XMUT204 Electronic Design

Practice Final Exam Questions (Answer)

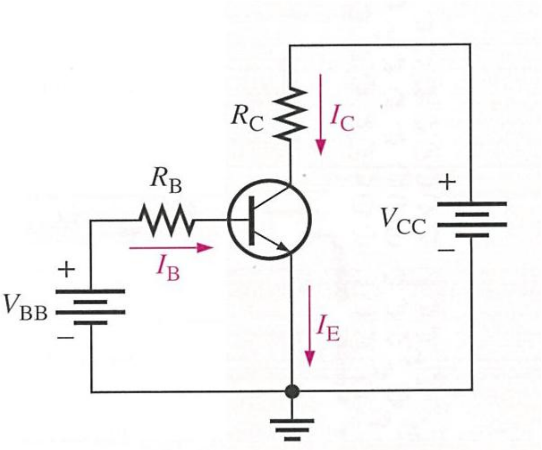
Section A **BJT Characteristics and Biasing** **[42.5 marks]**

1. Answer the following questions on the structure of an NPN BJT:

   a. Show (sketch) how you can use two power supplies to provide suitable bias and operating conditions for an NPN transistor to operate in the **forward active region**. Explain the conditions at each of the two junctions of the device and how these operating conditions enable diode operation. [2.5 marks]

   Solution

   Sketch of NPN transistor designed to operate in active region using two power supplies.



   b. On your sketch in part (a) indicate the currents that will flow in/out of the different regions of the transistor by using conventional current notation. Write down the expression(s) that relates these different currents and define the DC current gain of the transistor. [5 marks]

   Solution

In the given BJT transistor circuit, the currents in the circuit are: (2.5)

$$I_B + I_C = I_E$$

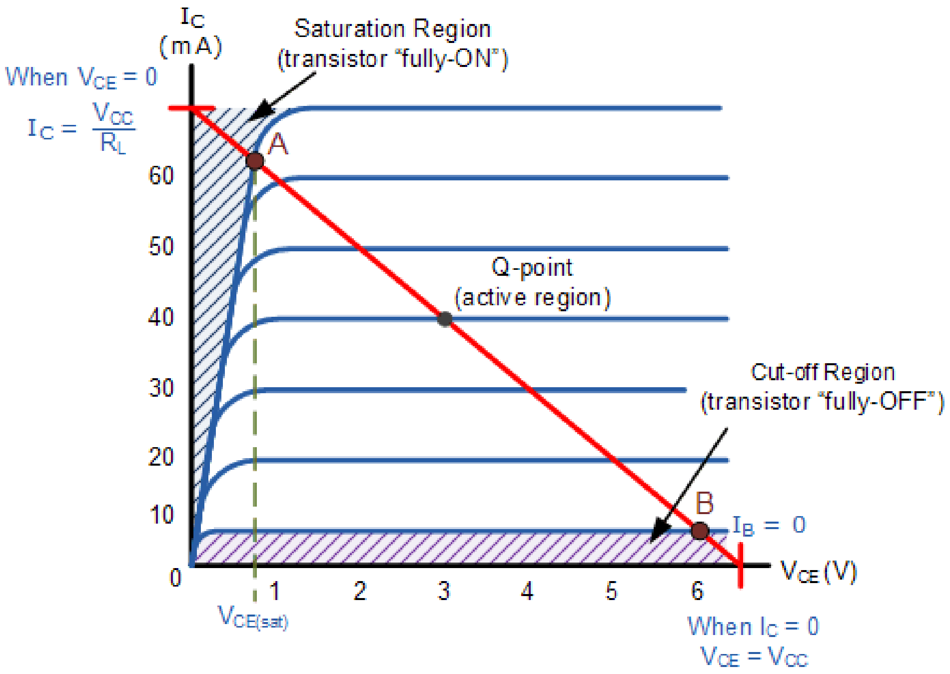
The DC current gain is: (2.5)

$$\beta_{DC} = \frac{I_C}{I_B}$$

c. Sketch the current-voltage characteristics of a BJT (I_C vs V_{CE} for constant I_B) and indicate the three important regions of operation. [2.5 marks]

Solution

Sketch of current-voltage characteristics of a BJT transistor with three regions of operation.

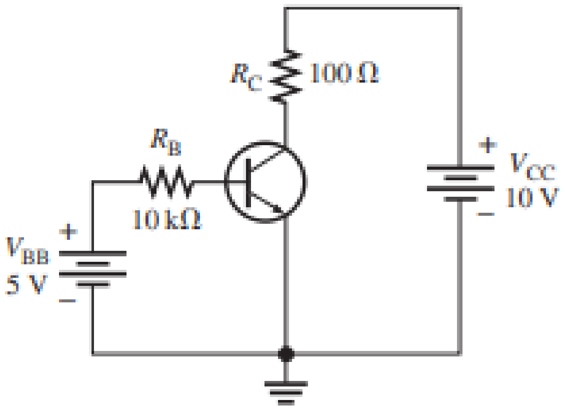


d. Contrast the bias and operating conditions in the saturation region to those of the forward active region to explain the shape of the I-V curve in this region. [2.5 marks]

Solution

Bias and operating condition in saturation region is nonlinear whereas in active region it is linear.

