

EE462G: Laboratory Assignment 8
BJT Common Emitter Amplifier

by

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I. Instructional Objectives

- Understand the basic operation of the bipolar junction transistor (BJT)
- Apply a DC load line to establish a DC operating point
- Perform a small signal analysis of a BJT circuit to compute small signal input and output resistance and gain
- Experimentally measure small signal input and output resistance and gain

II. Background

A transistor (MOSFET and BJT) can be used to amplify a time-varying input signal (AC), after DC voltages are added to the AC input to ensure that the transistor is operating in its linear region (saturation region for a MOSFET, forward active region for a BJT). Transistors are nonlinear devices that can be approximated with linear models over certain regions. DC levels in the transistor circuit can be set to bias the AC signals so they operate in the linear region of the voltage-current relationships. The transistor circuit's DC currents and voltages are referred to as either the DC operating point, quiescent operating point, or bias point. Once a transistor is biased in its linear region, its currents and voltages will vary linearly with input signal changes as long as they stay within the transistor's linear range. It is assumed that the transistor's input signal variations, as well as other circuit current and voltage variations, are small enough so as not to perturb the system into nonlinear regions of operation (triode or cutoff for a MOSFET, saturation or cutoff for a BJT).

Bipolar Junction Transistor (BJT) Biasing

Figure 1 shows a simple common-emitter bipolar junction transistor (BJT) amplifier biasing scheme. The time varying part of the input signal is omitted to focus on the DC bias point. For the actual circuit operation the input consists of an AC signal added to a DC level at the BJT's base (V_{BB}). The transfer characteristic (output amplitude as a function of the input amplitude) for this circuit can be derived as:

$$V_{out} = V_{CC} - \frac{\beta_f \cdot R_C}{R_B} (V_{BB} - V_f), \quad (1)$$

where β_f is the current gain between the collector and base current (I_c / I_b), and V_f is the internal voltage drop over the base-emitter junction (V_{BE}). At the operating point, V_{BB} and V_{out} are the DC or quiescent values of the input and output voltages. Ideally, for a given V_{BB} , V_{out} should not vary much even if the temperature varies or if different transistors of the same type are used. Unfortunately the BJT's current gain β_f cannot be controlled well during manufacturing and so its values vary significantly even for the same component. For the PN2222 BJT transistor, manufacturers specify that β_f may be anywhere from 100 to 300. Thus, a circuit biased correctly for one PN2222 transistor may not be biased correctly for another PN2222 transistor. A more robust biasing scheme can be developed using feedback through an emitter resistor so that the BJT's quiescent operating point is more robust to changes in β_f .

Figure 2 shows a more robust design with resistor R_E placed in the emitter branch of the circuit. The DC analysis of this new circuit for the collector current results in:

$$I_C = \frac{\beta_f(V_{BB} - V_f)}{R_B + (\beta_f + 1)R_E}. \quad (2)$$

Note that if $(\beta_f + 1)R_E \gg R_B$ and $\beta_f \gg 1$, the collector current can be approximated as

$$I_C = \frac{(V_{BB} - V_f)}{R_E}, \quad (3)$$

which is independent of β_f .

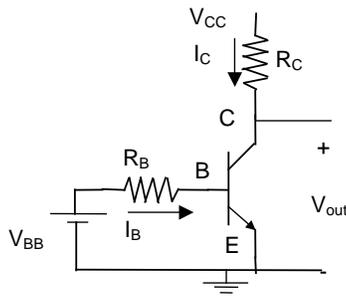


Fig. 1. Basic common emitter amplifier biasing.

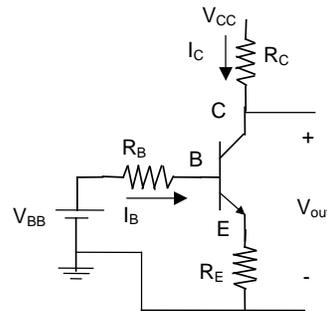


Fig. 2. Basic common emitter amplifier with reduced β_f sensitivity.

The schematics for these circuits indicate that two power supplies are required, one for V_{BB} and another for V_{CC} . The circuit in Fig. 3 shows a scheme where only one power supply is required. The Thévenin equivalent for the circuit consisting of V_{CC} , R_1 , and R_2 in Fig. 3 results in the biasing circuit of Fig. 2, where $V_{BB} = V_{th}$ and $R_B = R_{th}$. With these Thévenin equivalents substituted into the circuit, the circuit is identical to the circuit in Fig. 2 with the exception that the input bias voltage V_{BB} is now dependent on V_{CC} . The V_{BB} voltage is now controlled by the proper choice of R_1 and R_2 . This eliminates the need for a separate power supply to control V_{BB} .

