PHYS 431 – Lab 4: Transistor Circuits

Parts List

- Resistors: 100, 330, 1k, 3.3k, 5.6k, 10k, 56k, 10k potentiometer
- Capacitors: 0.1 $\mu$F, 1 $\mu$F
- Transistors: 2N3904 NPN (or equivalent)

4.1 Goals of this Lab

Note: you have two weeks to finish this lab, and you may work with a partner if you wish.

Following our introduction to transistors in Lab 3, this time we will study some common transistor circuits. For convenience, the transistor connection conventions are reproduced below in Fig. 1. This lab specifies the 2N3904 NPN transistor, although sometimes we run out of specific transistor types. Any general-purpose NPN transistor can be used for this lab, although it is a good idea to check it with the DVM first to make sure it works. As long as $\beta$ is somewhere in the range 50–200, you should be fine. This is also a good way to make sure you have the pin assignment correct. Please note in your log book which transistor you are using.

Figure 1: Transistor connections
4.2 Emitter Follower

An emitter follower circuit is a unity-gain buffer stage that is very useful for coupling together different parts of a circuit in a way to avoid loading down a source. Here we will use the follower to better understand source and load impedances and loading in a more complicated circuit.

4.2.1 Simple Follower

Wire up the emitter follower circuit shown below in Fig. 2. Input a sine wave with amplitude symmetric about ground. Compare input and output of your follower. Increase the input amplitude beyond 5 V. Sketch the input and output wave forms. Does the output follow the input?

![Figure 2: Basic emitter follower](image)

![Figure 3: Symmetric (or split-rail) emitter follower](image)

4.2.2 Symmetric Follower

Replace the emitter resistor connection to ground with a connection to $-15$ V, as shown in Fig. 3. Keep the 3.3kΩ emitter resistor and the 330Ω base resistor. Again look at input and output wave forms. Sketch the results and note any changes. Note, this is why power supplies used for analog signals often have both positive and negative voltage values (known as split-rail supplies). With only one supply voltage, an AC signal needs to be biased away from ground to work with a simple follower.

4.2.3 Impedances

We wish to measure the input and output impedances of our follower circuit. Make sure you understand what you expect before starting to make measurements. Build the circuit shown in Fig. 4 below. The combination of the function generator and $R_B$ form a fairly ‘bad’ voltage source with a large output impedance ($51kΩ$). We can think of these elements as the source feeding a signal into the emitter-follower at $V_B$.

We have also added a capacitively-coupled ‘load’ on the output of our follower at $V_{out}$. The capacitor keeps the load resistor from changing the DC transistor behavior, while at higher frequency the capacitor impedance becomes negligible and the load impedance is approximately given by the 1 kΩ resistor. To understand why, using what you know about complex impedances, show that the magnitude of the impedance of the load (everything from $V_{out}$ to ground) is given by $Z = R \left[ 1 + 1/(\omega RC)^2 \right]^{1/2}$. 
Find the critical frequency where the resistor and capacitor have similar impedances using the component values for $R$ and $C$ in this circuit and roughly sketch what the total impedance magnitude will be as a function of frequency.

Figure 4: Transistor impedance

4.2.4 Initial Estimates

An important property of the emitter follower is that it presents a large input impedance and a small output impedance. This can be useful to avoid excessive loading between a source and a load for AC signals, as shown schematically in Fig. 5.

The AC input impedance of the follower+load seen by the source is about $Z_{\text{in}} \approx \beta (R_E \| Z_{\text{load}})$, where $Z_{\text{load}}$ is the AC load that comes after the follower, and $R_E$ is the emitter resistor (3.3 kΩ here). This means that the voltage source appears to be driving the equivalent load circuit (starting at the transistor base) as shown in Fig. 6, assuming a high enough frequency that we can assume the capacitor has negligible impedance.

On the other hand, the output impedance of the source + follower driving the load is about $Z_{\text{out}} \approx (Z_{\text{source}} / \beta) \| R_E$, where $Z_{\text{source}}$ is the source impedance of the signal being delivered to the follower. Thus we have the equivalent source circuit driving the load at $V_{\text{out}}$ as shown in Fig. 7.