2. Determine I_B, I_C, I_E, V_{BE}, V_{CE}, and V_{CB} in the circuit of given below. The transistor has a β_{DC} = 150. [15 marks]



Solution

From the equation given below, $V_{BE} = 0.7$ V. The base, collector, and emitter currents are calculated as follows: (7.5)

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = 430\ \mu\text{A}$$

$$I_C = \beta_{DC} I_B = (150)(430\ \mu\text{A}) = 64.5\text{ mA}$$

$$I_E = I_C + I_B = 64.5\text{ mA} + 430\ \mu\text{A} = 64.9\text{ mA}$$

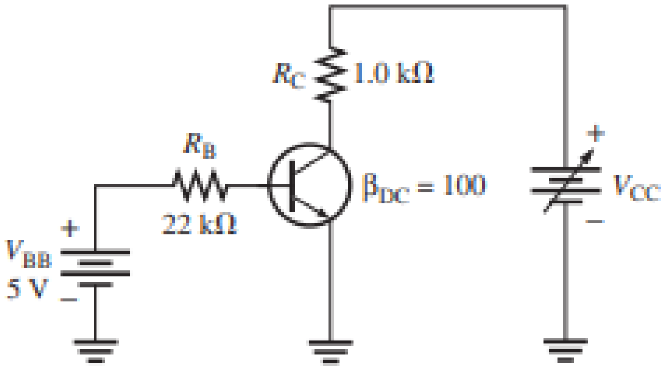
Solve for V_{CE} and V_{CB} as $V_{BE} = 0.7$ V. (7.5)

$$V_{CE} = V_{CC} - I_C R_C = 10\text{ V} - (64.5\text{ mA})(100\ \Omega) = 10\text{ V} - 6.45\text{ V} = 3.55\text{ V}$$

$$V_{CB} = V_{CE} - V_{BE} = 3.55\text{ V} - 0.7\text{ V} = 2.85\text{ V}$$

Since the collector is at a higher voltage than the base, the collector-base junction is reverse-biased.

3. The transistor in the figure below has the following maximum ratings: $P_{D(\max)}$ = 800 mW, $V_{CE(\max)}$ = 15 V, and $I_{C(\max)}$ = 100 mA. Determine the maximum value to which V_{CC} can be adjusted without exceeding a rating. Which rating would be exceeded first? [15 marks]



Solution

First, find I_B so that you can determine I_C: (5)

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{ V} - 0.7\text{ V}}{22\text{ k}\Omega} = 195\ \mu\text{A}$$

$$I_C = \beta_{DC} I_B = (100)(195\ \mu\text{A}) = 19.5\text{ mA}$$

The current I_C is much less than $I_{C(\max)}$ and ideally will not change with V_{CC}. It is determined only by I_B and β_{DC}.

The voltage drop across R_C is: (2.5)

$$V_{R_C} = I_C R_C = (19.5\text{ mA})(1\text{ k}\Omega) = 19.5\text{ V}$$

Now you can determine the value of V_{CC} when $V_{CE} = V_{CE(\max)} = 15$ V (2.5)

$$V_{R_C} = V_{CC} - V_{CE}$$

So

$$V_{CC(\max)} = V_{CE(\max)} + V_{R_C} = 15\text{ V} + 19.5\text{ V} = 34.5\text{ V}$$

V_{CC} can be increased to 34.5 V, under the existing conditions, before $V_{CE(\max)}$ is exceeded. However, at this point, it is not known whether $P_{D(\max)}$ has been exceeded, or not. (2.5)

$$P_D = V_{CE}(\max) I_C = (15\text{ V})(19.5\text{ mA}) = 293\text{ mW}$$

Since $P_{D(\max)}$ is 800 mW, it is not exceeded when $V_{CC} = 34.5$ V. So, $V_{CE(\max)} = 15$ V is the limiting rating in this case. If the base current is removed causing the transistor to turn off, $V_{CE(\max)}$ will be exceeded first because the entire supply voltage, V_{CC}, will be dropped across the transistor. (2.5)

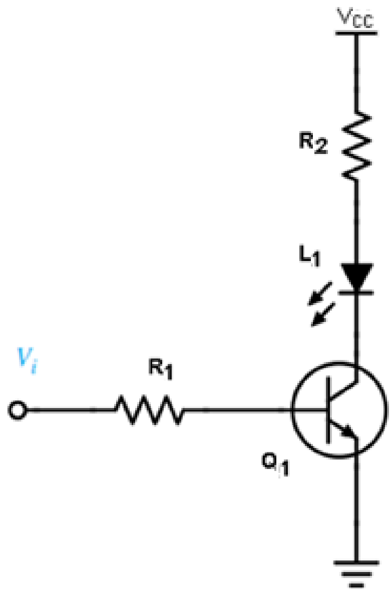
Section B BJT Switching Applications [17.5 marks]

1. BJT can be designed for switching applications such as digital logic circuits.
   a. Describe the regions of operation of BJT for switching application. [2.5 marks]

      Solution

      For switching applications, BJT is required to be operated at the saturation and cut-off regions.

   b. Calculate values of the resistors in the biasing configuration of the following BJT switching circuit.



