FINAL EXAM, SEMESTER 1 2012/2013

Answer: Question 1

(a)

$$I_o R_E = V_T \ln\left(\frac{I_{REF}}{I_o}\right)$$ 0.5

$$I_{REF} = I_o e^{\frac{I_o R_E}{V_T}} = (20\mu)(e^{(20\mu)(4.2\text{k})/0.026} = 0.506\text{ mA}$$ 2

$$V_{BE1} = V_T \ln\left(\frac{I_{REF}}{I_{S1}}\right) = 0.026\ln\left(\frac{0.506\text{m}}{4x10^{-15}}\right) = 0.6646\text{ V}$$ 1.5

0.5

$$I_{REF} R_1 = V^+ - V_{BE1}$$

$$R_1 = \frac{V^+ - V_{BE1}}{I_{REF}} = \frac{10 - 0.6646}{0.506\text{m}} = 18.45\text{ k}\Omega$$ 1.5

$$V_{BE2} = V_{BE1} - I_O R_E = 0.6646 - (20\mu)(4.2\text{k}) = 0.5806\text{ V}$$ 2

(b)

At $I_O = I_{REF}$:

$$V_{GS2} = V_{GS1} = V_{DS1} \Rightarrow V_{DS1} = V_{DS2}$$ 0.5

$$V_{GS3} = V_{DS3} = V_{GS1}$$

$$\Rightarrow V_{DS4} = V_{DS3} = V_{DS2}$$ 1

$$V_{D4} = V^- + V_{DS2} + V_{DS4} = -5 + 1.8 + 1.8 = -1.4\text{ V}$$ 1.5

$$dV_{D4} = 2.5 - (-1.4) = 3.9\text{ V}$$ 1

$$r_{O4} = r_{O2} = \frac{1}{\lambda I_O} = \frac{1}{(0.025)(200\mu)} = 200\text{ k}\Omega$$ 1

$$dI_O = \frac{dV_{D4}}{R_O} = \frac{(dV_{D4})}{(g_m r_{O4} r_{O2})} = \frac{(3.9)}{(300\mu)(200\text{k})(200\text{k})} = 0.325\,\mu\text{A}$$ 1.5

$$I_{O(new)} = I_O + dI_O = (200 + 0.325)\mu\text{A} = 200.325\,\mu\text{A}$$ 1.5

Answer: Question 2

(a)

i) Calculate the one-sided small-signal differential voltage gain (A_d) of the differential amplifier. [1.5 marks]

$$A_d = \frac{g_m R_C}{2} \quad \boxed{0.5}$$

$$g_m = \frac{I_C}{V_T} = \frac{I_Q}{2V_T} = \frac{2\text{m}}{2(26\text{m})} = 38.46\ \text{mA/V} \quad \boxed{0.5}$$

$$A_d = \frac{(38.46\text{m})(5\text{k})}{2} = 96.15 \quad \boxed{0.5}$$

ii) The constant current source of Figure 1 that is providing the current I_Q is implemented using the basic two transistor current source. Find the value of A_{cm} , the common-mode voltage gain of the differential-amplifier, with equation given below. Assume R_B = 0. [2 marks]

$$R_O(2\text{TCS}) = r_O = \frac{V_A}{I_Q} = \frac{100}{2\text{m}} = 50\ \text{k}\Omega \quad \boxed{1}$$

$$r_\pi = \frac{\beta V_T}{I_C} = \frac{100(26\text{m})}{1\text{m}} = 2.6\ \text{k}\Omega \quad \boxed{0.5}$$

$$A_{cm} = -49.5\text{x}10^{-3} \quad \boxed{0.5}$$

iii) The input voltages for the differential amplifier are v_{B1} = 210 x 10^{-6} sin ωt V and v_{B2} = 190 x 10^{-6} sin ωt V. Calculate the output voltage of the differential amplifier, taking into account the effect of the non-ideal current source. Use values from previous calculations. What is the output voltage if an ideal current source is used instead? Justify your answer. [4 marks]

