# EIE3100 Analog Circuit Fundamentals 模拟电路设计原理 Cluesheet

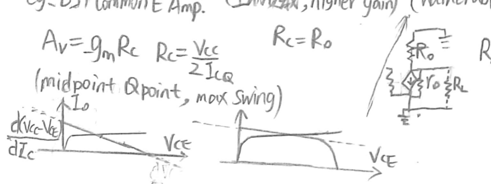
## § IC Design Philosophy: minimize size, power

- large&med Resistors&Capacitors $\xrightarrow{use}$ Transistors
- biasing Resistors $\xrightarrow{use}$ const current source
- Coupling/Bypass Capacitors $\xrightarrow{use}$ direct coupling techniq
- power supply ≈ 1V (avoid breakdown thin oxide layer)
  ⇒ transistor overdrive voltage 0.1V~0.2V only
- Device Variety
  - BJT: special analog applications (eg. HQ GPOpAmp)
  - Complementary MOS: compatibility with digital, photosensitive

§ Resistive Load $\xrightarrow{use}$ Active load (主动负载, higher gain) (vulnerable for loading effect)
eg. BJT Common E Amp.

$A_V=-g_mR_C$ $R_C=\frac{V_{CC}}{2I_{CQ}}$ (midpoint Qpoint, max swing) $R_C=R_o$ $R_C=R_o\|r_o\|R_L$

$\frac{d(V_{CC}-V_E)}{dI_C}$ $I_o$ $V_{CE}$ $V_{CE}$

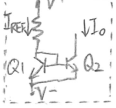


(COMP) 0→D:?→M:Lbl 0:Y→X:[expr]→Y:
Sol Eq Newt 牛顿法解方程 M+:1→D→D:D ⇒ $E^{-9}$M+ ⇒ Goto 0:
$E^{-9}$(1+X=(Y−X M−:X ⇒ Goto 0:M

## § IC Biasing Using const. Current Source

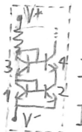
**BJT**

Basic two-transistor ~ $I_o=\left(\frac{1}{1+\frac{2}{\beta}}\right)I_{REF}$ $R_o=r_{o2}$

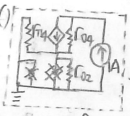


Basic three-transistor ~ $I_o=\left(\frac{1}{1+\frac{2}{\beta(\beta+1)}}\right)I_{REF}$ $R_o=r_{o3}$

Cascode Current Source



$I_{E3}=\frac{I_{REF}(\beta_3+1)}{(\beta_3+2)}$ (AC)

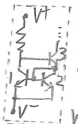


$R_o=(r_{o2}\|r_{\pi4})+g_{m4}(r_{o2}\|r_{\pi4})r_{o4}\approx g_{m4}r_{\pi4}r_{o4}=\beta r_{o4}$

$I_{C1}=I_{C2}=I_{E4}=\frac{I_{E3}\beta_1}{(\beta_1+2)}$

$I_o=\frac{I_{E4}\beta_3}{\beta_3+1}=\frac{\beta_1\beta_3I_{REF}}{(\beta_1+2)(\beta_3+2)}$

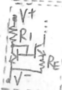
Wilson Current Source



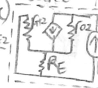
$I_o=\frac{\beta_3}{\beta_3+1}I_{E3}$ $I_{C2}=I_{C1}=\frac{\beta I_{E3}}{\beta+2}$ $R_o=\frac{\beta r_{o3}}{2}$

$I_{REF}=I_{C1}+\frac{I_o}{\beta_3}=\frac{\beta(\beta_3+1)+\beta+2}{(\beta+2)\beta_3}I_o$

Widlar Current Source



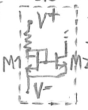
$\frac{I_{REF}}{I_o}=e^{\frac{V_{BE1}-V_{BE2}}{V_T}}=e^{\frac{R_EI_o}{V_T}}$ (AC)



$R_o=(R_E\|r_{\pi2})+r_{o2}+(R_E\|r_{\pi2})g_{m2}r_{o2}\approx r_{o2}(1+(R_E\|r_{\pi2})g_{m2})$

**FET**

Basic two-transistor MOSFET



$I_{REF}=K_{n1}(\underbrace{V_{GS1}}_{V_{GS}}-V_{TN})^2$ $K_{n(p)}=\frac{k'_{n(p)}}{2}\left(\frac{W}{L}\right)$ $R_o=r_{o2}$