The LED in circuit given below requires 30 mA to emit a sufficient level of light. Use double of the minimum value of base current as a safety margin to ensure saturation knowing V_{CC} = 9 V, $V_{CE(\text{sat})}$ = 0.3 V, β_{DC} = 50, V_{LED} = 1.6 V, and V_{IN} = 5 V. [7.5 marks]

Solution

For the given switching BJT transistor circuit:

The collector current is: (2.5)

$$R_C = \frac{\left[V_{CC} - V_{LED} - V_{CE(\text{sat})}\right]}{I_C} = \frac{9 - 1.6 - 0.3}{30\text{ mA}} = 236.7\ \Omega$$

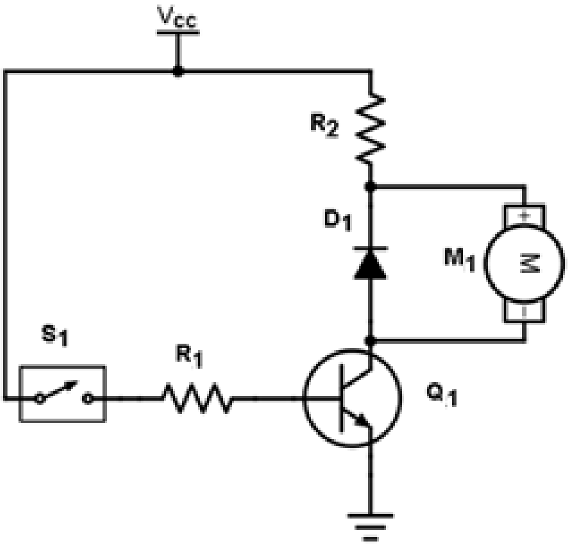
The base current is: (2.5)

$$I_B = \frac{I_C}{\beta_{DC}} = \frac{30\text{ mA}}{50} = 0.6\text{ mA}$$

The base resistor is: (2.5)

$$R_B = \frac{V_{IN} - V_{BE}}{I_B} = \frac{5 - 0.7}{0.6\text{ mA}} = 7.17\text{ k}\Omega$$

2. Describe how a BJT can be used to control the speed of the DC motor as shown in the circuit given in the figure below. Referring to this circuit, is it possible to regulate the speed of the motor from standstill to full speed? Briefly describe the role of the diode in the circuit. [7.5 marks]



Solution

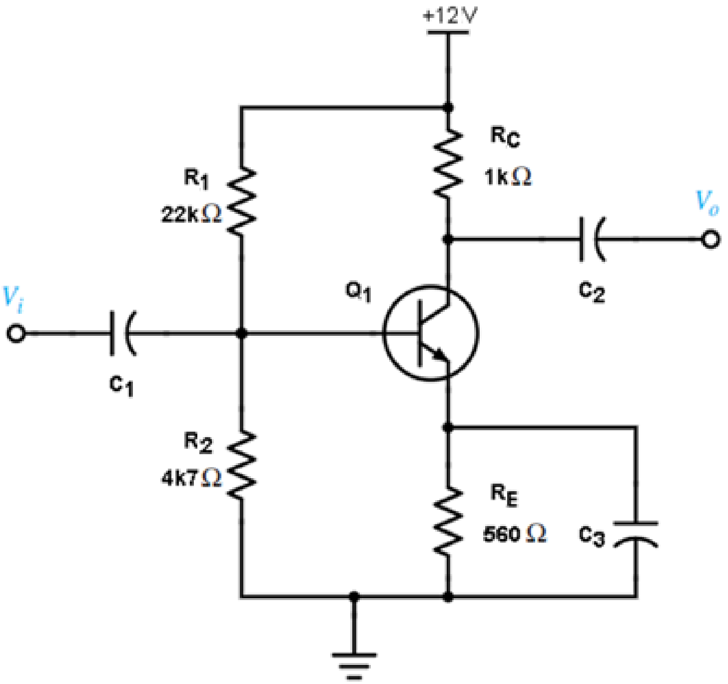
By switching the transistor in cut-off and saturation regions, we can turn ON and OFF the motor repeatedly. (2.5)

It is possible to regulate the speed of the motor from standstill to full speed by switching the transistor at variable frequencies. We can get the switching frequency pulses from control device or IC like microcontroller. (2.5)

For this application, the DC motor is an inductive load, so we must place a freewheeling diode across it to protect the circuit. (2.5)

Section C BJT Amplifiers [62.5 marks]

1. BJT transistors are typically used in applications such as pulse switching and signal amplification. Study the circuit below and then answer the questions that follow:



a. Calculate the DC operating conditions (V_B, V_E, I_E, I_C, and V_C) of the circuit. [12.5 marks]

Solution

The DC operating conditions of the common-emitter amplifier:

Base voltage: (2.5)

$$V_B = V_{CC}\left(\frac{R_2}{R_1 + R_2}\right) = 12\left(\frac{4.7\ \text{k}\Omega}{22\ \text{k}\Omega + 4.7\ \text{k}\Omega}\right) = 2.11\ \text{V}$$

