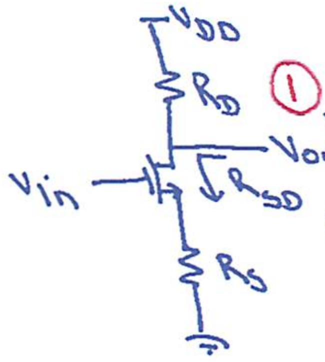
(FEEDBACK in GREEN)

Analogue Electronics 2 (E2.2) 2014 – SOLUTIONS

Q1 – BOOKWORK/CALCULATION FOR NEW EXAMPLE

1 (a) Source degeneration is when a circuit element (eg. resistor) is connected between the source terminal (in a MOSFET) and the common node (i.e. GND for NMOS and VDD for PMOS). 1



1

$$A_V = -\frac{R_D}{\frac{1}{g_m} + R_S}$$

1

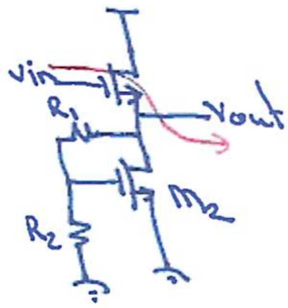
Advantages (compared to CS)

1. output resistance R_{SD} is increased from r_{o1} to $(g_{m1} r_{o1} R_S + R_S + r_{o1})$ 1/2
2. Large signal operation is linearised (i.e. larger small signal region). 1/2

Disadvantages (compared to CS)

1. reduced voltage (o/p) headroom. 1/2
2. reduced voltage gain. 1/2

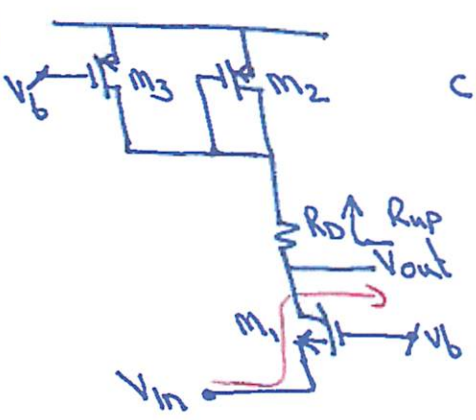
(b) (i)



Source follower 1 $\therefore A_V = \dfrac{R_S \| r_o}{\frac{1}{g_m} + R_S \| r_o}$ 1

$R_S = r_{o2} \| (R_1 + R_2)$ $\therefore A_V = \dfrac{r_{o1} \| r_{o2} \| (R_1 + R_2)}{\frac{1}{g_{m1}} + r_{o1} \| r_{o2} \| (R_1 + R_2)}$ 3

(ii)



C.G. amplifier 1 $\therefore A_V = +g_m(r_o \| R_D)$ 1

$A_V = +g_{m1}(r_{o1} \| R_{up})$ 1

$R_{up} = R_D + \frac{1}{g_{m2}} \| r_{o2} \| r_{o3}$

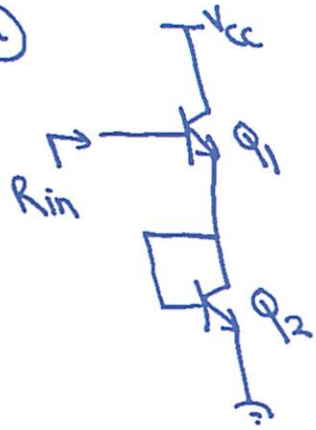
$\approx R_D + \frac{1}{g_{m2}} \| r_{o3}$

(assuming $\frac{1}{g_{m2}} \ll r_{o2}$) 1

$\therefore A_V = +g_{m1}\left(r_{o1} \| \left(R_D + \frac{1}{g_{m2}} \| r_{o3}\right)\right)$ 1

Parts (a–c) generally answered well.