With these considerations in mind, estimate $Z_{\text{in}}$ and $Z_{\text{out}}$ for the emitter follower, assuming a high enough frequency that you can treat the capacitor impedance as negligible. If you are confused by this discussion, talk to the TA before continuing.

Note we have designed this circuit to still have some significant loading, so that we can measure this effect in the next section. In a properly designed follower, the input impedance to the follower
Figure 6: Equivalent circuit seen by the source

would be at least a factor of 10 higher than the source impedance (or alternately the output impedance would be at least a factor of 10 lower than the load impedance).

Figure 7: Equivalent circuit seen by the load

4.2.5 Output Impedance
To measure $Z_{\text{out}}$ of the follower at the point labeled $V_{\text{out}}$, we consider the Thévenin equivalent circuit of the 51 kΩ source resistor as seen through the transistor in parallel with the 3.3 kΩ emitter resistor. This is driving a load consisting of the 1 kΩ resistor (we will use a frequency where the capacitor impedance is negligible). The equivalent output impedance and the load impedance form a voltage divider producing $V_{\text{out}}$ in between these two impedances. Operating at a frequency well above $\omega_{\text{3db}}$ of the load, measure the output amplitude with and without the 1 kΩ load attached, and use these amplitudes and what you know about voltage dividers to determine $Z_{\text{out}}$.

Do your measurements agree with your expectations from Section 4.2.4?

4.2.6 Input Impedance
To measure $Z_{\text{in}}$, measure the amplitude of the signal at the source $V_{\text{in}}$ compared to $V_B$. Now the source impedance and the input impedance of the follower create a voltage divider, and from measuring the fraction of the input amplitude seen at $V_B$ you can determine the ratio of these two impedances. Hence, by measuring the signal amplitude at the base, and comparing to $V_{\text{in}}$ we can determine $Z_{\text{in}}$.

Again, do your measurements agree with your expectations from Section 4.2.4?

4.3 Current Source
The arrangement shown in Fig. 8 can serve as an approximate current source. Use a 10 kΩ variable resistor with the wiper wired to one end as shown as the load to be driven by the current source. Make sure you understand which direction to turn the potentiometer to increase or decrease the resistance. Measure the current delivered to the load by measuring the voltage drop across the 100 Ω resistor with a DVM. Starting with the lowest value of load resistance, vary (slowly!) the load resistance while
measuring the current. How good is this current source? In other words, how constant is the current supplied to the load before the transistor starts to saturate?

The ‘compliance’ of a current source is usually quoted in terms of the maximum $\Delta V$ the source can provide across a load while maintaining a constant current. Turn the load resistance up until the current flowing had dropped by 20% from the initial value with no load, then measure $\Delta V$ across the load resistor. Use your measurements of current and $\Delta V$ to determine the maximum resistance this current source can drive.

![Figure 8: Simple current source](image)

4.4 Common-emitter Amplifier

We will now explore the most common transistor amplifier circuit. Set up the common-emitter amplifier shown in Fig. 9.

4.4.1 DC characteristics

Ground the input ($V_{\text{in}}$) and measure the DC operating voltages of the amplifier. In other words, measure $V_B$, $V_C$, and $V_E$. Compare your readings to what you would expect using our standard transistor design rules.

4.4.2 AC gain

Input a small-amplitude sine wave at $V_{\text{in}}$. Measure the voltage gain of the amplifier $V_{\text{out}}/V_{\text{in}}$ over the frequency range 50 Hz to 10 kHz. Make a rough plot of gain versus $\log_{10}$ of frequency. What is the measured $\omega_{3\text{db}}$ point? Does this agree with your expectation? Is $V_{\text{out}}$ centered around ground? What could you do if you wanted it to be (there are two obvious possibilities)?
4.4.3 Clipping

What is the maximum amplitude of the output signal that can be produced by this circuit without distortion (clipping)? Turn up the amplitude of the input until you start to see flat regions in the output signal at either the top or the bottom of the waveform. What causes this distortion? Do you have an idea how this could be improved?

![Common emitter amplifier diagram](image)

Figure 9: Common emitter amplifier