Emitter voltage: (2.5)

$$V_E = V_B - V_{BE} = 2.11\ \text{V} - 0.7\ \text{V} = 1.41\ \text{V}$$

Emitter current: (2.5)

$$I_E = \frac{V_E}{R_E} = \frac{1.41\ \text{V}}{560\ \Omega} = 2.52\ \text{mA}$$

Collector current: (2.5)

$$I_C = I_E = 2.52\ \text{mA}$$

Collector voltage: (2.5)

$$V_C = V_{CC} - I_C R_C = 12 - (2.52\ \text{mA})(1\ \text{k}\Omega) = 12\ \text{V} - 2.52\ \text{V} = 9.48\ \text{V}$$

b. Calculate the small signal voltage gain of the circuit without capacitor C_3 in place. [5 mark]

Solution

Small signal voltage gain (without bypass emitter capacitor):

AC emitter resistance: (2.5)

$$r_e' = \frac{25\text{ mV}}{\text{I}_\text{E}} = \frac{25\text{ mV}}{2.52\text{ mA}} = 9.92\ \Omega$$

The voltage gain of the amplifier: (2.5)

$$A_V = \frac{R_C}{R_E + r_e'} = \frac{1\text{k}\Omega}{560\ \Omega + 9.92\ \Omega} = 1.75$$

c. Calculate the small signal voltage gain with capacitor C_3 in place. [2.5 marks]

Solution

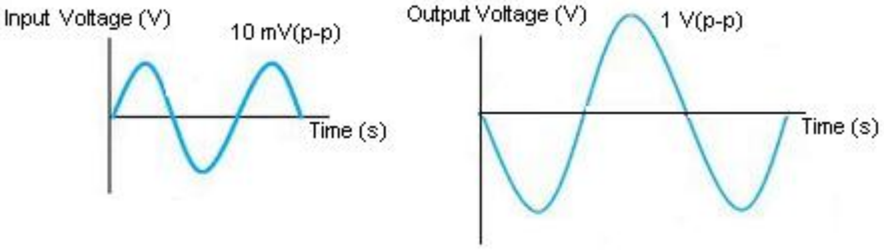
Small signal voltage gain (with bypass emitter capacitor):

$$A_V = \frac{R_C}{r_e'} = \frac{1\text{ k}\Omega}{9.92\ \Omega} = 100.8$$

d. A small ac signal with V_{RMS} = 10 mV is now placed at the input. Sketch the expected output signal with C_3 in place assuming a high impedance load at the output. [2.5 marks]

Solution

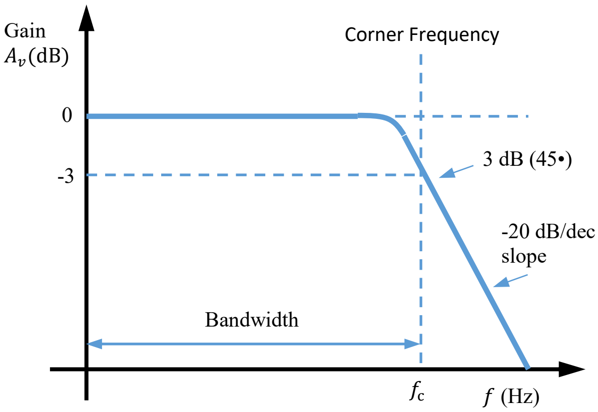
Sketch of output signal vs. input signal with bypass emitter capacitor:



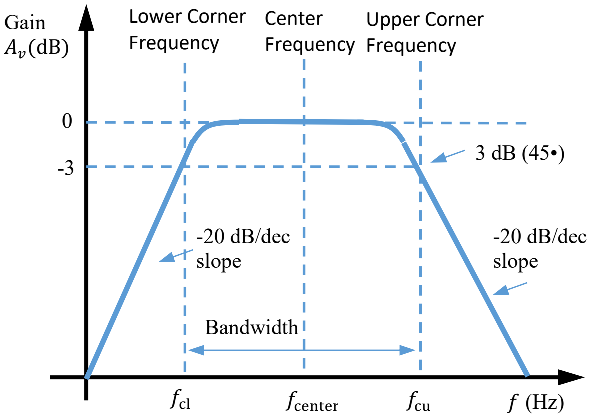
e. Sketch the expected frequency response of the small signal voltage gain magnitude for the cases with and without the bypass capacitor C_3. [5 marks]

Solution

Sketches of frequency response of common-emitter BJT amplifier:



Without bypass emitter capacitor.



With bypass emitter capacitor.

f. If the operating frequency of the amplifier is between 500 Hz to 10 MHz, calculate value of the input decoupling capacitor. [7.5 marks]

Solution

The input resistance into the amplifier is: (2.5)

$$R_{in} \approx R_1 \parallel R_2 = 22\ \text{k}\Omega \parallel 4.7\ \text{k}\Omega = 3.87\ \text{k}\Omega$$

In combination with the input capacitor, this input resistance will cause a frequency cut-off: (2.5)

$$f_c = \frac{1}{2\pi C_{in} R_{in}}$$

We need a low frequency limit of 500 Hz. By rearranging the above equation, design for cut-off frequency of 50 Hz: (2.5)

$$C_{in} = \frac{1}{2\pi R_{in}(50\ \text{Hz})} = \frac{1}{2\pi(3870)(50)} = 822\ \text{nF}$$

Following E12 standard, the value of input capacitor is 820 nF

g. As part (f), calculate value of the output decoupling capacitor.

