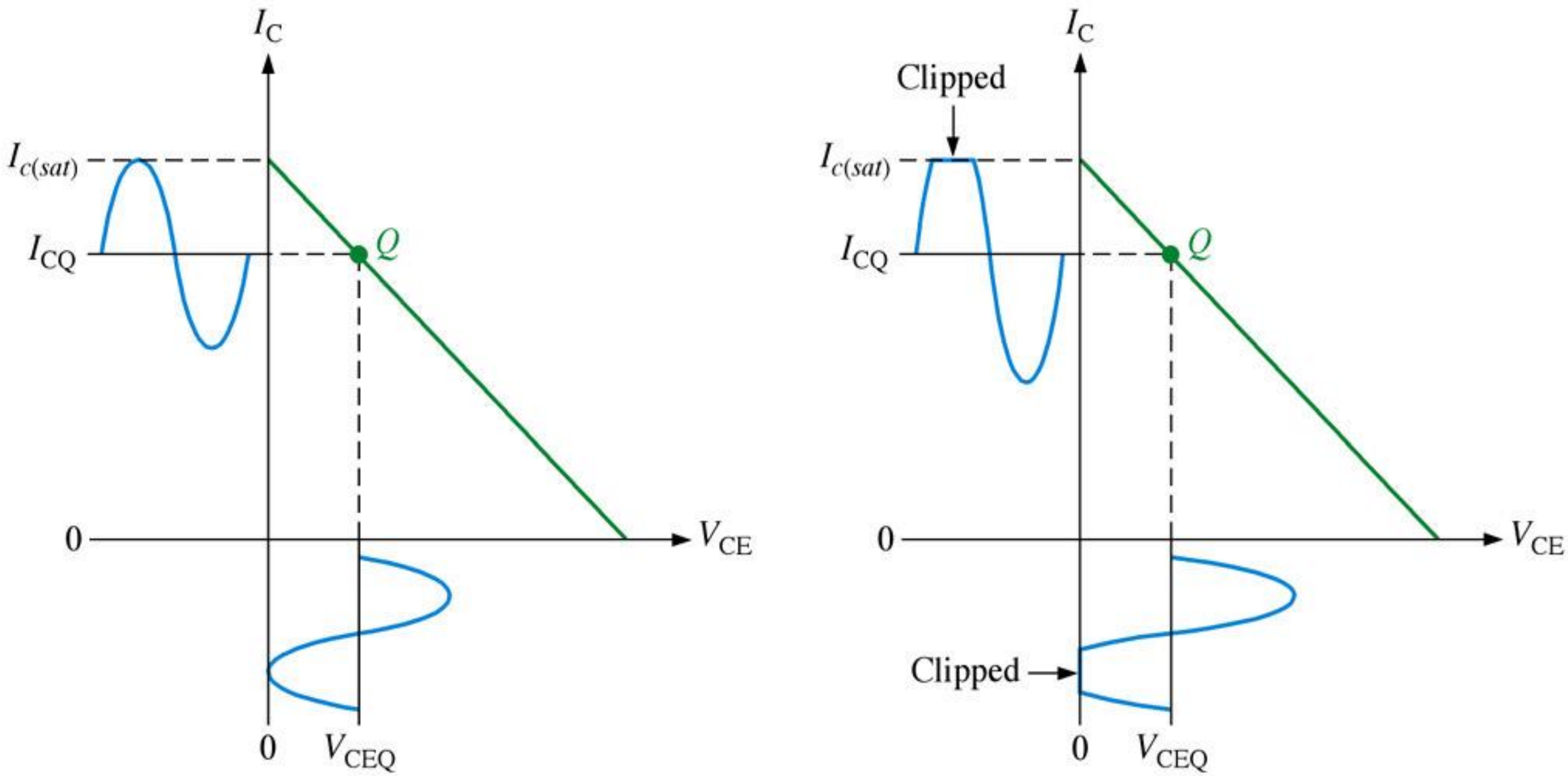
Q-POINT CLOSER TO CUTOFF.



(a) Amplitude of V_{ce} and I_c limited by cutoff

(b) Transistor driven into cutoff by a further increase in input amplitude

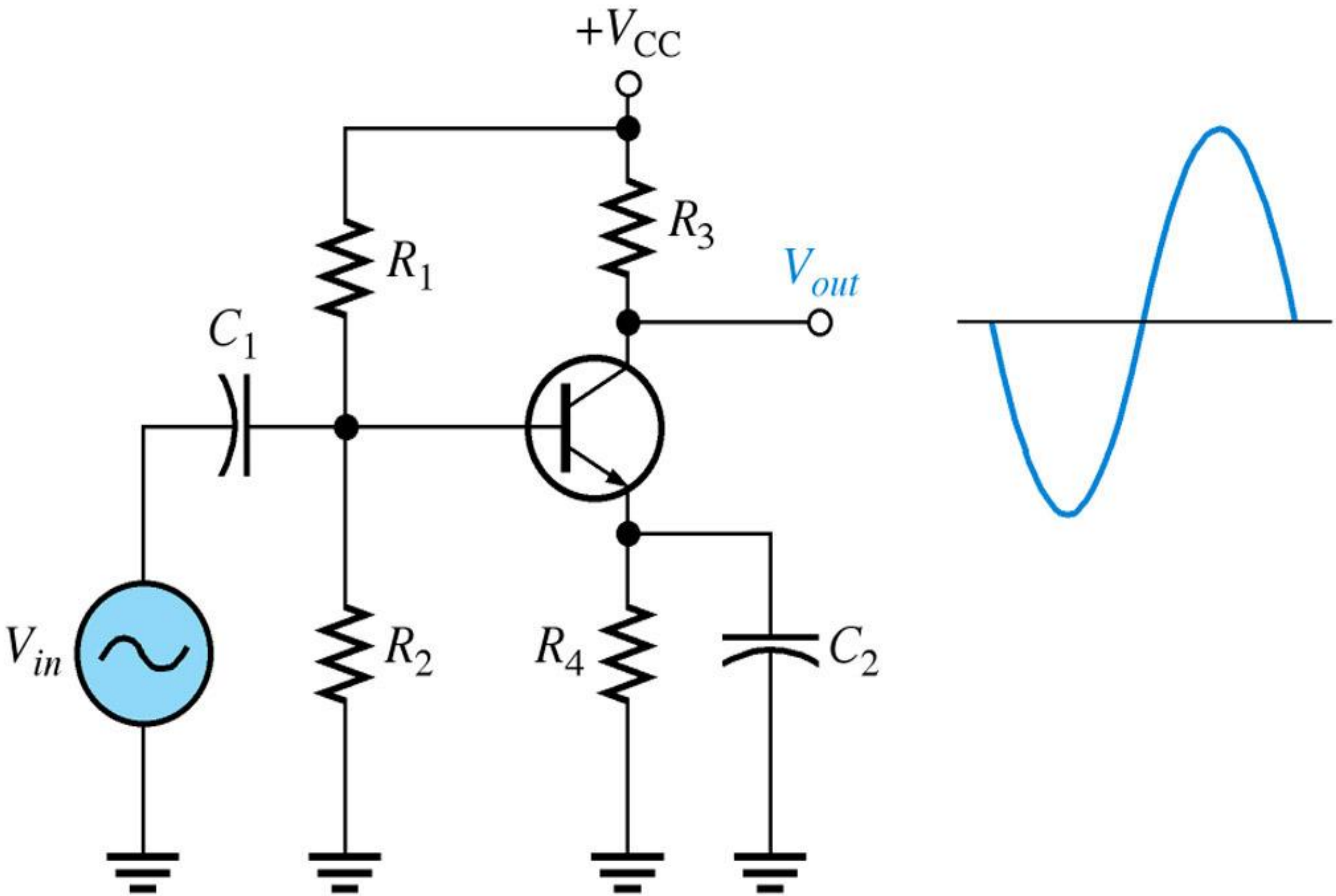
Q-POINT CLOSER TO SATURATION.



(a) Amplitude of V_{ce} and I_c limited by saturation

(b) Transistor driven into saturation by a further increase in input amplitude

CLASS A POWER AMPLIFIER WITH CORRECT OUTPUT VOLTAGE SWING.



WHY IS CLASS A SO INEFFICIENT ?

- Single transistor can only conduct in one direction.
- D.C. bias current is needed to cope with negative going signals.
- 75 % (or more) of the supplied power is dissipated by d.c.
- Solution : eliminate the bias current.

Class A

- Class A amplifiers have very low distortion (lowest distortion occurs when the volume is low)
- They are very inefficient and are rarely used for high power designs.
- The distortion is low because the transistors in the amp are biased such that they are half "on" when the amp is idling

Class A

- As a result of being half on at idle, a lot of power is dissipated in the devices even when the amp has no music playing!
- Class A amps are often used for "signal" level circuits (where power requirements are small) because they maintain low distortion.

Class-A Benefits

- The first is circuit simplicity.
- The signal is subjected to comparatively little amplification, resulting in an open loop gain which is generally fairly low.
- This means that very little overall feedback is used, so stability and phase should be excellent over the audio frequencies.
- Do not require any frequency compensation.

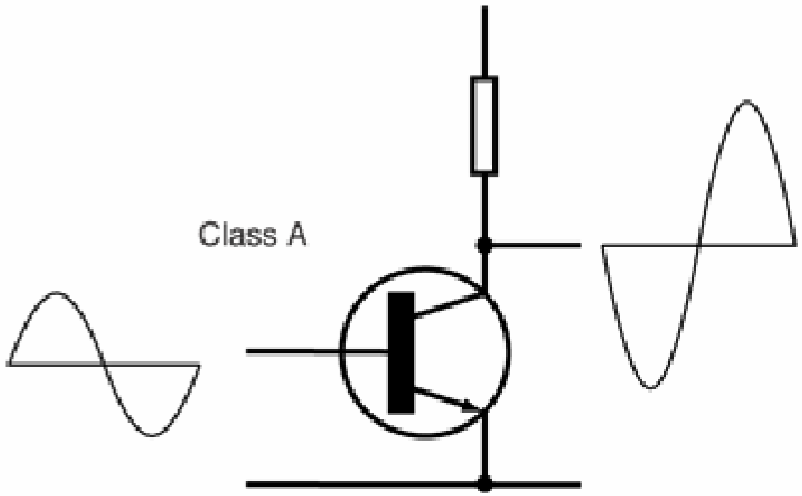
Class-A Benefits

- No cross over distortion
- No switching distortion
- Lower harmonic distortion in the voltage amplifier
- Lower harmonic distortion in the current amplifier
- No signal dependent distortion from the power supply
- Constant and low output impedance
- Simpler design

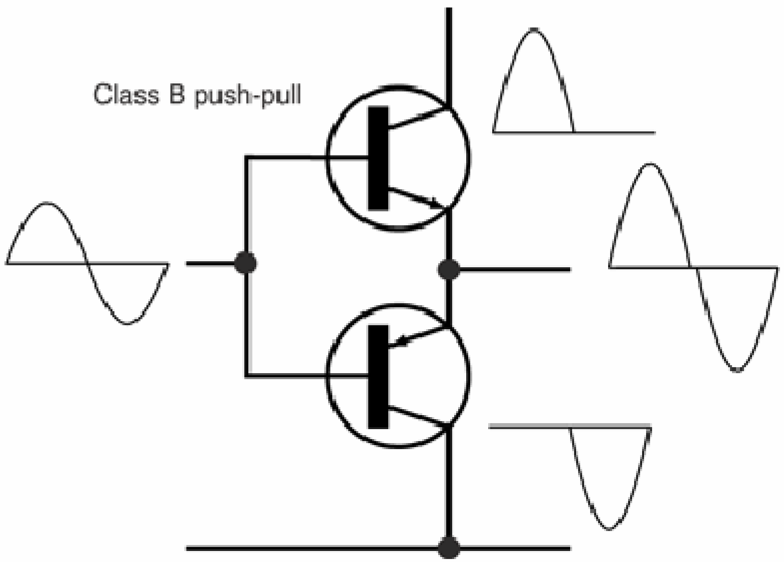
Power Amplifier Classes – “B”

- Class “B”
  - opposite of class A: both output devices are never allowed to be on at the same time
  - each output device is on for exactly one half of a complete sinusoidal signal cycle
  - class B designs show high efficiency but poor linearity around the crossover region (due to the time it takes to turn one device off and the other device on, which translates into extreme crossover distortion)
  - class B designs restricted to low power applications, e.g., battery operated equipment, such as communications audio

