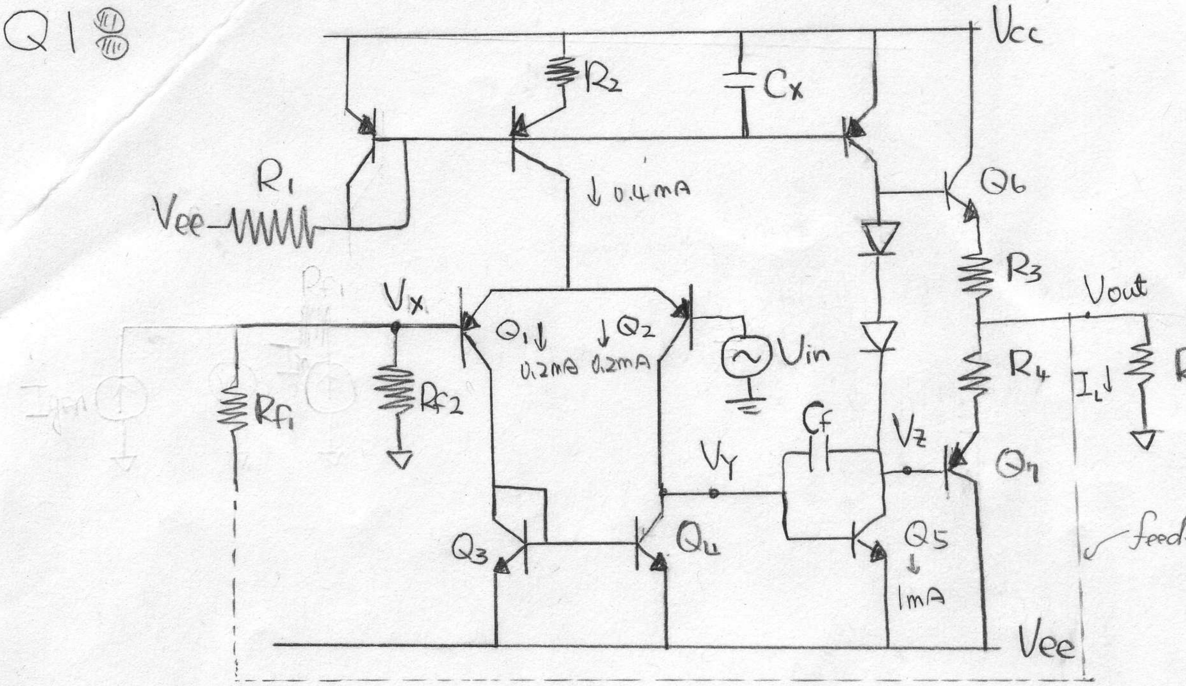
Q1



$V_{cc} = +3.3\,(V)$

$V_{ee} = -3.3\,(V)$

$C_x = \infty$

$R_L = 10\,(K\Omega)$

$R_{f1} = 9\,(K\Omega)$

$R_{f2} = 1\,(K\Omega)$

Transistor parameters are listed in the table below

	I_C (mA)	β	V_A (V)	g_m (mS)	C_{cb} (pF)	τ_F (ns)	*1 C_{be} (pF)	*2 f_T (MHz)
Q_1	0.2	∞	∞	7.7	3	0.5	3.85	178.65
Q_2	0.2	∞	∞	7.7	3	0.5	3.85	178.65
Q_3	0.2	∞	∞	7.7	3	0.5	3.85	178.65
Q_4	0.2	∞	100	7.7	3	0.5	3.85	178.65
Q_5	1	∞	100	38.5	3	0.5	19.25	275.09
Q_6	0.2	∞	∞	7.7	100	20	154	4.82
Q_7	0.2	∞	∞	7.7	100	20	154	4.82

*1 $C_{be} = g_m \tau_F + C_{je}$. Since C_{je} is not given, we assume $C_{je} = 0\,(F)$

