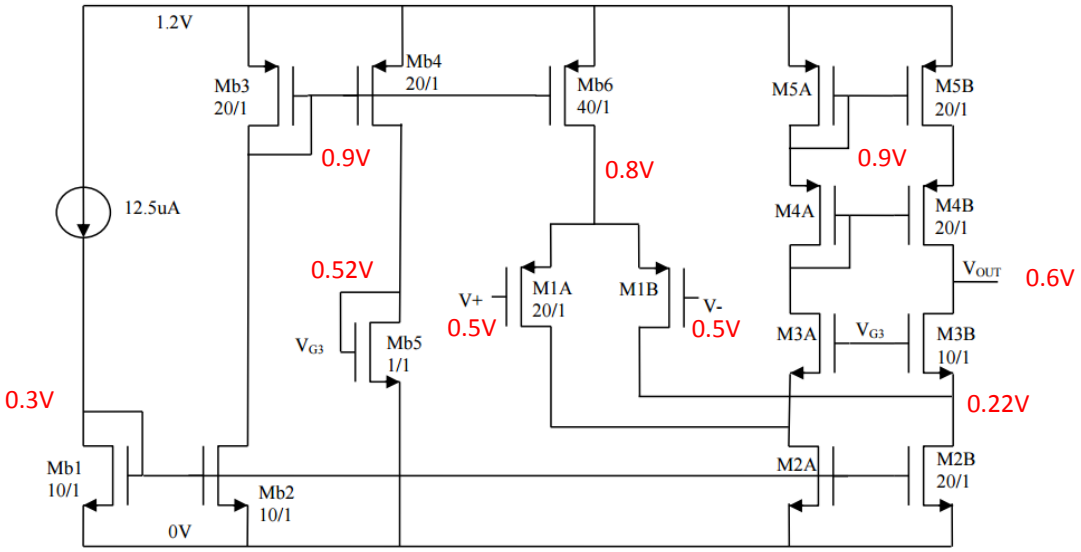
EE140 HW9 Solutions

1. For the PMOS-input folded cascode op-amp below, assume quadratic model and the following process specs $\mu_n C_{ox}=250\mu A/V^2$, $\mu_p C_{ox}=125\mu A/V^2$, $\lambda=1/(10V)$, $-V_{tp}=V_{tn}=0.2V$, $C_{ox}=5fF/um^2$, $C'_{ol}=0.5fF/um$.



a) i)

Transistor	Overdrive Voltage	Current
Mb1	100 mV	12.5 µA
Mb2	100 mV	12.5 µA
Mb3	100 mV	12.5 µA
Mb4	100 mV	12.5 µA
Mb5	320 mV	12.5 µA
Mb6	100 mV	25 µA
M1	100 mV	12.5 µA
M2	100 mV	25 µA
M3	100 mV	12.5 µA
M4	100 mV	12.5 µA
M5	100 mV	12.5 µA

a) ii) See annotations on schematic above.

a) iii)

Transistor	gm	ro
M1	250 µS	800 kΩ
M2	500 µS	400 kΩ
M3	250 µS	800 kΩ
M4	250 µS	800 kΩ
M5	250 µS	800 kΩ

b) Gm = gm1 = 250 µS
Ro: If λn=λp and Itail=Id2, then Ro = ¼ (gm ro) ro = ¼ (200) 800k = 40 MΩ
Av = Gm*Ro = 10,000 V/V

c) Input common mode range
Max = Vdd - Vov6 - Vov1 - Vtp = (1.2-0.1-0.1-0.2) = 0.8 V
Min = Vg3 – Vov3 – Vtn – Vtp = (0.32+0.2) – 0.1 – 0.2 – 0.2 = 20 mV (approximately ground)

Output swing
Max = Vdd – Vov5 – Vtp – Vov4 = (1.2-0.1-0.2-0.1) = 0.8 V
Min = Vg3 – Vov2 – Vtn + Vov3 = (0.32+0.2-0.1-0.2+0.1) = 0.32 V

d) Vg3_min = Vov2 + Vov3 + Vtn = 400 mV

New input common mode range
Max = Vdd - Vov6 - Vov1 - Vtp = (1.2-0.1-0.1-0.2) = 0.8 V (unchanged)
Min = Vg3 – Vov3 – Vtn – Vtp = 0.4 – 0.1 – 0.2 – 0.2 = -0.1 V

New output swing
Max = Vdd – Vov5 – Vtp – Vov4 = (1.2-0.1-0.2-0.1) = 0.8 V (unchanged)
Min = Vg3 – Vov2 – Vtn + Vov3 = (0.4-0.1-0.2+0.1) = 0.2 V

e) CL = 1 pF

i) Dominant pole at output = 1/(Ro * CL) = 25,000 rad/s

ii) Cgs5 = (2/3) W*L*Cox + Col*W ≈ 80 fF
$\omega_{p,mirror}$ = gm5/(2*Cgs5) = 250 µS / (160fF) ≈ 1.6 Grad/s
$\omega_{z,mirror}$ = gm5/(Cgs5) = 250 µS / (80fF) ≈ 3.2 Grad/s