Class A vs. Class B

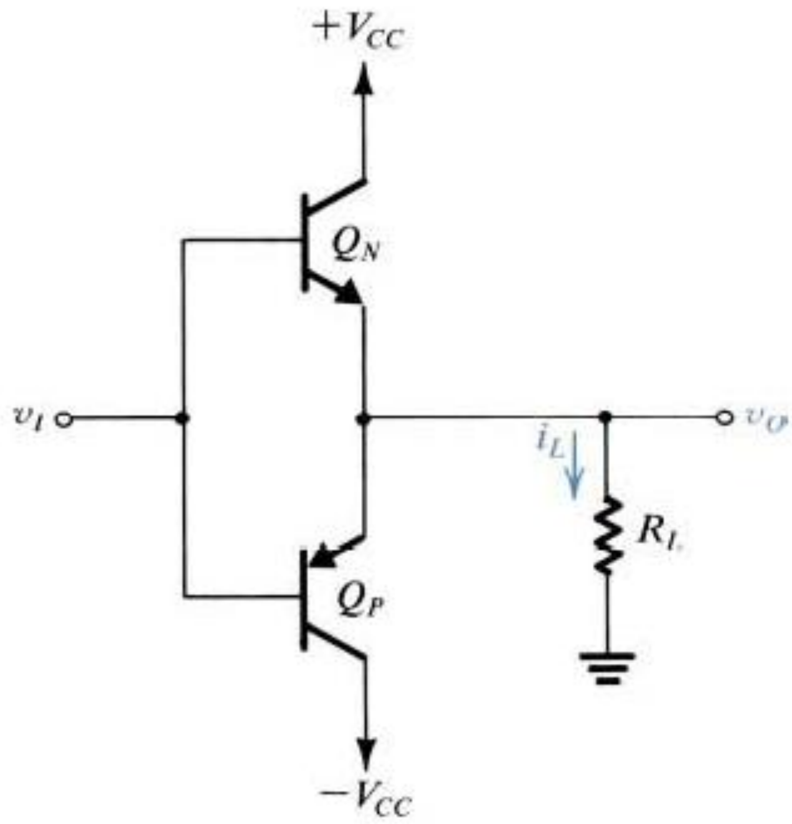


Class A Amplifier



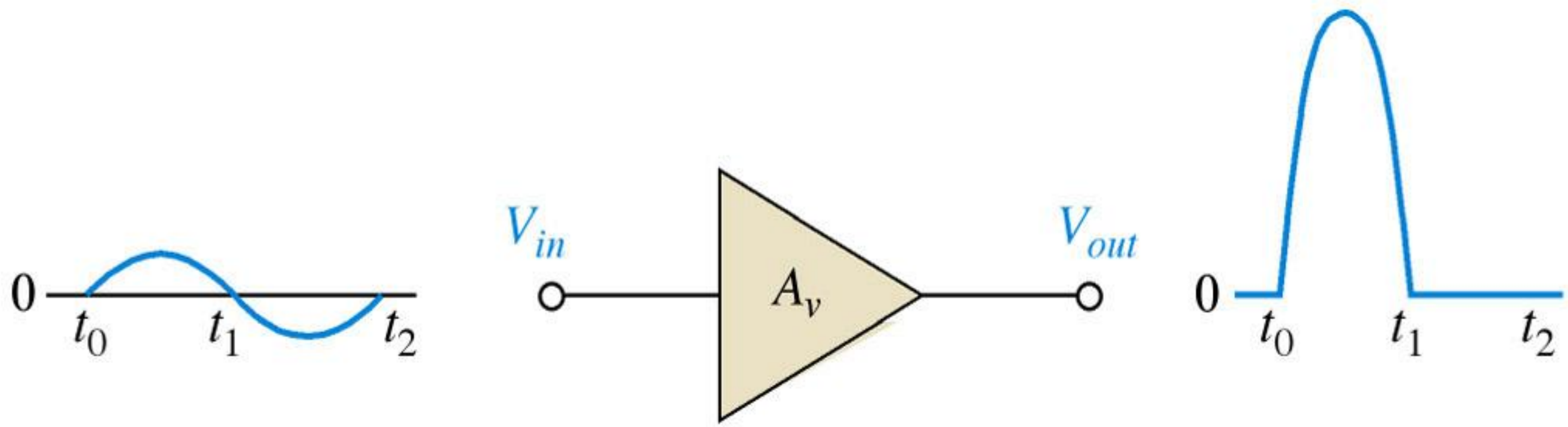
Class B Push-Pull Amplifier

CIRCUIT OPERATION

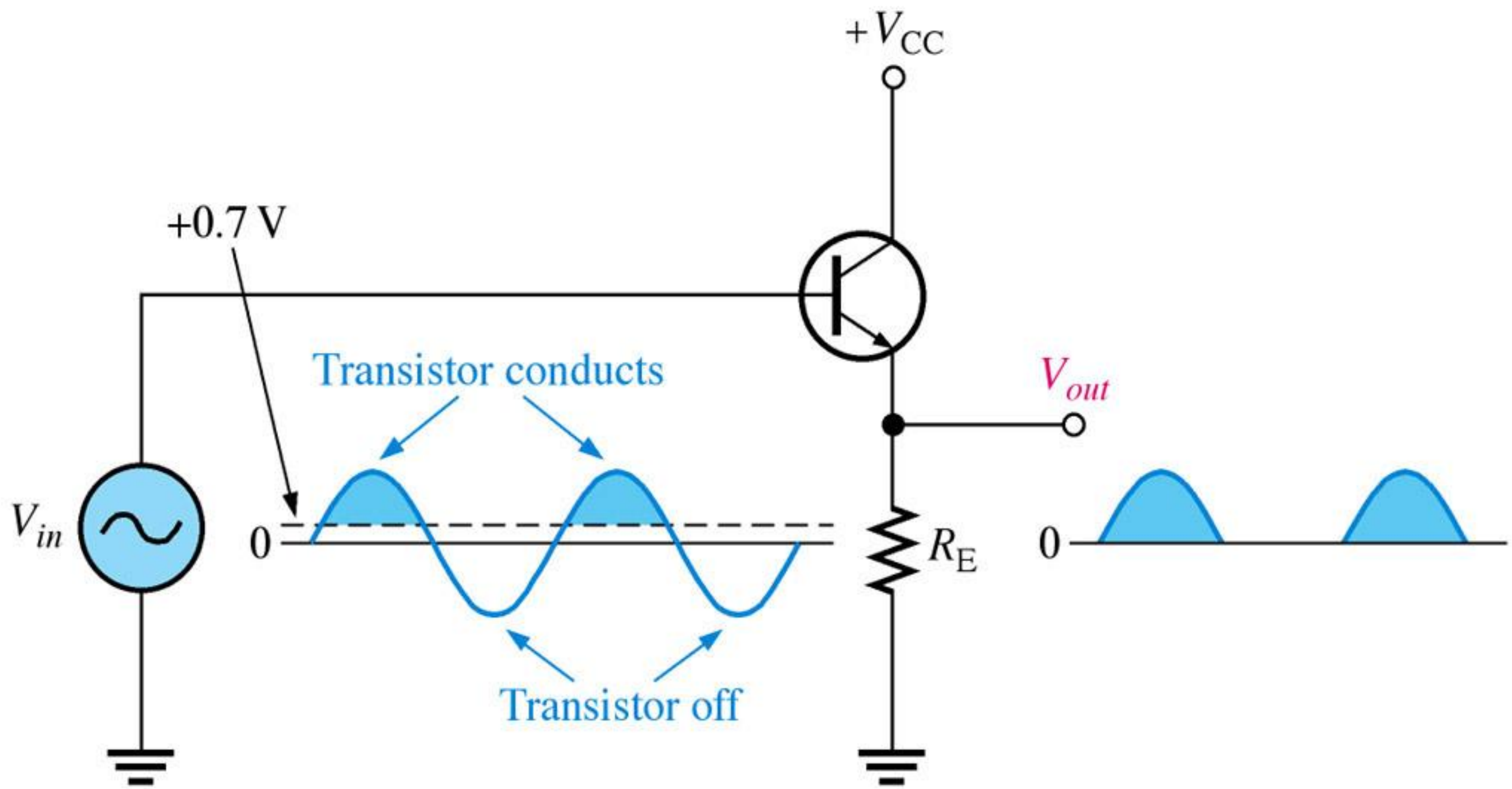


Class B output stage.

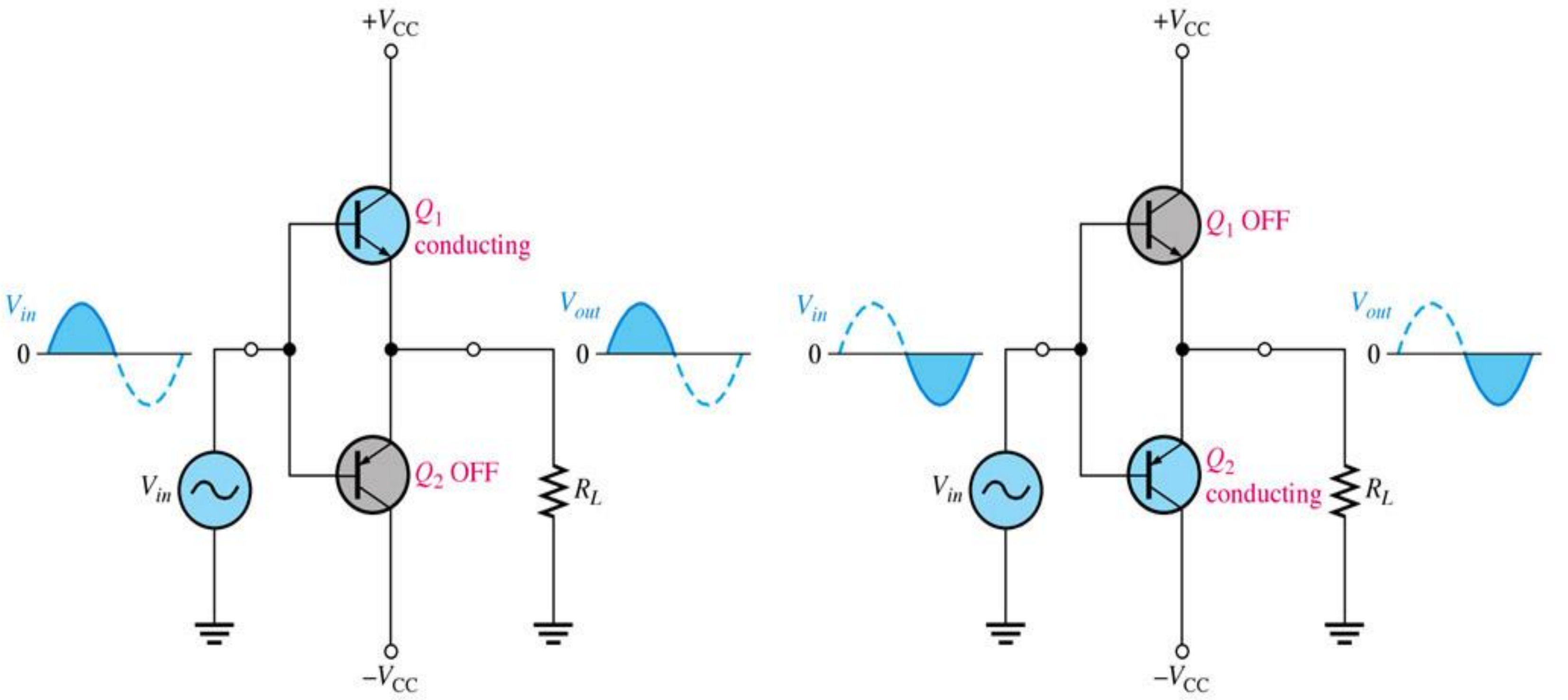
BASIC CLASS B AMPLIFIER OPERATION (NONINVERTING).



COMMON-COLLECTOR CLASS B AMPLIFIER.



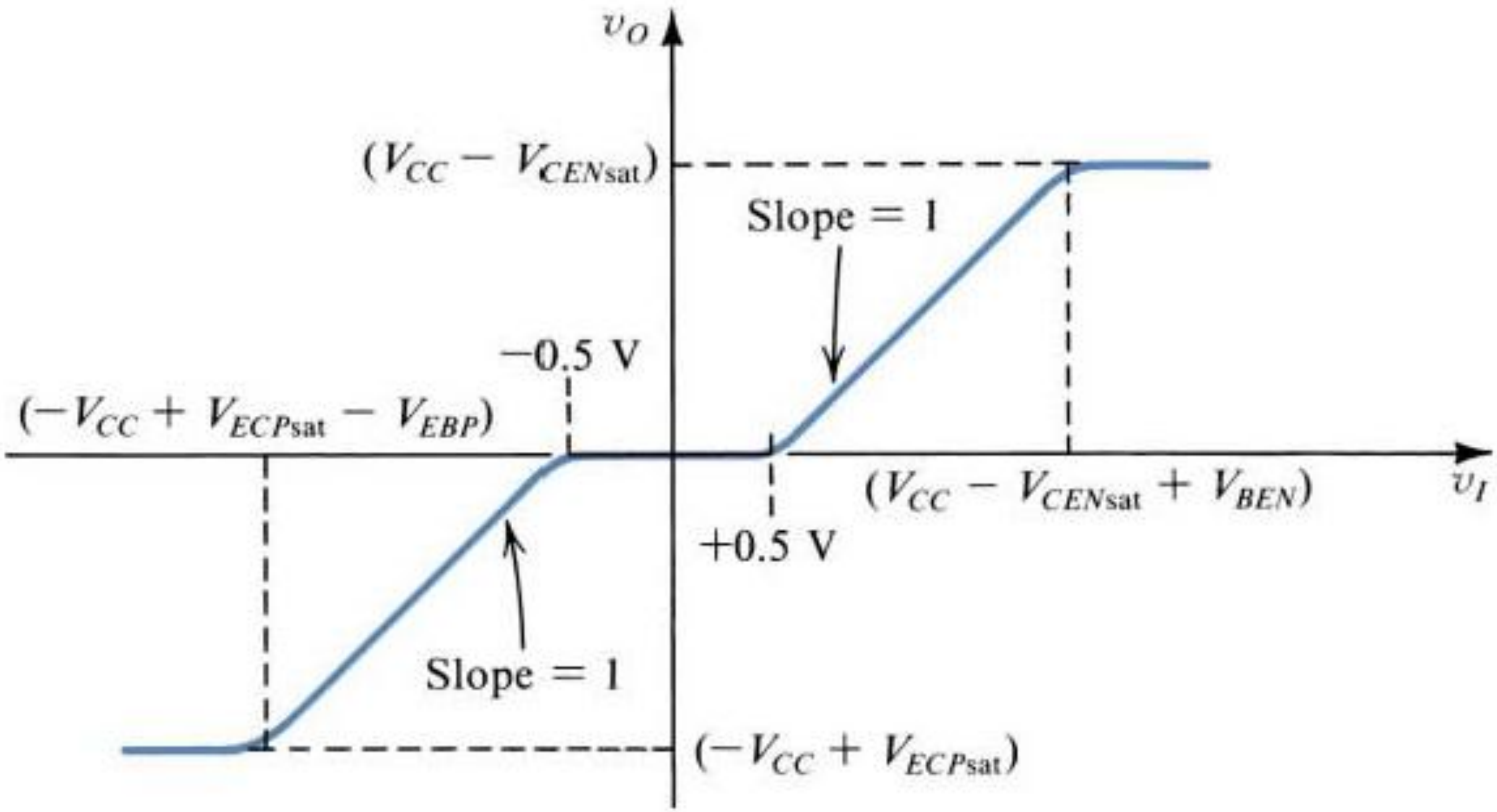
CLASS B PUSH-PULL AC OPERATION.



