

Lecture 12 - Operational Amplifier circuits III - output amplifiers

The third and final stage of an Op-Amp is the output stage. It must have high input impedance (to match the high output impedance of the Darlington), and low output impedance, to give the completed Op-Amp the desired output characteristics. The required circuit is therefore a common-collector, or emitter-follower amplifier. The following discussion can be broadened to all power amplifiers - i.e. amplifiers that can deliver high currents into a load (i.e. high current gain) with maximum efficiency (i.e. low output impedance and quiescent current).

Class A amplifiers

Class A amplifiers are biased ON for 100 % of the input signal cycle. They are therefore inefficient (high quiescent power dissipation), but have low distortion.

Class B amplifiers

Class B amplifiers are biased ON for 50 % of the full cycle. They have no quiescent power dissipation, but have high distortion.

Class AB amplifiers

Class AB amplifiers combine the properties of a class A and class B amplifiers. They are ON for > 50 % of the signal cycle, have small quiescent power dissipation, but high distortion.

Class C amplifiers

Class C amplifiers are ON for < 50 % of the clock cycle, and have no quiescent power dissipation, but have high distortion.

Mark 1 emitter-follower

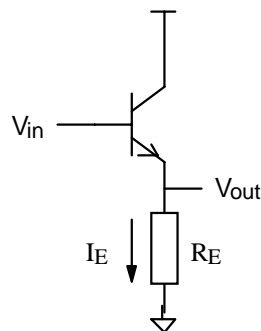


Figure 12.1. Class C emitter-follower

For a simple emitter-follower (EF), transistor only conducts for $V_{in} > V_{BE(on)} \approx 0.7 \text{ V}$. Therefore transistor is only on for portion of cycle that is less than 50 % of the cycle. This is a **class C** amplifier.

There is collector current ONLY for large enough signal current, but no quiescent current. No output for remainder of signal cycle = high distortion.

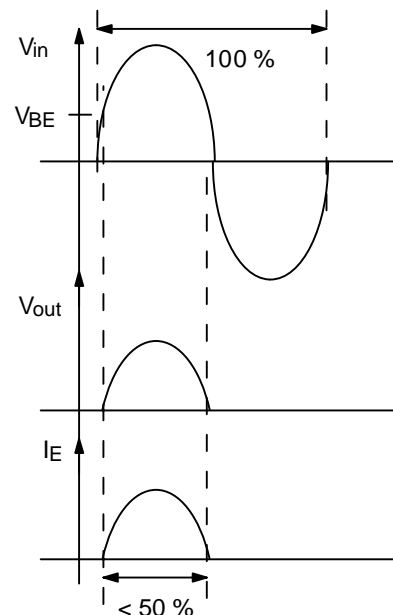


Figure 12.2. Current/voltage waveforms for class C emitter-follower.

Mark 2 emitter-follower

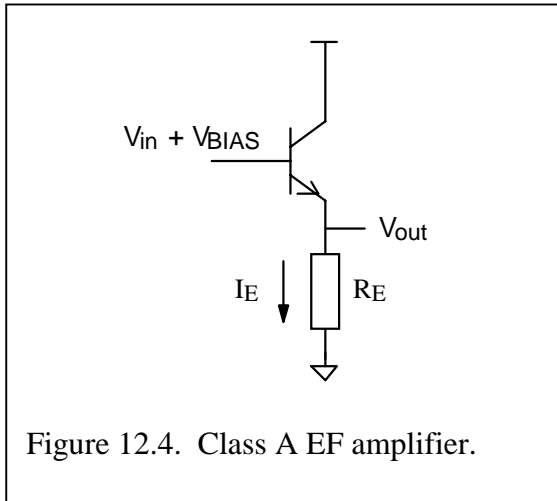


Figure 12.4. Class A EF amplifier.

The amplifier is DC biased so that transistor is on for full signal cycle. Require $V_{BIAS} > V_{peak} + V_{BE(on)}$ to ensure transistor is always on. This is a **class A** amplifier. Quiescent $I_{CQ} \approx I_{EQ} = (V_{BIAS} - 0.7)/R_E$. Current flow for whole cycle = inefficient.

Output voltage follows input for whole signal cycle = low distortion.