iii) Cgs5 = (2/3) W*L*Cox + Col*W ≈ 40 fF
$\omega_{p,cascode}$ = gm3/Cgs3 = 250 µS / (40fF) ≈ 6.3 Grad/s

iv) ω_u = gm1/CL = 250 µS / (1pF) = 250 Mrad/s

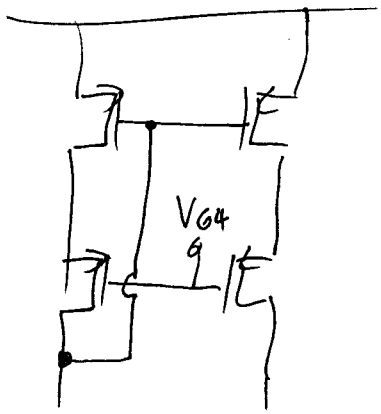
v) $$PM = 180 - \text{atan}\left(\frac{\omega_u}{\omega_{P1}}\right) - \text{atan}\left(\frac{\omega_u}{\omega_{p,mirror}}\right) + \text{atan}\left(\frac{\omega_u}{\omega_{z,mirror}}\right) - \text{atan}\left(\frac{\omega_u}{\omega_{p,cascode}}\right)$$

PM = 180 – 90 – 9 + 4 – 2 = 83 degrees
Close enough to approximate as a one pole amplifier.

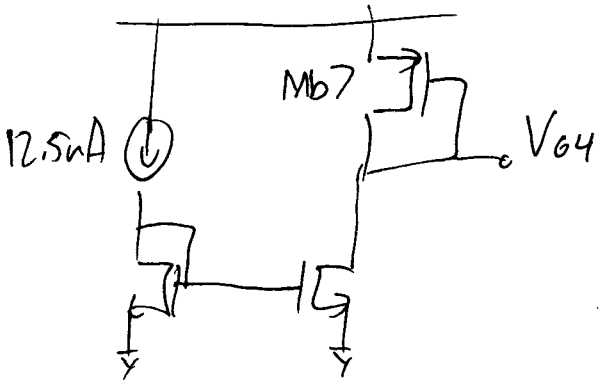
Rubric for Problem 1:

#1) 31 pts
a) i) 5 pts for correctly filled out table
a) ii) 4 pts - 1/2 pt each for the 8 voltages listed
a) iii) 4 pts for correctly filled out table
b) 3 pts, 1 each for Gm,Ro,Av
c) 4 pts, 1 each for input max/min, and output max/min
d) 5 pts, 1 for Vg3_min and 1 each for input max/min, and output max/min
e) i) 1 pt
e) ii) 2 pts, 1 for pole, 1 for zero
e) iii) 1 pt
e) iv) 1 pt
e) v) 1 pt for PM approximately 90

(2) a)



b)



Use the existing 12.5uA source to mirror a current over to M67

Want $V_{SG4} = V_{DD} - V_{OV5}$ & $V_{G4} = V_{DD} - V_{OV5} - V_{tp} - V_{OV4}$

To get 2x V_{OV} for M67, size it to be $\frac{1}{4}\left(\frac{W}{L}\right)_4$ and leave the others the same size.

#2) 6 pts
a) 2 pts for correctly redrawing
b)
2 pts for drawing bias circuit
1 pt for what gate voltage to bias it with
1 pt for dimensions and why

(3) a) The second stage gain is inverting so this is still negative feedback,

b) $f = \frac{R_2}{R_1 + R_2}$

$$V_{out} = \frac{A}{1+Af} V_{in} \approx \frac{R_1+R_2}{R_2} V_{in} \quad \text{for large } A$$

c) $A = A_v\, g_m (R_L // r_o // (R_1 + R_2))$

$$T = Af = A_v\, g_m \frac{(R_L // r_o) \cdot R_2}{R_1 + R_2 + R_L // r_o}$$

#3) 5 pts
a) 1 pt for second stage is inverting; negative feedback
b) 2 pts; 1 pt for f, 1 for Vout
c) 2 pts for writing an expression for loop gain

(4) a) Gain is $\frac{C_1}{C_2}$ so integer ratios from 1-8

b) $A_V = 8$ because it has the smallest feedback factor ($f = 1/9$) and gain error is $\frac{-1}{Af}$

c) $\frac{1}{Af} = 0.4\%$ $\quad A \geq \frac{1}{\left(\frac{1}{9}\right)(0.004)}$ $\quad A \geq 2250\ V/V$

d) Need about 6τ to get to $<0.4\%$

$6\tau = 10\,\mu s \quad \tau = 5/3\ \mu s$

Amp will be the slowest at highest gain setting

$GB = \frac{1}{f} \cdot \frac{1}{\tau} = \frac{9}{5/3\ \mu s}$ $\quad GB \geq 5.4\ 10^6\ rad/s$

#4) 4 pts
a) 1 pt for ratios of 1-8
b) 1 pt for identifying gain of 8 as f=1/9
c) 1 pt for calculating Ao
d) 1 pt for calculating bandwidth

(5) a) compares at ground

b) No. If $V_{in} > V_{ref}/2$ then $V+$ swings below ground.

#5) 2 pts
a) 1 pt for bottom rail
b) 1 pt for it swings below bottom rail

(240A only) #6) 6 pts
a) 2 pts
b) 4 pts