*2 $f_T = \dfrac{0.159 \cdot g_m}{C_{be} + C_{cb}}$

(iii) Feedback Network Loading to the amplifier

Feedback network loaded on input node is $\underline{R_{f1} \,//\, R_{f2}}$

Feedback network loaded on output node is $\underline{R_{f1} + R_{f2}}$

(a) DC bias condition

• R_1

$\because I_c @ Q_5 = 1mA$

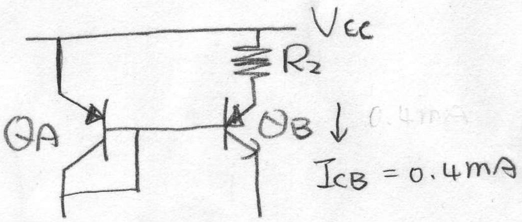
$\therefore$ Current following through R_1 is also $1mA$

$$\therefore \quad 1mA = \frac{V_{cc} - V_{be} - V_{ee}}{R_1}$$

$$\Rightarrow \quad R_1 = \frac{3.3(V) - 0.7(V) - (-3.3(V))}{1\,mA} = \underline{5.9\,(k\Omega)}$$

• R_2

Consider the upper left 2 pnp (Current mirrors) drawn below



$$V_{be} = \frac{KT}{q} \ln\left(\frac{I_c}{I_s}\right)$$

$$\therefore \quad V_{be,QA} = V_{be,QB} + R_2 I_{CB}$$

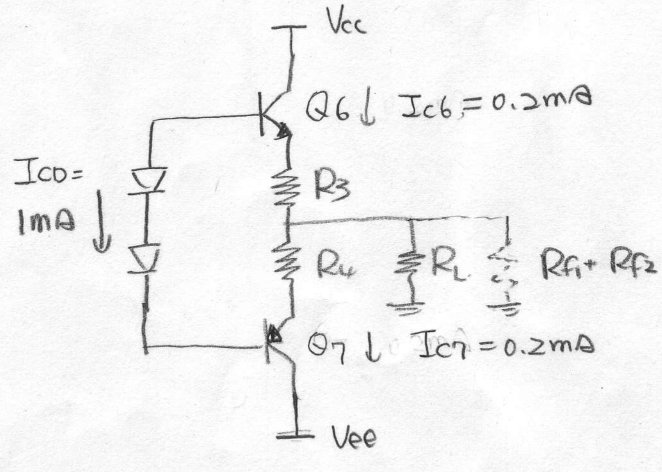
$$\Rightarrow \frac{KT}{q} \ln \frac{I_{CA}}{I_s} = \frac{KT}{q} \ln \frac{I_{CB}}{I_s} + R_2 I_{CB} \quad [\text{ all BJTs have the same } I_s]$$

$$\Rightarrow R_2 = \frac{KT}{q} \cdot \ln \frac{I_{CA}}{I_{CB}} \Big/ I_{CB} = 26(mV) \cdot \ln\left(\frac{1(mA)}{0.4(mA)}\right) \Big/ 0.4(mA)$$

$$\approx \underline{60\,(\Omega)}$$

• R_3, R_4

Consider the voltage drop across two diodes shown in the right figure.



$$V_D = V_{be,Q6} + I_{c6} \cdot R_3 + I_{c7} \cdot R_4 + V_{be,Q7}$$

assume $V_{be,Q6} = V_{be,Q7}$, and $R_3 = R_4$

$$\therefore \quad 2 \cdot \left(\frac{KT}{q} \cdot \ln\left(\frac{I_{CD}}{I_s}\right)\right) = 2\left(\frac{KT}{q} \cdot \ln\left(\frac{I_{c6}}{I_s}\right)\right) + 2 \cdot I_{c6} \cdot R_3$$

$$\Rightarrow \underset{(R_4)}{R_3} = \frac{KT}{q} \ln\left(\frac{I_{CD}}{I_{c6}}\right) \Big/ I_{c6} = 26(mV) \cdot \ln\left(\frac{1(mA)}{0.2(mA)}\right) \Big/ 0.2(mA) = \underline{209\,(\Omega)}$$