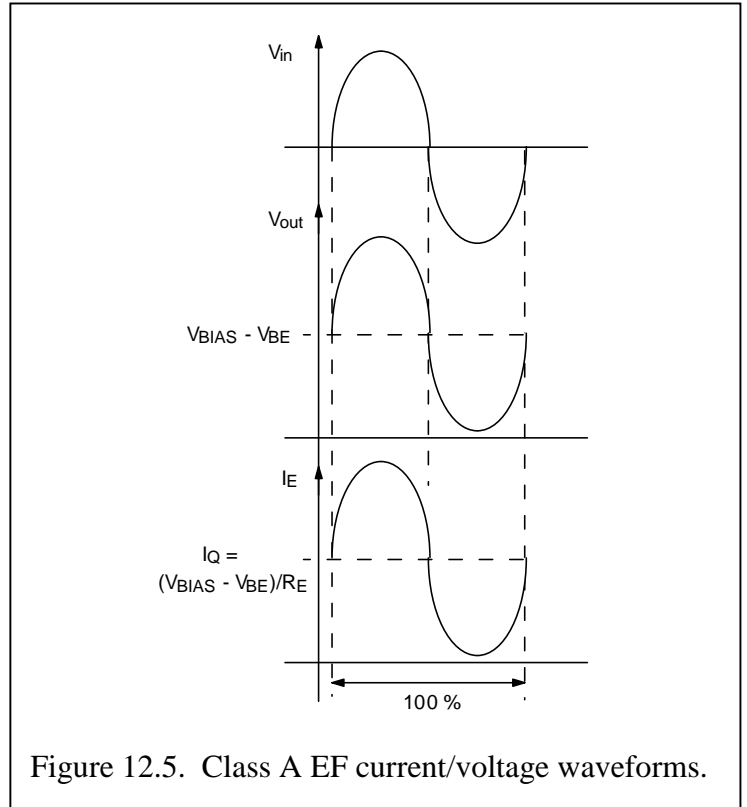


Figure 12.5. Class A EF current/voltage waveforms.

Mark 3 emitter-follower - the push-pull amplifier

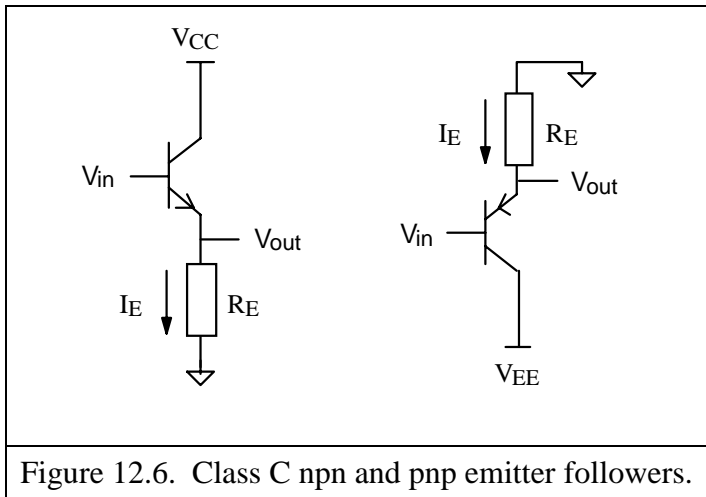


Figure 12.6. Class C npn and pnp emitter followers.

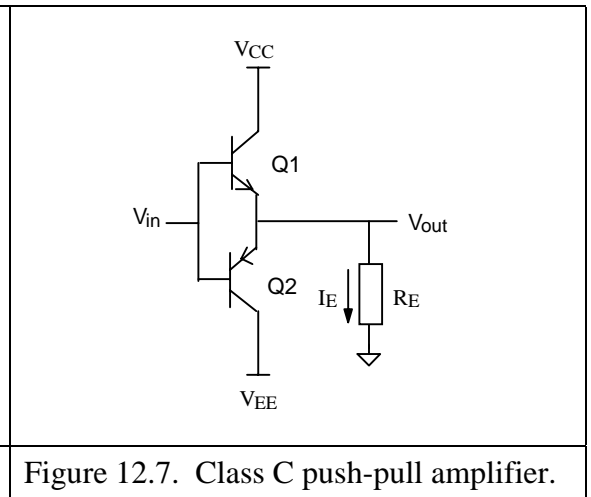
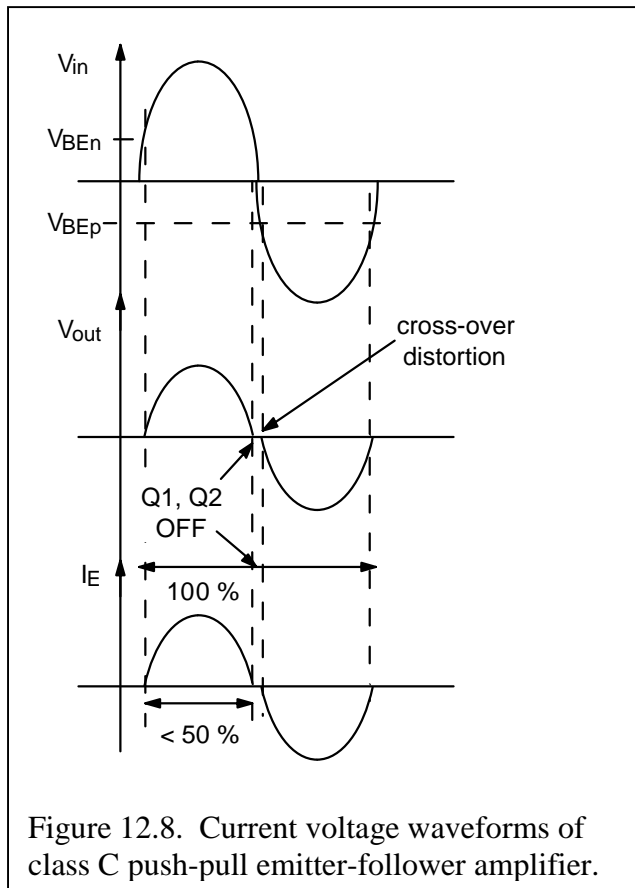