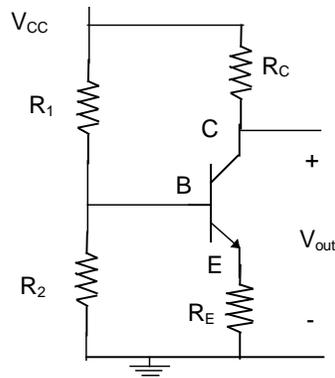


Fig. 3. Basic common emitter amplifier biasing with reduced β_f sensitivity and employing a single DC voltage.

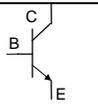
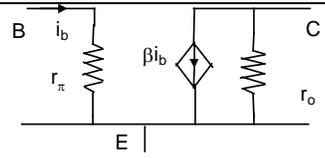
Choosing the resistors R_1 and R_2 such that $R_B \ll (\beta_f + 1)R_E$ is equivalent to making the current through R_1 and R_2 large enough such that the BJT's base current can be neglected in comparison. The base voltage is thus determined only by V_{CC} and the R_1 and R_2 voltage divider. The DC Operating point of this circuit is stable for two primary reasons:

- The base voltage is determined primarily by the voltage divider R_1 and R_2 and is effectively independent of the transistor parameters (especially β_f).
- The emitter resistor R_E stabilizes the DC operating point through negative feedback. If β_f increases for any reason, such as temperature change, the subsequent rise in emitter current will increase the voltage drop across R_E , thereby increasing V_E and V_B (since the drop across V_{BE} is a constant). The voltage drop across R_B is then smaller, causing a drop in I_B that counteracts the attempted increase in I_E .

Once the circuit in Fig. 3 is biased, it may be used as a voltage amplifier by connecting an input signal source to the base of the transistor, and connecting a load to the collector. These connections are coupled through a capacitor, as shown in Fig. 4, in order to prevent the source and load from altering the BJT's DC operating point. The capacitor C_{in} between the signal source and base voltage of the transistor keeps the DC voltage at the transistor base from being affected by the AC source's low impedance. In the same way, capacitor C_{out} ensures that the added load resistance does not change the DC voltage at the collector. These capacitors perform this function by being open circuits at DC. At the small AC signal frequencies, the capacitor values are chosen to have low impedance, allowing the AC signals to pass through. By the proper choice of C_{in} and C_{out} these capacitors can be treated as short circuits at the frequencies of interest.

The negative feedback that stabilizes the BJT's DC operating point also reduces the gain of the amplifier. The capacitor C_E in Fig. 4 remedies this problem by shorting out R_E for AC signals (also called "small" or "incremental" signals). Thus, the capacitor C_E effectively bypasses R_E ensuring the maximum AC gain.

The analysis of semiconductor circuits operating in their linear range is accomplished using a two-step analysis approach. The first step is the nonlinear DC or quiescent analysis. A loadline can be used to do this analysis. The second step is an AC incremental analysis where each element of the circuit is replaced by its linearized small signal model. Small signal models of common circuit elements are summarized in Table 1. A simplified small-signal model of the BJT is shown in Fig. 5. When doing a small-signal analysis each circuit element is replaced with its small signal equivalent producing a new small-signal equivalent schematic of the original circuit. Because the incremental circuit is linear, all of the linear circuit theory can be brought to bear in analyzing the small signal equivalent circuit including phasors, Fourier analysis, impulse response, and superposition. Also, once the linear circuit has been obtained, approximations can be used to simplify it further. For example, capacitors can often be treated as short circuits at the frequencies of interest.

Circuit element	Schematic	Small signal circuit element	Small signal schematic
Wire	—	Wire	—
Resistor		Resistor	
Capacitor		Capacitor or short for small $1/(j\omega C)$	 or 
Inductor		Inductor or open for large for small $(j\omega L)$	 or 
DC voltage source		Short	—
DC current source		Open	— —
NPN BJT		Current controlled current source	

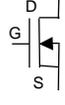
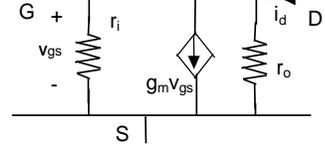
N - channel MOSFET		Voltage controlled current source	
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Table 1. Summary of circuit elements and their small signal equivalents.