(ii) R_{ce4}, R_{ce5}

$$R_{ce4} = \frac{V_{be,Q5} + V_A}{I_{c4}} = \frac{0.7(V) + 100(V)}{0.2(mA)} = \underline{503.5(k\Omega)}$$

at steady-state condition, $I_{c6} = I_{c7} = 0.2(mA)$

$\therefore I_L = 0(mA) \Rightarrow V_{out} = 0(V)$

$$\therefore V_{CE5} = V_{out} - I_{c7} \cdot R_4 - V_{be,Q7} - V_{ee}$$

$$= 0(V) - 0.2(mA) \cdot 209(\Omega) - 0.7(V) + 3.3(V)$$

$$= 2.56(V)$$

$$\therefore R_{ce5} = \frac{V_{ce5} + V_A}{I_{c5}} = \frac{2.56(V) + 100(V)}{1(mA)} = \underline{102.56(k\Omega)}$$

(iii) Open-loop Gain [Mid-band]

refer to the notations in the schematic (page 1)

1.
$$\frac{V_{out}}{V_Z} = \frac{R_L // (R_{f1}+R_{f2})}{1/g_{m7} + R_4 + R_L//(R_{f1}+R_{f2})} = \frac{5(k\Omega)}{1/7.7\times10^{-3}(S) + 209(\Omega) + 5(k\Omega)} \approx 0.94$$

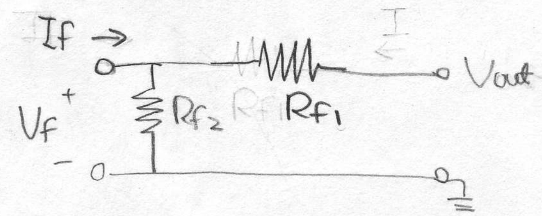
2.
$$\frac{V_Z}{V_Y} = -g_{m5}R_{ce5} \approx -38.5(mS) \cdot 102.56(k\Omega) = -3949$$

3.
$$\frac{V_Y}{V_{in}} = -g_{m1} \cdot R_{ce4} = -7.7(mS) \cdot 503.5(k\Omega) \approx -3877$$

The open-loop gain $\frac{V_{out}}{V_{in}} = 0.94 \cdot (-3949) \cdot (-3877) = 1.44\times10^7$

(iiii) Closed-loop Gain.

Feedback Network



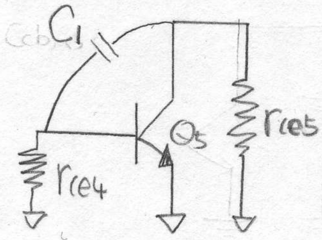
$$\beta = \left.\frac{V_f}{V_{out}}\right|_{I_f=0} = \frac{R_{f2}}{R_{f1}+R_{f2}} = \frac{1}{10}$$

$$\therefore\ T = A\beta = (1.44\times10^7)\cdot\left(\frac{1}{10}\right) = 1.44\times10^6$$

(iiii) C_f

Assume the dominate pole is located at collector-base junction of Q5

By MOTC



$$a_1 = C_1 R_{11}^o = (C_f + C_{cb5})\cdot R_{11}^o \quad \text{——} ①$$

$C_1 = C_f + C_{cb5}$

$$R_{11}^o = r_{ce4}\cdot[1-(-g_{m5}r_{ce5})] + r_{ce5}$$

$$= 503.5(k\Omega)\cdot[1+3949] + 102.56(k\Omega)$$

$$\doteqdot \underline{1.984(G\Omega)}$$

also, $a_1 = \dfrac{0.159}{f_{p,OL}}$, $f_{p,OL} = \dfrac{f_{p,CL}}{1+T}$,

$f_{p,OL}$: open-loop BW.