[7.5 marks]

Solution

The output resistance of the amplifier is: (2.5)

$$R_{out} \approx R_C = 1\ \text{k}\Omega$$

In combination with the output capacitor, this output resistance will cause a frequency cut-off: (2.5)

$$f_c = \frac{1}{2\pi C_{out} R_{out}}$$

We need a low frequency limit of 500 Hz. By rearranging the above equation, design for cut-off frequency of 50 Hz: (2.5)

$$C_{out} = \frac{1}{2\pi R_{out}(50\text{ Hz})} = \frac{1}{2\pi(1000)(50)} = 3185\text{ nF}$$

Referring to E12 standard, the value of the output capacitor is 3.3 μF.

h. Describe also how the value that you have chosen for the bypass capacitor will affect the bandwidth of frequency response of the amplifier. [12.5 marks]

Solution

Overall, the gain of the amplifier is still low at lower frequencies where the high impedance, $Z = 1/(2\pi f C)$ of the bypass capacitor will dominate. Choose a value for this capacitor and from parts (d) and (e) knowing the cut-off frequency of 50 Hz, so the impedance of the bypass capacitor is: (2.5)

$$Z_C = \frac{1}{2\pi f C_{bypass}}$$

The effective resistance of R_E and C_{bypass} is then: (2.5)

$$Z_{\text{effective}} = R_E \parallel Z_C = \frac{R_E Z_C}{R_E + Z_C}$$

Calculate and plot for a range of frequencies. Assume the total impedance of the amplifier is given as: (2.5)

$$Z_{tot} = r_e + Z_{\text{effective}}$$

Calculate gain from the following equation and plot the graph. (2.5)

$$A_v = \frac{R_C}{Z_{tot}}$$

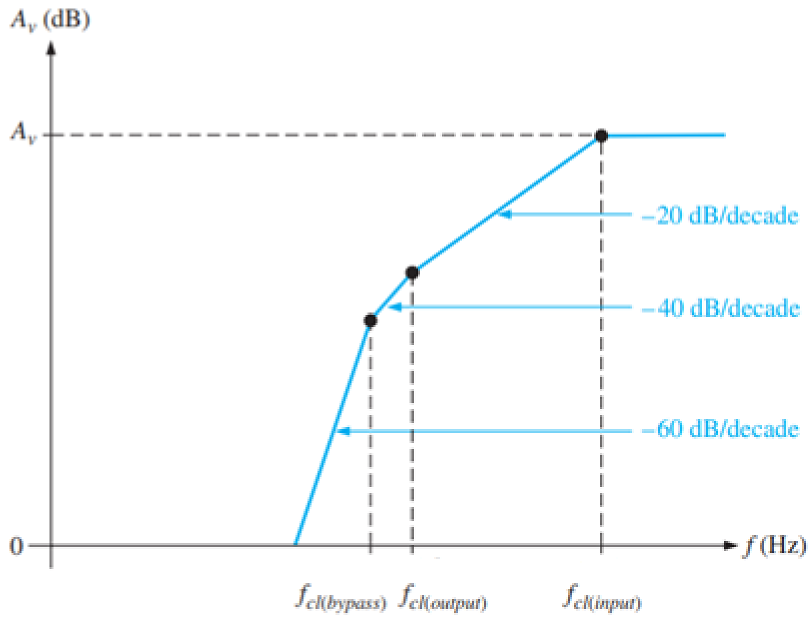
From the equations given above, for a different value of capacitor, this curve of the frequency response of the amplifier will look slightly different, so it is important to choose the value of bypass emitter capacitor which would not change much the gain of the amplifier. (2.5)

i. Sketch and briefly describe the voltage gain vs. frequency of the amplifier. [7.5 marks]

Solution

The frequency response of the amplifier at low frequency region is dominated by cut-off frequencies due to the decoupling capacitors e.g. input decoupling capacitor ($f_{cl(\text{input})}$) and output decoupling capacitor ($f_{cl(\text{output})}$) and also due to the bypass emitter capacitor ($f_{cl(\text{bypass})}$). For this circuit, it was designed that the cut-off frequencies are in this order: $f_{cl(\text{bypass})} < f_{cl(\text{output})} < f_{cl(\text{input})}$.
(2.5)

Notice that the gain of the amplifier is decreasing at 20 dB/decade from its midrange frequency gain (A_v) at cut-off frequency of the input decoupling capacitor (f_{cl}(input)). The gain further decreases at 20 dB/decade at cut-off frequency of the output decoupling capacitor (f_{cl}(output)) and experiences a further drop at 20 dB/decade at cut-off frequency of the bypass emitter capacitor (f_{cl}(bypass)). (2.5)



The sketch of voltage gain vs. frequency of the amplifier is as shown in the figure above. Notice the three lower frequency cut-off frequencies of the frequency response of the amplifier circuit due to the coupling capacitors and bypass capacitor. (2.5)

Section D BJT Further Circuits [90 marks]