To obtain the complete circuit solution, the quiescent and small signal solutions are added together. Thus, any circuit voltage or current is equal to the sum of the DC (quiescent) and AC (small signal or incremental) parts (i.e.):

$$V = V_Q + v_{inc}, \quad (4)$$

Lower case letters are typically used for the AC component and upper case letters are used for the DC component. In the small signal model of the BJT, shown in Fig. 4, r_π is the incremental resistance of the base-emitter junction, β is the ratio $\Delta i_C / \Delta i_B$ at constant collector to emitter voltage, and $r_o = \Delta V_{CE} / \Delta i_C$ at constant base current. The resistor r_o accounts for the small slope of the I-V characteristics in the forward-active region. It is large and often treated as infinite. The BJT input resistance r_π is computed once the DC or quiescent analysis is complete just as the MOSFET's g_m is computed once the DC or quiescent analysis is complete. The resistance r_π is found from linearizing the nonlinear base-emitter characteristic, which is an exponential function that models the diode-like interface.

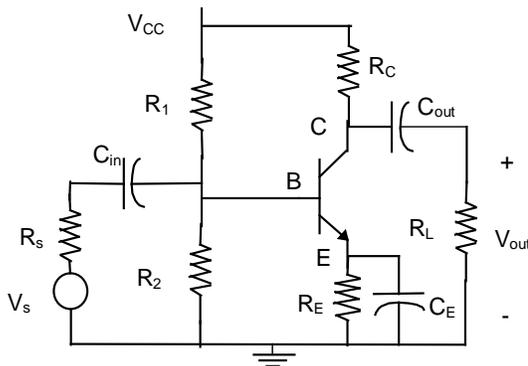


Fig. 4. Basic common emitter amplifier biasing with reduced β sensitivity and employing a single DC voltage with an AC input voltage.

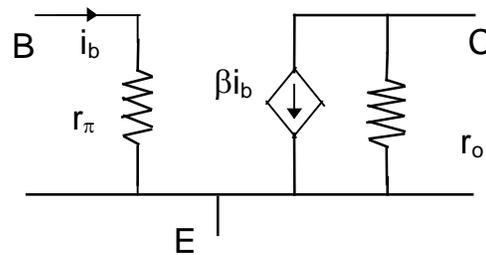


Fig. 5. Incremental or small signal model of a BJT.

III. Pre-Laboratory Exercises

In all of your small signal calculations you may assume r_o is infinite.

Setting up DC Parameters for Quiescent State

1. Derive the equation for the DC load line for the BJT circuit in Fig. 3 or equivalently Fig. 4 in terms of the variables V_{CC} , R_C , β_f , and R_E . (Hint: this equation will be in the format $i_C = (\dots - V_{CE}) / \dots$)
2. Use Matlab to plot the DC load line superposed with the characteristic curves (I_C vs. V_{CE}) of the NPN BJT you will be using in the lab (PN2222 with $\beta_f = 200$ and $V_{CESat} = .3V$). Choose values of R_C and R_E equal to $1k\Omega$ and 470Ω respectively. Choose $V_{CC} = 12V$, and choose a range of I_B values that cross the load line.
3. Determine the quiescent operating point I_{CQ} and V_{CEQ} such that it is at the midpoint of the DC load line (to result in good symmetry for output voltage swing), and determine the value of R_1 and R_2 , which will maintain that operating point and provide bias stability in conjunction with the emitter resistor. Make $I_{R_1} = 100 I_B$ with β_f equal to 200 and assume $V_{BEf} = 0.6V$.
4. Use SPICE to find the circuit's DC operating point for the circuit in Fig. 3 with the values given/determined in the previous problems. Change β_f to 260 and then 50. Determine the change in the operating point (I_{CQ} and V_{CEQ}) that for each β_f value (keep the same resistor values). Comment on the changes in the quiescent points relative to the change in β_f .

Small-Signal Model Resistances:

5. Assume the base current is related to the base emitter voltage by the ideal diode model.

$$i_b = I_S (e^{qV_{BE}/KT} - 1)$$

For typical base to emitter voltages the minus 1 in the ideal diode model can be neglected. Here q equals the charge of an electron, K = Boltzman's constant, and T is the thermodynamic temperature. At room temperature ($\approx 25C \approx 300K$) $KT/q = 25mV$.

- (a) At what value of v_{BE} is the exponential equal to 10?

