Basic Differential Amplifiers

I. Introduction

In this document, just the basic concept of differential amplifier will be covered.

II. Initial Thoughts

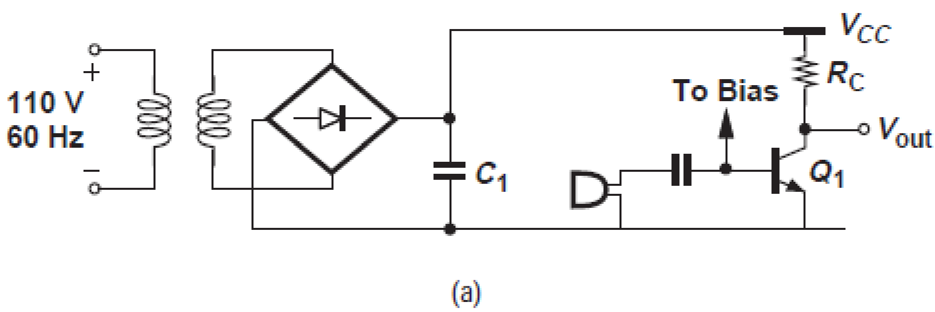


Figure. CE Amplifier powered by a rectifier

Since the rectifier cannot be an ideal rectifier, it will contain noises, which perturb the CE amplifier signal. Power supply must be at constant for transistor amplifiers. Let’s look at how it perturbs the main signal.

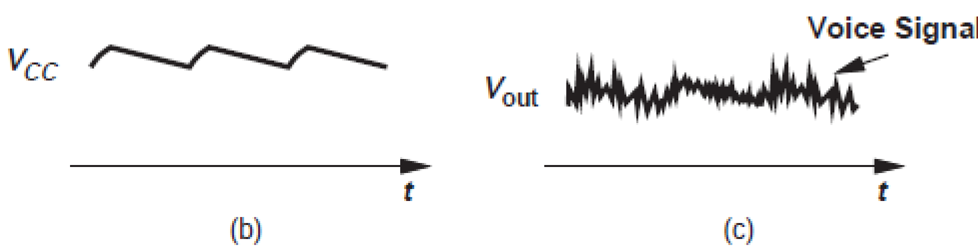
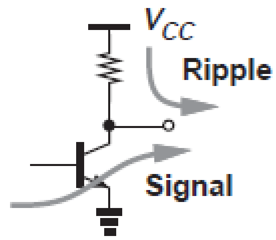


Figure. Input signal is voice signal

Voice/audio signal is one of the signal types that requires almost zero distortion since a slight change in the original input signal may reduce the quality of the whole signal. At the circuit level, let’s look at what happens:



(d)

Figure. Ripple and Signal are mixed

It might be an interesting topic how they are “mixed”. Convolution? Frequency mixing? Superimposing? From the above figure, it suggests me that the type of “mixing” process may be “superimposing”.

Now, back to topic, it’s the main issue how we can suppress such “noise” or “hum” in the output signal.

(1) Increasing the capacitor, C_1
(2) Considering the differential topology

The problem with (1)?

The size of the capacitor should be so much larger (almost infinitely large) to lower the ripple amplitude. <<To be honest, I don’t see how it works that way.>>

For practical issue, we can’t increase the capacitor size. Therefore, we need to change the topology of the amplifier to make the circuit (or the output signal) insensitive to the power supply level. Let’s first see what governs the output level.

$$V_{out} = V_{CC} - R_C I_C$$

This suggests that if there’s a small change in the power supply so is there at the output.

$$V_{out} = (V_{CC} + \Delta V_{CC}) - R_C I_C$$

Note that both V_{out} and V_{CC} are referenced to ground which infers that if the V_{out} is not referenced to ground, the problem can be solved: output voltage will not be perturbed by the presence of small change in V_{CC}. Let’s see the following circuit:

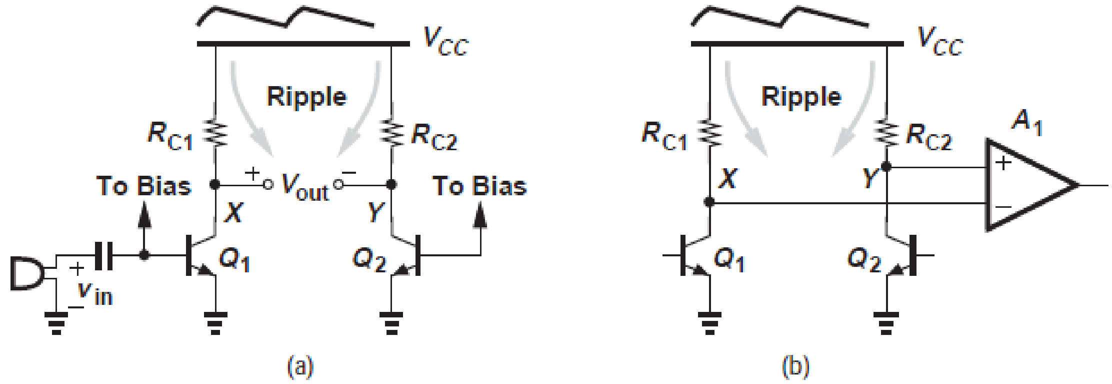


Figure 10.2 Use of two CE stages to remove effect of ripple.