(a) During a positive half-cycle

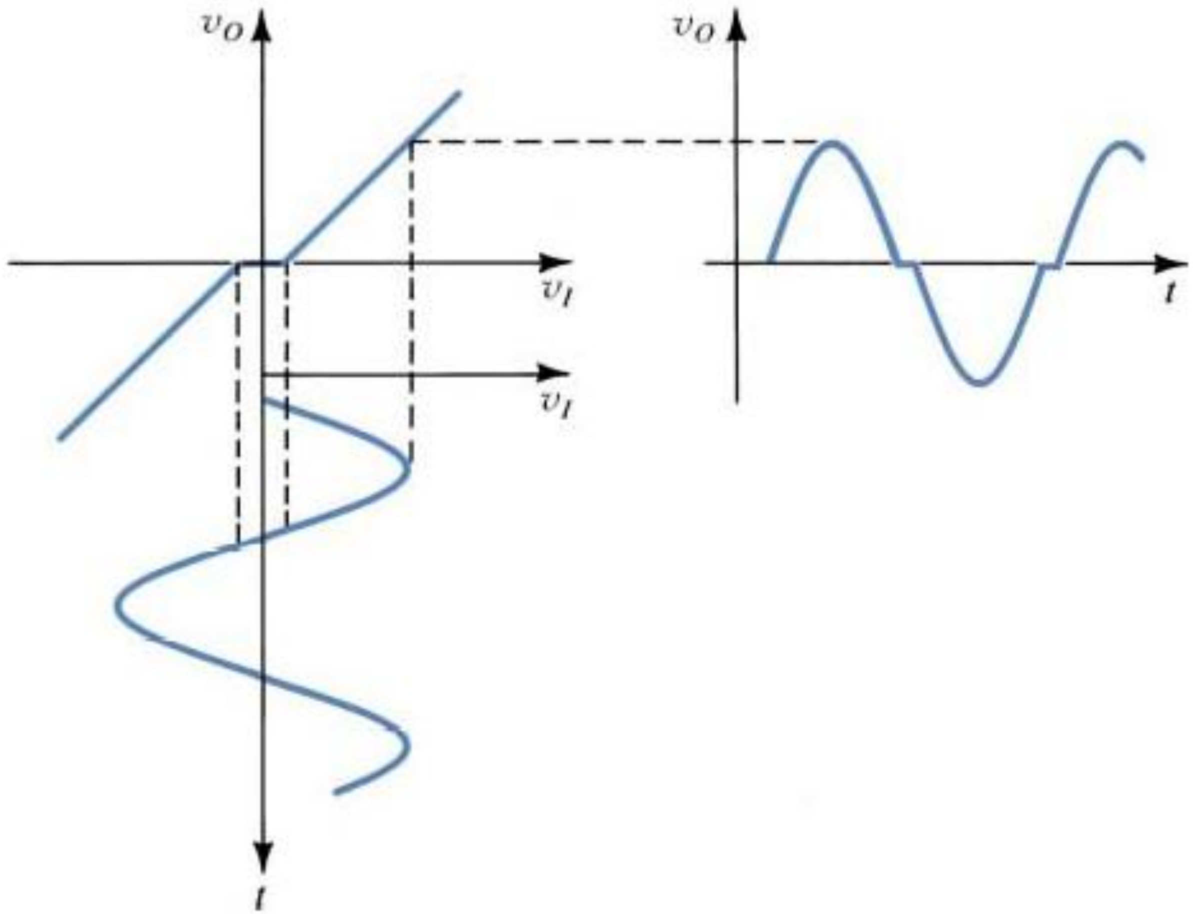
(b) During a negative half-cycle

Transfer Characteristics



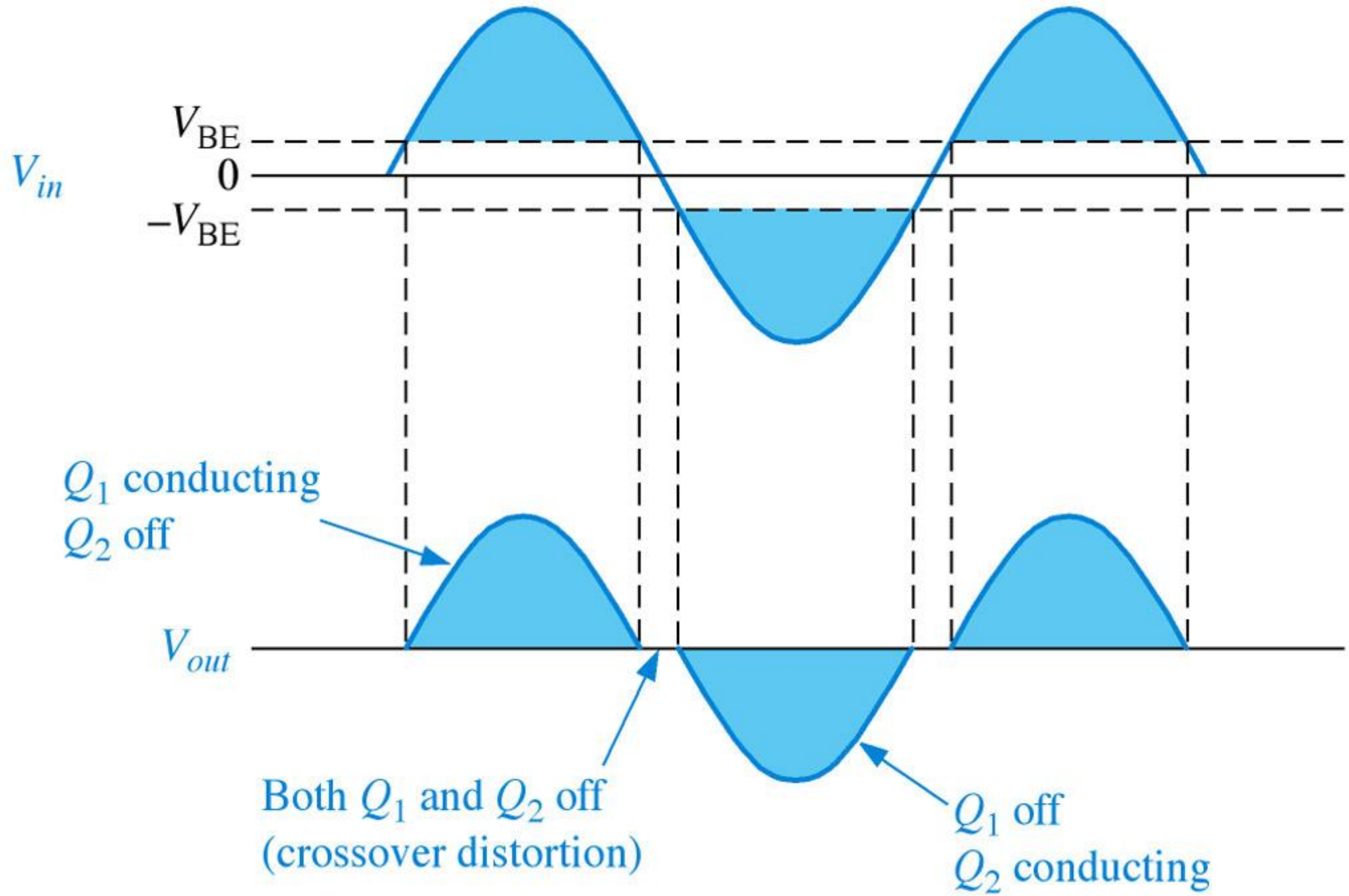
Transfer characteristic for the class B output stage.

Crossover Distortion

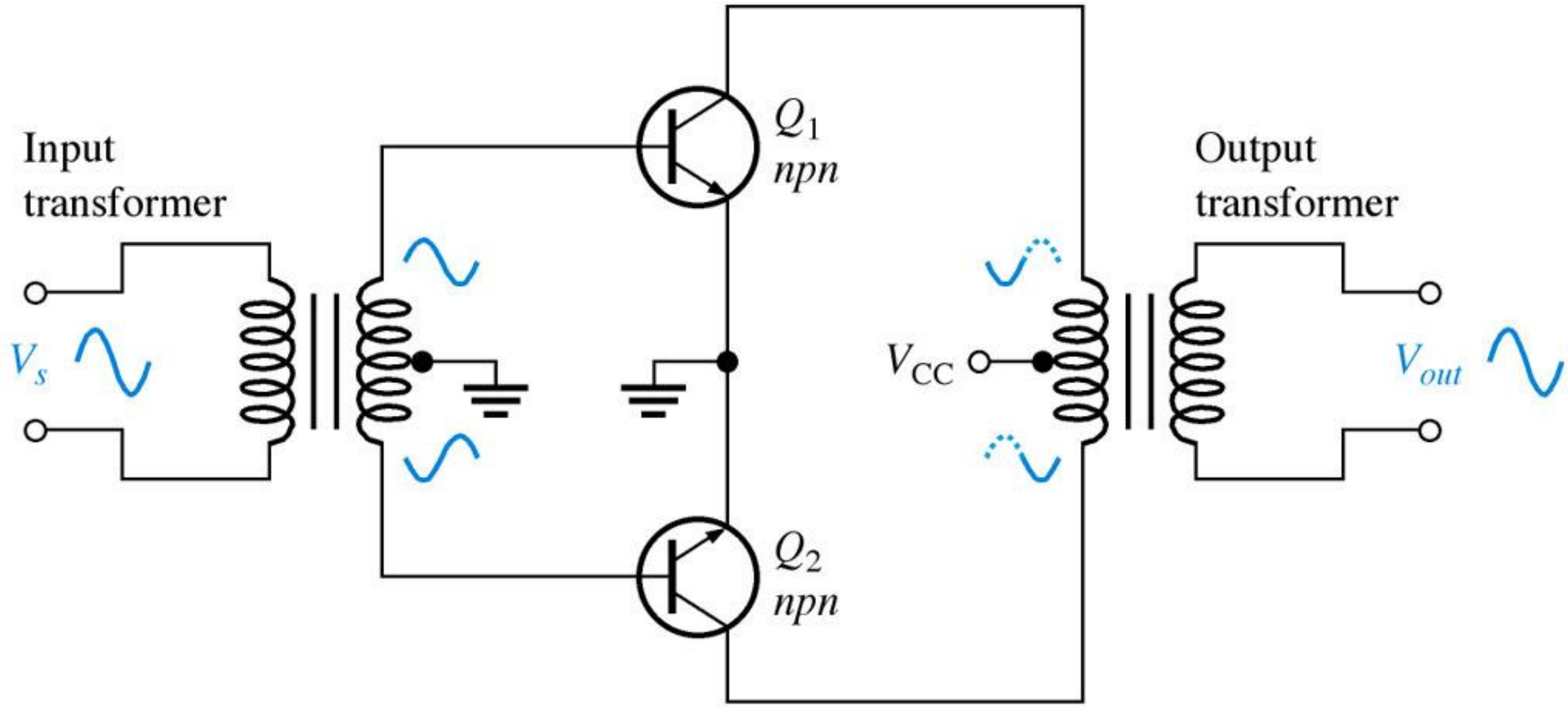


How the dead band in the class B transfer characteristic results in crossover distortion.

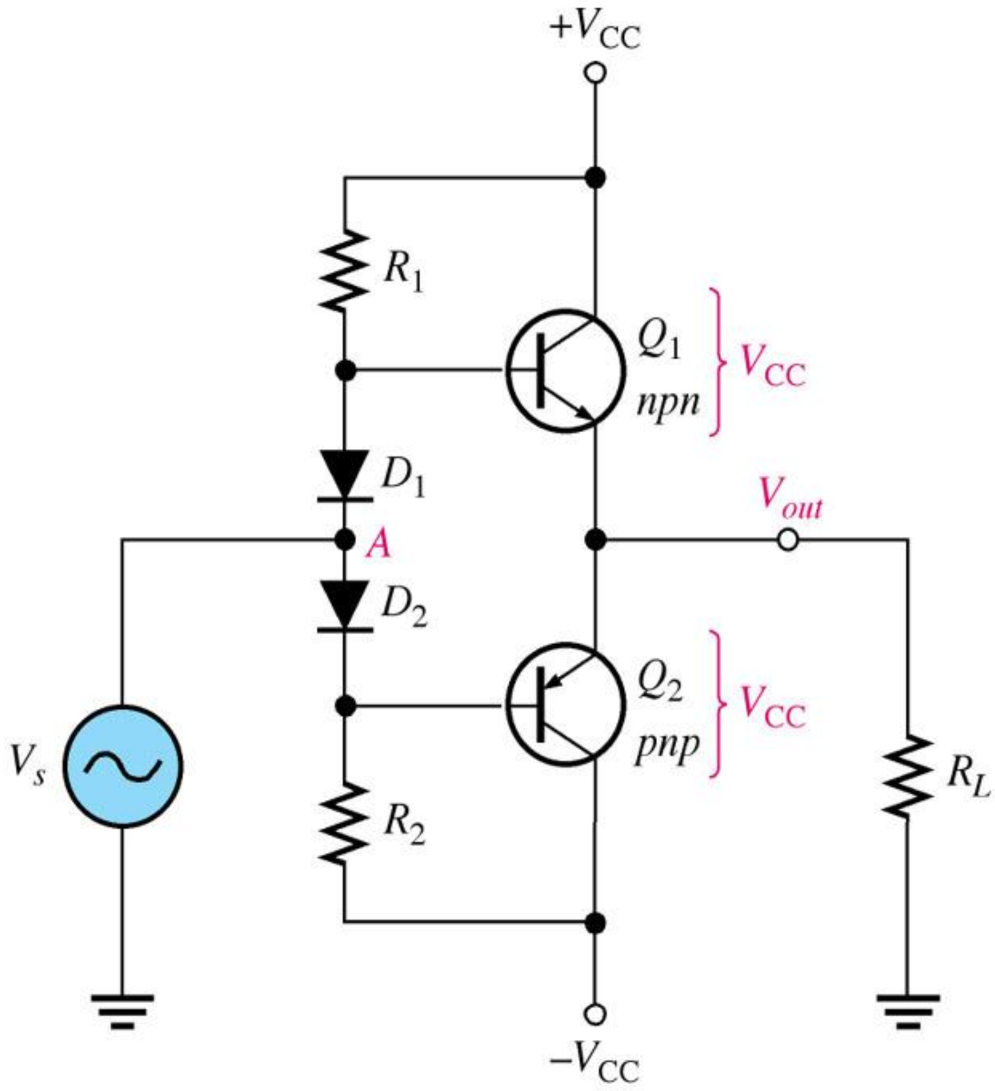
ILLUSTRATION OF CROSSOVER DISTORTION IN A CLASS B PUSH-PULL AMPLIFIER. THE TRANSISTORS CONDUCT ONLY DURING THE PORTIONS OF THE INPUT INDICATED BY THE SHADED AREAS.