MOSFET Current mirror (with MOSFET Ref. Current)

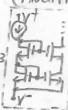
$V_{DS3}+V_{DS1}=V^+-V^-$ let $x=\sqrt{\left(\frac{W}{L}\right)_1\left(\frac{L}{W}\right)_3}$

$I_{REF}=k'_{n1}\left(\frac{W}{L}\right)_1(V_{DS1}-V_{TN})^2=k'_{n3}\left(\frac{W}{L}\right)_3(V_{DS3}-V_{TN})^2$

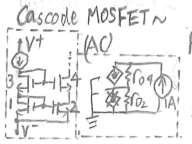
$x(V_{DS1}-V_{TN})=V^+-V^--V_{DS1}-V_{TN}\Rightarrow V_{DS1}=\frac{V^+-V^-+(x-1)V_{TN}}{1+x}$

Wilson MOSFET ~ (Modified)

$R_o\approx g_mr_{o1}r_{o3}$

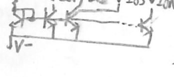


Cascode MOSFET ~ (AC)



$R_o=r_{o2}+r_{o4}(1+g_{m4}r_{o2})\approx g_mr_{o2}r_{o4}$

Multitransistor ~

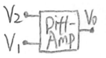


$I_{o1}=I_{o2}=\cdots=I_{oN}=\frac{I_{REF}}{1+\frac{(1+N)}{\beta}}$

Multioutput ~

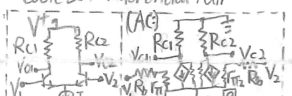
$I_o=\frac{NI_{REF}}{1+\frac{(1+N)}{\beta}}$

## § Differential Amplifier (Diff-Amp 差分放大器)



$V_o=A_{vol}(V_1-V_2)$ $V_d=V_1-V_2$ $2V_{cm}=V_1+V_2$ $V_1=V_{cm}+\frac{V_d}{2}$ $V_2=V_{cm}-\frac{V_d}{2}$

Basic BJT Differential Pair



$I_1=I_Se^{\frac{V_{BE1}}{V_T}}$
$I_2=I_Se^{\frac{V_{BE2}}{V_T}}$
$V_{BE1}-V_{BE2}=V_d$
$I_1+I_2=I_Q$

$V_d(A_d)$ Direct Analysis

$I_{1(2)}\propto e^{\frac{V_{BE1(2)}}{V_T}}$

$I_2=\frac{e^{\frac{V_{BE2}}{V_T}}I_Q}{e^{\frac{V_{BE1}}{V_T}}+e^{\frac{V_{BE2}}{V_T}}}=\frac{I_Q}{e^{\frac{V_d}{V_T}}+1}$

$\left.\frac{\partial I_2}{\partial V_d}\right|_{V_d=0}=\left.\frac{-I_Qe^{\frac{V_d}{V_T}}}{(e^{\frac{V_d}{V_T}}+1)^2V_T}\right|_{V_d=0}=\frac{-I_Q}{4V_T}=-\frac{g_m}{2}$ (one sided output)

$A_d, A_{cm}$, CMRR (Common-mode Rej. Ratio) AC Analysis

(KCL at E): $\frac{2(V_{cm}-V_E)}{R_b+r_\pi}+\frac{2g_m(V_{cm}-V_E)r_\pi}{R_b+r_\pi}=\frac{V_E}{R_o}$

$\Rightarrow V_E=\frac{2V_{cm}(1+g_mr_\pi)}{\frac{R_b+r_\pi}{R_o}+2(1+g_mr_\pi)}=\frac{2V_{cm}}{2+\frac{R_b+r_\pi}{(1+g_mr_\pi)R_o}}$

$V_o=V_{C2}=-g_{m2}V_{\pi2}R_{C2}=-\frac{g_mr_{\pi2}}{r_{\pi2}+R_b}(V_{cm}-\frac{V_d}{2}-V_E)R_{C2}$

$=-\frac{g_mr_{\pi2}R_{C2}}{r_{\pi2}+R_b}\left(V_{cm}-\frac{V_d}{2}-\frac{2V_{cm}}{2+\frac{R_b+r_\pi}{(1+g_mr_\pi)R_o}}\right)=-\frac{g_mr_{\pi2}R_{C2}}{r_{\pi2}+R_b}\left(\underbrace{\frac{V_{cm}}{1+\frac{2(1+g_mr_\pi)R_o}{R_b+r_\pi}}}_{A_{cm}}-\underbrace{\frac{V_d}{2}}_{A_d}\right)$