$$V_O = A_d V_d + A_{cm} V_{cm} \quad \boxed{1}$$

$$V_d = v_{B1} - v_{B2} = (210x10^{-6} - 190x10^{-6})\sin\omega t\ \text{V} = 20x10^{-6}\sin\omega t\ \text{V} \quad \boxed{0.5}$$

$$V_{cm} = (v_{B1} + v_{B2})/2 = [(210x10^{-6} + 190x10^{-6})\sin\omega t\ \text{V}]/2 = 200x10^{-6}\sin\omega t\ \text{V} \quad \boxed{0.5}$$

$$V_O = [(96.15)(20x10^{-6}) + (-49.5x10^{-3})(200x10^{-6})]\sin\omega t\ \text{V} = 1.914x10^{-3}\sin\omega t\ \text{V} \quad \boxed{0.5}$$

For Ideal current source, its *Ro* is infinite, hence *Acm* is zero [0.5 mark]

Thus, *Vo = AdVd* [0.5 mark]

Vo = (96.15)(20 x 10^{-6}) sin ωt V = 1.923x10^{-3} sin ωt V [0.5 mark]

iv) Calculate the value of Vcm (max) of this differential amplifier. [4.5 marks]

	Vcm(max)	= VB when Q1, Q2 almost entering saturation mode,	
i.e.	VCE	= VCE(sat) = 0.3V	[0.5 mark]
	VCE	= VC - VE	[0.5 mark]
	VC	= V^+ - ICRC = 15-(1m)(5k) = 10V	[1 mark]
	VE	= VB - VBE(on) = VB - 0.7V	[1 mark]
	VCE(sat)	= 0.3V = 10 - (Vcm(max) - 0.7)	[1 mark]
	Vcm(max)	= 10.7 - 0.3 = 10.4V	[0.5 mark]

Answer: Question 2

(b)

i) Determine the relationship between I_O and I_Q such that the amplifier dc currents are balanced. [3 marks]

ii) Calculate the value of I_O given that I_Q = 0.2 mA and β =100. [1 mark]

$$I_{B5} = \frac{I_{E5}}{(1+\beta)} = \frac{I_{B3}+I_{B4}}{(1+\beta)} = \frac{I_{C3}+I_{C4}}{\beta(1+\beta)}$$ [1mark]

The current $I_{C3} + I_{C4} \cong I_Q$ [0.5 mark]

$$\left. \begin{aligned} I_{C1} &= I_{C3} + I_{B5} \\ I_{C1} &= I_{C4} + I_O \end{aligned} \right\}$$ [0.5 mark]

Hence, to keep the current balanced: $I_O = I_{B5} = \dfrac{I_Q}{\beta(1+\beta)}$ [1mark]

Given, I_Q = 0.2 mA, hence:

$$I_O = \frac{0.2\text{ m}}{100(1+100)} = 19.8\text{ nA}$$ [1 mark]

Answer: Question 3

(a) $V_{GS5} = V_{GS7}$ {Identical transistors} [0.5]
$V_{GS5} + V_{GS7} = 2\ V_{GS5} = V^+ - V^- = 10 - (-10) = 20$ V [0.5]
$V_{GS5} = 10\text{V} = V_{GS7}$ [0.5]
$I_1 = K_n\,(V_{GS5} - V_{TN})^2 = K_n\,(V_{GS7} - V_{TN})^2$ [1]
$I_1 = (0.2\text{m})(10\text{-}2)^2 = 12.8$ mA [0.5]
$I_Q = I_1 = 12.8$ mA [1]
$I_{D1} = ½\ I_Q = 6.4$ mA [1]

(b) $v_o = (g_m)v_d\,(r_{o2} \,||\, r_{o4} \,||\, R_L)$ therefore $A_d = (g_m)(r_{o2} \,||\, r_{o4} \,||\, R_L)$ [1.5]

$g_m = 2\sqrt{(K_n\, I_{D1})} = 2\sqrt{[(0.2\text{m})(6.4\text{m})]} = 2.26$ mA/V [1]