$f_{p,CL}$: closed-loop BW.

$$\therefore\ a_1 = \frac{0.159\times(1+T)}{f_{p,CL}} \quad \text{——} ②$$

by solving ① and ②

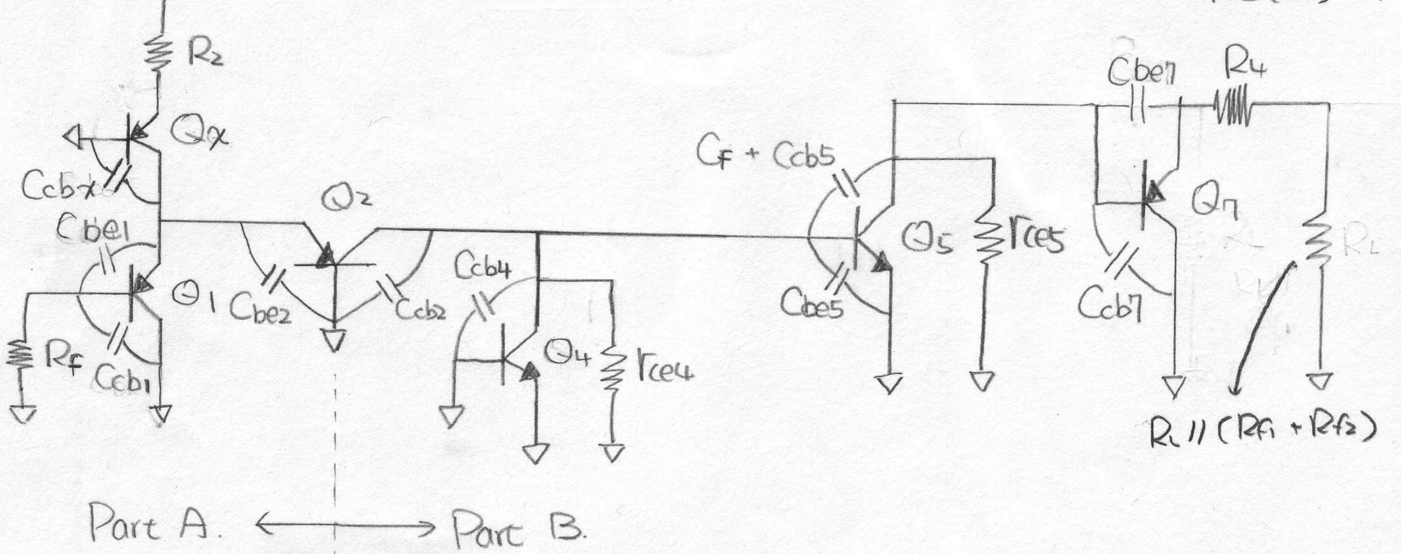
$$C_f = \frac{0.159\times(1+T)}{R_{11}^o\cdot f_{p,CL}} - C_{cb,Q5}$$

$$= \frac{0.159\times(1+1.44\times10^6)}{1.984(G\Omega)\cdot 2(MHz)} - 3(pF) \approx \underline{55(pF)}$$

(b) High Frequency Analysis

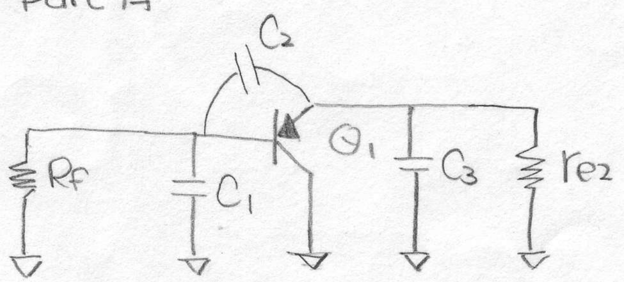
Redraw the schematic as following.

$$R_F = R_{F1} // R_{F2} = 9(k\Omega) // 1(k\Omega)$$
$$= 900(\Omega)$$



Due to the common-base stage (Q_2), we may separate the circuit into two parts to analyze. (Part A, Part B)