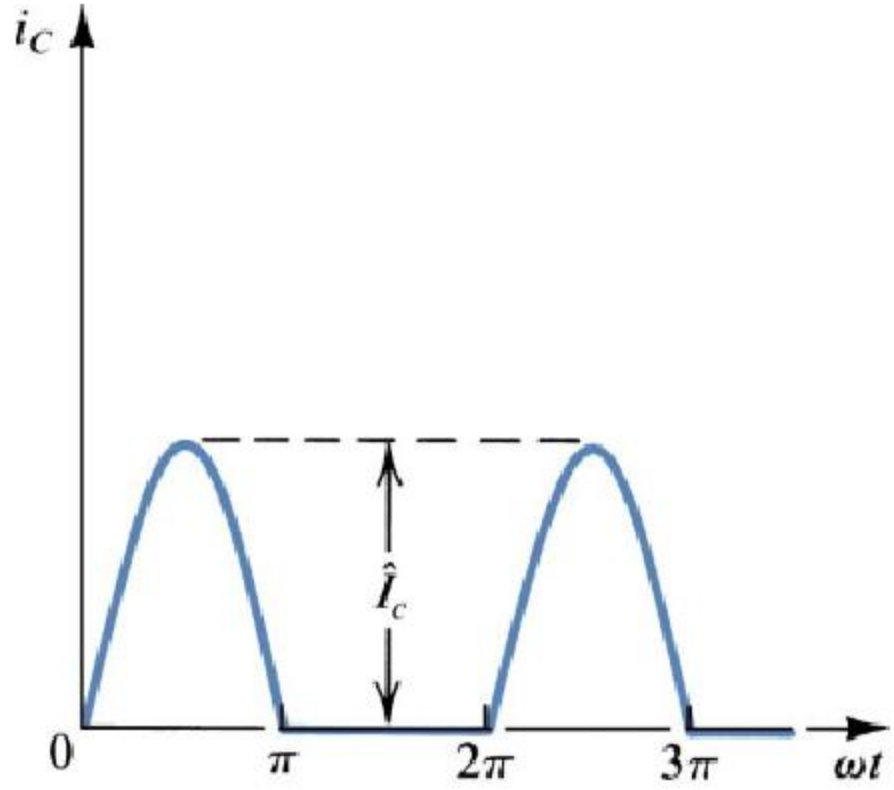


TRANSFORMER COUPLED PUSH-PULL AMPLIFIERS. Q_1 CONDUCTS DURING THE POSITIVE HALF-CYCLE; Q_2 CONDUCTS DURING THE NEGATIVE HALF-CYCLE. THE TWO HALVES ARE COMBINED BY THE OUTPUT TRANSFORMER.

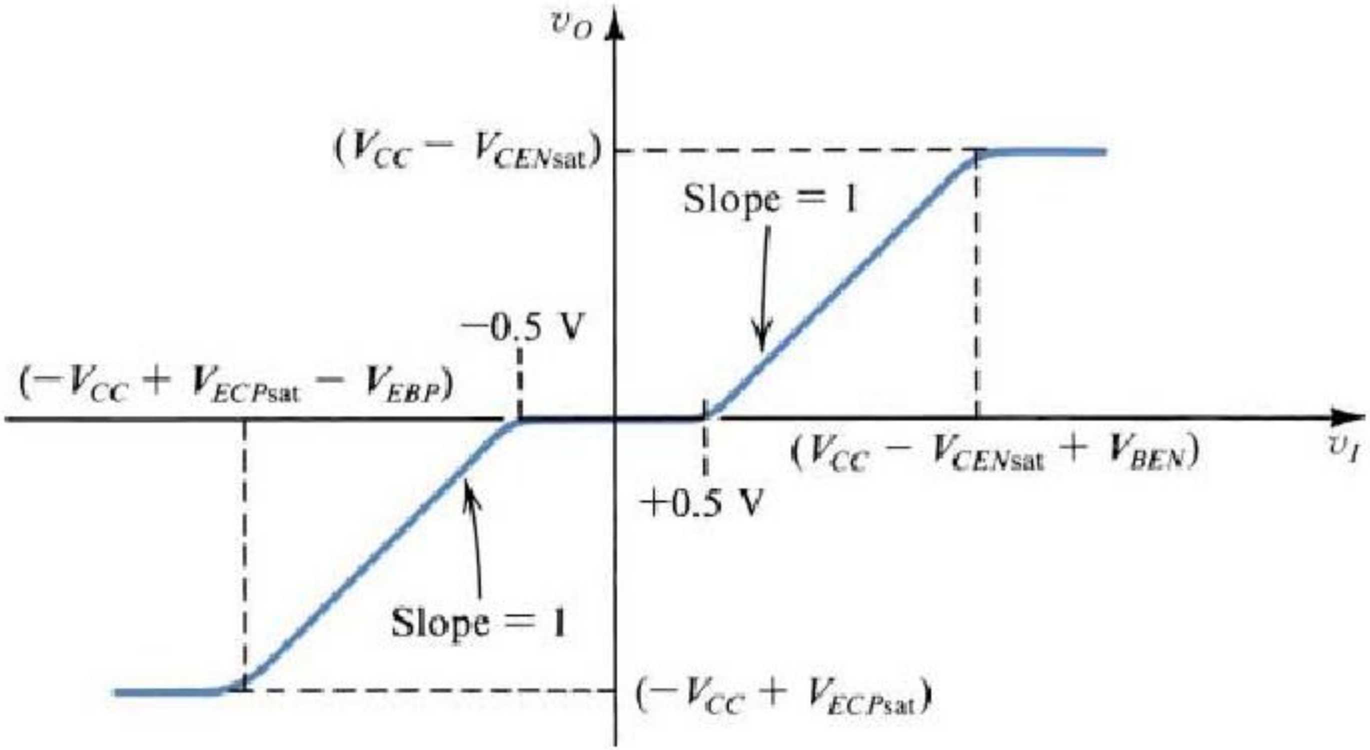


BIASING THE PUSH-PULL AMPLIFIER TO ELIMINATE CROSSOVER DISTORTION.



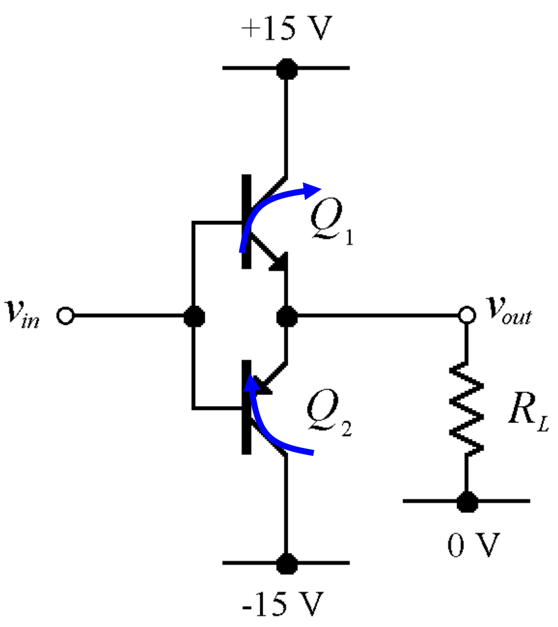


Collector current waveforms for transistors operating in class B amplifier stages



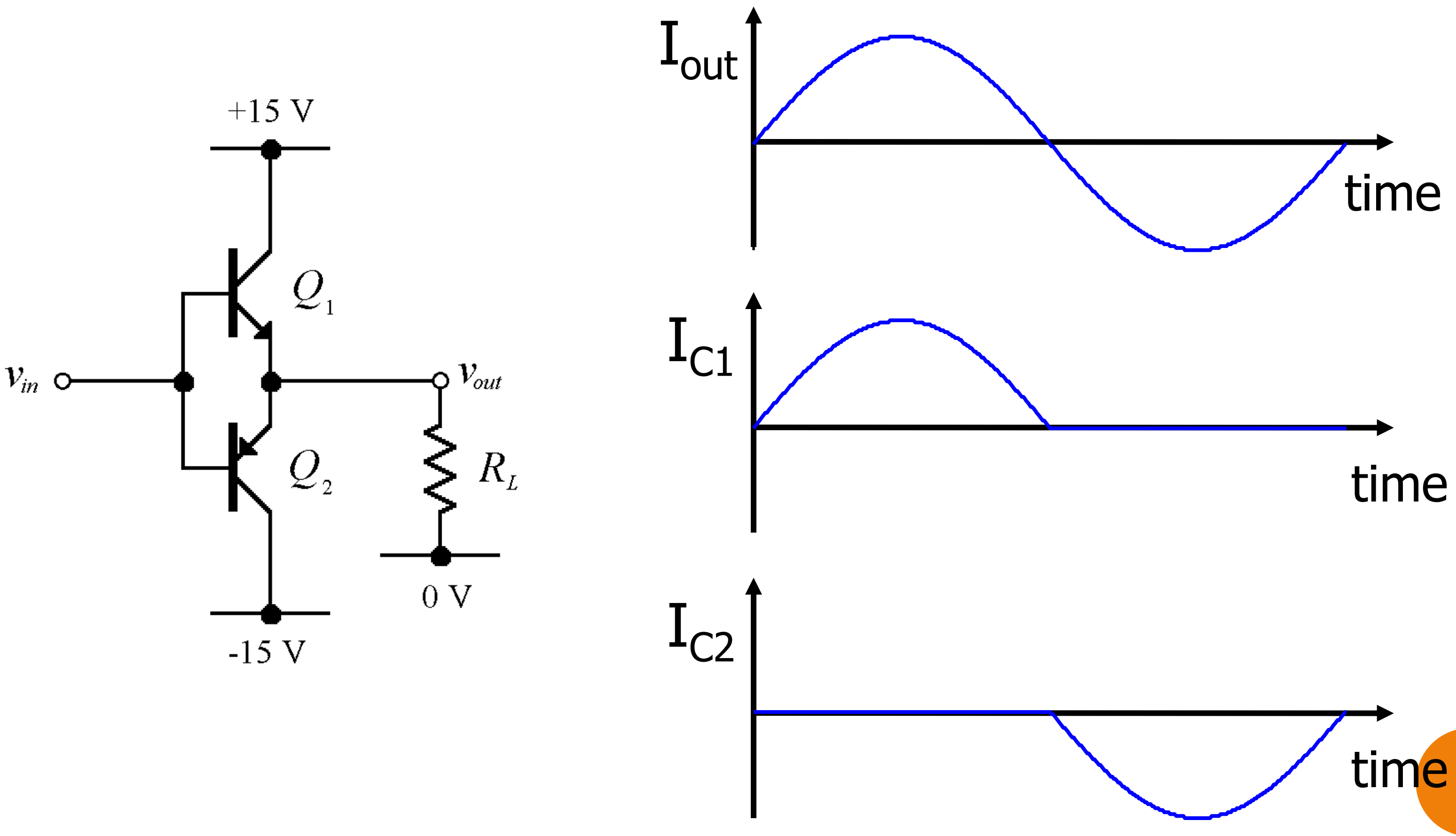
Transfer characteristic for the class B output stage.

Class B Output Stage

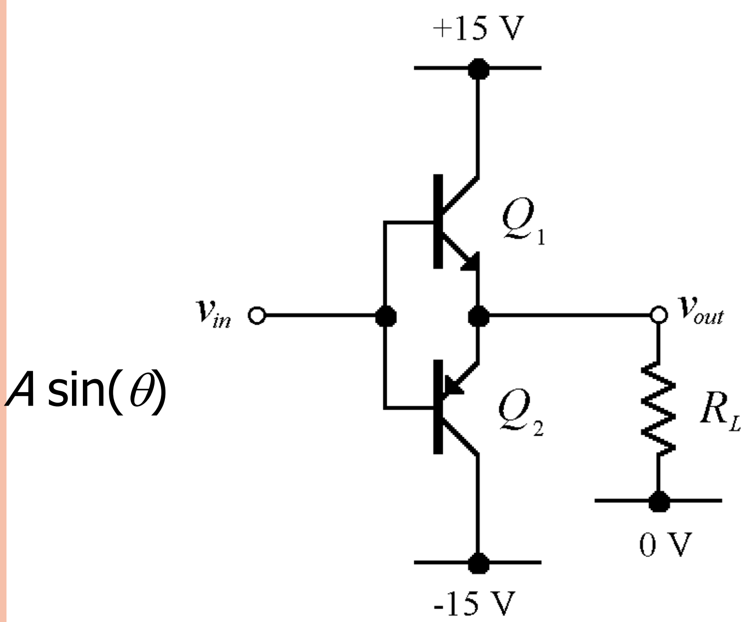


- Q_1 and Q_2 form two unbiased emitter followers
  - Q_1 only conducts when the input is positive
  - Q_2 only conducts when the input is negative
- Conduction angle is, therefore, 180°
- When the input is zero, neither conducts
- i.e. the quiescent power dissipation is zero

Class B Current Waveforms

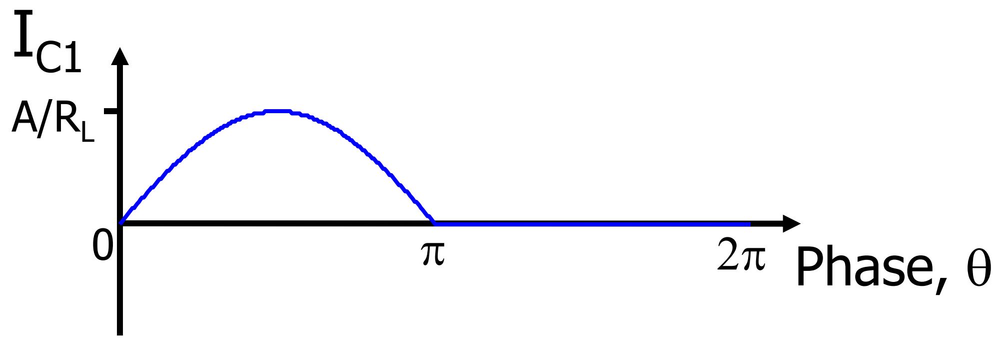


Class B Efficiency



Average power drawn from the positive supply:

$$P_{(+ve)} = V_S \overline{I_{C1}}$$

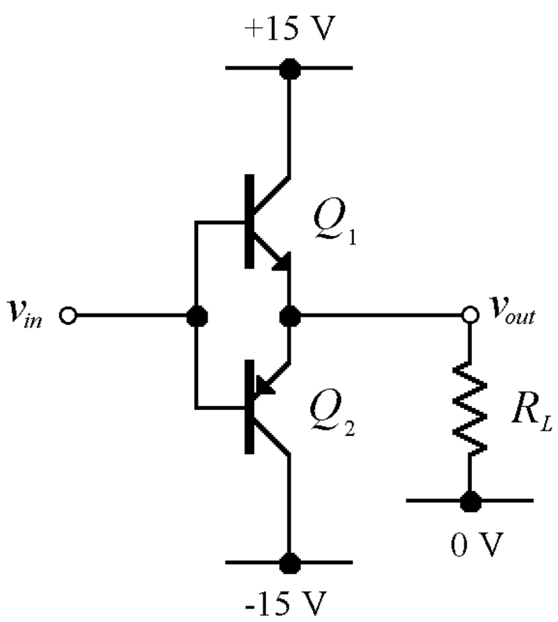


$$\overline{I_{C1}} = \frac{1}{2\pi}\int_0^{2\pi} I_{C1}(\theta)\mathrm{d}\theta = \frac{1}{2\pi}\int_0^{\pi} \frac{A}{R_L}\sin(\theta)\mathrm{d}\theta = \frac{A}{\pi R_L}$$

Efficiency / Power Dissipation

- Peak efficiency of the class B output stage is 78.5 %, much higher than class A.
- Unlike class A, power dissipation varies with output amplitude.
- Remember, there are two output devices so the power dissipation is shared between them.

