NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 1 EXAMINATION 2017-2018

EE2002 - ANALOG ELECTRONICS

November / December 2017 Time Allowed: 2½ hours

INSTRUCTIONS

1. This paper contains 5 questions and comprises 10 pages.
2. Answer ALL questions.
3. All questions carry equal marks.
4. This is a closed book examination.
5. Unless specifically stated, all symbols have their usual meanings.
6. A List of Formulae is provided in Appendix A on pages 8 to 10.

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1. (a) For the ideal Op-Amp in negative feedback shown in Figure 1(a) on page 2, derive the expression for the closed-loop gain $A_{VCL} = (v_{OUT}/v_{IN})$.

   Note: *Parallel resistance of R_a and R_b can be written as $R_a // R_b$ without expanding it.*

   (10 Marks)

Note: Question No. 1 continues on page 2.

9.

$\frac{V_{in} - V_+}{V_+} = \frac{R_1}{R_2} + 1$

$\frac{V_{in}}{V_+} = 1 + \frac{R_1}{R_2}$

$\frac{V_{out}}{V_x} = \frac{R_8}{(R_5+R_6) \| R_7} + 1$

$\frac{R_8 + (R_5+R_6) \| R_7}{(R_5+R_6) \| R_7}$

$\frac{V_x - V_-}{R_2} = \frac{V_x}{R_5+R_6}$

$1 - \frac{V_-}{V_x} = \frac{R_6}{R_5+R_6}$

$\frac{R_5}{R_5+R_6} = \frac{V_-}{V_x}$

$\frac{V_x}{(R_5+R_6) \| R_7} = \frac{V_{out} - V_x}{R_8}$

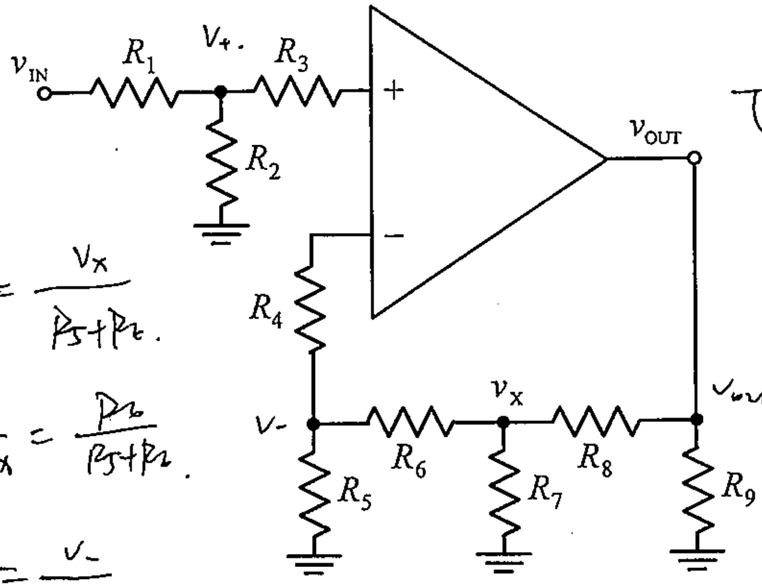
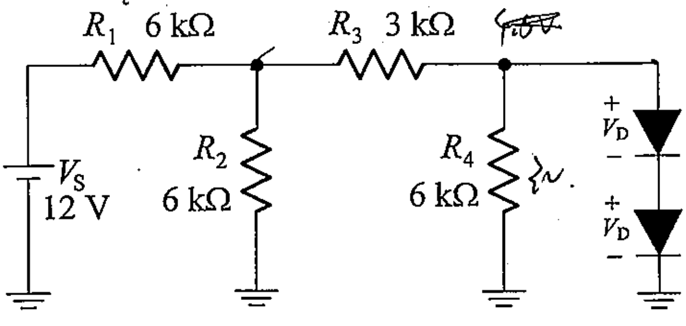


Figure 1(a)

(b). In Figure 1(b), the empirical diode junction equation $V_D = nV_T \ln(I_D/I_S)$ for both diodes D_1 and D_2 where V_T is 26 mV, I_S = 5 × 10^{-15} A, n = 1 and V_S = 12 V. Find the quiescent point(s) or Q-point(s) (I_D, V_D) of the diodes D_1 and D_2 (in mA and V, respectively, up to 3 significant decimal places).

Hint: *The diodes are identical.*

(10 Marks)



$V = 3V$

Figure 1(b)

2. For the MOSFET amplifier shown in Figure 2 on page 3, assume that V_{DD} = 10 V, V_{TN} = 1 V, K_n = 2 mA/V², $r_o = \infty$, R_S = 1 kΩ, R_{G1} = 6.5 MΩ, R_{G2} = 3.5 MΩ, R_D = 1 kΩ, R_M = 1 MΩ, and R_L = 5 MΩ. Assume that the capacitors have infinite values.

$I_D = \frac{K_n}{2}(V_{GS} - V_{TN})^2 \cdot R_D$

Note: Question No. 2 continues on page 3.

(a) Determine the Q-point for the transistor.