(c) (i)



(use $R_{in} = r_\pi + (\beta+1) R_E$) 1

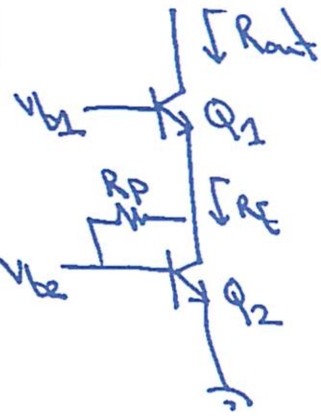
where $R_E = \frac{1}{g_{m2}} \| r_{\pi 2} \| r_{o2}$ 1

$\therefore R_{in} = r_{\pi 1} + (\beta+1)\left(\frac{1}{g_{m2}} \| r_{\pi 2} \| r_{o2}\right)$ 1

$\approx r_{\pi 1} + (\beta+1)\left(\frac{1}{g_{m2}}\right)$ 1

(assuming $\frac{1}{g_{m2}} \ll r_{\pi 2} < r_{o2}$) 1

(ii)



emitter degeneration. 1

$\therefore R_{out} = g_{m1} r_{o1} (R_E \| r_{\pi 1}) + (R_E \| r_{\pi 1}) + r_{o1}$ 1

where $R_E = R_p \| r_{o2}$ 1

$\therefore R_{out} = g_{m1} r_{o1} (R_p \| r_{o2} \| r_{\pi 1}) + (R_p \| r_{o2} \| r_{\pi 1}) + r_{o1}$

2

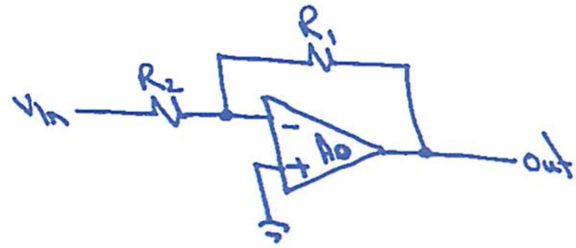
(d) (i) output voltage range of a differential amplifier depends on the number of devices that are "stacked" which may limit the headroom. This is because all devices must remain in saturation (i.e. $V_{GS} - V_{TH} \leq V_{DS}$). for example, using cascode devices will limit the O/P range. 3

(ii) The slew rate of an amplifier gives a measure on how fast the output can change. As this is fundamentally due to the output current charging and discharging the load, the SR is limited by the bias current (or "drivability"). 2

(d) many students make no reference to any circuit specifics, e.g. ensuring transistors remain in saturation, bias currents, etc.

(e) $A_V(\text{O.L}) = 106\,dB = 10^{\left(\frac{106}{20}\right)} = 200{,}000$ 1

$A_V(\text{C.L}) = 200$

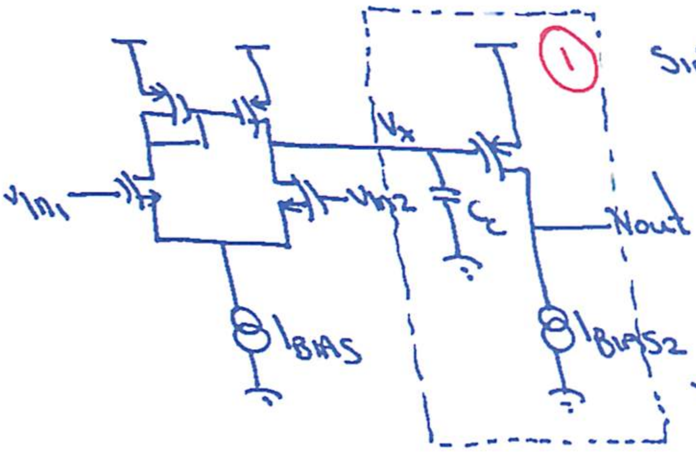


$$A_V(\text{CL}) = -\frac{R_1}{R_2}\left(1 - \frac{1}{A_0}\left(1 + \frac{R_1}{R_2}\right)\right) \quad 2$$

$$= -200\left(1 - \underbrace{\frac{1}{200000}(1+200)}_{\varepsilon \; 1}\right)$$

