ES 154 Assignment #3

Due: 2:00pm, Tuesday, October 13th, 2009

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Problem 1 (5 pt)

Consider an *npn* bipolar junction transistor (BJT). Plot $I_C = I_s \exp(V_{BE}/V_T)$ as a function of V_{BE} using computer. Use $I_s = 5 \times 10^{-15}$A. From the curve, we can appreciate how drastic the exponential function is: observe that for $V_{BE} < 0.5$V, I_C is less than 1 μA (this is quite a small collector current, and the BJT may be thought of as turned off for V_{BE} <0.5 V in a typical operation); observe that for $V_{BE} > 0.8$V, I_C is larger than 100 mA (this is quite a large collector current for a typical BJT operation); observe that V_{BE} in the range of 0.6 V $\sim$ 0.7 V corresponds to a large range of practical collector current values, owed to the rapid exponential dependency. This is why V_{BE} may be approximated as $V_{BE} \approx 0.6\text{V} \sim 0.7\text{V}$ when the BJT is in action.

Problem 2 (40 pt)

Figure 1 shows a common emitter amplifier using a BJT. As you will see in this problem, the collector current I_C and output voltage V_o are extremely sensitive to the variation of the input voltage V_i in this circuit, and thus, Fig. 1 is not a practical way of arranging a common emitter amplifier. The circuit, however, is simple, and thus, it is often used as a vehicle to illustrate several important concepts we discussed in class, such as input-output transfer characteristic, large signal response, small signal gain, small signal model, and different BJT operation regions.

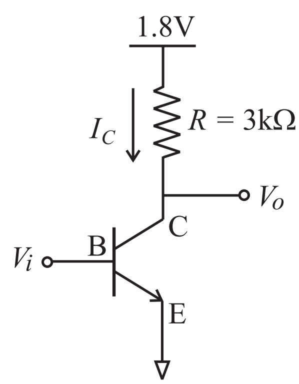

Figure 1: Common emitter amplifier. For the *npn* BJT, use: $\beta = 200$; $I_s = 5 \times 10^{-15}$A; $V_{CE,sat}$=0.2V; $V_A = \infty$; $\tau_F = 0.1$ns.

(a) Sketch the amplifier's transfer characteristic, V_o versus V_i. Indicate important transition points in the transfer curve, and present their corresponding numerical voltage values (for both V_i and V_o).

(*Note*) As V_i is increased, V_o drops, and thus, at a certain point, the base-collector junction is forward biased, and the BJT enters the saturation region. Although the onset of the forward bias of the base-collector junction occurs when $V_i = V_o \approx 0.651$V, unless the base voltage is reasonably larger than the collector voltage, the forward current in the base-collector junction (which reduces I_C) is very small, as you saw in Problem 1 in the context of the base-emitter junction. The forward-bias effect (saturation) of the base-collector junction will become pronounced only after V_i is further increased to increase the base-collector junction forward bias to 0.4 $\sim$ 0.5V, at which point the collector voltage is around 0.2V. This is what $V_{CE,sat} = 0.2$V means in the figure caption. We already discussed this in class, but I wanted to emphasize it once again to help you sketch the transfer characteristic.

(b) Choose an operating point where the collector voltage is 0.9 V. What is the corresponding input (base) *dc* bias voltage, $V_{B,0}$?

(c) Using the transfer characteristic, calculate the small signal gain at the operating point chosen above.

(d) Draw the small signal model for the amplifier at the operating point chosen in (b). Calculate all component values in the small signal model. Using the small signal model, calculate the low-frequency small signal gain, input impedance, and output impedance. Check the consistency between the small signal gain obtained here and that obtained in (c).

(e) Suppose $V_i(t) = V_{B,0} + 2 \times 10^{-6} \cdot \sin(\omega_0 t)$ (unit: volt), where $V_{B,0}$ is the input (base) *dc* bias voltage you calculated in (b). Assume a low frequency. Sketch $V_i(t)$ and $V_o(t)$, while showing their magnitude and phase differences.

(f) Suppose $V_i(t) = V_{B,0} + 0.5 \cdot \sin(\omega_0 t)$ (unit: volt), where $V_{B,0}$ is again the input (base) *dc* bias voltage you calculated in (b). Sketch $V_i(t)$ and $V_o(t)$, indicating their relative magnitude and phase differences.

Problem 3 (40 pt)

Figure 2 is again a common emitter amplifier, but this time, a resistor R_s is sandwiched between the base of the BJT and the input voltage V_i.

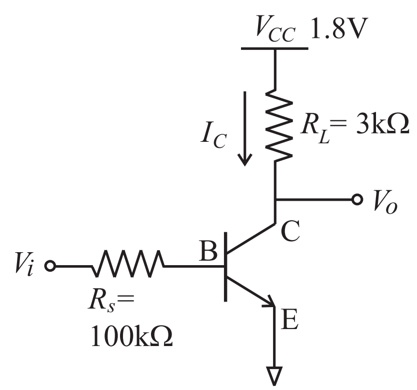

Figure 2: Common emitter amplifier with resistor R_s at the base. For the *npn* BJT, use: $\beta = 200$; $I_s = 5 \times 10^{-15}$A; $V_{CE,sat}$=0.2V; $V_A = \infty$; $\tau_F = 0.1$ns.