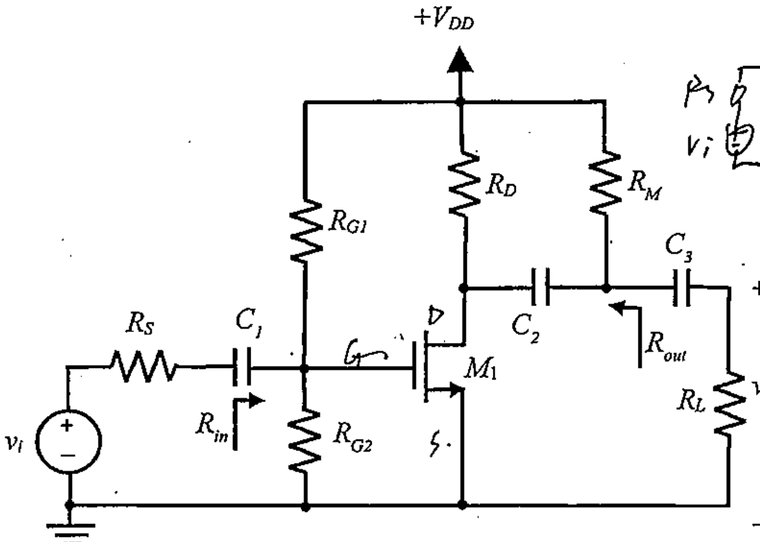
(5 Marks)

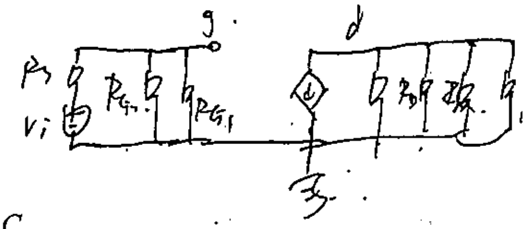
(b) Determine the voltage gain $A_v = \frac{v_o}{v_i}$, the input resistance R_{in} and the output resistance R_{out} of the amplifier.

(12 Marks)

(c) Determine the input small signal range for this amplifier.

(3 Marks)





$\frac{V_g}{v_i} = \frac{R_G}{R_S + R_G}$

$\frac{V_o}{V_g} = -g_m R_L'$

$R_{in} = R_G = R_{G1} \| R_{G2}$

$R_{out} = R_D \| R_M$.

Figure 2

3. For the differential amplifier circuit shown in Figure 3 on page 4. The voltage sources, v_1 and v_2, represent the ground referenced ac input signals such that the differential input signal $v_{id} = v_1 - v_2$ and the common-mode input signal $v_{ic} = \frac{v_1 + v_2}{2}$. The differential amplifier is biased by a constant current source with a DC current I_{SS} of 300 μA and an ac resistance R_{SS} of 175 kΩ. The matched pMOS transistors, M_1 and M_2, have $K_p = 250$ μA/V^2, $V_{TP} = -1.5$ V and $\lambda = 0.01$ V^{-1}. The output v_{out} is taken from the drain terminal of M_1 to drive the load resistance R_L.

Note: Question No. 3 continues on page 4.

$\frac{v_o}{v_g} = \frac{-i_d R}{v_g} = \frac{-g_m v_{gs} R}{v_{gs} + g_m v_{gs} 2R_{SS}} = \frac{-g_m R}{1 + g_m 2R_{SS}}$

(a) If the DC voltages at the gates of M_1 and M_2 are both zero, determine the Q-point of the transistors. Verify that the pMOS transistors are operating in the saturation mode.

(6 Marks)

(b) For single-ended output and $R_L = \infty$, determine the differential-mode gain, common-mode gain and common-mode rejection ratio (CMRR) of the amplifier.

(10 Marks)

(c) Determine the differential-mode input resistance and single-ended output resistance of the amplifier.

(4 Marks)

$V_{gs} = V_g - V_s = V_{ic} - i_x 2R_{SS}$

$v_o = i_x R$

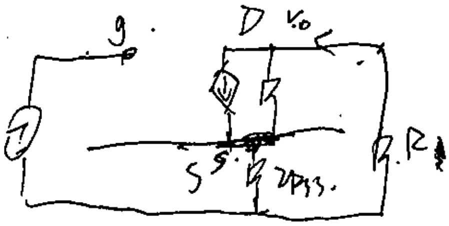
$v_s = i_x 2R_{SS} + (i_x - g_m v_{gs}) r_o$

$\frac{V_D + 12}{75k} = I_D$

$V_D - V_S = V_{D3}$

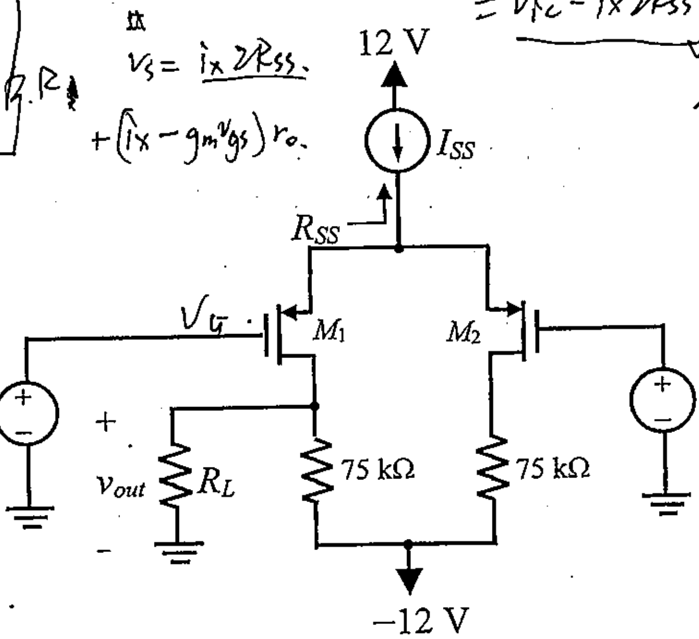
$V_G - V_D$

$g_m \frac{I_d}{4}$



$V_b = 0 \quad V_{ic}: v_1$

$= g_m v_{gs} R = g_m (v_{ic} - v_s) R = g_m v_{ic} R - g_m i_x 2R_{SS} R = g_m v_{ic} R - g_m g_m$