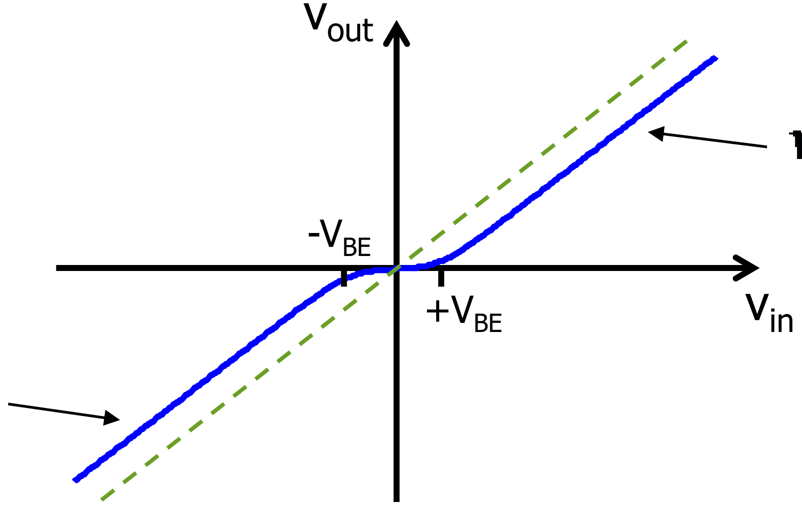
Cross-Over Distortion



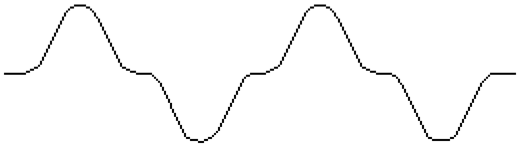
- A small base-emitter voltage is needed to turn on a transistor
- Q_1 actually only conducts when $v_{in} > 0.7$ V
- Q_2 actually only conducts when $v_{in} < -0.7$ V
- When $0.7 > v_{in} > -0.7$, nothing conducts and the output is zero.
- i.e. the input-output relationship is not at all linear.

Actual Input-Output Curve

$$v_{out} \approx v_{in} + V_{BE}$$

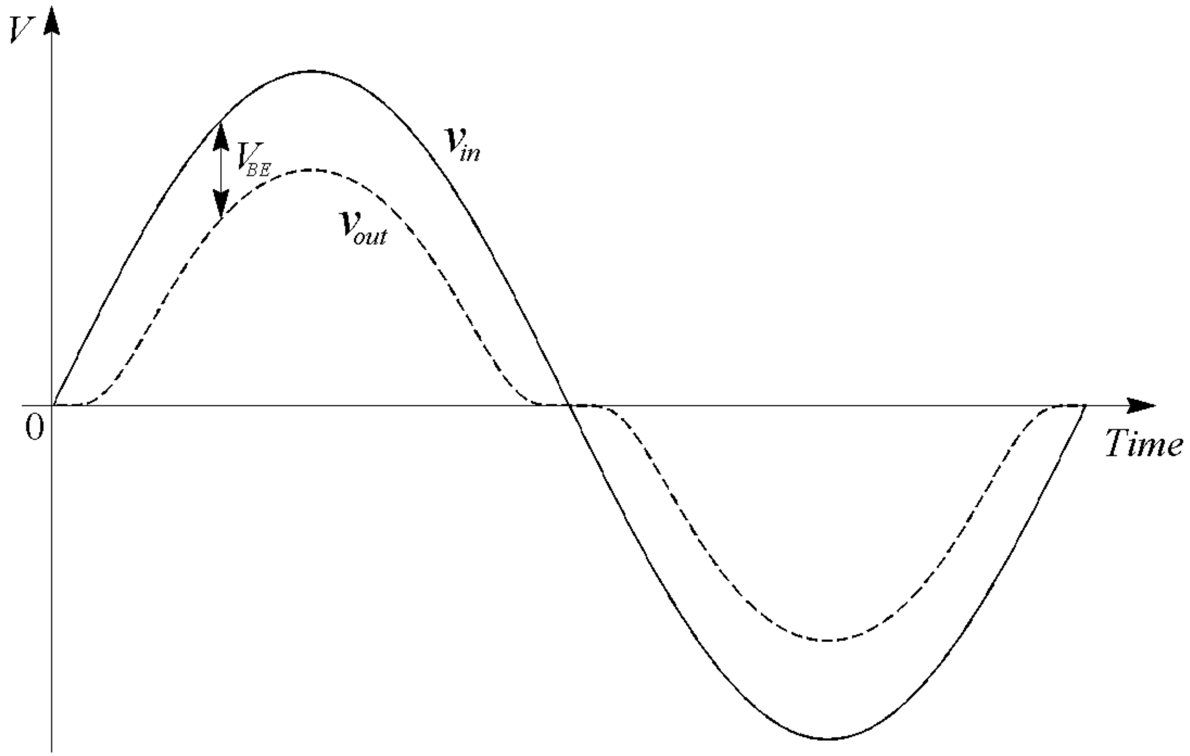


$$v_{out} \approx v_{in} - V_{BE}$$



Crossover Distortion

Effect of Cross-Over Distortion



Class B

- A class B output stage can be far more efficient than a class A stage (78.5 % maximum efficiency compared with 25 %).
- It also requires twice as many output transistors…
- …and it isn't very linear; cross-over distortion can be significant.

Class B

- Class B amplifiers are used in low cost designs or designs where sound quality is not that important.
- Class B amplifiers are significantly more efficient than class A amps.
- They suffer from bad distortion when the signal level is low (the distortion in this region of operation is called "crossover distortion").

Class B

- Class B is used most often where economy of design is needed.

- Before the advent of IC amplifiers, class B amplifiers were common in clock radio circuits, pocket transistor radios, or other applications where quality of sound is not that critical.

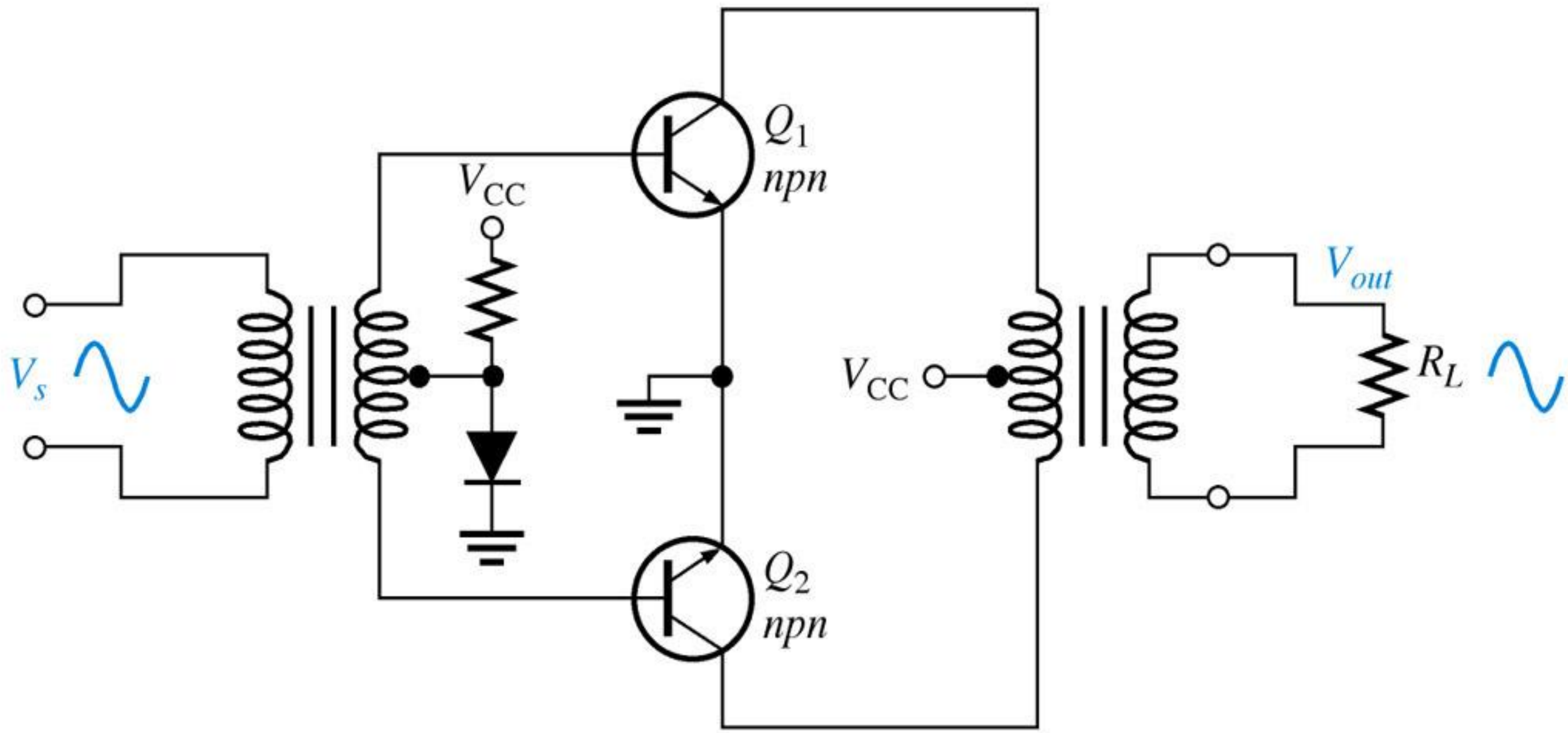
Power Amplifier Classes – "AB"

- Class "AB"
  - intermediate case: both devices are allowed to be on at the same time, *but just barely*
  - output bias is set so that current flows in a specific output device appreciably more than a half cycle but less than the entire cycle (enough to keep each device operating *so they respond instantly* to input voltage demands)
  - the inherent non-linearity of class B designs is eliminated, without the gross inefficiencies of the class A design
  - combination of good efficiency (around 50%) with excellent linearity that makes class AB the most popular consumer audio amplifier design