(i) Part A



$C_1 = C_{cb1}$

$C_2 = C_{be1}$

$C_3 = C_{cbx} + C_{be2}$

$$a_1 = C_1 R_{11}^{0} + C_2 R_{22}^{0} + C_3 R_{33}^{0}$$

$$= C_1 \cdot R_F + C_2 \cdot \left[R_F \cdot \left(1 - \frac{r_{e2}}{r_{e1} + r_{e2}}\right) + r_{e1} // r_{e2} \right] + C_3 \left(r_{e1} // r_{e2} \right)$$

$$= 3(pF) \cdot 900(\Omega) + 3.85(pF) \cdot \left[900(\Omega)\left(1 - \frac{1}{2}\right) + \frac{0.5}{7.7(mS)} \right]$$

$$+ 6.85(pF) \cdot \frac{0.5}{7.7(mS)}$$

$$\approx \underline{5.45 (nSec)}$$

$$a_2 = R_{11}^0 C_1 C_2 R_{22}^1 + R_{11}^0 C_1 C_3 R_{33}^1 + R_{22}^0 C_2 C_3 R_{33}^2$$

$$= R_f \cdot (r_{e1} // r_{e2}) \cdot [C_1C_2 + C_1C_3 + C_2C_3]$$

$$= 900(\Omega) \cdot \left(\frac{0.5}{7.7(mS)}\right) \cdot [3(pF) \cdot 3.85(pF) + 3(pF) \cdot 6.85(pF) + 3.85(pF) \cdot 6.85(pF)]$$

$$= \underline{3.42\,(nSec)^2}$$

examine $\frac{a_2}{a_1} = 0.628(nSec) << a_1 = 5.45(nSec)$

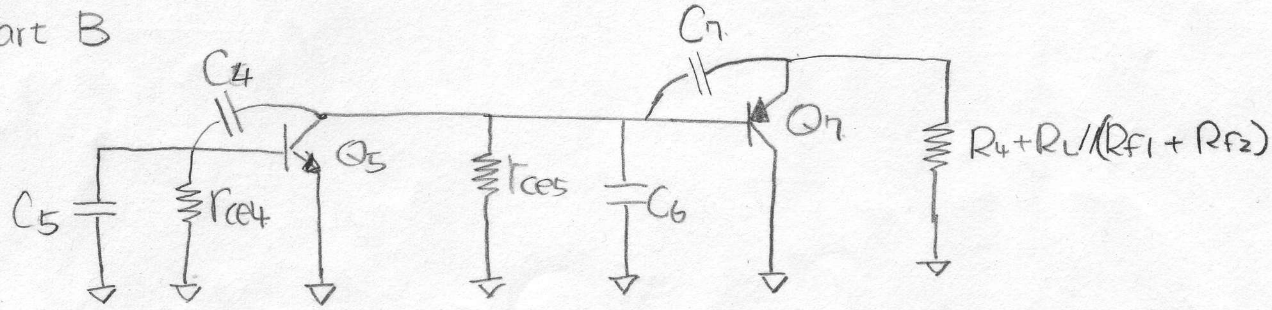
↳ 8 times

we may estimate the poles by separation pole approximation.

$$f_{p1} = \frac{0.159}{a_1} \simeq \underline{29.2\,(MHz)}$$

$$f_{p2} = \frac{0.159}{a_2/a_1} \simeq \underline{253.2\,(MHz)}$$

(1A) Part B



$C_4 = C_f + C_{cb5} = 58\,(pF)$

$C_5 = C_{cb2} + C_{cb4} + C_{be5} = 25.25\,(pF)$

$C_6 = C_{cb7} = 3\,(pF)$

$C_7 = C_{be7} = 154\,(pF)$

- From the description of the question, we know $C_4 R_{44}^0$ is very big.