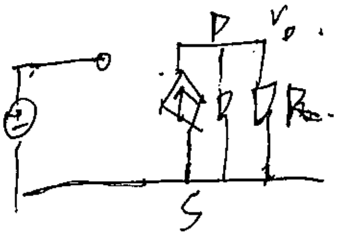


Figure 3

4. (a) Consider the current mirror circuit shown in Figure 4(a) on page 5. Assume all transistors are in saturation and ignore Early effect. It is given that $I_{REF} = 100\ \mu A$, $V_{DD} = 10$ V, $K_n' = K_p' = K' = 10\ \mu A/V^2$, $|V_{TP}| = |V_{TN}| = |V_T| = 0.6$ V and (W/L) sizes of the transistors are written next to each of them in the figure. Also, the drain current equation for a MOSFET is given by: $I_D = \frac{K'}{2}(\frac{W}{L})(|V_{GS}| - |V_T|)^2$.

$\Rightarrow |V_{GS}| = |V_T| + \sqrt{\frac{2I_D}{K'(\frac{W}{L})}} =$

Note: Question No. 4 continues on page 5.

200μA 300μA.

(i) Find the values of I_{out1} and I_{out2}.

(2 Marks)

(ii) What are the values of V_A and V_B? 2.0 1.4V.

(5 Marks)

(b) For the same circuit in Figure 4(a), include Early effect now and do a small signal analysis to find an algebraic expression of the impedance R_{OUT} on the drain node of M_4 (with voltage V_B). Your answer should be in terms of g_m and r_o of the MOSFET. Indicate clearly the g_m and r_o of the i-th transistor as $g_{m,i}$ and $r_{o,i}$, respectively. For example, the g_m and r_o for transistor M_2 should be written as $g_{m,2}$ and $r_{o,2}$, respectively.

(7 Marks)

(c) Consider the circuit in Figure 4(b) on page 6. If $V_{BE} = 0.7$ V, $V_A = 50$ V, $\beta = 60$ and $A_{E2} = 5A_{E1}$ where A_E denotes emitter area, find the value of I_{out} in mA correct up to two decimal places.

(6 Marks)

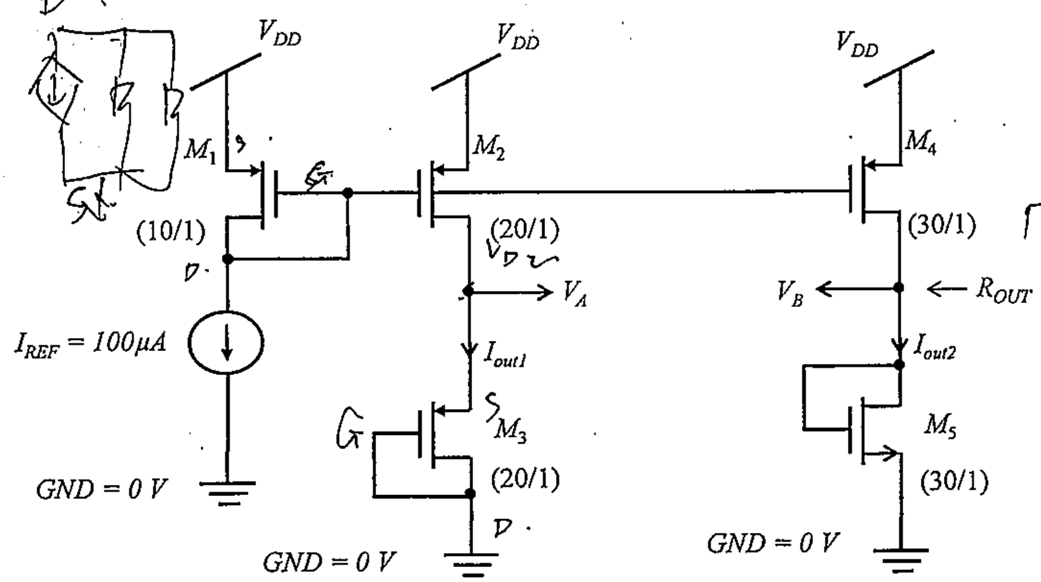


Figure 4(a)

$V_{SG} = V_{SD}$.

$I_{out1} = I_{D3} = \frac{k}{2}\left(\frac{W}{L}\right)_3 (|V_{GS}| - V_T)^2$.

V_{GS3}

V_S.

Note: Question No. 4 continues on page 6.