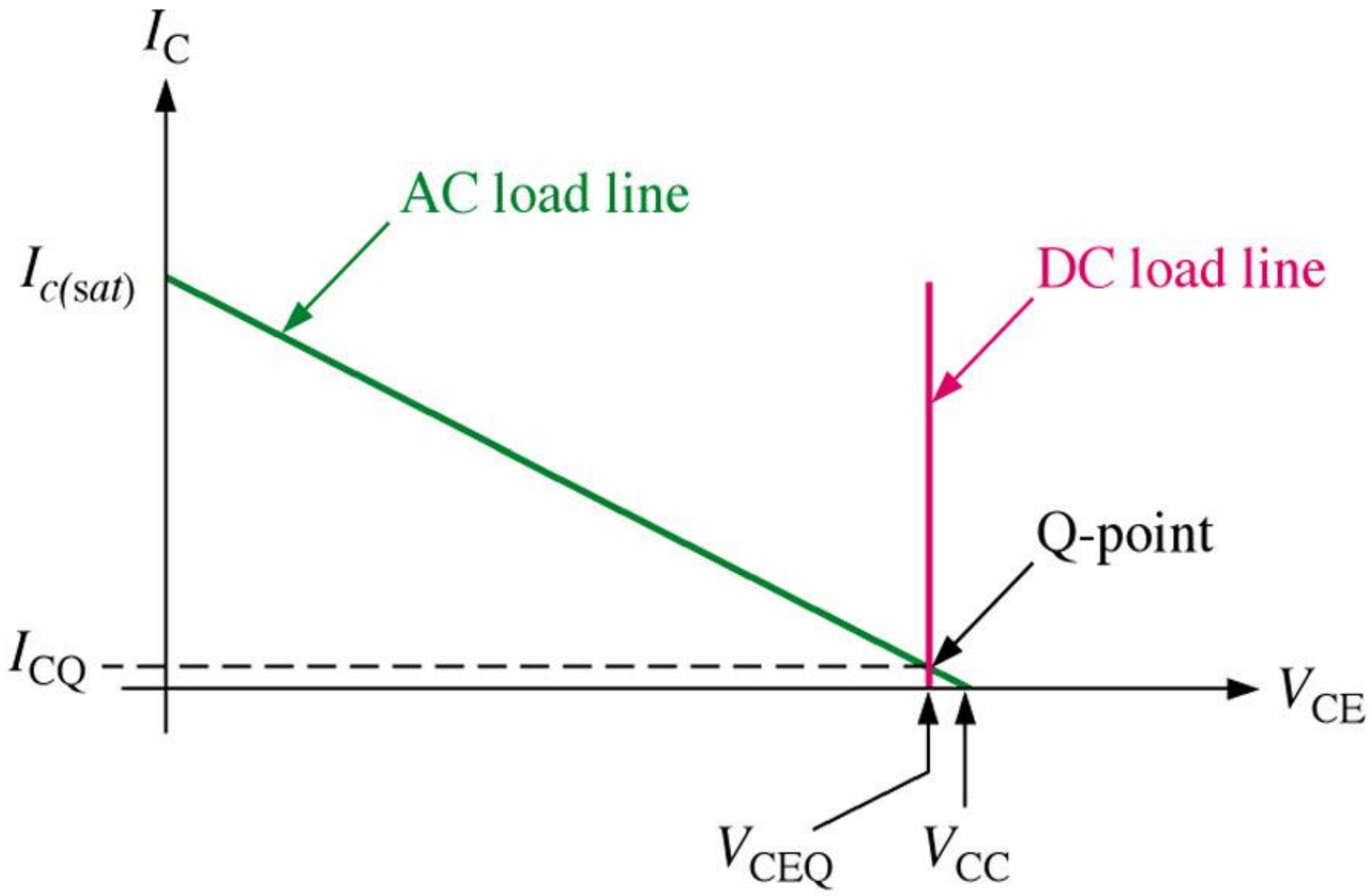
Class AB

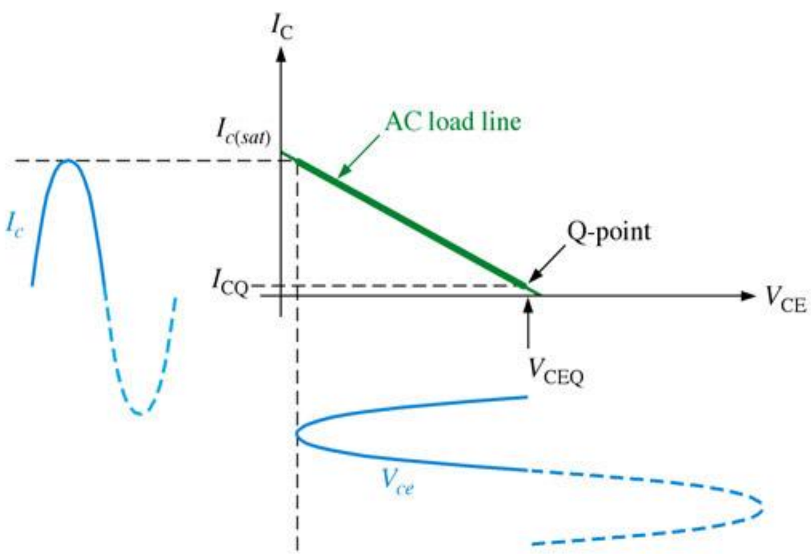
- Class AB is probably the most common amplifier class currently used in home stereo and similar amplifiers.
- Class AB amps combine the good points of class A and B amps.
- They have the improved efficiency of class B amps and distortion performance that is a lot closer to that of a class A amp.

ELIMINATING CROSSOVER DISTORTION IN A TRANSFORMER-COUPLED PUSH-PULL AMPLIFIER. THE DIODE COMPENSATES FOR THE BASE-EMITTER DROP OF THE TRANSISTORS AND PRODUCES CLASS AB OPERATION.

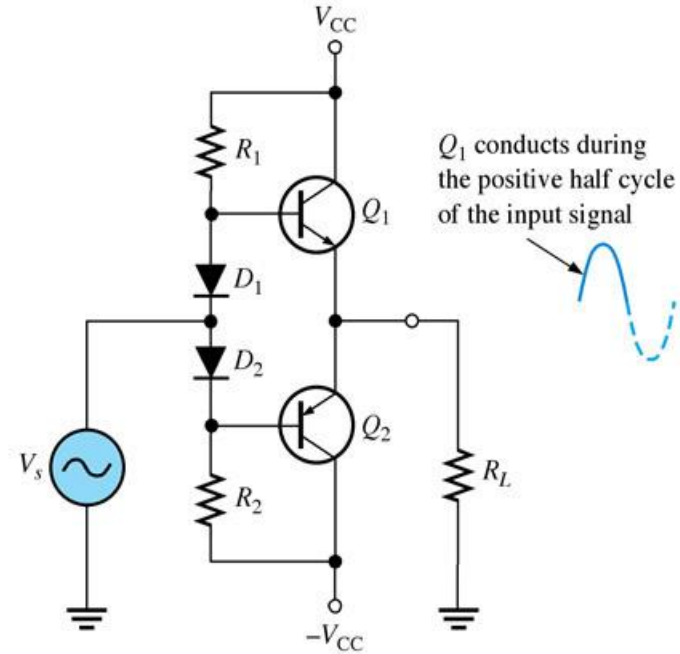


LOAD LINES FOR A COMPLEMENTARY SYMMETRY PUSH-PULL AMPLIFIER. ONLY THE LOAD LINES FOR THE *NPN* TRANSISTOR ARE SHOWN.