$$a_1 = C_4 R_{44}^0 + \cancel{C_5 R_{55}^0} + \cancel{C_6 R_{66}^0} + \cancel{C_7 R_{77}^0} \approx C_4 R_{44}^0$$

$$= 58(pF) \cdot [503.5(k\Omega) \cdot (1 + 3949) + 102.56(k\Omega)] = 0.115\,(Sec)$$

too small

$$a_2 = \begin{bmatrix} C_4 R_{44}^{0}\, C_5 R_{55}^{4} \\ + \\ C_4 R_{44}^{0}\, C_6 R_{66}^{4} \\ + \\ C_4 R_{44}^{0}\, C_7 R_{77}^{4} \end{bmatrix} + \begin{bmatrix} C_5 R_{55}^{0}\, C_6 R_{66}^{5} \\ + \\ C_5 R_{55}^{0}\, C_7 R_{77}^{5} \end{bmatrix} + \begin{bmatrix} C_6 R_{66}^{0}\, C_7 R_{77}^{6} \end{bmatrix}$$

too small

$$\approx C_4 R_{44}^{0} \left[C_5 R_{55}^{4} + C_6 R_{66}^{4} + C_7 R_{77}^{4} \right]$$

$$\therefore \frac{a_2}{a_1} = C_5 R_{55}^{4} + C_6 R_{66}^{4} + C_7 R_{77}^{4}$$

$$= 25.25(pF) \cdot 26(\Omega) + 3(pF) \cdot 26(\Omega) + 154(pF) \cdot 128(\Omega) = 20.4(nSec)$$

$$R_{55}^{4} = r_{ce4} \,//\, \frac{1}{g_{m5}} \,//\, r_{ce5} \approx 26(\Omega)$$

$$R_{66}^{4} = r_{ce5} \,//\, \frac{1}{g_{m5}} \,//\, r_{ce4} \approx 26(\Omega)$$

$$R_{77}^{4} = \left[\left(r_{ce5} \,//\, \frac{1}{g_{m5}} \,//\, r_{ce4}\right) \cdot (1 - A_V) + \frac{1}{g_{m7}} \,//\, (R_4 + R_L \,//\, (R_{F1} + R_{F2}) \right]$$

$$= \left[26(\Omega) \cdot (1 - 0.94) + \frac{1}{7.7(ms)} \,//\, (209(\Omega) + 10(k\Omega) \,//\, 10(k\Omega) \right] \approx 128\Omega$$

$$\because \frac{a_2}{a_1} = 20.4(nSec) << a_1 = 0.115(Sec)$$

$\therefore$ we may estimate the poles by separation pole approximation

$$\therefore f_{P3} = \frac{0.159}{a_1} \approx \underline{1.38(Hz)}$$

$$f_{P4} = \frac{0.159}{a_2 / a_1} \approx \underline{7.79(MHz)}$$

To summarize part A and B

There are four poles in the circuit.

f_{P3}	$<$ f_{P4}	$<$ f_{P1}	$<$ f_{P2}
1.38(Hz)	7.79(MHz)	29.2(MHz)	253.2(MHz)

f_{P3} is the dominant pole.

