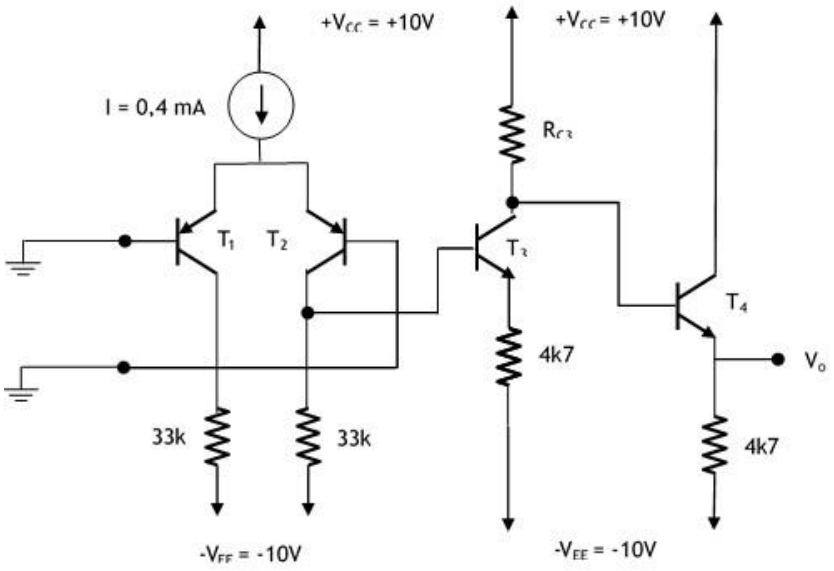
IMPORTANT: Besides your **calculator** and the sheets you use for calculations you are only allowed to have an A4 sized **"copy sheet"** during this exam. Notes, problems and alike are not permitted. **Please submit your "copy sheet" along with your solutions.** You may get your "copy sheet" back after your solutions have been graded. ***Do not forget to write down units and convert units carefully! Cell phones are not allowed and should be placed on the front desk before the exam.***

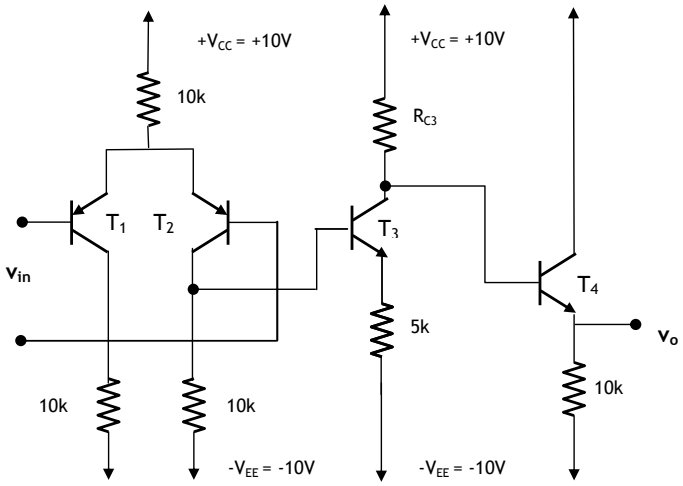
EHB222E INTRODUCTION TO ELECTRONICS (11394)
Midterm Exam #2 ✎ 8 December 2015 ⌛ 13.30-15.30
İnci ÇİLESİZ, PhD, Hacer ATAR YILDIZ, PhD
EEF 4104

---

1. You know the 3-stage BJT amplifier circuit from your first exam. Analyze the circuit at DC and AC with **$|V_{BE}| = 0{,}6$ V**, **$h_{FE} = h_{fe} = 200$** for all four transistors. **Do not neglect base currents.**
   a. Design a current source that will provide **0,4 mA biasing current** to the differential stage. (10)
   b. Choose **R_{C3}** such that, T_3 is in active mode (10)
   c. Find the gain **v_o/v_i** , input and output resistances with **$V_T = 25$ mV.** (20)



2. Analyze the 3-stage amplifier circuit below right. For all transistors **$h_{FE} = h_{fe} = 100$, $V_T = 25$ mV, $|V_{BE}| = 0{,}6$ V, $h_{oe} = h_{re} = 0$.**
   a. Find the collector currents of all 4 transistors and value of R_{C3}, such that, waveform distortion at the output V_o is minimum and symmetrical. (20)
   b. Calculate the total voltage gain, input and output resistance of the 3-stage BJT amplifier. Also calculate CMRR of the first stage. (40) If you could not find collector currents and R_{C3} in (a), you may assume **$I_{C1} = I_{C2} = I_{C3} = I_{C4} = 1$ mA and $R_{C3} = 10$k.**