$\therefore \quad \varepsilon = 0.1005\%$ 1

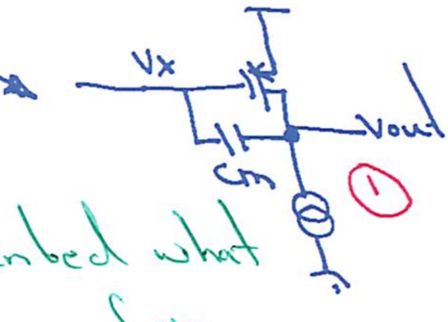
(f) The typical procedure to improve phase margin in op-amp design is to add a compensation capacitance such as to limit the bandwidth so sufficient phase margin is achieved. By exploiting the Miller effect this capacitor value 2



Since $\frac{V_{out}}{V_x} = A_{V2}$ (-ve amplification stage)

a floating capacitor placed across this will appear as:

$C_c = C_m(1 + |A_{V2}|)$ at the input 1

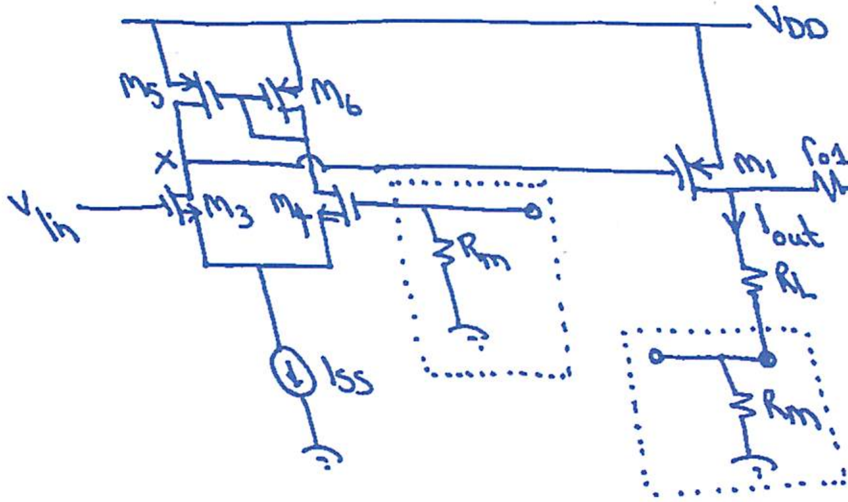


(f) Here most students simply described what Millers theorem is — without any reference to compensation design.

Q2- A NEW THEORETICAL APPLICATION

2 a (i) open loop gain → need to "break" the loop.

Students generally find this question hard



1

$$\boxed{A_{OL} = \frac{I_{out}}{V_{in}}}$$

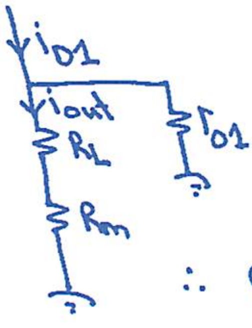
Many didn't get this

$$G_m\,(\text{open loop gain}) = \frac{I_{out}}{V_{in}} = \frac{V_x}{V_{in}} \cdot \frac{I_{out}}{V_x} \quad 1/2$$

$$\frac{V_x}{V_{in}} = -g_{m3}(r_{o3} \| r_{o5}) \quad 1$$

$$\frac{I_{out}}{V_x} = \frac{I_{out}}{I_{D1}} \times \frac{I_{D1}}{V_x} \quad 1/2$$