Interestingly, the ripple present in the power supply cancelled each other at the output if we consider the voltage level of the difference between two outputs.

$$v_X = A_v v_{in} + v_{ripple}$$

$$v_Y = v_{ripple}$$

Q2 doesn't not carry input signal, it behaves as "constant current source". However, when I simulate a simple circuit model. Collector current of Q2 follows sinusoidal waveform but the change in amplitude is very small value which might be why the author treat it like a constant current source.

This is just a foundation for differential amplifier. Let us move on to the practical consideration.

III. Differential Signal

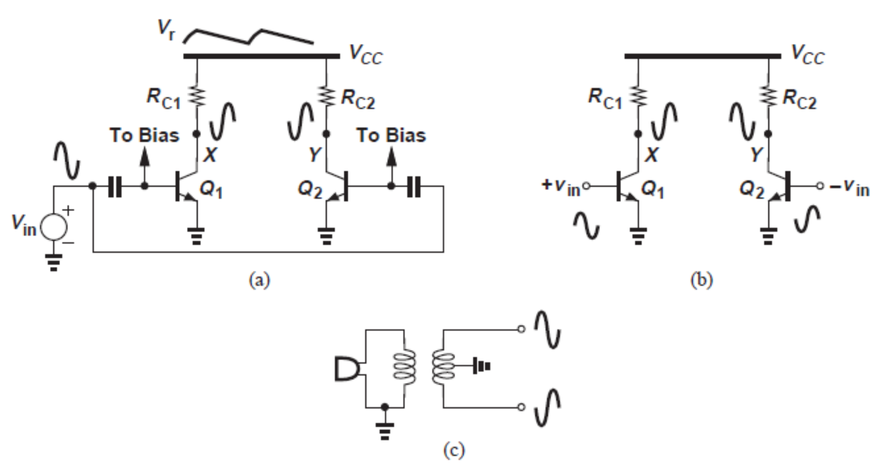


Figure 10.3 (a) Application of one input signal to two CE stages, (b) use of differential input signals, (c) generation of differential phases from one signal.

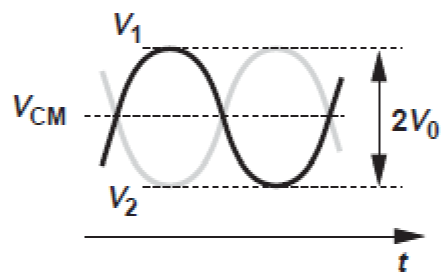
By injecting the input signals that are 180 out of phase each other, we can obtain:

$$v_X = A_v v_{in} + v_{ripple}$$

$$v_Y = -A_v v_{in} + v_{ripple}$$

$$v_{out} = v_X - v_Y = 2A_v v_{in}$$

From "***single-ended***" amplifier analysis, the output voltage contains both DC and AC signal in the form of superimposing the two voltages. In differential FET amplifier, the DC level is called "***Common-Mode***", denoted by V_{CM} since both outputs are referenced to this DC level.



(c)

Figure. CM level of output

$$V_{CM} = V_{CC} - R_C I_C$$

Note that this CM level can be affected by the ripple present in the power supply; however, the differential output voltage will not be affected as we've discussed the whole time.

IV. Qualitative Analysis

First, we are interested in the biasing condition of this differential amplifier. For simpler equations, let us use bipolar transistor for the analysis.

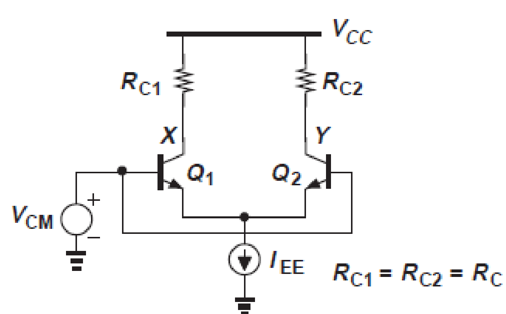


Figure 10.7 Response of differential pair to input CM change.