(a) The output voltage V_o and collector current I_C are much less sensitive to V_i in this case, as compared to the circuit of Fig. 1. Explain why qualitatively.

(b) Approximating that $V_{BE} \sim 0.6$V when the BJT is in action [Prob. 1], sketch the amplifier's transfer characteristic, V_o versus V_i. Use $V_{cc} = 1.8$V. Indicate important transition points in the transfer curve, and present their corresponding numerical voltage values (for both V_i and V_o). From the transfer characteristic, calculate and express the small signal gain both analytically and numerically [input operating point = 0.74V].

(c) For a more accurate calculation of the small signal gain from the transfer characteristic, we can use the following two equations together (you should first derive them):

$$V_o = V_{cc} - R_L I_s \exp\left(\frac{V_{BE}}{V_T}\right) \quad (1)$$

$$I_s \exp\left(\frac{V_{BE}}{V_T}\right) = \beta \frac{V_i - V_{BE}}{R_s} \quad (2)$$

From these equations, calculate the small signal gain

$$G = \frac{\partial V_o}{\partial V_i} \tag{3}$$

and express it both analytically and numerically at the input operating point of 0.74V. Continue to use $V_{cc} = 1.8$V. For the accurate numerical calculation, you should find the value of V_{BE} for $V_i = 0.74$V. This can be done by solving (2) using a graphical method (or any numerical method you like to use). How does the accurate small signal gain calculated here compare to the small signal gain approximately calculated in (b)? Compare them both analytically and numerically.

(d) Draw the small signal model for the amplifier at the input operating point of 0.74V and $V_{cc} = 1.8$V. Calculate the small signal gain from the small signal model. This should be consistent with (c).

(e) Repeat (b), (c), (d) above using $V_{cc} = 10$V. Use the input operating voltage of 1.4V. For $V_{cc} = 10$V, the discrepancy between the approximate and accurate calculations of the small signal gain is small. Explain why.

Problem 4 (40 pt)

Figure 3 shows a common emitter amplifier, which has resistor R_E placed between the emitter and ground. $V_{cc} = 10$V.

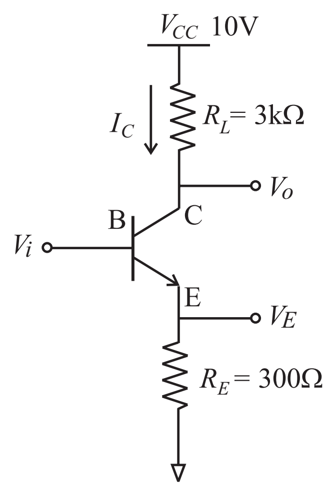

Figure 3: Common emitter amplifier with emitter degeneration. For the *npn* BJT, use: $\beta = 200$; $I_s = 5 \times 10^{-15}$A; $V_{CE,sat}$=0.2V; $V_A = \infty$; $\tau_F = 0.1$ns.

(a) The output voltage V_o and the collector current I_C are much less sensitive to V_i in this arrangement, in comparison to the circuit of Fig. 1. Explain why qualitatively.

(b) Approximating that $V_{BE} \sim 0.6$V when the BJT is in action [Prob. 1], sketch the amplifier's transfer characteristics, V_o versus V_i, together with V_E versus V_i. Indicate important transition points in the transfer curves, and present their corresponding numerical voltage values (for both V_i and V_o). From the input-output transfer characteristic, express and calculate the small signal gain both analytically and numerically [input operating point: 1V].

(c) From the small signal model of the amplifier, calculate the low-frequency small signal gain (compare it to the small signal gain calculated in (b) — are they in good agreement?), input impedance, and output impedance. Express them both analytically and numerically [input operating point: 1V].

Problem 5 (40 pt)

(a) Do two *pn* junction diodes, whose *p* portions are connected together through a metallic wire, [Fig. 4(a)] operate like an *npn* transistor? Explain.

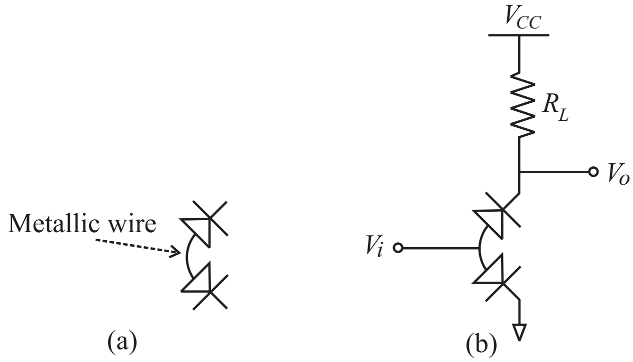

Figure 4: (a) Two *pn* junction diodes, whose *p* portions are connected together using a metallic wire. (b) A circuit using the two *pn* junction diodes.

(b) Figure 4(b) shows a circuit involving the two *pn* junction diodes put back to back. It is topologically similar to the common emitter BJT amplifier. Sketch the transfer characteristic, V_o versus V_i, of this circuit. Does it resemble the transfer curve of the common emitter BJT amplifier?