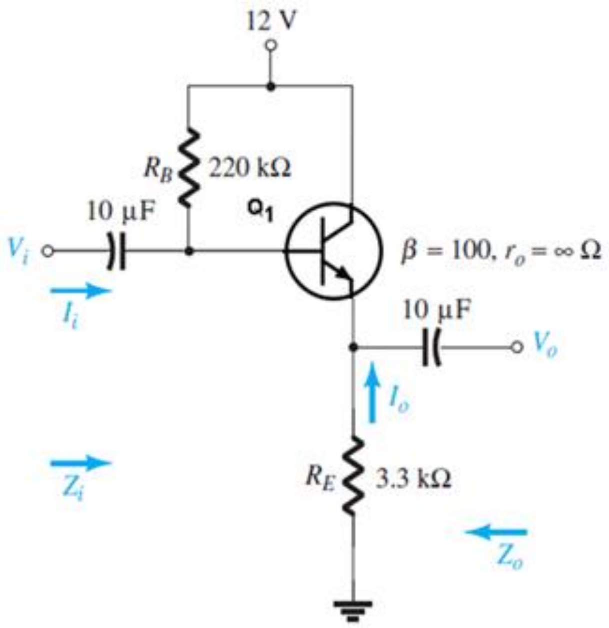
1. For a common collector amplifier circuit as shown in the figure below, assume the BJT is a Silicon transistor and its DC gain (β_{DC}) is 100 and r_o is ∞. Determine:
   a. AC internal emitter resistance, r_e. [7.5 marks]
   b. Input impedance, Z_i. [5 marks]

c. Output impedance, Z_o. [2.5 marks]

d. Voltage gain, A_v. [2.5 marks]

e. Repeat parts (b) to (d) with r_o = 25 kΩ and compare the results.

[12.5 marks]



Solution

a. The current at the base of the amplifier circuit is: (2.5)

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1)R_E} = \frac{12\text{ V} - 0.7\text{ V}}{220\text{ k}\Omega + (101)(3.3\text{ k}\Omega)} = 20.42\ \mu\text{A}$$

The current at the emitter is: (2.5)

$$I_E = (\beta + 1)I_B = (101)(20.42\ \mu\text{A}) = 2.062\text{ mA}$$

The AC internal emitter resistance of the BJT is: (2.5)

$$r_e = \frac{25\text{ mV}}{I_E} = \frac{25\text{ mV}}{2.062\text{ mA}} = 12.12\ \Omega$$

b. The impedance at the base is: (2.5)

$$Z_b = \beta r_e + (\beta + 1)R_E$$

$$= (100)(12.12\ \Omega) + (101)(3.3\text{ k}\Omega) = 334.42\text{ k}\Omega\ (\cong \beta R_E)$$

The input impedance is: (2.5)

$$Z_i = R_B \parallel Z_b = 220\text{ k}\Omega \parallel 334.42\text{ k}\Omega = 132.70\text{ k}\Omega$$

c. The output impedance is:

$$Z_o = R_E \parallel r_e = 3.3\text{ k}\Omega \parallel 12.12\ \Omega = 12.08\ \Omega\ (\cong r_e)$$

d. The voltage gain is:

$$A_v = \frac{V_o}{V_i} = \frac{R_E}{R_E + r_e} = \frac{3.3\text{ k}\Omega}{3.3\text{ k}\Omega + 12.12\ \Omega} = 0.996 \cong 1$$

e. Checking the condition, $r_o \gg 10R_E$, we have: (2.5)

$$r_o \geq 10(3.3\text{k}\Omega) = 33\text{ k}\Omega$$

But, in the circuit output resistance, r_o = 25 kΩ, so this design condition is not satisfied. (2.5)

Therefore: (2.5)

$$Z_b = \beta r_e + \frac{(\beta+1)R_E}{1 + \frac{R_E}{r_o}}$$

$$= (100)(12.12) + \frac{(100+1)(3.3\text{k}\Omega)}{1 + \left(\frac{3.3\text{ k}\Omega}{25\text{ k}\Omega}\right)} = 295.64\text{ k}\Omega$$

With r_o = 25 kΩ, the parameters of the circuit are: (7.5)

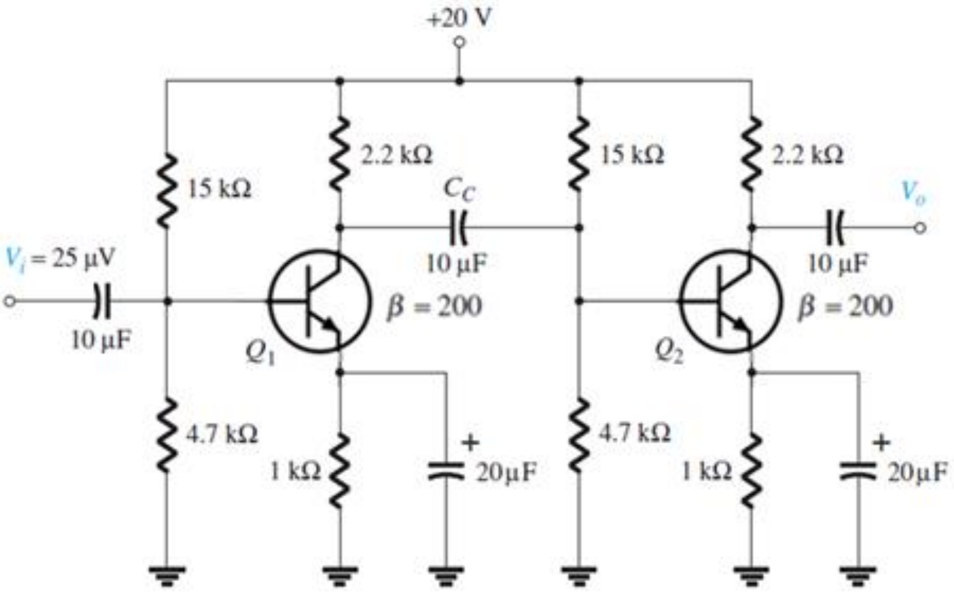
$$Z_i = R_B \parallel Z_b = 220\text{ k}\Omega \parallel 295.64\text{ k}\Omega = 126.14\text{ k}\Omega\ (\text{vs. } 132.70\text{ k}\Omega \text{ as before})$$