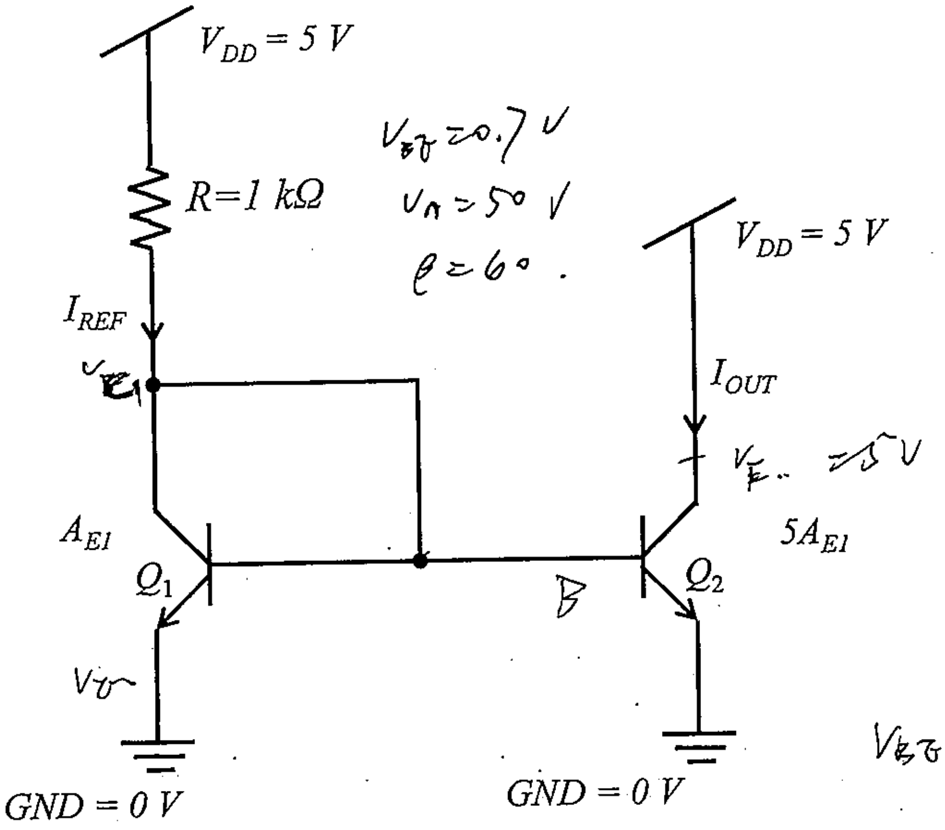
$I_x = g_m v_{gs}$.

$= g_m v_x$.

$R_{in} = \frac{V_A}{I_x} = \frac{1}{g_m}$.

$$I_{REF} = \frac{V_{DD} - V_{C1}}{R}.$$

$$I_{S0}\left(\frac{A_{E1}}{A}\right) e^{\frac{V_{BE}}{V_T}} \left(1+\frac{V_{CE}}{V_A}\right) + \frac{I_S}{\beta}\left(\frac{A_{E2}}{A}\right) e^{\frac{V_{BE}}{V_T}} (1+$$



$$\frac{n\left(1+\frac{V_{CE}}{V_A}\right)}{n+\left(1+\frac{2}{\beta}\right)(1-}$$

$V_{BE} = V_B - V_E$.

Figure 4(b)

5. (a) Consider the filter circuit shown in Figure 5(a) on page 7 and assume that the Operational Amplifier is ideal. Find an algebraic expression of the transfer function $H(s) = V_{out}/V_{in}$ of this circuit in terms of the resistors and capacitors R_1, R_2, R_3, C_1 and C_2.

(6 Marks)

(b) How many poles and zeros are there in the transfer function H(s) in part (a)? What are their (values) in terms of the resistors and capacitors R_1, R_2, R_3, C_1 and C_2?

(6 Marks)

(c) If $R_1 = 100\ k\Omega$, $R_2 = 10\ k\Omega$, $R_3 = 1\ k\Omega$, $C_1 = 10$ nF and $C_2 = 1$ nF, find the magnitudes of poles and zeros found in part (b) of this question.

(3 Marks)

Note: Question No. 5 continues on page 7.

$as[b+c(1+ds)]$. $s[(R_2+R_3)C_1R_1 + C_1R_1R_2$.

$ab s + acs(1+ds)$.

$abs + acs + acds^2$.

(d) For the circuit in Figure 5(b) with input at v_s and output at v_L, determine which capacitor contributes to the upper or higher cut-off frequency and explain the reason for your choice.

$sC_1R_1R_2 + sC_1R_1R_3 + s^2 C_1R_1R_3R_2C_2$.

$(R_2+R_3)sC_1R_1 + s^2C_1R_1$.

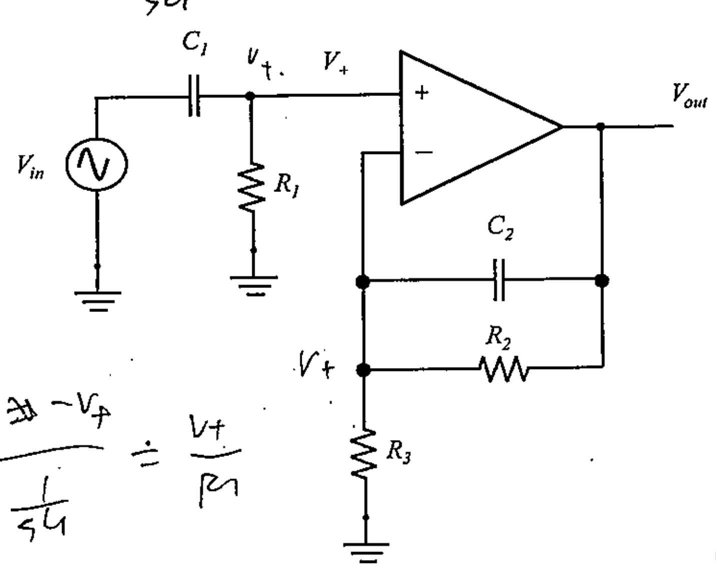
(2 Marks)

(e) Use the OCTC method to find the resistance seen by the contributing capacitor found in part (d) of this question.