(b) Bode plot

$20\log|A_{OL}| = 20\log|1.44\times10^7| = 143.2\,dB$

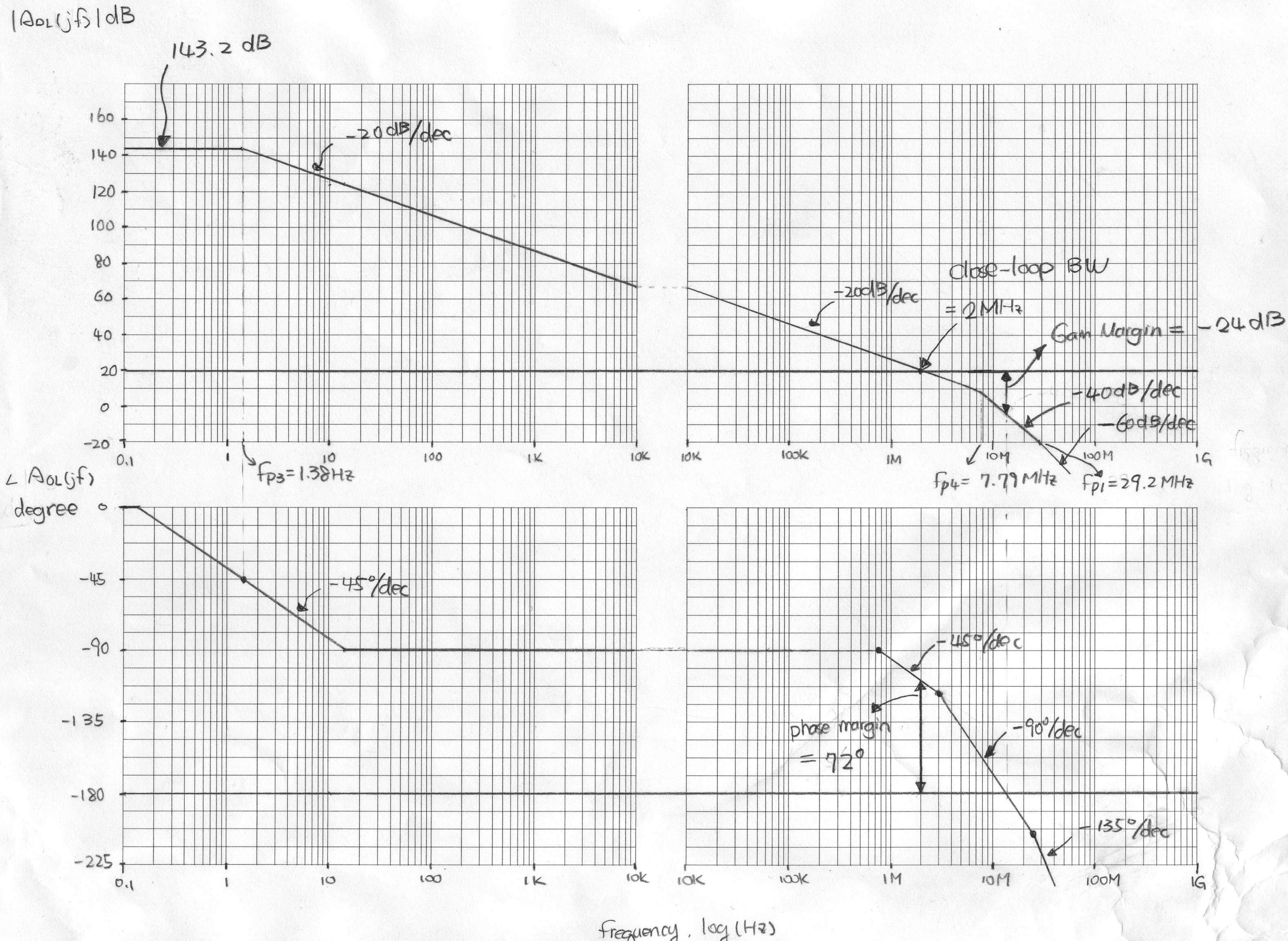
$20\log|\frac{1}{\beta}| = 20\log|10| = 20\,dB$

The intercept point of $20\log|A_{OL}|$ and $20\log|\frac{1}{\beta}|$ is the 3dB closed-loop bandwidth

$$\therefore \begin{cases} f_{P,OL} = 1.38\,Hz \\ f_{P,CL} = 2\,MHz \\ \text{phase margin} = 72^\circ \\ \text{gain margin} = -24\,dB \end{cases}$$

$\Rightarrow$ This amplifier is stable.

The plot is shown in next page.



|AOL(jf)| dB
143.2 dB
-20dB/dec
-20dB/dec
close-loop BW
= 2MHz
Gain Margin = -24dB
-40dB/dec
-60dB/dec
fp3=1.38Hz
fp4= 7.79MHz
fp1=29.2MHz
∠ AOL(jf)
degree
-45°/dec
-45°/dec
-90°/dec
-135°/dec
phase margin
= 72°
frequency, log (Hz)

P9