Version of March 1, 2011

Lab 6: Bipolar Junction Transistors, Emitter Followers

Reference Reading: Chapter 5, Sections 5.1, 5.2 and 5.3.1.
Three lab periods will be devoted to this lab.
Goals:

1. Understand basic transistor operation
2. Understand the need for a biasing network and the design criteria for AC circuits
3. Demonstrate power gain, high input resistance, low output resistance
4. Understand the implication of power gain without voltage gain

1 Introduction

Active circuits are ones which can yield "gain" in the sense of being able to yield greater power output than input. In most cases, more power can be delivered to a load by passing the signal through an amplifier than directly from a signal source. Obviously, the gained power has to come from somewhere and this is generally from a DC voltage supply (often called a D.C. power supply for this reason).

We begin with a simple "voltage follower" circuit that provides an output voltage that "follows" the input voltage (i.e., is essentially equal to the input voltage). How can such a seemingly useless circuit have any function? Because it can be a *power amplifier*: because the follower's output impedance (essentially a resistance) can be quite low compared to that of the signal source, the follower can supply more power to a load than a high impedance source could.

In Lab 7, you will examine the common emitter amplifier circuit; this can have both voltage and power gain.

For both labs 6 and 7, we use a simple model for *npn* transistor operation (to understand the underlying principles requires an understanding of how electrons behave in crystals – the subject of a course in solid state physics; in class, we will give a quick introduction):

1. The collector must be more positive than the emitter. This is clearly necessary in order for current to flow from collector to emitter.
2. The base-emitter and base-collector junctions behave like diodes:
   (a) When the base-emitter junction is reverse biased, the transistor is turned off and no current flows from collector to emitter. The base-emitter junction is like the handle of a valve – it controls the current flow through the collector-emitter circuit.

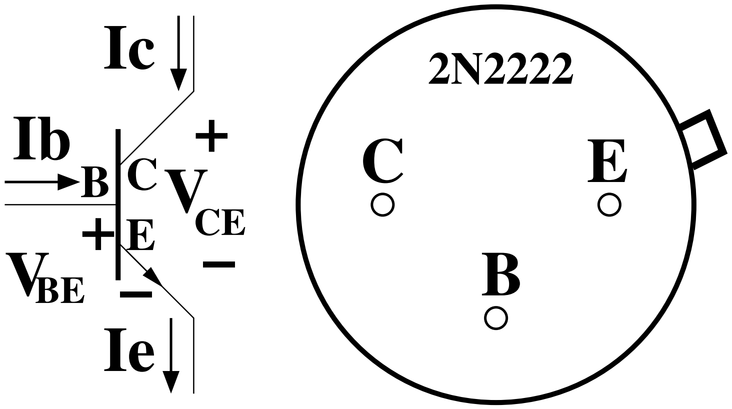

Figure 1: NPN transistor schematic symbol, notation, and lead configuration for the 2N2222.

   (b) When the base-emitter is forward biased and the base-collector is reverse biased, the transistor is in the "active" or "linear" operating range. A forward biased diode has a "diode drop" of 0.6 to 0.7 Volts (0.65 V).

   (c) When both junctions are forward biased, the transistor is "saturated" and, typically, $V_{CE} \approx 0.1 - 0.2$ Volts.

3. Maximum values of I_C and V_{CE} cannot be exceeded without burning out the transistor.

4. If 1 - 3 are obeyed, then $I_C \approx h_{FE} I_B = \beta I_B$. β (or h_{FE}) is roughly constant in the active or linear operating range. Typical values are in the range 50 - 250 and can vary substantially from transistor-to-transistor even for a given transistor type. A good circuit design is one that does not depend critically on the exact value of β but only on the fact that β is a large number.

Figure 1 illustrates the definitions of transistor voltages and currents. Note that it is always true that

$$I_E = I_C + I_B \, . \tag{1}$$

In the active range,

$$I_E = (\beta + 1) I_B \approx I_C, \tag{2}$$

the approximation holding for large β, and

$$V_B \approx V_E + 0.65\text{Volts}. \tag{3}$$

You will apply these equations many times – remember them!

Also shown is a picture of the 2N2222 transistor as seen from the side with the leads. You should remember that the metal transistor can is usually connected to the collector – *be careful to not let wires touch the can!*

You can verify that a transistor is functional by checking the two diode junctions with an ohmmeter. With the positive (red) lead on the base of an NPN transistor, you should see conduction to both emitter and collector; with the negative (black) lead on the base, you should not see conduction to either other lead.