For voltages above this value (forward bias) the base current can be approximated as

$$i_b = I_S \cdot e^{qV_{BE}/KT}$$

- (b) Linearize the ideal diode model for a forward biased base to emitter junction using a Taylor series expansion about a quiescent point V_{BEQ} (Hint - use first two terms of the Taylor series, where $a = V_{BEQ}$ and $f(x) = i_b(V_{BE})$).

Show that the incremental base current is related to the incremental base to emitter voltage by $i_b = \Delta i_b = \Delta v_{BE} / r_\pi$ where

$$r_\pi = (KT / q) / I_{BQ} = 25mV / I_{BQ}.$$

6. Compute r_π for a $\beta = 200$ at the quiescent operating point computed in the previous problems.

Small-Signal Gain Computations:

7. If there is no capacitor C_E ($C_E = 0$), show that the voltage gain of the amplifier with $R_s = 0$ and $R_L = \infty$ is approximately $G = -R_C / R_E$. Compute the gain using the component values derived in the previous problems.
8. With $R_s = 0$ and $R_L = \infty$, determine the gain of the circuit when C_E shorts out R_E ($C_E = \infty$) (both symbolically and numerically).

Small-Signal Input-Output Impedances:

9. Determine the input and output resistance of the circuit with and without C_E (assume C_E shorts out resistor in AC analysis when present). Do not include R_s and R_L in your calculations.
10. Determine the minimum values for $C_{in} = C_{out} = C_E$ so that they may be treated as short circuits at 8kHz. Assume the smallest resistance in the circuit is $R_S = 50\Omega$.
11. For $\beta_f = 200$, $R_L = 1k\Omega$, and using the components computed above, create a SPICE model for the circuit in Fig. 4 and perform a transient analysis with an input sinusoid at 8 kHz with an amplitude that does not severely distort at the output. Use the SPICE plots to find the AC voltage gain, current gain, input resistance, and output resistance for the case where C_E is and is not included. Let your program run for 0.5ms. Include copies of the plots you used to extract the values used in your computations.

IV. Laboratory Exercise

1. **Transfer characteristics of transistor:** Measure the PN2222 BJT's collector characteristic curves on the Agilent 4155B semiconductor parameter analyzer. Determine the BJT's forward current gain β_f .
2. **BJT common emitter amplifier DC parameters:** Construct the BJT common emitter amplifier using the Pre-lab values for R_1 , R_2 , R_E , R_C , and V_{CC} . Measure the circuit's quiescent operating point by measuring V_{CEQ} , the exact value of R_C and the voltage across R_C in order to calculate I_{CQ} . Measure the quiescent operating point using your multi-meter.
3. **BJT common emitter amplifier AC parameters:** Apply an 5 kHz sine wave to the input through an input capacitor close to, or larger than, the value computed in the prelab for C_{in} . Measure the output voltage between the output capacitor C_{out} and load resistor $R_L = 1k\Omega$ (See Fig. 4, insert C_{in} and C_{out} do not use C_E at this time). Observe and record the input, and output signals on the oscilloscope. Make sure the capacitor polarities are correct. Record the input and output waveforms. Determine the voltage gain $\left(Gain = \frac{\hat{v}_{out}}{\hat{v}_{in}} \right)$. (**Discussion:** Compare with your pre-lab values.)
4. **Effects of emitter by-pass capacitor:** Insert capacitor C_E shown in Fig. 4 into the circuit of the previous problem. Apply an input 8kHz sine wave signal that does not push the BJT into saturation or cutoff - you may need to build a resistive divider to supply an input small enough. Simultaneously observe the input and output signals on your oscilloscope. Record the waveforms and determine the small signal voltage gain of the amplifier. (**Discussion: Compare with your pre-lab values.**)
5. **Frequency Dependent Transfer Characteristics:** For the circuit in the previous problem (C_E included), at a fix a frequency of 1000 Hz, sweep the amplitude from 0 to a value that saturates the amplifier output. As in the frequency sweep program you will need to create file with a sequence of amplitude values. A list or table of these values should be included in your data sheet. Save the output to a file for later processing. Write a Matlab program to plot the input amplitudes on the x-axis and output amplitudes on the y-axis (the TC of the amplifier). The Matlab plot does not have to be in the data sheet, but if should be included in the results of the lab write-up. Repeat this for 8 kHz and 80 kHz. (**Discussion: Indicate why the TC curve looks as it does and comment on the differences between input frequencies. What is causing these changes?**)
6. **Measuring input and output impedance:** Determine the input and output resistance of the BJT common emitter amplifier, with and without the emitter capacitor. (**Discussion: Compare your measurements with pre-lab computed values.**)