To avoid saturation, the output voltage level should be always greater than the CM level. Using the symmetry, the currents can be found:

$$I_{C1} = I_{C2} = \frac{I_{EE}}{2}$$

Active Region of transistor:

$$V_C > V_B > V_E$$

Applied voltages	B-E junction bias (NPN)	B-C junction bias (NPN)	Mode (NPN)
E < B < C	Forward	Reverse	Forward-active
E < B > C	Forward	Forward	Saturation
E > B < C	Reverse	Reverse	Cut-off
E > B > C	Reverse	Forward	Reverse-active
Applied voltages	**B-E junction bias (PNP)**	**B-C junction bias (PNP)**	**Mode (PNP)**
E < B < C	Reverse	Forward	Reverse-active
E < B > C	Reverse	Reverse	Cut-off
E > B < C	Forward	Forward	Saturation
E > B > C	Forward	Reverse	Forward-active

Figure. [2]

In conclusion, to avoid saturation region, DC levels can be determined as the follow:

$$V_X = V_Y = V_{CC} - R_C \frac{I_{EE}}{2} \geq V_{CM}$$

Let’s investigate the following circuit to better understand how differential pairs work. Please make sure getting this concept straight because it is *too important*.

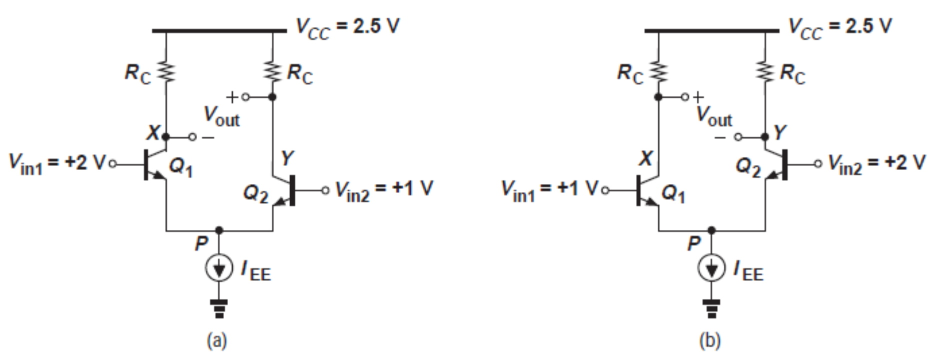


Figure 10.9 Response of bipolar differential pair to (a) large positive input difference and (b) large negative input difference.

In the Figure 10.9 (a): we see that if in1 is greater than in2, then the out2 will be greater than out1. In addition, since emitter current is conserved at all time (constant current source!) $I_{C1} > I_{C2}$. In summary:

If

$$V_{in1} > V_{in2}$$

Then,

$$V_{out1} < V_{out2}$$
$$I_{C1} > I_{C2}$$

In words, higher input level requires more collector current; therefore, lowering the output voltage. See Figure 10.9 (a)

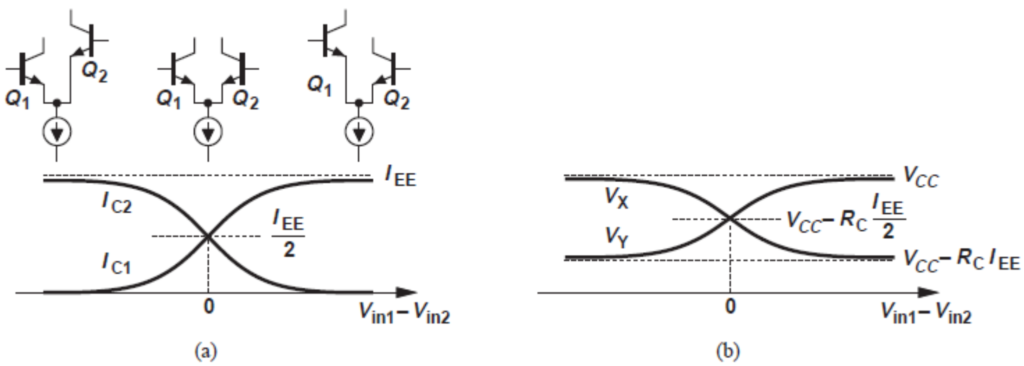


Figure 10.10 Variation of (a) collector currents and (b) output voltages as a function of input.

The graphs in Figure 10.10 can be modeled with hyperbolic tangent function. From the I-V characteristic of transistor, the current and voltage are related in the exponential form. In the document of even and odd function, it is shown that the exponential functions can lead to hyperbolic functions using the even and odd function properties.

V. References

[1] Fundamentals of Microelectronics, Behzad and

[2] https://en.wikipedia.org/wiki/Bipolar_junction_transistor