(3 Marks)

short.

$\frac{C_1R_1(R_2+R_3)}{C_1R_1R_2R_3C_2}$.



$\frac{V_{in} - V_+}{\frac{1}{sC_1}} = \frac{V_+}{R_1}$

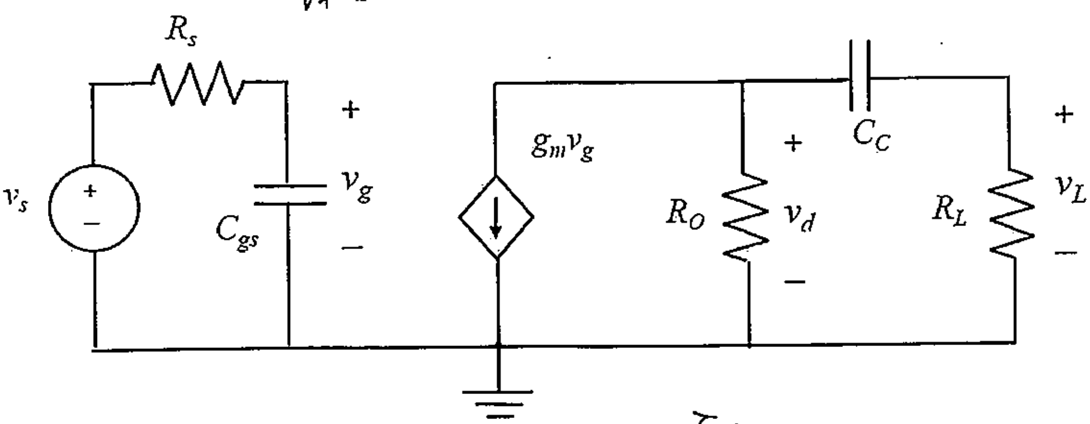
$\frac{V_{out} - V_+}{(\frac{1}{sC_2} \parallel R_2)} = \frac{V_+}{R_3}$.

$\frac{V_{out}}{V_+} = \frac{(\frac{1}{sC_2} \parallel R_2) + R_3}{R_3}$.

$\frac{V_{in}}{V_+} = \frac{\frac{1}{sC_1}}{R_1} + 1$

Figure 5(a)

$V_+ = \frac{R_1}{}$



$\frac{\frac{\frac{R_2}{sC_2}}{\frac{1}{sC_2}+R_2} + R_3}{R_3} \times \frac{R_1}{R_1 + \frac{1}{sC_1}}$.

Figure 5(b)

$\frac{R_1\left(\frac{R_2}{sC_2} + R_3\left(\frac{1}{sC_2} + R_2\right)\right)}{R_3\left(\frac{1}{sC_2}+R_2\right)\left(R_1 + \frac{1}{sC_1}\right)}$.

$\frac{sC_1R_1[R_2 + R_3(1+R_2sC_2)]}{R_3[1+sC_2R_2](sR_1C_1+1)}$.

$\frac{R_1R_2C_1 + R_1R_3(\cancel{C_1} + sC_1C_2R_2)}{R_3(C_1 + sC_2C_1R_2)(R_1sC_2C_1 + C_2)}$.

$sC_1R_1R_2 + sC_1R_1R_3 + s^2C_1R_2R_1R_2R_3$.

$\frac{R_1R_2 + R_1R_3(1+sC_2R_2)}{R_3(1+sC_2R_2)(R_1sC_2C_1+1)}$.

Appendix A

List of Selected Formulae

Op-Amps:

Closed-Loop Negative Feedback Inverting Gain, $A_{VCL} = \frac{v_o}{v_i} = -\frac{R_f}{R_i}$ Figure (a)

Closed-Loop Negative Feedback Non-Inverting Gain, $A_{VCL} = \frac{v_o}{v_i} = \left(1 + \frac{R_f}{R_i}\right)$ Figure (b)

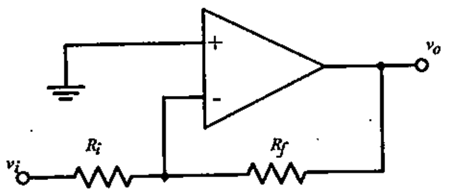


Figure (a)

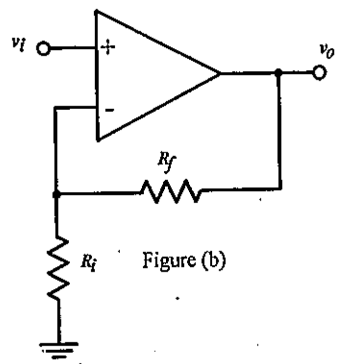


Figure (b)

Op-Amp's Slew Rate, $SR \geq \left|\frac{dv_o}{dt}\right|_{max} = A_{VCL}\omega a_m = A_{VCL}a_m 2\pi f$,

where $v_i = a_m \sin(\omega t)$, $v_o = A_{VCL}a_m \sin(\omega t)$ and $\left|\frac{dv_o}{dt}\right| = A_{VCL}\omega\, a_m \cos(\omega t)$

Op-Amp's frequency response: $A_{VOL}(jf) = \frac{A_o}{\left(1 + \frac{jf}{f_p}\right)}$