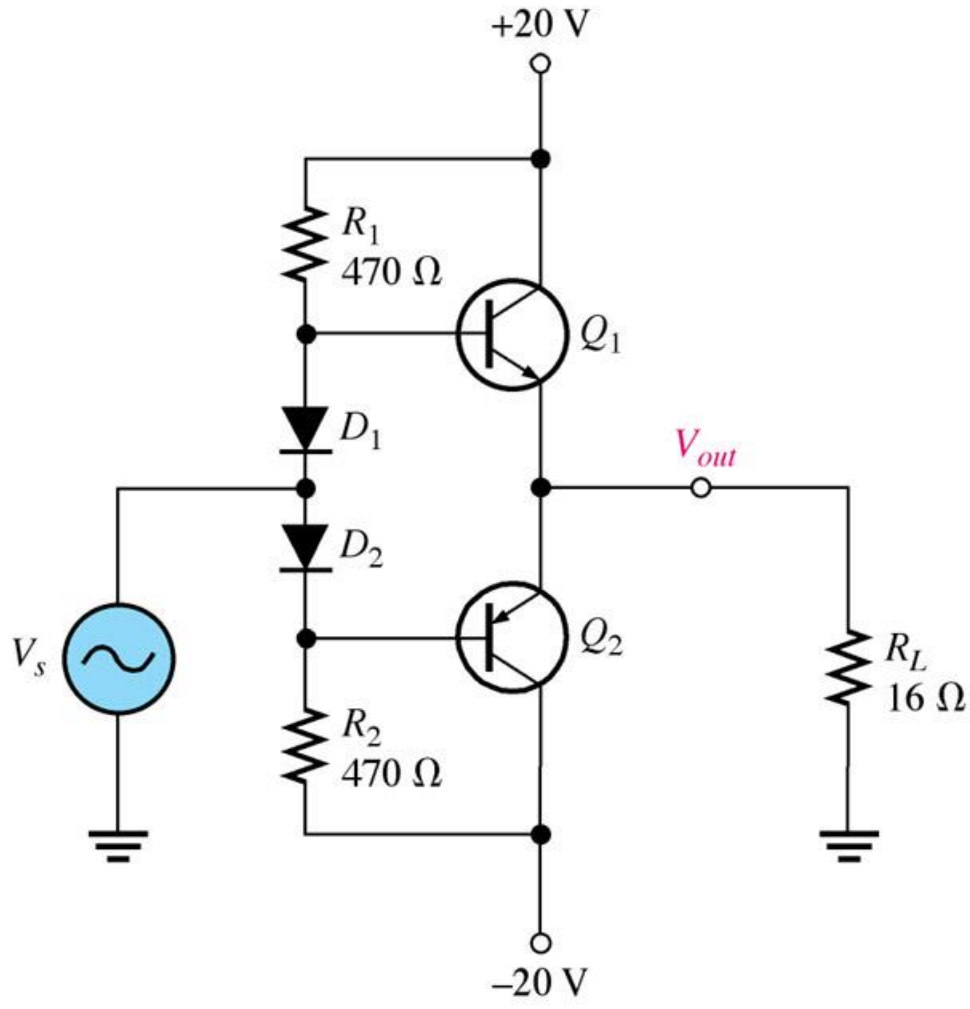




(a) AC load line for Q_1

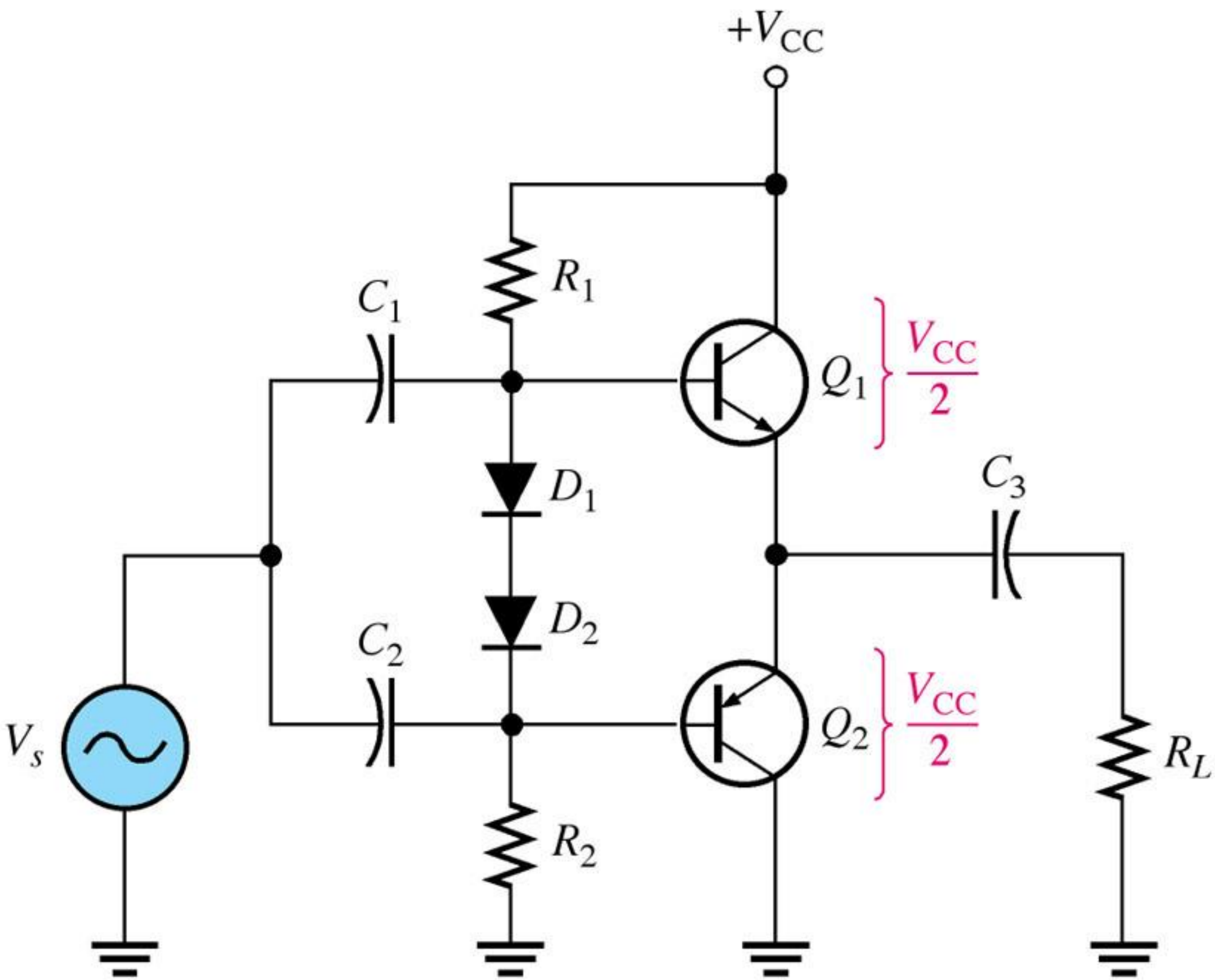


(b) Circuit

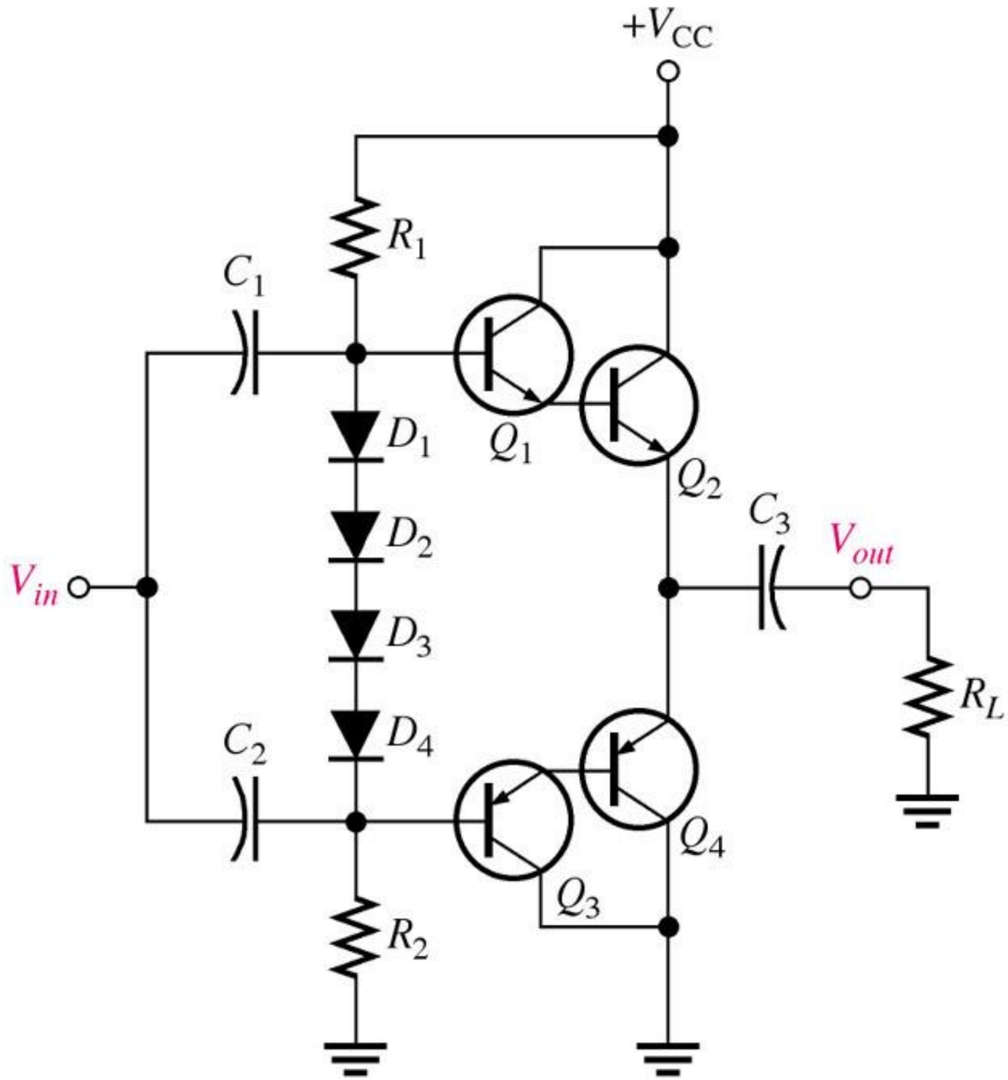


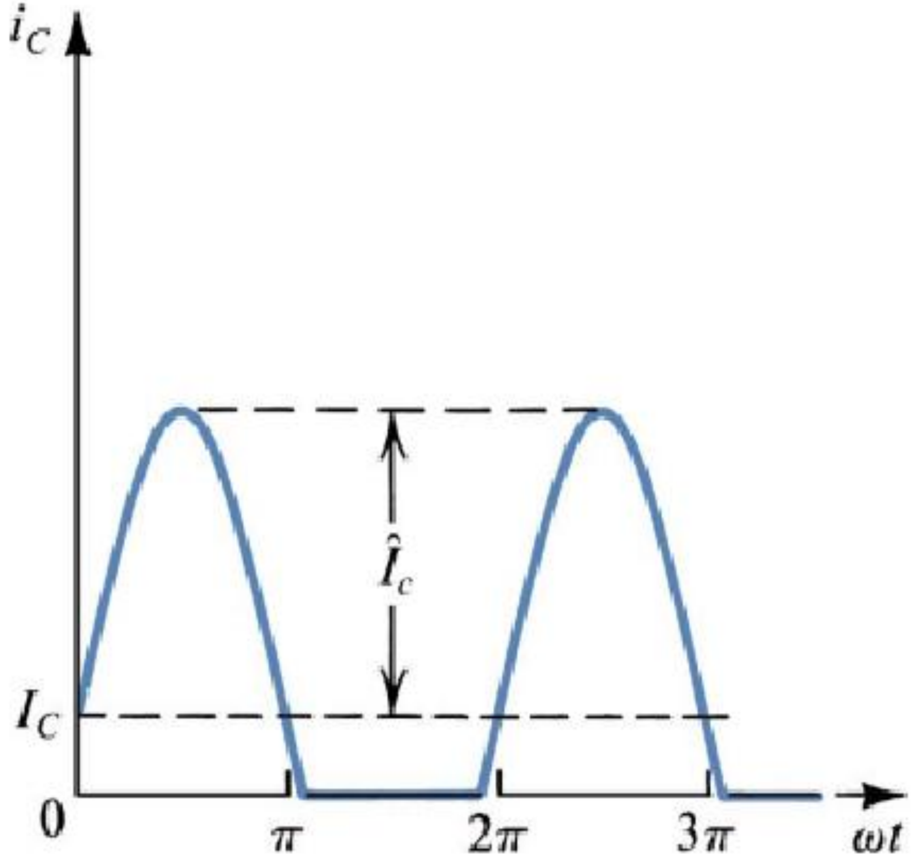
+20 V
R_1
470 Ω
Q_1
D_1
V_{out}
D_2
V_s
Q_2
R_L
16 Ω
R_2
470 Ω
–20 V

SINGLE-ENDED PUSH-PULL AMPLIFIER.



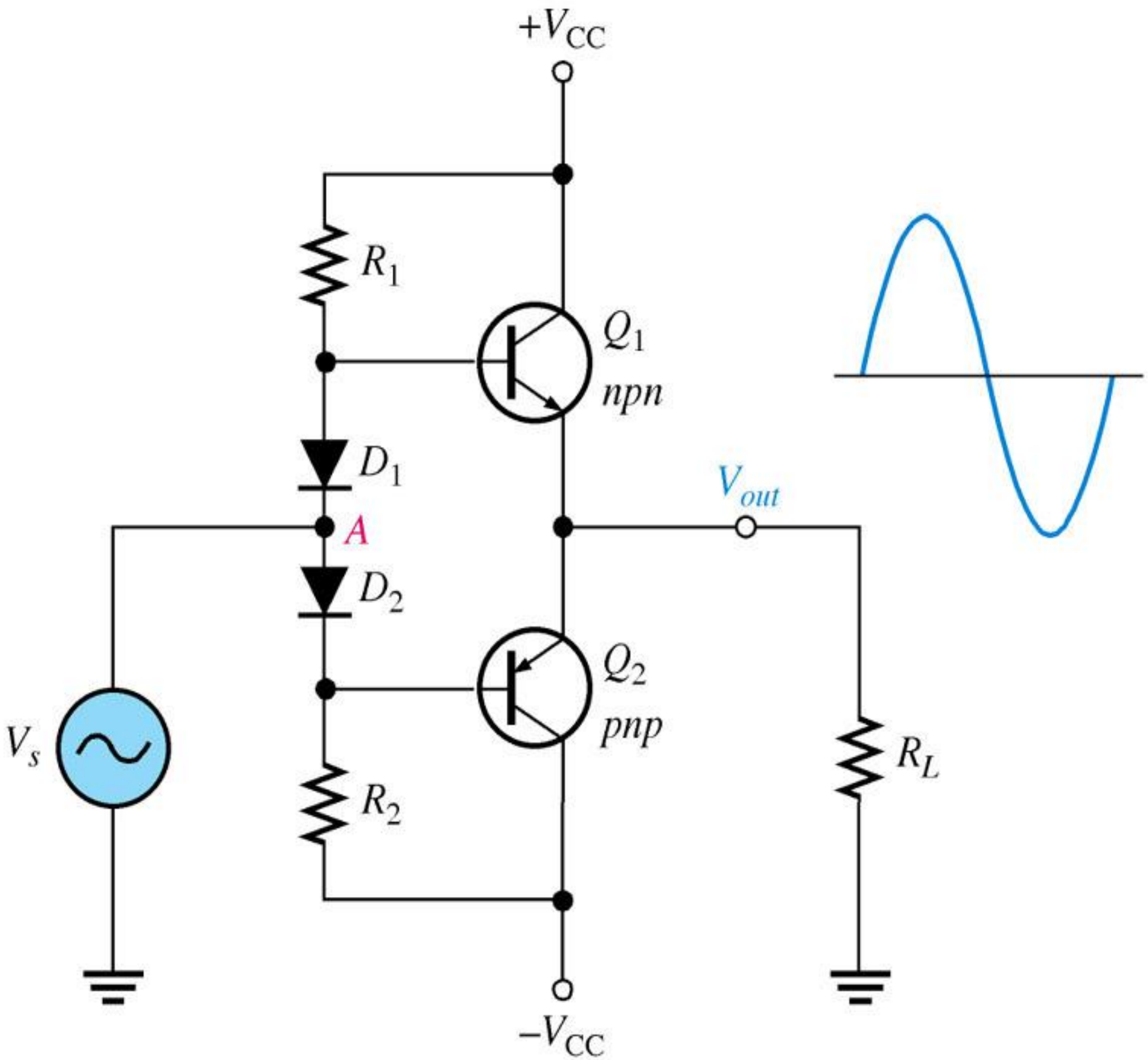
A DARLINGTON CLASS AB PUSH-PULL AMPLIFIER.



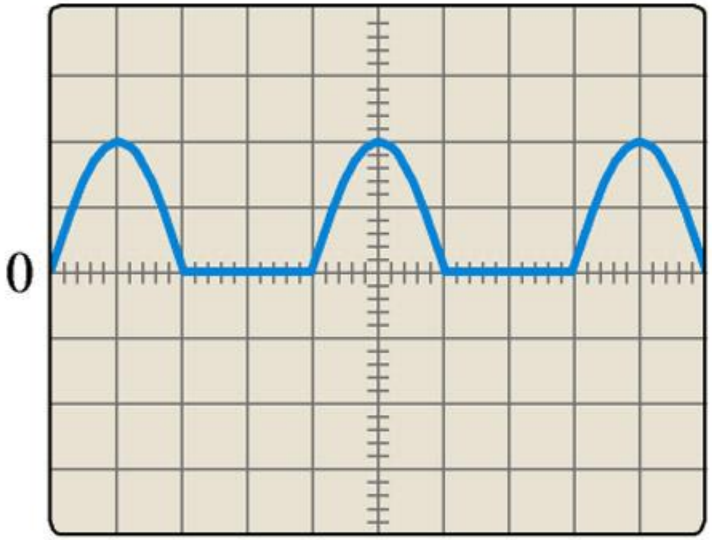


Collector current waveforms for transistors operating in class AB amplifier stage

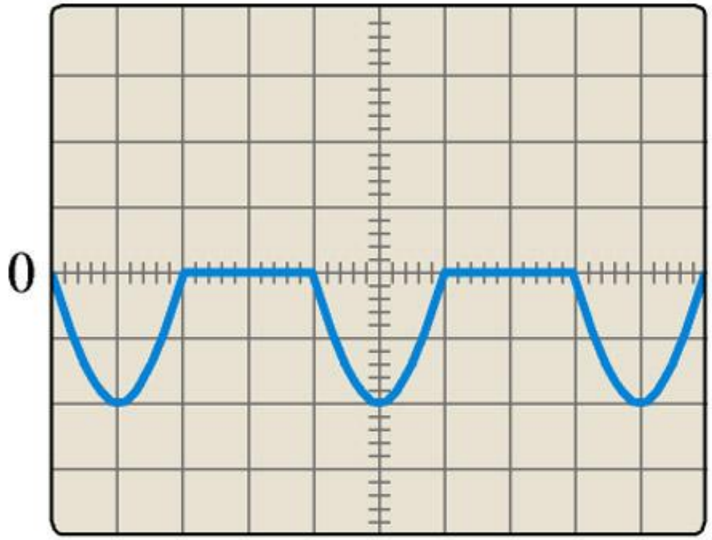
A CLASS AB PUSH-PULL AMPLIFIER WITH CORRECT OUTPUT VOLTAGE.



INCORRECT OUTPUT WAVEFORMS FOR THE AMPLIFIER



(a) D_1 open or Q_2 base-emitter open



(b) D_2 open or Q_1 base-emitter open

Class AB

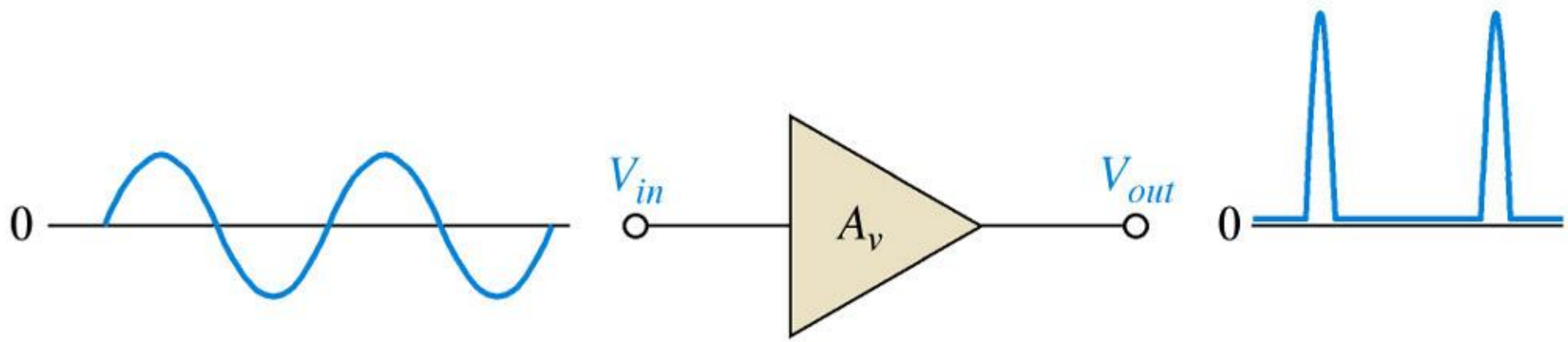
- With such amplifiers, distortion is worst when the signal is low, and generally lowest when the signal is just reaching the point of clipping.

- Class AB amps use pairs of transistors, both of them being biased slightly ON so that the crossover distortion (associated with Class B amps) is largely eliminated.