Figure 12.7. Class C push-pull amplifier.

Figure 12.6 shows how npn and pnp based **class C** amplifiers are built. The two circuits complement each other, and operate from complementary power supplies (i.e. $V_{EE} = -V_{CC}$). The two circuits can be combined (Fig. 12.7) to make a **class C push-pull** amplifier. There is no bias voltage added to V_{in} - this is a DC coupled amplifier. R_E is no longer an integral part of the circuit - it is an EXTERNAL load.

- $V_{in} > 0.7V$, Q1 conducts, Q2 is off. Q1 pushes current from V_{CC} through R_E to ground.
- $V_{in} < -0.7V$, Q1 is off and Q2 conducts. Q2 pulls current from ground through R_E to V_{EE} .



- $-0.7V < V_{in} < 0.7V$, both Q1 and Q2 are off. No output current or voltage.

The class C push-pull amplifier suffers from **cross-over** distortion. This arises from the part of the input signal cycle for which neither transistor is turned on. i.e.:

$$-0.7V < V_{in} < 0.7V$$

However, unlike the single transistor class C amplifier, the circuit does operated in the negative half cycle (c.f. Figs. 12.1 and 12.2), since the pnp and npn transistors complement each other. Nevertheless, this is a high distortion amplifier.

Current flow is only in response to input signal, so the circuit is efficient.

Mark 4 emitter-follower - the class B and class AB push-pull amplifier

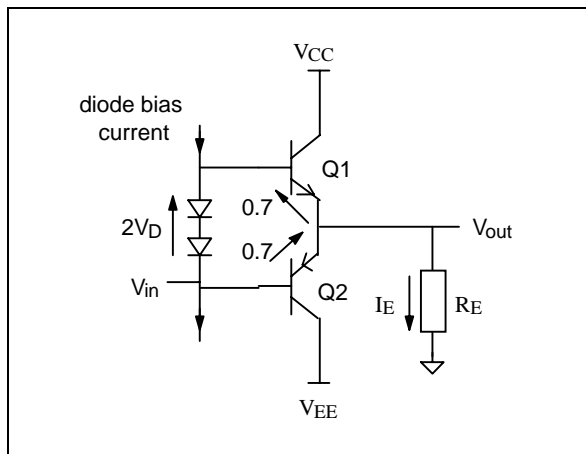


Figure 12.9. Class B amplifier with bias diodes.

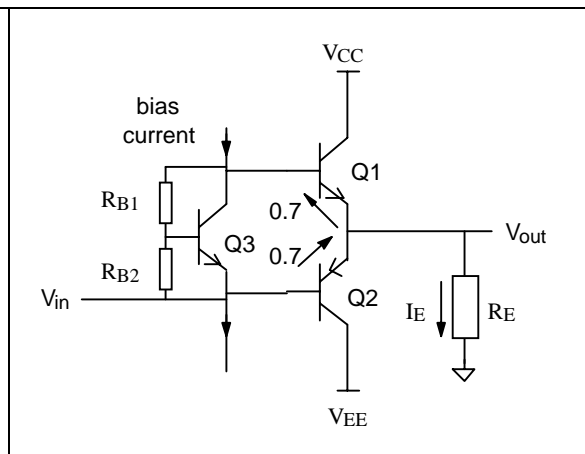


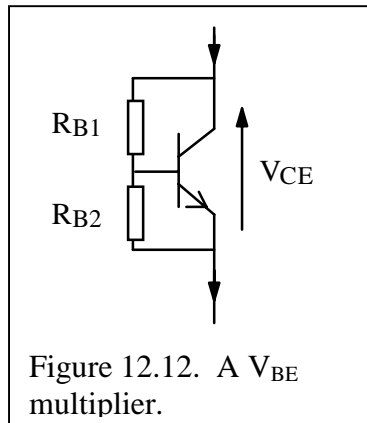
Figure 12.10. Class AB amplifier with V_{BE} multiplier.