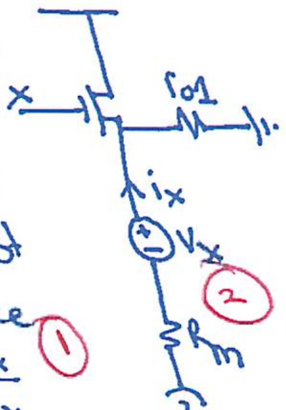
$$\frac{I_{D1}}{V_x} = g_{m1}$$



$$\frac{I_{out}}{I_{D1}} = \frac{r_{o1}}{r_{o1} + (R_L + R_m)} \quad 1$$

$$\therefore\ G_m = \frac{+g_{m1} g_{m3} r_{o1} (r_{o3} \| r_{o5})}{r_{o1} + R_L + R_m} \quad 1$$

(ii) $R_{out}(OL)$



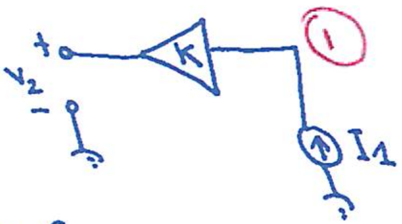
2

Need to replace R_L with a test voltage source 1 and $\therefore R_{out} = \frac{v_x}{i_x}$

$$\boxed{R_{out}(OL) = r_{o1} + R_m} \quad 2$$

Many students didn't understand how R_{out} of 2-terminal O/P (I_{out}) is determined.

(b) <u>feedback factor K</u>



$K = \frac{V_2}{I_1}$

$\therefore V_2 = I_{out} \cdot R_m$

$\therefore K = \frac{V_2}{I_{out}} = R_m$ 1

Error signal = i/p − feedback $= V_{in} - R_m I_{out} = \varepsilon$ 1

$\therefore \varepsilon = \frac{V_{in}}{1 + G_m \cdot K}$ 1 $= \frac{V_{in}}{1 + R_m G_m}$ 1

(c) Transconductance amplifier ∴ voltage in, current out.

∴ Ideally $R_{in} = \infty$

$R_{out} = \infty$

∴ −ve feedback will increase both R_{in} and R_{out}.

$\therefore R_{out} = (1 + \text{loopgain})\, R_{out}(OL)$

$= (1 + R_m G_m)(R_m + r_{o1})$

Very few got this point

(d) Loop gain $= (1 + R_m G_m)$ 1 So either R_m can be increased or $G_m(OL)$ 1

Ideally R_m should be kept small ∴ need to increase $G_m(OL)$ 1

$$G_m(OL) = \frac{g_{m1}\, g_{m3}\, r_{o1} (r_{o3} \| r_{o5})}{r_{o1} + R_L + R_m}$$

If bias current is increased eg. I_{SS}, this would increase g_{m1} but would also decrease r_{o3}, r_{o5}. 1

However can increase g_{m1} (and/or g_{m3}) by increasing its (W/L). 1

(e) R_m should ideally be kept small so majority of voltage drop is across the load. (2)

→ Given $V_{DD} = 10V$ and $I_{out} = 5mA$

However R_m also needs to provide sufficient bias voltage to sustain device M_4 in saturation. (1)

$\therefore V(R_m) > V_{GS}(sat)$

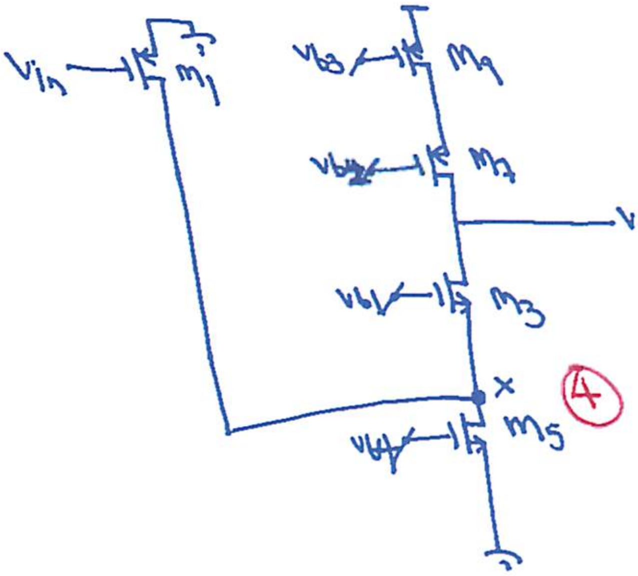
→ Lets design for $V(R_m) = 0.5V$ (1)