$$Z_o = R_E \parallel r_e = 12.12\ (\text{as obtained earlier})$$

$$A_v = \frac{(\beta+1)\frac{R_E}{Z_b}}{\left(1 + \frac{R_E}{r_o}\right)} = \frac{(100+1)\left(\frac{3.3\text{ k}\Omega}{295.64\text{ k}\Omega}\right)}{\left(1 + \frac{3.3\text{ k}\Omega}{25\text{ k}\Omega}\right)} = 0.996 \cong 1$$

This is matching the earlier result. (2.5)

2. In the following BJT multistage amplifier, the DC and AC gains of transistors Q_1 and Q_2 are $\beta_{DC1} = \beta_{AC1} = 200$ and $\beta_{DC2} = \beta_{AC2} = 200$. The amplifier's input is connected to a 25 µV voltage source. Assume the BJTs are Silicon transistors.



a. Calculate the no load voltage gain and output voltage of the amplifier. [25 marks]

b. Calculate the overall gain and output voltage if a 4.7 kΩ load is applied to the second stage and compare with the results of part (a). [5 marks]

c. Calculate the input impedance of the first stage and the output impedance of the second stage. [5 marks]

Solution

a. The DC bias analysis results in the following for each transistor: (10)

$$V_B = \left(\frac{R_1}{R_1 + R_2}\right) V_{CC} = \left(\frac{4.7\ \text{k}\Omega}{4.7\ \text{k}\Omega + 15\ \text{k}\Omega}\right)(20\ \text{V}) = 4.8\ \text{V}$$

$$V_E = V_B - V_{BE} = 4.8\ \text{V} - 0.7\ \text{V} = 4.1\ \text{V}$$

$$I_E \cong I_C = \frac{V_E}{R_E} = \frac{4.1\ \text{V}}{1\ \text{k}\Omega} = 4.1\ \text{mA}$$

$$V_C = V_{CC} - I_C R_C = 20\ \text{V} - (4.1\ \text{mA})(2.2\ \text{k}\Omega) = 10.98\ \text{V}$$

At the bias point, AC emitter internal resistance is: (2.5)

$$r_e = \frac{25\ \text{mV}}{I_E} = \frac{25\ \text{mV}}{4.1\ \text{mA}} = 6.10\ \Omega$$

The impedance of the second stage is: (2.5)

$$Z_{i2} = R_1 \parallel R_2 \parallel \beta r_e$$

This results in the following gain for the first stage: (2.5)

$$A_{v1} = -\frac{R_C \parallel (R_1 \parallel R_2 \parallel \beta r_e)}{r_e}$$

$$= -\frac{2.2\text{k}\Omega \parallel 15\text{k}\Omega \parallel 4.7\text{k}\Omega \parallel (200)(6.10\ \Omega)}{6.10\ \Omega} = -104$$

For the unloaded second stage, the gain is: (2.5)

$$A_{v2(\text{noload})} = -\frac{R_C}{r_e} = -\frac{2.2\ \text{k}\Omega}{6.10\ \Omega} = -361$$

Resulting in an overall gain of: (2.5)

$$A_{v(\text{total}-\text{noload})} = A_{v1}A_{v2(\text{noload})} = (-104)(-361) \cong 37.5 \times 10^3$$

The output voltage is then: (2.5)

$$V_o = A_{v(\text{total}-\text{noload})}V_i = (37.5 \times 10^3)(25\ \mu\text{V}) = 937.5\ \text{mV}$$

b. The overall gain with the 4.7 kΩ load applied is: (2.5)

$$A_{v(\text{total})} = \frac{V_o}{V_i} = \left(\frac{R_L}{R_L + Z_o}\right) A_{v(\text{total}-\text{noload})}$$

$$= \left(\frac{4.7\ \text{k}\Omega}{4.7\ \text{k}\Omega + 2.2\ \text{k}\Omega}\right)(36.1 \times 10^3) \cong 24.6 \times 10^3$$

Which is considerably less than the unloaded gain because R_L is relatively close to R_C. Thus, the output voltage is: (2.5)

$$V_o = A_{v(\text{total})}V_i = (24.6 \times 10^3)(25\ \mu\text{V}) = 615\ \text{mV}$$

c. The input impedance of the first stage is: (2.5)

$$Z_{i1} = R_1 \parallel R_2 \parallel \beta r_e = 4.7\ \text{k}\Omega \parallel 15\ \text{k}\Omega \parallel (200)(6.34\ \Omega) = 0.94\ \text{k}\Omega$$