By using a small amount of base bias, it is possible to eliminate cross-over distortion. For class B operation, we have:

- $V_{in} > 0V$, Q1 on, Q2 off and $V_{out} = V_{in}$
- $V_{in} < 0V$, Q2 on, Q1 off and $V_{out} = V_{in}$

- $V_{in} = 0V$, Q2 on, Q1 on and $V_{out} = V_{in}$

In a class B amplifier, each transistor operates for exactly 50 % of the cycle. In Fig. 12.9 the input is applied to the base of Q2. There is a base-bias current that ensures the voltage difference is 2 diode voltage drops ($2V_D$) between the bases of Q1 and Q2. This should **exactly** compensate for the base-emitter drops of the transistors. The circuit is rarely used for two reasons - it is easier to build transistors on an IC, and $2V_D$ is not guaranteed to equal $V_{BEp} + V_{BE n}$.

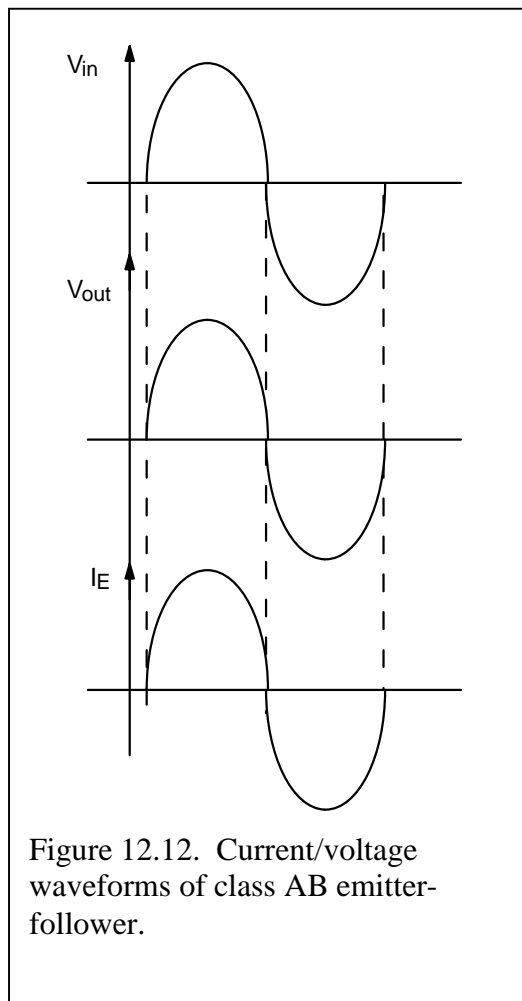


A class AB amplifier is biased to guarantee that either Q1 or Q2 is on for any part of the input cycle. It uses attributes from the class A and class B circuits (hence the designation). Figure 12.10 shows a class AB amplifier. The amplifier of Fig. 12.10 uses a V_{BE} multiplier (Q3, R_{B1} and R_{B2}).

When Q3 is biased in the forward active region, then the voltage drop across $R_{B2} = V_{BE} \approx 0.7V$. The collector-emitter voltage drop will therefore be

$$V_{CE} = V_{BE} \frac{R_{B1} + R_{B2}}{R_{B2}}$$

Class AB operation requires $V_{CE} > V_{BE n} + V_{BE p}$ of output transistors Q1 and Q2 to ensure that there is no part of the signal cycle for which they are both off. There is a small quiescent current and there is no cross-over distortion.



Harmonic distortion

Although the class AB push-pull amplifier will be free of cross-over distortion, there will still be some distortion of the signal. There is no voltage gain in the circuit, only current gain. The voltage gain in the Op-Amp circuit is in the Darlington amplifier stage, hence the input to the emitter-follower will be large. The voltage swings may in fact be close to V_{CC} and V_{EE} .