$\therefore R_m = \frac{0.5V}{5mA} = 100\,\Omega$ (1)

Mostly no Justification given

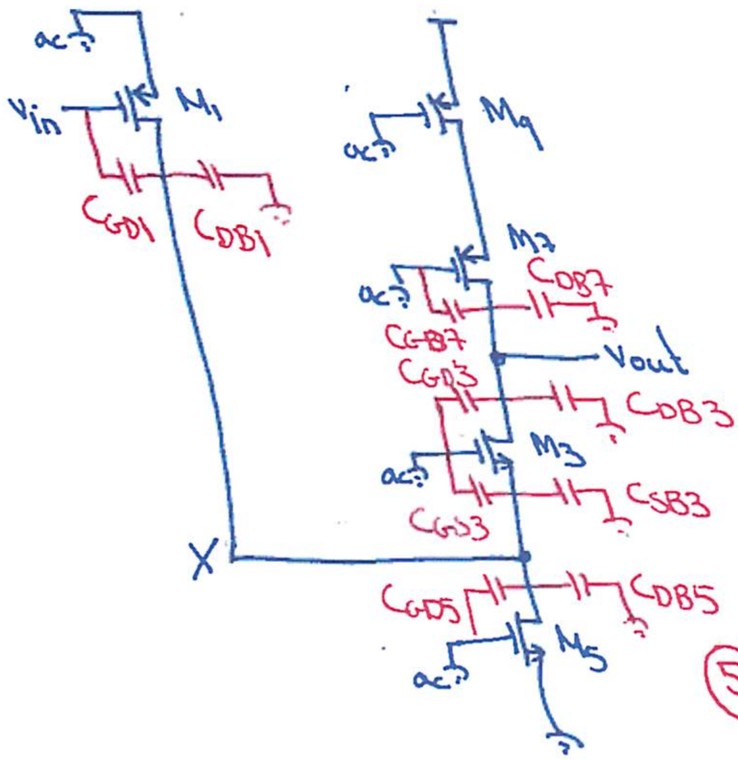
Q3 — CALCULATION FOR A NEW EXAMPLE

3 a (i) Assuming perfect symmetry, sources of diff. pair can be connected to AC. ground. 1



4 (−1/2 mark each mistake)

(ii) with parasitics associated with nodes X and Vout.



5 (−1/2 mark each mistake)

for (i) and (ii) OK as single diagram

✓ OK

(b) $A_v = -G_m R_{out}$

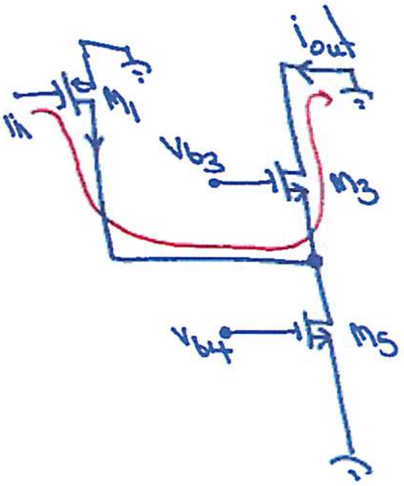
$R_{out} = R_{up} \| R_{down}$ $\quad R_{up} = g_{m7} r_{o7} r_{o9} + r_{o7} + r_{o9}$