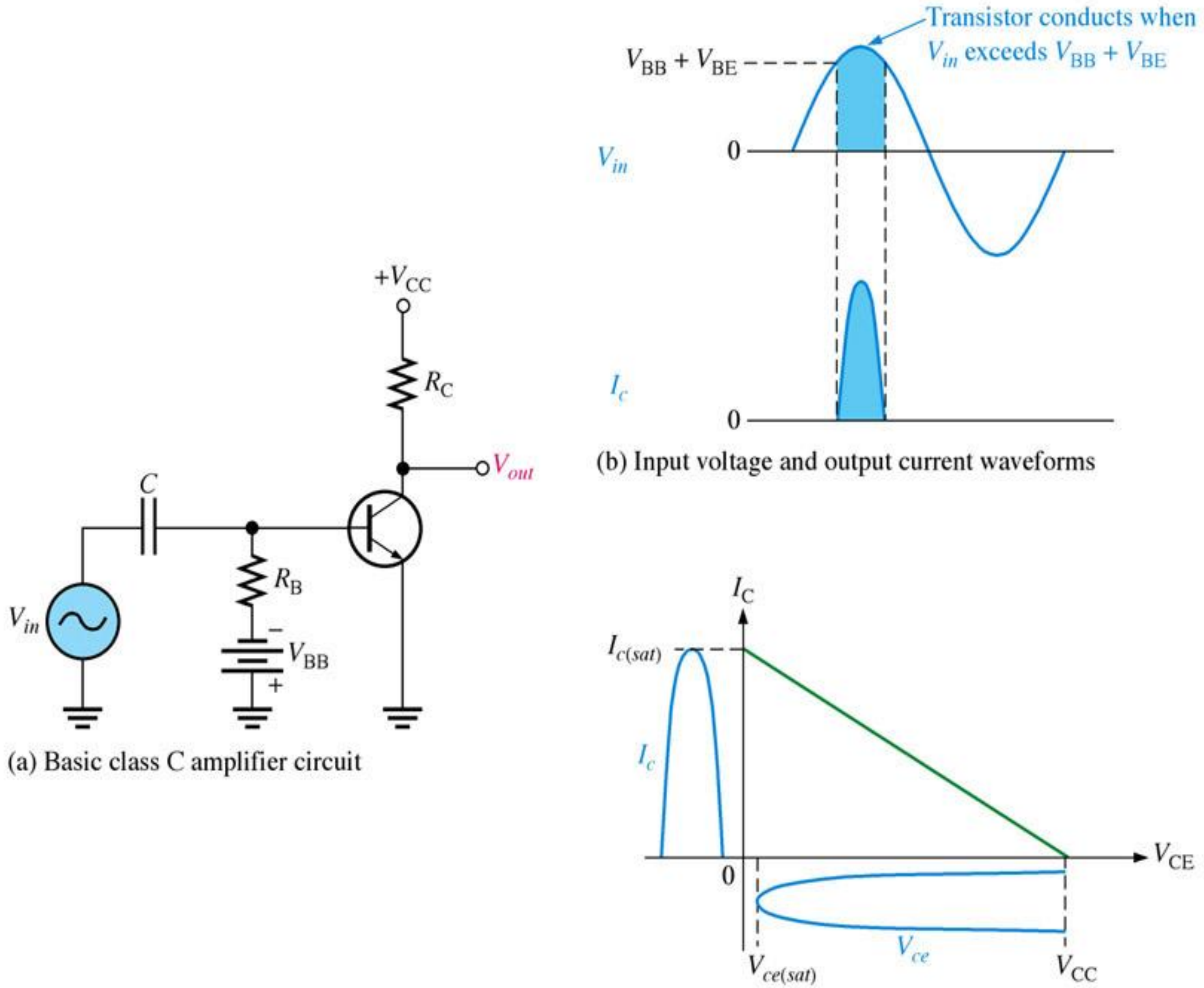
Class C

- Class C amps are never used for audio circuits.
- They are commonly used in RF circuits.
- Class C amplifiers operate the output transistor in a state that results in tremendous distortion (it would be totally unsuitable for audio reproduction).

BASIC CLASS C AMPLIFIER OPERATION (NON INVERTING).



BASIC CLASS C OPERATION.

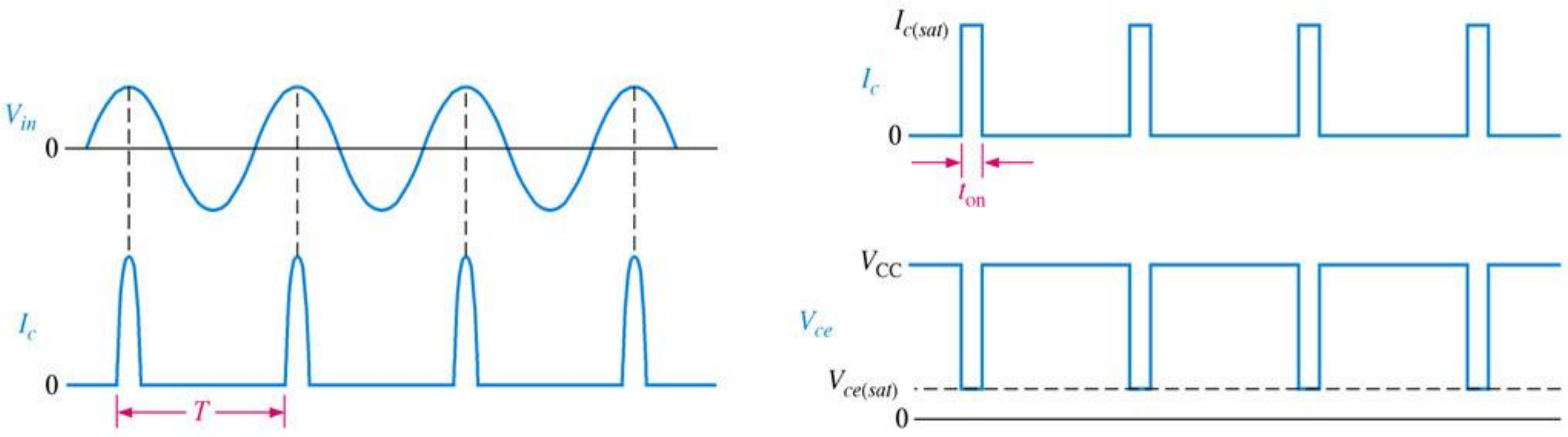


(a) Basic class C amplifier circuit

(b) Input voltage and output current waveforms

(c) Load line operation

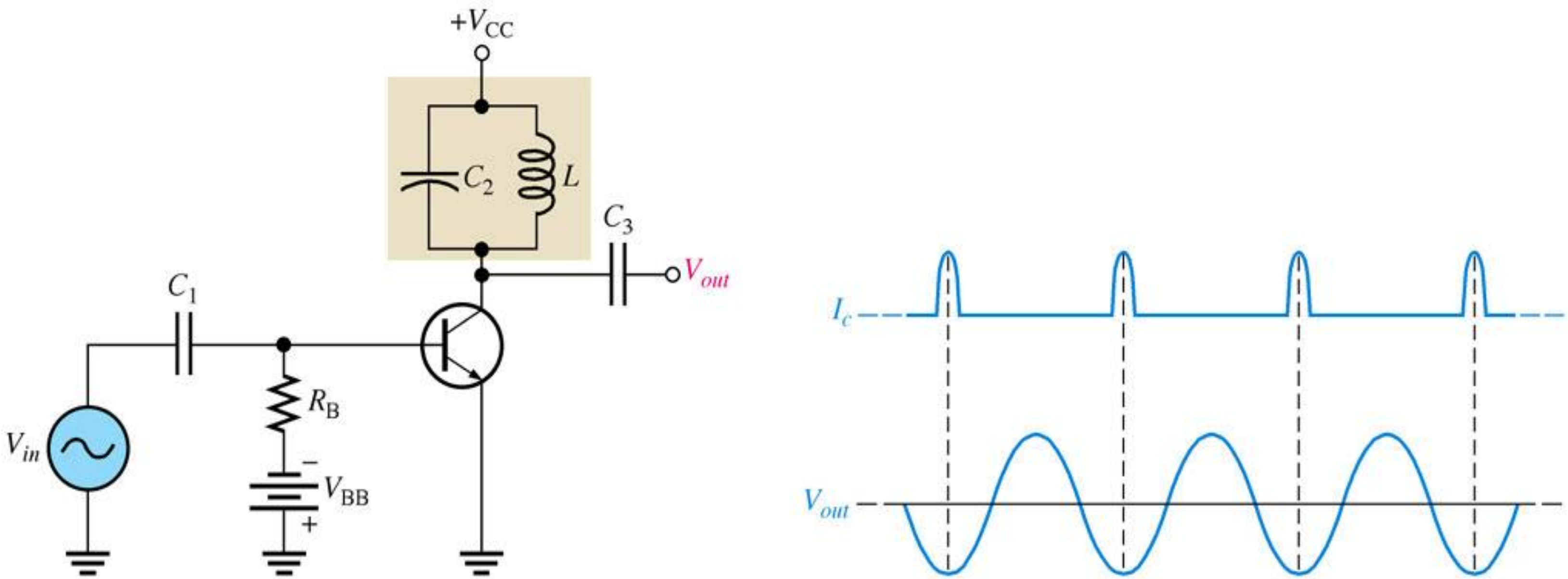
Class C waveforms.



(a) Collector current pulses

(b) Ideal class C waveforms

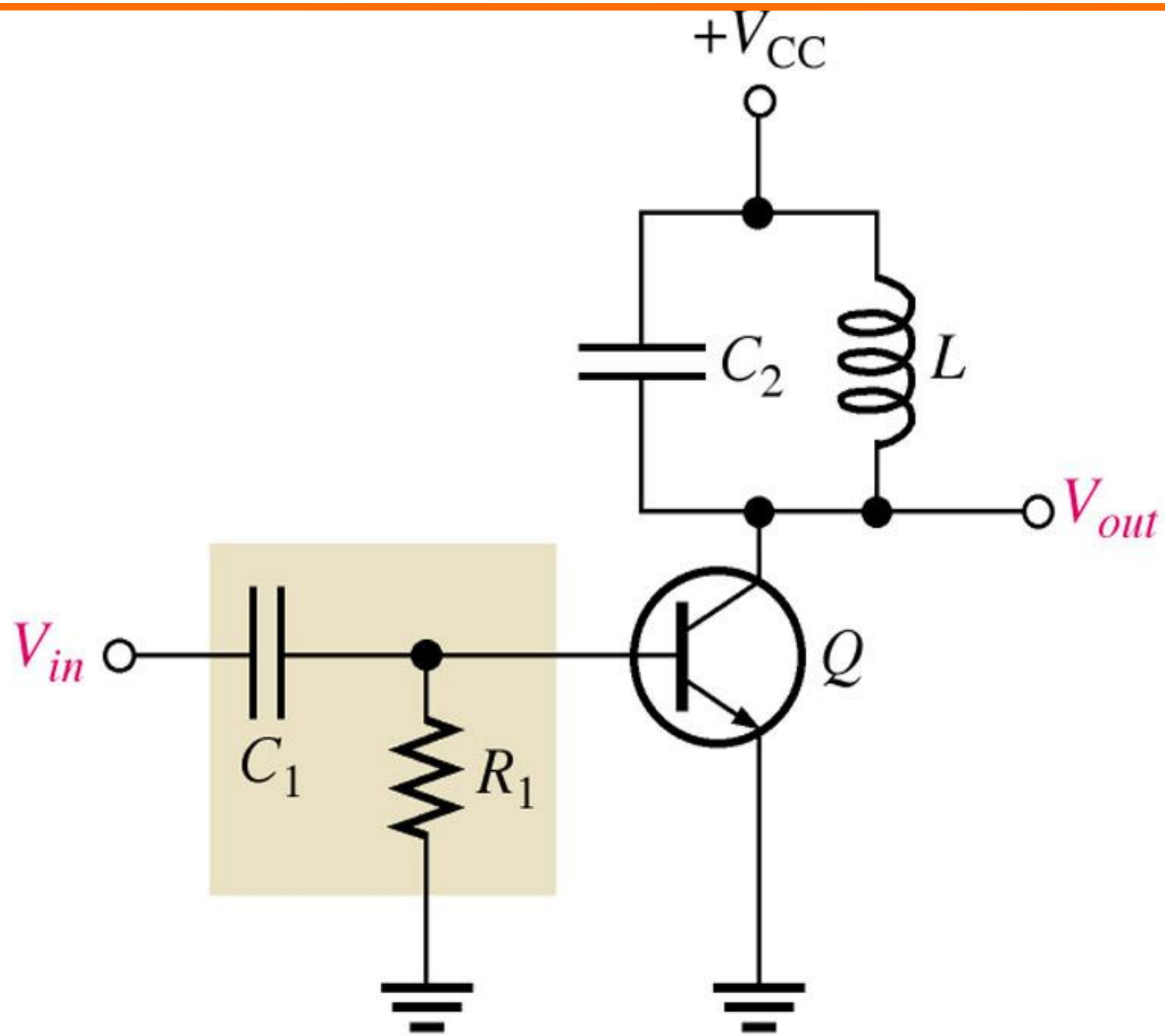
TUNED CLASS C AMPLIFIER.

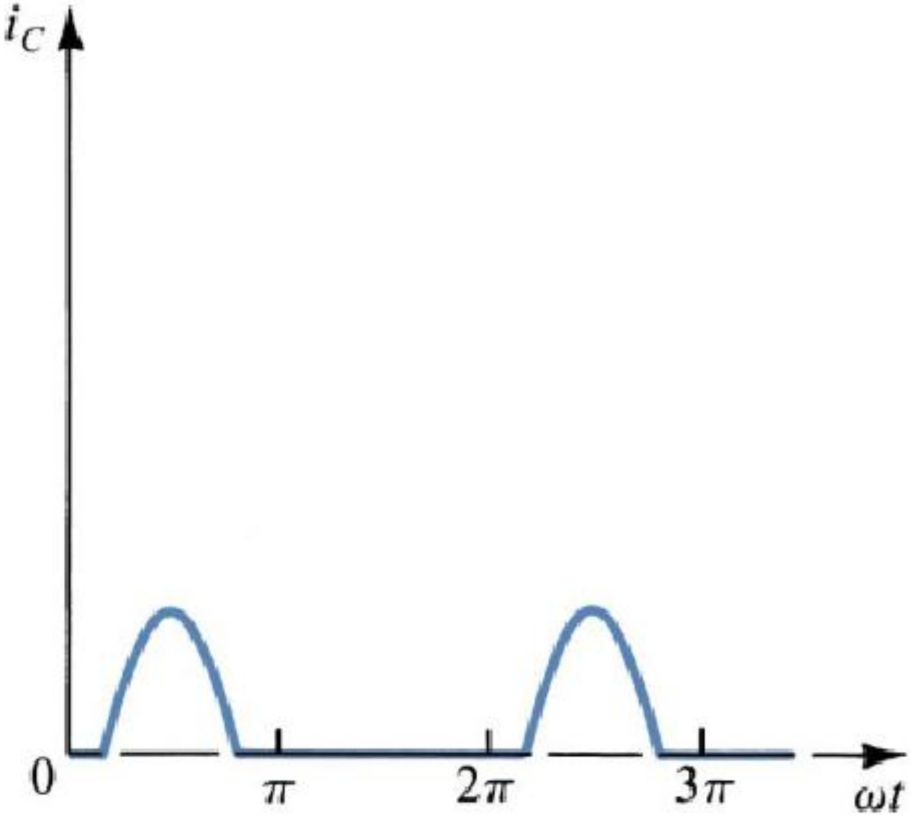


(a) Basic circuit

(b) Output waveforms

TUNED CLASS C AMPLIFIER WITH CLAMPER BIAS.





Collector current waveforms for transistors operating in class C amplifier stage

Class C

- However, the RF circuits where Class C amps are used, **employ filtering** so that the final signal is completely acceptable.

- Class C amps are **quite efficient**.