$r_{o2} = 1/(\lambda_n\, I_{D1}) = 1/(0.02)(6.4\text{m}) = 7.812$ kΩ [1]
$r_{o4} = 1/(\lambda_p\, I_{D1}) = 1/(0.015)(6.4\text{m}) = 10.417$ kΩ [1]
$(r_{o2} \,||\, r_{o4} \,||\, R_L) = (7.812\text{k})||(10.417\text{k})||(100\text{k}) = 4.273$ kΩ [0.5]

$A_d = (2.26$ mA/V) x (4.273 kΩ) = 9.668 [1]

(c) $CMRR = 20 \log\,[A_d\,/\,A_{cm}] = 60$ dB [1, 0.5]
$A_{cm} = A_d\,/\,[10^{60/20}] = 9.668\text{x}10^{-3}$ [1, 0.5]

(d) Select two answers:
Increase the current source output resistance. [1]
Increase the diff amp output resistance by using cascode active loads. [1]
Reduce the loading effect by increasing load resistance, R_L. [1]

Answer: Question 4

(a) Q3 and Q4 are lateral pnp devices which provide additional protection against voltage breakdown. This is because the breakdown voltage of a lateral pnp B-E junctions is a lot higher than the reverse biased npn B-E junction.

2

(b)

$$I_{C10} = I_S e^{\frac{V_{BE10}}{V_T}}$$ 0.5

$$V_{BE10} = V_T \ln\left(\frac{I_{C10}}{I_S}\right) = 0.026 \ln\left(\frac{10\mu}{1x10^{-14}}\right) = 0.5388\ \text{V}$$ 1.5

$$I_{C10}R_4 = V_{BE11} - V_{BE10}$$ 0.5

$$R_4 = \frac{V_{BE11} - V_{BE10}}{I_{C10}} = \frac{0.6 - 0.5388}{10\mu} = 6.12\ \text{k}\Omega$$ 1.5

(c)

$$r_{\pi 6} = \frac{\beta V_T}{I_{C6}} = \frac{200(0.026)}{5\mu} = 1.04\ \text{M}\Omega$$ 2

(d)

$$R_O = r_{O4} \| R_{act1}$$ 1

$$r_{O4} = \frac{V_A}{I_{C4}} = \frac{50}{5\mu} = 10\ \text{M}\Omega$$ 1.5

$$R_{act1} = r_{O6}\left[1 + g_{m6}(R_2 \| r_{\pi 6})\right]$$ 1

$$r_{O6} = r_{O4} = \frac{V_A}{I_{C6}} = \frac{50}{5\mu} = 10\ \text{M}\Omega$$ 1

$$r_{\pi 6} = 1.040\ \text{M}\Omega$$ 0.5

$$g_{m6} = \frac{I_{C6}}{V_T} = \frac{5\mu}{0.026} = 0.1923\ \text{mA/V}^2$$ 1

$$R_{act1} = 10M\,[1 + (0.1923\text{m})(1\text{k})] = 10.92\ \text{M}\Omega$$ 1

$$R_O = 10\text{M} \| 10.92\text{M} = 5.220\ \text{M}\Omega$$ 1

Answer: Question 5

a) State the main disadvantage of both Class A and Class B output stages. Comment on the power conversion efficiency of both output stages. [2 marks]

Disadvantage of class A is that the power conversion efficiency is low, [0.5 mark]
the maximum attainable efficiency is only 25% [0.5 mark]

The disadvantage of Class B is that it suffers from cross-over distortion [0.5 mark]
although the efficiency can be up to 78.5% [0.5 mark]

b) .

i) Find the minimum required I_Q and the value of R. [4 marks]

IQmin = |most negative IL| = |vomin/RL| [1 mark]
= |-8V/1kΩ| = 8 mA [1 mark]

R =(V+ - VBE3(on) - V-) / IQ [1 mark]
=(10 - 0.7 - (-10))/8m = 2.41 kΩ [1 mark]

ii) For $v_o = 0$, find the power dissipated in the transistor Q_1, and the power dissipated in the current source (Q_2, Q_3, and R). [5 marks]