$R_{down} = g_{m3} r_{o3} (r_{o5} \| r_{o1}) + r_{o3} + (r_{o5} \| r_{o1})$

generally missed this

$\therefore$ assuming $g_m r_o \gg 1$ 1

$R_{out} \approx g_{m7} r_{o7} r_{o9} \| g_{m3} r_{o3} (r_{o5} \| r_{o1})$ 1



$i_{out} = i_{d3}$

$i_{d3} + i_{d5} = i_{d1}$ (assuming $\frac{1}{g_{m3}} \ll r_{o5}$, then $i_{d3} \approx i_{d1}$) 1

$i_{d1} = v_{in} g_{m1}$

$\therefore \frac{i_{out}}{v_{in}} = G_m = g_{m1}$ 1

not all students got this assumption

$\therefore A_v = -g_{m1}\left[g_{m7} r_{o7} r_{o9} \| g_{m3} r_{o3} (r_{o1} \| r_{o5})\right]$ 1

(c) $g_m = \sqrt{2 \mu C_{ox} \frac{W}{L} I_D}$, $\quad r_o = \frac{1}{\lambda I_D}$ 1

$g_{m1} = \sqrt{2(200\mu)(200)\,200\mu} = 4\text{mS}$

$g_{m3} = \sqrt{2(200\mu)(1)\,250\mu} = 316\mu\text{S}$

$g_{m7} = \sqrt{2(100\mu)\left(\frac{5}{2}\right)250\mu} = 353\mu\text{S}$

$r_{o7} = \frac{1}{0.2(250\mu)} = 20\text{k}\Omega$

$r_{o1} = \frac{1}{0.2(200\mu)} = 25\text{k}\Omega$ 3

$r_{o3} = \frac{1}{0.1(250\mu)} = 40\text{k}\Omega$

$r_{o5} = \frac{1}{0.1(50\mu)} = 200\text{k}\Omega$

$r_{o9} = \frac{1}{0.2(250\mu)} = 20\text{k}\Omega$

$A_v = -4\text{m}\,(141.2\text{K} \| 280.9\text{K})$

$= -376$

$= 51.5\text{dB}$ 1

(d) $f_{px} = \dfrac{1}{2\pi R_x C_x}$ (1)

$f_{pout} = \dfrac{1}{2\pi R_{out} C_{out}}$ (1)

Since $C_{DB} = C_{SB} = \emptyset$

$C_x = C_{GD1}\left(1 + \dfrac{g_{m1}}{g_{m3}}\right) + \cancel{C_{DB1}} + C_{GD5} + \cancel{C_{DB5}} + C_{GS3} + \cancel{C_{SB3}}$ (1)

$R_x = r_{o1} \| r_{o5} \| \dfrac{1}{g_{m3}} \| r_{o3} \approx \dfrac{1}{g_{m3}}$ (assuming $g_m \ll r_o$) (1)

$100(0.2)\left(1 + \dfrac{1}{79}\right) = 20.3\text{fF}$

$4(0.2) = 0.8\text{fF}$

$\dfrac{2}{3}(12)(4) = 32\text{fF}$

$C_{out} = C_{GD7} + \cancel{C_{DB7}} + C_{GD3} + \cancel{C_{DB3}}$ (1)

R_{out} = as in (b).

(e) $C_x = \left[(0.2)100\left(1 + \dfrac{1}{79}\right) + (0.2)\left(\dfrac{4}{2}\right) + \dfrac{2}{3}(12)(2)(2)\right]\text{fF}$

$= 53\text{fF}$ (1)

$R_x = \dfrac{1}{g_{m3}} = \dfrac{1}{316\mu S} = 3.16\text{k}\Omega$ (1)

$R_{out} = 422\text{k}\Omega$ (from (c))

$C_{out} = 5(0.2) + 2(0.2) = 1.4\text{fF}$ (1)

$\therefore f_{px} = \dfrac{1}{2\pi(3.16\text{k})53\text{fF}} = 950\text{MHz}$ (1)

$f_{pout} = \dfrac{1}{2\pi(1.4\text{fF})(94\text{K})} = 1209\text{MHz}$ (1)

(Many numerical errors in calculation here)