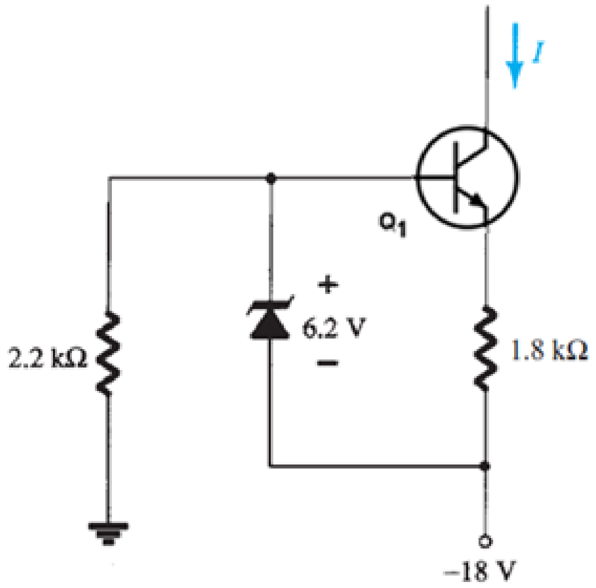
Whereas the output impedance for the second stage is: (2.5)

$$Z_{o2} = R_C = 2.2\ \text{k}\Omega$$

3. In the Zener based current source circuit as shown in the figure below, the rated operating voltage of Zener diode is 6.2 V.

   a. What type of current source circuit is this? Describe the disadvantage and advantage using Zener diode in the circuit, instead of a resistor. [5 marks]

   b. Calculate the constant current I. [2.5 marks]



Solution

a. This current source is a sink type constant current source. It provides a constant current to the load.

Zener improves the stability of the current delivered to the load as opposed to resistor that is prone for fluctuations in the operating temperature.

A Zener diode is more expensive than a resistor.

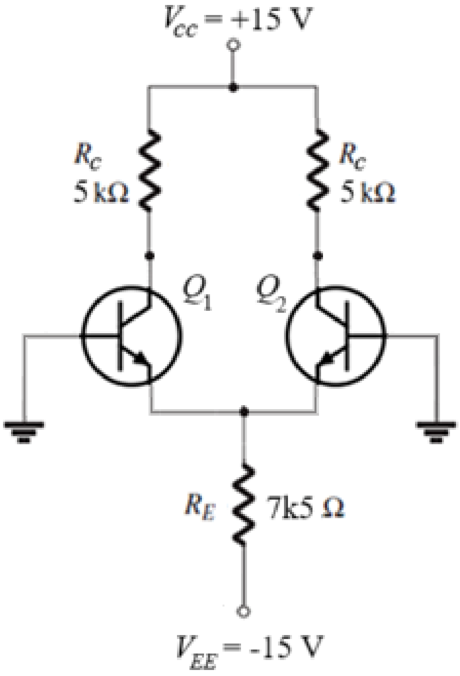
b. Assume that $I_C = I_E$ due to large gain of the transistor and V_{BE} = 0.7 V, the current I in the circuit is calculated from:

$$I = I_E = \frac{V_Z - V_{BE}}{R_E} = \frac{6.2\text{ V} - 0.7\text{ V}}{1.8\text{ k}\Omega} = 3.06\text{ mA}$$

4. Given the following BJT differential amplifier circuit, perform the following circuit analysis tasks.

   a. What are the ideal currents and voltages in the circuit? [10 marks]

   b. One of the inputs in the circuit is given 1 mV voltage source, what is the AC output voltage? If $\beta = 300$, what is the input impedance of the circuit? [15 marks]



Solution

a. Assume that the transistors in the differential amplifier circuit are identical in terms of their characteristics i.e. gain, input and output resistances, etc. (2.5)

Referring to the differential amplifier circuit, the tail current is: (2.5)

$$I_T = \frac{V_{EE}}{R_E} = \frac{15\text{ V}}{7.5\text{ k}\Omega} = 2\text{ mA}$$

Each emitter current is half of the tail current: (2.5)

$$I_E = \frac{I_T}{2} = \frac{2\text{ mA}}{2} = 1\text{ mA}$$

Each collector has a quiescent voltage of approximately: (2.5)

$$V_C = V_{CC} - I_C R_C = 15\text{ V} - (1\text{ mA})(5\text{ k}\Omega) = 10\text{ V}$$

b. We analysed the DC equivalent circuit in part (a). Ideally, 15 V is across the emitter resistor, producing a tail current of 2 mA as calculated before. (2.5)

This means that the DC emitter current in each transistor is: (2.5)

$$I_E = 1\text{ mA}$$

Now, we calculate the AC emitter resistance: (2.5)

$$r_e' = \frac{25\text{ mV}}{I_E} = \frac{25\text{ mV}}{1\text{ mA}} = 25\ \Omega$$

The voltage gain is: (2.5)

$$A_v = \frac{R_C}{r'_e} = \frac{5\ \text{k}\Omega}{25\ \Omega} = 200$$

The AC output voltage is: (2.5)

$$V_{out} = \beta V_{in} = 200(1\ \text{mV}) = 200\ \text{mV}$$

The input impedance of the differential amplifier is: (2.5)

$$Z_{in(\text{base})} = 2\beta r'_e = 2(300)(25\ \Omega) = 15\ \text{k}\Omega$$