Gain-Bandwidth Product: $A_o f_p = f_o = \frac{1}{\beta}(BW)_{CL}$

where $\frac{1}{\beta} = \frac{R_f + R_i}{R_i}$

$t_r = \frac{0.35}{(BW)_{CL}}$

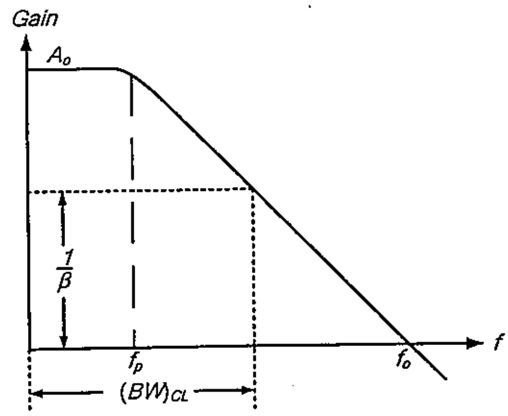


Figure (c)

Diodes:

$v_D \approx nV_T \ln\left(\frac{i_D}{I_S}\right)$ or $i_D \approx I_S e^{\left(\frac{v_D}{nV_T}\right)}$

where $e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} + \ldots\ldots\ldots$

Diode conductance: $g_D = \frac{1}{r_D} = \frac{I_D}{nV_T}$

BJT in Forward Active Region:

Ignore early effect: $i_C = I_S \exp\left(\frac{|v_{BE}|}{V_T}\right)$

With early effect: $i_C = I_S \exp\left(\frac{|v_{BE}|}{V_T}\right)\left(1+\frac{|v_{CE}|}{V_A}\right)$

where I_S: Saturation current,
V_T: Thermal voltage, assume 25 mV at room temperature,
V_A: Early voltage.
For npn transistor, $|v_{BE}| = v_{BE}$ and $|v_{CE}| = v_{CE}$;
For pnp transistor, $|v_{BE}| = v_{EB}$ and $|v_{CE}| = v_{EC}$.

Small-signal model parameters of BJT:

$g_m = \frac{I_C}{V_T}$, $r_\pi = \frac{\beta}{g_m}$ and $r_O = \frac{V_A + |V_{CE}|}{I_C} \approx \frac{V_A}{I_C}$

where I_C : DC collector current at Q-point
V_{CE}: DC collector-emitter voltage at Q-point

Criterion for small-signal operation of BJT: $|v_{be}| \le 0.2\ V_T$

MOSFET in Saturation Region:

Criterion: $V_{DS} \ge V_{GS} - V_{TN}$ for NMOS;
$|V_{DS}| \ge |V_{GS}| - |V_{TP}|$ for PMOS
where V_{TN}, V_{TP}: Threshold voltage,
V_{DS}: DC drain-source voltage,
V_{GS}: DC gate-source voltage.

Ignore channel-length modulation effect: $i_D = \frac{K_n}{2}(v_{GS} - V_{TN})^2$ for NMOS,

$i_D = \frac{K_p}{2}(|v_{GS}| - |V_{TP}|)^2$ for PMOS.

With channel-length modulation effect: $i_D = \frac{K_n}{2}(v_{GS} - V_{TN})^2(1+\lambda v_{DS})$ for NMOS,

$i_D = \frac{K_p}{2}(|v_{GS}| - |V_{TP}|)^2(1+\lambda |v_{DS}|)$ for PMOS.

where λ: channel length modulation parameter,
For NMOS $K_n = K_n'\left(\frac{W}{L}\right)$ and $K_n' = \mu_n C_{ox}$; For PMOS $K_p = K_p'\left(\frac{W}{L}\right)$ and $K_p' = \mu_p C_{ox}$.

MOSFET in Triode Region:

Criterion: $V_{DS} < V_{GS} - V_{TN}$ for NMOS;
$|V_{DS}| < |V_{GS}| - |V_{TP}|$ for PMOS

Ignore channel-length modulation effect: $i_D = K_n\left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right)v_{DS}$ for NMOS,

$i_D = K_p\left(|v_{GS}| - |V_{TP}| - \frac{|v_{DS}|}{2}\right)|v_{DS}|$ for PMOS.

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With channel-length modulation effect: $i_D = K_n\left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right)v_{DS}(1+\lambda v_{DS})$ for NMOS,

$$i_D = K_p\left(|v_{GS}| - |V_{TP}| - \frac{|v_{DS}|}{2}\right)|v_{DS}|(1+\lambda|v_{DS}|) \text{ for PMOS.}$$

Small-signal model parameters of MOSFET

For NMOS: $g_m = \sqrt{2K_n I_D(1+\lambda V_{DS})} \approx \sqrt{2K_n I_D}$ and $r_o = \dfrac{\frac{1}{\lambda}+V_{DS}}{I_D} \approx \dfrac{1}{\lambda I_D}$

For PMOS: $g_m = \sqrt{2K_p I_D(1+\lambda|V_{DS}|)} \approx \sqrt{2K_p I_D}$ and $r_o = \dfrac{\frac{1}{\lambda}+|V_{DS}|}{I_D} \approx \dfrac{1}{\lambda I_D}$

where I_D: DC drain current at Q-point
V_{DS}: DC drain-source voltage at Q-point

Criterion for small-signal operation:
For NMOS: $|v_{gs}| \le 0.2(V_{GS} - V_{TN})$
For NMOS: $|v_{gs}| \le 0.2(|V_{GS}| - |V_{TP}|)$
where V_{GS}: DC gate-source voltage at Q-point.