GOOD LUCK

SOLUTIONS:

1. DC characteristics are to be studied.
   a. You do your own design!
   b. Without neglecting the base currents of the differential (the very first) stage, for V_i = 0 V

$$I_{C1} = I_{C2} = \frac{h_{FE}}{h_{FE}+1} \cdot \frac{I_{ref}}{2} = \frac{200}{200+1} \cdot \frac{0{,}4mA}{2} \Rightarrow I_{C1} = I_{C2} = \underline{\underline{0{,}199mA}}$$

$$-(I_{C2} - I_{B3})33k + V_{BE3} + (h_{FE}+1)I_{B3}4k7 = 0$$

$$I_{C3} = h_{FE}\frac{33k * I_{C2} - V_{BE3}}{(h_{FE}+1)4k7 + 33k} = 200\frac{33k * 0{,}199mA - 0{,}6V}{(200+1)4k7 + 33k} = \underline{\underline{1{,}2mA}}$$

Now we need to find the base voltage of T_3. $V_{B3} = -10V + (I_{C2} - I_{B3})33k = \underline{\underline{-3{,}63V}}$

For T_3 to be in active mode $V_{B3} \le V_{C3}$. I take $V_{C3} = -3{,}5V > -3{,}63V$. Thus

$$V_{C3} = V_{B4} = -10V + 4k7 \cdot I_{E4} + V_{BE4} = -10V + 4k7 \cdot I_{B4}(h_{FE}+1) + 0{,}6V = -3{,}5V$$

$$\Rightarrow I_{C4} = h_{FE} \cdot I_{B4} = h_{FE}\frac{10V - 3{,}5V - 0{,}6V}{4k7 \cdot (h_{FE}+1)} = \underline{\underline{1{,}0mA}}$$

For T_3 to be in active mode

$$V_{C3} = -3{,}5V = 10V - R_{C3}(I_{C3} + I_{B4}) \Rightarrow R_{C3} \le \frac{10V + 3{,}5V}{(I_{C3} + I_{B4})} = \underline{\underline{11k1}}$$

AC Analysis: Let'a first calculate the AC resistances

$$r_{e1} = r_{e2} = \frac{V_T}{I_{C1}} = \underline{\underline{125{,}6\Omega}}; r_{e3} = \frac{V_T}{I_{C3}} = \underline{\underline{20{,}5\Omega}}; r_{e4} = \frac{V_T}{I_{C4}} = \underline{\underline{25{,}1\Omega}}$$

Now the gain is $\frac{v_o}{v_i} = \frac{v_o}{v_{b3}} \cdot \frac{v_{b4}}{v_{b3}} \cdot \frac{v_{b3}}{v_i} = \frac{4k7}{4k7 + r_{e4}} \cdot \frac{-R_{C3} \parallel r_{i4}}{4k7 + r_{e3}} \cdot \frac{33k \parallel r_{i3}}{2r_{e1/2}}$ with

$$r_i = r_{i1/2} = 2h_{fe}r_{e1/2} = 2 \cdot 200 \cdot \frac{25mV}{0{,}199mA} = \underline{\underline{50k25}};$$

$$r_{i3} = h_{fe}(r_{e3} + 4k7) = 944k$$

$$r_{i4} = h_{fe}(r_{e4} + 10k) = 945k$$

Resulting in $\frac{v_o}{v_i} = \frac{4k7}{4k7 + r_{e4}} \cdot \frac{-11k11 \parallel r_{i4}}{4k7 + r_{e3}} \cdot \frac{33k \parallel r_{i3}}{2r_{e1/2}} = 0{,}994 \cdot (-2{,}36) \cdot 126{,}9 \cong \underline{\underline{-293{,}6}}$

$$r_o = r_{o4} = R_{E4} \parallel \left[r_{e4} + \frac{R_S}{h_{fe}} \right] = R_{E4} \parallel \left[r_{e4} + \frac{r_{o3}}{h_{fe}} \right] = \underline{\underline{51\Omega}} \text{ where } r_{o3} = R_{C3} = \underline{\underline{5k35}}$$