For the emitter follower, we will (in class) determine the input resistance to be

$$R_i = (\beta + 1) R_e, \tag{4}$$

where R_e is the equivalent resistance from the emitter terminal to ground. For the output resistance we will obtain,

$$R_o = \frac{R_s}{\beta + 1}, \tag{5}$$

where R_s is the equivalent source resistance. Hence, a large β helps make the input resistance high (the circuit draws only a small amount of current and therefore receives the maximum voltage signal from the source) and the output resistance low (the output voltage is independent of the load–i.e., of the current drawn–down to small loads). *When you see such statements as these, you should think of (and even draw) Thèvenin equivalent circuits; here, draw (i) the equivalent circuit of a source and the input of the transistor circuit and (ii) the equivalent for the transistor circuit output and a load – justify the statements.*

2 Preliminary Lab Questions

The work in this section must be completed and signed off by an instructor before you start working on the lab. Do this work in your lab book.

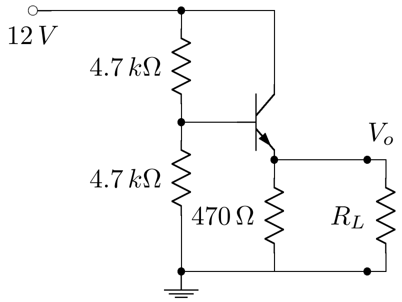

Figure 2: Figure for the pre-lab work.

1. Draw the *voltage divider* and the Thevenin equivalent of the voltage divider from the figure above. Be sure to determine both V_{th} and R_{th}.
2. Draw the *emitter follower* and the Thevenin equivalent (as seen looking into the base) of the emitter follower. (You may assume $\beta \approx 100$ for this transistor.)
3. What is the effect of the emitter follower on the output of the voltage divider?

4. Draw the Thevenin equivalent for the entire circuit as seen from the output of the transistor. You do not need to compute V_{th} and R_{th}, but **EXPLAIN** how you would measure them.

3 Equipment and Parts

In this lab we will utilize the following equipment. This equipment is located at your lab station.

1. The Tektronix TDS 2012B digital osciliscope.
2. Two P2220 probes for the osciliscope.
3. One USB memory stick which is no larger than 2GB.
4. The Interplex Electronics 1200CA-1 power brick and bus connector.
5. The Stanford Research Systems DS335 signal generator.
6. One BNC to alligator cable.
7. The Metex 4650 digital meter.
8. The Global Specialities PB10 protoboard.

You will also need the following components in order to carry out this lab. It makes more sense to get them as you need them, rather than all at once before the start of the lab.

1. $10\,\Omega$ resistor.
2. $100\,\Omega$ resistor.
3. $4.7\,k\Omega$ resistor.
4. One $2N2222$ npn switching transistor.
5. Additional resistors and capacitors you choose to match your circuit designs.

4 Procedure

First, you will demonstrate the *impedance transformer* property of the emitter follower using just DC voltages. To take advantage of this same property, but applied to AC signals, requires some additional complications that you will learn about in 4.2.

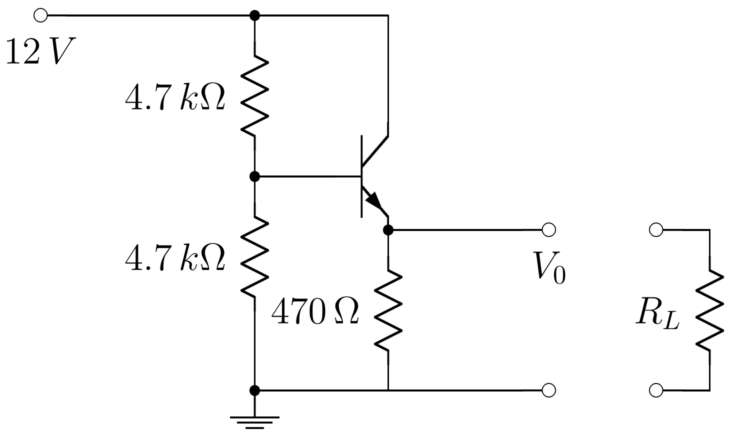

Figure 3: DC Emitter Follower Circuit. This circuit is an impedance transformer in that the I-V characteristic of the output terminals (∘) has a slope that corresponds to a smaller source resistance than does the I-V characteristic of the "Voltage Divider Source" by itself. Because the circuit delivers more power to a small load, R_L, than the "Voltage Divider Source" would by itself, the emitter follower can have significant power gain.

4.1 DC Emitter Follower

Use an emitter follower circuit to make a good voltage source out of a lousy one. You should recall from previous work what constitutes a "good" voltage source. The circuit in Figure 3 shows a voltage divider driving an emitter follower circuit. The large resistances ($4.7\,k\Omega$) in the divider mean that any load driven by the divider would need to have a resistance much larger than $4.7\,k\Omega$, making this "lousy voltage source".

We are going to combine this with the transistor "emitter follower" to make a voltage source whose output terminals are indicated by the two open dots near V_0 in Figure 3. You should think of everything up to those dots as being the new and improved "voltage source" whose characteristics you want to measure.