Miller Effect

The equivalent shunt input capacitance: $C_X = C \times (1 + A_V)$

The equivalent shunt output capacitance: $C_Y = C \times (1 + \frac{1}{A_V})$

where $-A_V$: the gain of the voltage amplifier
C: the original capacitance between the input and output terminals of the voltage amplifier

Frequency Response

By using OCTC and SCTC methods, the upper cut-off frequency is estimated by $\omega_{H\text{-}3dB} \approx \dfrac{1}{\sum_i C_i R_i}$

and the lower cut-off frequency is estimated by $\omega_{L\text{-}3dB} \approx \sum_i \dfrac{1}{C_i R_i}$

where C_i: the contributing capacitor for the cut-off frequency
R_i: the equivalent resistance seen by the capacitor C_i

END OF PAPER

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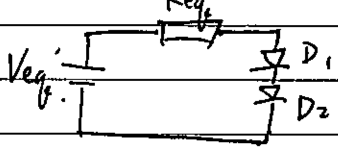
1. (a) $\dfrac{V_{in}-V_+}{V_+} = \dfrac{R_1}{R_2}$, $\dfrac{V_x - V_-}{R_6} = \dfrac{V_x}{R_5+R_6}$, $\dfrac{V_{out}-V_x}{R_8} = \dfrac{V_x}{(R_5+R_6)//R_7}$

$$\Rightarrow \frac{V_{out}}{V_{in}} = \frac{(R_1+R_2)\ R_5\ [R_8+(R_5+R_6)//R_7]}{R_2\,(R_5+R_6)\,[(R_5+R_6)//R_7]}$$

(b)



According to Thevenin Theorem.

$$V_{eq} = \frac{R_2//(R_3+R_4)}{R_1+R_2//(R_3+R_4)} V_S \cdot \frac{R_4}{R_3+R_4} = 3V.$$

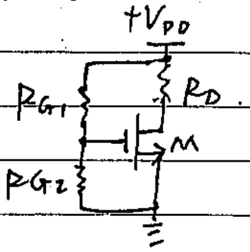
$$R_{eq} = ((R_1//R_2)+R_3)//R_4 = 3\,k\Omega.$$

Then, $I_D = \dfrac{3V - 2V_D}{3k\Omega}$ and $V_D = nV_T \ln(\frac{I_D}{I_S}) = 0.026 \ln \frac{I_D}{15\times10^{-5}A}$

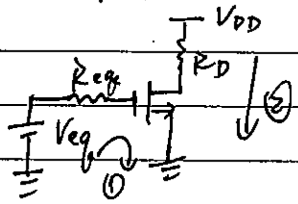
~~$V_D = 0.7V \rightarrow I_D = 53.3\,mA \Rightarrow V_D = 0.632V \Rightarrow I_D = 57.9\,mA$~~

$\rightarrow V_D = 0.634V \rightarrow I_D = 57.7\,mA \rightarrow V_D = 0.634V \rightarrow I_D = 57.7\,mA.$

2. (a)



$\Rightarrow$



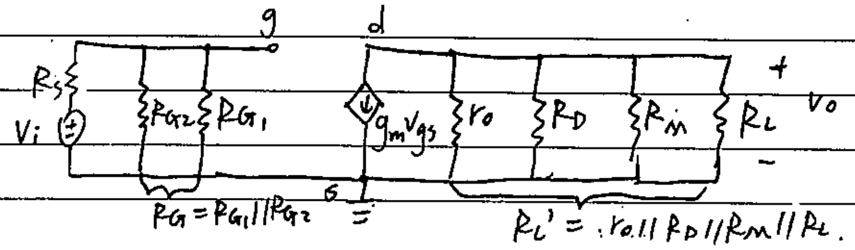
$V_{eq} = \dfrac{R_{G2}}{R_{G1}+R_{G2}} V_{DD} = 3.5V.$

$R_{eq} = R_{G1}//R_{G2} = 2.275\,M\Omega.$

① $V_{eq} = V_{GS}$

② $V_{DS} = V_{DD} - I_D R_D \Rightarrow V_{DS} = 3.75V,\ I_D = 6.25\,mA$

(b)

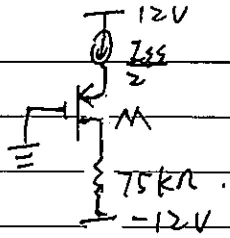


$\dfrac{V_o}{V_g} = \dfrac{V_d}{V_g} = \dfrac{-g_m V_{gs} R_L'}{V_{gs}} = -g_m R_L'$, $A_{vt} = \dfrac{V_o}{V_g}\cdot\dfrac{V_g}{V_i} = -g_m R_L' \cdot \dfrac{R_G}{R_G+R_S}$

$R_{in} = R_G = R_{G1}//R_{G2}$, $R_{out} = R_D//R_m//r_o \approx R_D//R_m$

(c) $|V_{in}| \leq 0.2(V_{GS}-V_{TN})(1+g_m R_{S1})(\dfrac{R_{in}+R_S}{R_{in}})$

3. (a)

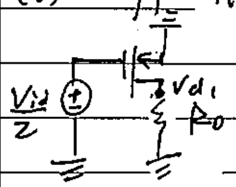


$I_D = I_S = \frac{I_{SS}}{2} = 150\,\mu A = \frac{K_P}{2}(|V_{GS}| - |V_{TP}|)^2$.

$\Rightarrow |V_{GS}| = 2.60\,V$.