2. DC characteristics are to be studied.

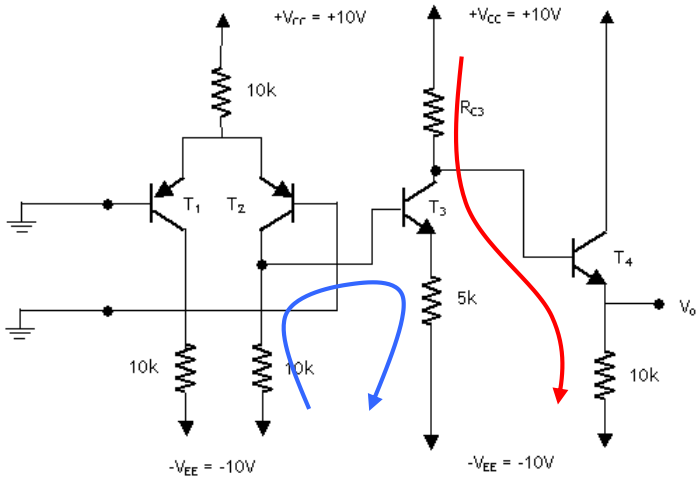
DC Analysis: The first stage of the 3-stage amplifier is a differential stage. Since both transistors are ideal, their collector currents are the same

$$I_{C1} = I_{C2} = \frac{h_{FE}}{h_{FE}+1}\left[\frac{V_{CC}-V_{EB1}}{2R_E}\right] = \frac{100}{101}\cdot\frac{10V+V_{BE1}}{20k} = \frac{100}{101}\cdot\frac{10V-0{,}6V}{20k} \cong \underline{\underline{0{,}47mA}}$$

Now, following the blue loop

$$-(I_{C2}-I_{B3})10k + V_{BE3} + (h_{FE}+1)I_{B3}5k = 0$$

$$I_{C3} = h_{FE}\frac{10k * I_{C2} - V_{BE3}}{(h_{FE}+1)5k+10k} = \underline{\underline{0{,}8mA}}$$



We are told that waveform distortion at the output V_o should be minimum and symmetrical. That means V_0 = 0V.

$$I_{E4} = \frac{0V-(-V_{EE})}{10k} \text{ or}$$

$$(h_{FE4}+1)I_{B4}10k = 10V$$
$$\Rightarrow I_{C4} = h_{FE4}I_{B4} = \underline{\underline{0{,}99mA}}$$

Also, $V_{B4} = +V_{CC} - R_{C3} * (I_{C3}+I_{B4}) = +10V - R_{C3} * (0{,}91mA + 9{,}9\mu A) = V_{BE4} = 0{,}6V$

Therefore, $R_{C3} = \frac{10V-0{,}6V}{0{,}8mA+9{,}9\mu A} = \underline{\underline{11k6}}$

AC Analysis: Let'a first calculate the AC resistances

$$r_{e1} = r_{e2} = \frac{V_T}{I_{C1}} = \frac{25mV}{0{,}47mA} = \underline{\underline{53{,}2\Omega}}; r_{e3} = \frac{V_T}{I_{C3}} = \frac{25mV}{0{,}8mA} = \underline{\underline{31{,}25\Omega}}; r_{e4} = \frac{V_T}{I_{C4}} = \frac{25mV}{0{,}99mA} = \underline{\underline{25{,}25\Omega}}$$

$$A_v = \frac{v_o}{v_{in}} = \frac{v_o}{v_{b4}}\cdot\frac{v_{b4}}{v_{b3}}\cdot\frac{v_{b3}}{v_{in}} = +\frac{R_{e4}}{r_{e4}+R_{e4}}\cdot\left[-\frac{R_{C3}\parallel r_{i4}}{r_{e3}+R_{e3}}\right]\cdot\left[+\frac{R_{C2}\parallel r_{i3}}{2r_{e1}}\right]$$

$$r_{i3} = h_{fe}(r_{e3}+R_{e3}) = 100(31{,}25+5k) = \underline{\underline{503k}}$$
$$r_{i4} = h_{fe}(r_{e4}+R_{e4}) = 100(25{,}25+10k) = \underline{\underline{1M}}$$

$$\Rightarrow A_v = \frac{10k}{25{,}25+10k}\cdot\left[-\frac{11k6\parallel 1M}{31{,}25+5k}\right]\cdot\left[\frac{10k\parallel 503k}{2*53{,}2}\right] = 0{,}997*(-2{,}279)*92{,}167 \cong \underline{\underline{-209{,}5}}$$

$$r_o = r_{o4} = R_{E4} \| \left[r_{e4} + \frac{R_S}{h_{fe}} \right] = R_{E4} \| \left[r_{e4} + \frac{r_{o3}}{h_{fe}} \right] = \underline{\underline{139\Omega}} \text{ where } r_{o3} = R_{C3} = \underline{\underline{11k6}}$$

$$CMRR = 20\log_{10} \left| \frac{2R_E + r_{e1/2}}{r_{e1/2}} \right| = 20\log_{10} \left| \frac{2 \cdot 10k + 53{,}2\Omega}{53{,}2\Omega} \right| = \underline{\underline{51{,}5dB}}$$