The emitter follower is therefore operating as a LARGE SIGNAL amplifier. The circuit will not be in the linear small signal domain, and the transfer function will be EXPONENTIAL since

$$\alpha I_E = I_C = I_S \left(\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right) \text{ and } v_o = I_E R_E =$$

$$I_C R_E / \alpha.$$

The series expansion of an exponential is

$$e^x = 1 + x + \frac{x^2}{2} + \frac{x^3}{3!} + \dots$$

For small signals ($x \ll 1$), e^x is approximately linear, but for large values, the high order terms dominate. Therefore,

$$I_C = I_S \left(v_{in}/V_T + \frac{(v_{in}/V_T)^2}{2} + \frac{(v_{in}/V_T)^3}{3!} + \dots \right), \text{ since } V_{BE} = v_{in}.$$

The first term is linear, and does not distort the signal. The polynomial (quadratic, cubic, etc) terms will generate HARMONICS. If $v_{in} = A \cos \omega t$, where ω is the FUNDAMENTAL frequency then the quadratic term is

$$\frac{1}{2} \left(\frac{v_{in}}{V_T} \right)^2 = \frac{A^2}{2V_T^2} \cos^2 \omega t = \frac{A^2}{4V_T^2} (1 + \cos 2\omega t), \text{ and the cubic term is}$$

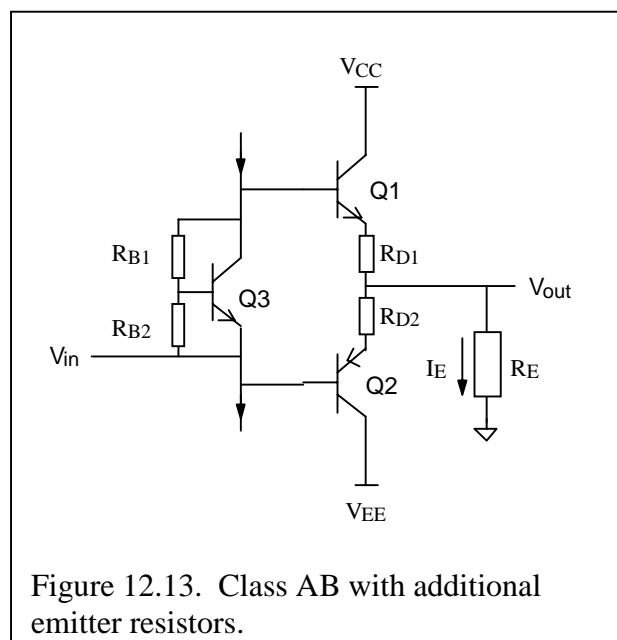
$$\frac{1}{6} \left(\frac{v_{in}}{V_T} \right)^3 = \frac{A^3}{6V_T^3} \cos 3\omega t = \frac{A^3}{12V_T^3} (1 + \cos 2\omega t) \cos \omega t = \frac{A^3}{24V_T^3} (3 \cos \omega t + \cos 3\omega t).$$

Clearly, we could carry on to infinity for all the terms, generating successively more accurate values for the COEFFICIENTS for each of the cosine terms that contain multiples or harmonics of the fundamental frequency (2ω , 3ω , etc). For each harmonic we add up all the coefficients to produce the amplitude of the signal generated at that frequency, such that

$$v_{out} = \frac{I_C R_E}{\alpha} = \frac{R_E}{\alpha} (H_1 \cos \omega t + H_2 \cos 2\omega t + H_3 \cos 3\omega t + \dots)$$

The first order linear term (H_1) is NOT a distortion term whereas all higher terms are.

Emitter degeneration



The addition of emitter "degeneration" resistors reduces distortion. Previously, we had $V_{in} = V_{BE}$. This is not true for Fig. 12.13 since there will be a voltage drop across the degeneration resistors R_{D1} or R_{D2} between the input and the output. The overall change in V_{BE} will be reduced to $V_{BE} = v_{in} - I_E R_D$, thus the non-linearity will be reduced. i.e.

$$v_{out} = I_E R_E = \frac{I_S R_E}{\alpha} \left(\exp \left(\frac{v_{in} - I_E R_D}{V_T} \right) - 1 \right)$$

where $R_D = R_{D1} = R_{D2}$.

The effect of R_D is to introduce negative or degenerative feedback (note minus sign in exponential), hence desensitising and linearising the circuit.

The overall evaluation of the harmonics generated by the circuit is now more complex (and will not be treated in detail!). The resistors R_{D1} and R_{D2} also have a protective function. In the event that the output is short-circuited, they will limit the current in Q1 or Q2, preventing damage.

Base bias

The base bias circuit (see Fig. 12.10) requires a constant current source. This is supplied using current mirror techniques, as normal.