$\Rightarrow |V_{DS}| = V_{DD} - I_D R_D - (-|V_{GS}|) = 3.35\,V > |V_{GS}| - |V_{TP}|$

(b) Differential-mode.



$V_{d1} = -g_m\left(\frac{V_{id}}{2}\right) R_D$

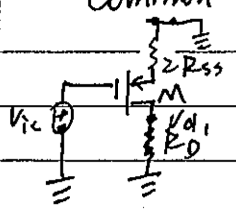
$A_{dm\text{-}se} = \frac{V_{d1}}{V_{id}} = -\frac{g_m R_D}{2}$

(c)

$R_{in} = R_{id} = \infty$

$R_{out} = r_o \,//\, R_D \approx R_D$

Common-mode.



$V_{d1} = -g_m V_{gs} R_D$

$V_{ic} = V_{gs} + g_m V_{gs} 2R_{SS}$

$\Rightarrow A_{cm\text{-}se} = \frac{V_{d1}}{V_{ic}} = \frac{-g_m R_D}{1 + 2g_m R_{SS}} \approx \frac{-R_D}{2R_{SS}}$.

$CMRR = \left|\frac{A_{dm\text{-}se}}{A_{cm\text{-}se}}\right| = g_m R_{SS}$

4. (a) $I_{out1} = \frac{K'}{2}\left(\frac{W}{L}\right)_2 (|V_{GS}| - |V_T|)^2$

$I_{out2} = \frac{K'}{2}\left(\frac{W}{L}\right)_4 (|V_{GS}| - |V_T|)^2$

and $I_{REF} = \frac{K'}{2}\left(\frac{W}{L}\right)_1 (|V_{GS}| - |V_T|)^2 = 100\,\mu A$.

thus, $I_{out1} = 200\,\mu A$, $I_{out2} = 300\,\mu A$.

$|V_{GS}| = |V_T| + \sqrt{\frac{2I_{REF}}{K'\left(\frac{W}{L}\right)_1}} = 2.014\,V$.

$V_A = V_{S3} = |V_{GS}| + V_{G3} = 2.014\,V + 0\,V = 2.014\,V$.

$V_B = V_{G5} = |V_{GS}| + V_{S5} = 2.014\,V + 0\,V = 2.014\,V$.

(b) Didn't answer.

(c) $I_{C1} = I_S\left(1 + \frac{V_{CE1}}{V_A}\right) e^{\frac{V_{BE}}{V_T}}$, $I_{C2} = I_S\left(1 + \frac{V_{CE2}}{V_A}\right) e^{\frac{V_{BE}}{V_T}}$,

$I_{B1} = \frac{I_{C1}}{\beta_1} = \frac{I_S\left(1 + \frac{V_{CE1}}{V_A}\right) e^{\frac{V_{BE}}{V_T}}}{\beta\left(1 + \frac{V_{CE1}}{V_A}\right)} = \frac{I_S}{\beta} e^{\frac{V_{BE}}{V_T}}$, $I_{B2} = \frac{I_{C2}}{\beta_2} = \frac{I_S}{\beta} e^{\frac{V_{BE}}{V_T}}$

Since $\because I_S = I_{S0}\left(\frac{A_E}{A}\right)$ and $A_{E2} = 5A_{E1}$

$\Rightarrow MR = \frac{I_{out}}{I_{REF}} = \frac{5}{1 + \frac{5+1}{\beta}} = 4.545$.

$I_{REF} = \frac{V_{DD} - V_{C1}}{R} = \frac{V_{DD} - V_B}{R} = \frac{V_{DD} - V_{BE}}{R} = \frac{5V - 0.7V}{1\,k\Omega} = 4.3\,mA$.

$I_{out} = MR \cdot I_{REF} = 19.55\,mA$

5. (a) $\frac{V_{in}-V_+}{\frac{1}{sC_1}} = \frac{V_+}{R_1}$, $\frac{V_{out}-V_+}{\frac{1}{sC_2}//R_2} = \frac{V_+}{R_3}$

$\Rightarrow \frac{V_+}{V_{in}} = \frac{sC_1R_1}{1+sC_1R_1}$, $\frac{V_{out}}{V_+} = \frac{R_2+R_3(1+sC_2R_2)}{R_3(1+sC_2R_2)}$

$\Rightarrow H(s) = \frac{V_+}{V_{in}} \cdot \frac{V_{out}}{V_+} = \frac{sC_1R_1}{1+sC_1R_1} \cdot \frac{R_2+R_3(1+sC_2R_2)}{R_3(1+sC_2R_2)}$

$$= \frac{sC_1R_1(R_2+R_3+sC_2R_2R_3)}{R_3(1+sC_1R_1)(1+sC_2R_2)}$$

$$= \frac{C_1R_1(R_2+R_3)}{R_3} \frac{s\left(1+\frac{s}{\frac{R_2+R_3}{C_2R_2R_3}}\right)}{\left(1+\frac{s}{1/C_1R_1}\right)\left(1+\frac{s}{1/C_2R_2}\right)}$$

(b) zeros: 0 , $-\frac{R_2+R_3}{C_2R_2R_3}$

poles: $-\frac{1}{C_1R_1}$, $-\frac{1}{C_2R_2}$.

(d) Short C_{gs}, $V_g = 0$. $\Rightarrow$ reduce voltage gain. $\Rightarrow$ C_{gs} contributor.
Short C_c, $v_L = v_d$, increases. $\Rightarrow$ increase voltage gain $\Rightarrow$ C_c helper.

(e) $R_{C_{gs}} = R_s$.

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