1. First, in your notebook, draw the circuit with the input (the voltage divider) replaced by its Thèvenin equivalent. Draw the transistor circuit attached to this equivalent. Next, draw the same equivalent circuit of the voltage divider with the transistor circuit replaced by its equivalent as seen from the base; what is the value of the load resistance seen by the voltage divider?

2. On the same graph you will use for the emitter follower output, draw the *expected* I-V curve for the divider circuit; i.e., for the Thèvenin equivalent just drawn. Use axes that show the global behavior, going from zero to the maximum values of I and V.

3. Build the circuit shown in Fig. 3. You can use the on-board 12V power supply as the DC source. *With multi-part circuits, it is always a good idea to build and test the circuit in sections. Follow this sequence:*

   (a) Build the voltage divider first. Test the output voltage and verify that it is as expected. You might want to put a load resistor across the output to make sure your work above is correct.
   (b) Add the transistor and emitter resistor but keep $R_L = \infty$. It is advisable to ground the negative side of the DC power supply used to supply 12V to the divider and the transistor. Note that because the DC supply is such a good voltage source (constant voltage regardless of current being supplied), you can think of it as independently supplying 12V to both parts of the circuit.
   (c) What is the voltage divider output now? Is this as expected?
   (d) Is V_0 the expected value?
   (e) If your measurements for any of the above are puzzling, check the DC supply voltage – is this being shorted out? Is the power turned on?

4. Measure and plot, on the same axes as above, the I-V curve for the emitter follower output (do this by varying the load on your circuit in a way similar to that used in Lab 1). From this plot, determine the equivalent output resistance, R_o, of the circuit and compare to equation 5.

5. Determine the answers to the following questions:
   (a) What is the power delivered to a load in the two cases (with and without the emitter follower) when $R_L = 500\Omega$?
   (b) How sensitive is this circuit to the precise value of β?
   (c) What would happen to the functioning of this circuit if we chose voltage divider resistors of $100k\Omega$ (perhaps to reduce power consumption)?
   (d) What are the minimum and maximum input voltages this circuit can "follow" (given a fixed 12V supply at the collector)?

4.2 AC Emitter Follower

Before going further, you should understand how the circuit in Fig. 4 operates. What are the functions of C_1 and C_2? What do R_1 and R_2 achieve? Once you understand the design principles of this circuit, follow the steps below to select appropriate components for an audio amplifier.

- Follow the design procedure in the example at the end of section 5.3.1 of the textbook to determine appropriate values of components for the audio amplifier circuit. Here, we are using the same $V_{CC} = 12$ Volts but use $I_C = 10\,mA$ instead of $1\,mA$. Be sure to record your calculations in your lab notebook.

- Test the functioning of your circuit at, say, $1\,kHz$ to see how large an input voltage you can use with a large load resistor (say, $R_L = 10\,k\Omega$).

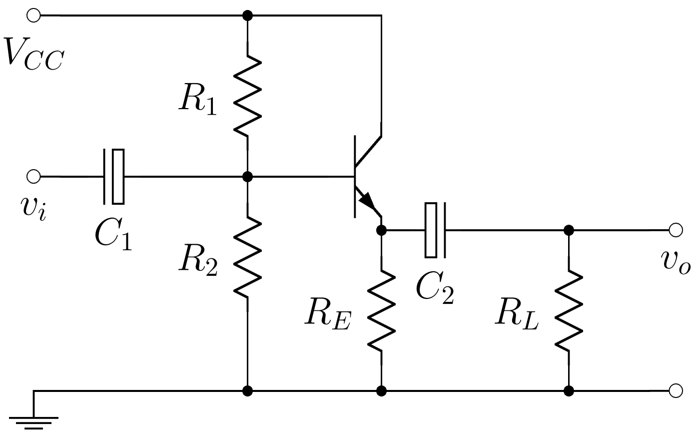

Figure 4: The AC emitter follower circuit.

- Measure the frequency response from just below your designed cut-off frequency up to the highest possible frequencies. Do this using an input amplitude which is somewhat smaller than the maximum possible (say $5\,V$ amplitude). Compare the results with $R_L = 1\,k\Omega$ and $R_L = 100\Omega$ (just check a few relevant frequencies for these last tests, so you can map out the response in the region in which it is changing).
- From your frequency response, predict how this circuit would respond to triangle or square wave inputs. Try it for some appropriate period of the input wave (using a value of R_L for which the circuit works well), and see if you are right. Try 5 or 10 kHz waves, if the expected distortion isn't clearly visible, try higher or lower frequencies. Include a sketch of the resulting waveforms (or capture and plot it) and appropriate discussions in your lab notebook.
- Test a design using different quiescent current, I_C. Try $1mA$ and make minimal changes in the circuit (do R_1 and R_2 need to be changed? explain). Test the circuit operation: can large AC signals still be passed? Does the low-frequency cut-off change? Is the high-frequency behavior still the same?