PQ1 = (IC1)(VCE1) [1 mark]
= (IQ)(VC1-VE1) = (8m)(10-0) = 80 mW [1 mark]

PQ2 = (IC2)(VCE2)
= (IQ)(VC2-VE2) = (8m)(0--10) = 80 mW [1 mark]

PQ3 = (IC3)(VCE3)
= (IQ)(VBEon) = (8m)(0.7) = 5.6 mW [1 mark]

PResistor = $(I)^2(R)$ [0.5 mark]
= $(8m)^2(2.41k)$ = 0.154 mW [0.5 mark]

iii) Determine the conversion efficiency for a symmetric sine-wave output voltage with peak value of 8V. [5 marks]

Power conversion efficiency = PL/PS x 100% [1 mark]
PL = $0.5(Vp)^2/RL$ [1 mark]
= $0.5(8)^2/(1k)$ = 32 mW [0.5 mark]
PS = $(V^+-(V^-))(2IQ)$ [1 mark]
= (20)(2x8m) = 320 mW [0.5 mark]
Efficiency = 32m/320mx100% = 10% [1 mark]

Answer: Question 6

(a) .

v_O	$= (1+R_2/R_1)v_2$	[1]
v_2	$= [R_4/(R_3+R_4)]v_I$	[1]
v_O	$= (1+R_2/R_1)\ [R_4/(R_3+R_4)]v_I$	[1]
A_v	$= v_O/v_I \quad = (1+R_2/R_1)\ [R_4/(R_3+R_4)]$	[1]
	$= [1+(200k/25k)][50k/(50k+25k)] = (9)(2/3) = 6$	[1]

(b) .

v_O	$= (-R_4/R_3)v_{O1}$	[1]
v_{O1}	$= (-R_2/R_1)v_I$	[1]
v_O	$= (-R_4/R_3)(-R_2/R_1)v_I$	[1]
	$= [(-60k/150k)(-100k/20k)(0.12)] = 0.24$ V	[1]

(c) .

(i) Difference amplifier [1]

(ii) $R_3 = R_4 = 100$ kΩ

$$A_v = \frac{R_4}{R_3}\left(1+\frac{2R_2}{R_1+R_{1POT}}\right) = \frac{100k}{100k}\left(1+\frac{2R_2}{R_1+R_{1POT}}\right) = \left(1+\frac{2R_2}{R_1+R_{1POT}}\right)$$

[1]

A_v is maximum (i.e. $A_v = 100$) when $R_{1POT} = 0$, i.e.

$$100 = \left(1+\frac{2R_2}{R_1+0}\right)$$ [1]

$99\ R_1 = 2\ R_2$ {Eqn 1} [0.5]

A_v is minimum (i.e. $A_v = 10$) when $R_{1POT} = 100$ kΩ, i.e.

$$10 = \left(1+\frac{2R_2}{R_1+100k}\right)$$ [1]

$9(R_1 + 100\text{k}) = 2\ R_2$ {Eqn 2} [0.5]

{Eqn 1} = {Eqn 2}

$99\ R_1 = 9\ R_1 + 900$k [1]

➔ $R_1 = 10$ kΩ [1]

➔ $R_2 = (\ 99\ R_1\ ) / 2 = 495$ kΩ [1]

(iii) $v_{I1} = 1.00$ V, $v_{I2} = 1.15$ V, $R_4 = 2\ R_3$, $R_{1POT} = 40$ kΩ, $R_1 = 10$ kΩ, $R_2 = 496$ kΩ,

$$A_v = \frac{R_4}{R_3}\left(1+\frac{2R_2}{R_1+R_{1POT}}\right) = \frac{2R_3}{R_3}\left(1+\frac{2(495k)}{10k+40k}\right) = 41.6$$ [1.5]

$$v_O = A_v(v_{I2}-v_{I1}) = (41.6)(1.15-1.00) = 6.24\text{V}$$ [1.5]