$CMRR=\left|\frac{A_d}{A_{cm}}\right|=\frac{1}{2}\left(1+\frac{2(1+g_mr_\pi)R_o}{R_b+r_\pi}\right)$

(Two sided Output)

$V_o=V_{C2}-V_{C1}=-\frac{g_mr_\pi(V_2-V_E)R_{C2}}{r_{\pi2}+R_{b2}}-\left(-\frac{g_mr_\pi(V_1-V_E)R_{C1}}{r_{\pi1}+R_{b1}}\right)$ ($g_m, r_\pi, R_b, R_c$ match) $A_d=\frac{r_\pi}{r_\pi+R_b}g_mR_c$, $A_{cm}=0$

If $R_c$ mismatch ($R_{C1}-R_{C2}=2\Delta R_c$)

$A_{cm}=\frac{g_m(2\Delta R_c)\cdot r_\pi(V_{cm}-V_E)}{(V_{cm})(r_\pi+R_b)}=\frac{g_m2\Delta R_cr_\pi}{r_\pi+R_b}\left(1-\frac{1}{1+\frac{2(1+g_mr_\pi)R_o}{R_b+r_\pi}}\right)$

$=g_m(2\Delta R_c)\frac{r_\pi}{r_\pi+R_b+(1+g_mr_\pi)R_o}$

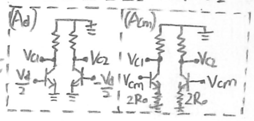
$\approx g_m(2\Delta R_c)\frac{r_\pi}{2g_mr_\pi R_o}=\frac{\Delta R_c}{R_o}$ $A_d=\frac{r_\pi}{r_\pi+R_b}g_m\frac{R_{c1}+R_{c2}}{2}$ $CMRR=\left|\frac{A_d}{A_{cm}}\right|\approx\frac{g_mR_oR_c}{\Delta R_c}$

If $g_m$ mismatch ($g_{m1}-g_{m2}=2\Delta g_m$, $\frac{g_{m1}+g_{m2}}{2}=g_m$) ($R_b=0$)

$A_{cm}=(2\Delta g_m)R_c\frac{r_\pi}{r_\pi+R_b+(1+g_mr_\pi)R_o}\approx\frac{2\Delta g_mR_c}{1+2R_og_m}$

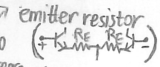
$A_d=\frac{r_\pi}{r_\pi+r_b}g_mR_c$ $CMRR\approx\frac{1+2R_og_m}{2(\Delta g_m/g_m)}$

Small-signal AC Equi. Half circuit Analysis ($A_d$) ($A_{cm}$)



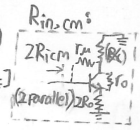
$R_{in,d}$: $r_\pi=\frac{V_d/2}{I_b}$ $R_{id}=2r_\pi$

emitter resistor to increase $R_{id}$



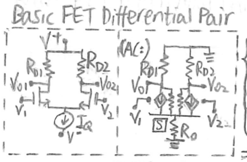
$R_{id}=2[r_\pi+(1+\beta)R_E]$

$R_{in,cm}$: 2$R_{icm}$ (2 parallel)



$R_{icm}=\left(\frac{r_\mu}{2}\right)\|[(1+\beta)R_o]\|[(1+\beta)\frac{r_o}{2}]$ B-C reversed-biased diff R

Basic FET Differential Pair



$V_d(A_d)$ Direct Analysis

$i_{D1}=K_n(V_{GS1}-V_{TN})^2$
$i_{D2}=K_n(V_{GS2}-V_{TN})^2$
$I_Q=i_{D1}+i_{D2}$
$V_{GS1}-V_{GS2}=V_d$
$\sqrt{i_{D1}/K_n}-\sqrt{i_{D2}/K_n}=V_d$

$\Rightarrow i_{D1}+i_{D2}-2\sqrt{i_{D1}i_{D2}}=V_d^2K_n\Rightarrow i_{D1(2)}=\frac{I_Q}{2}\pm\frac{V_d\sqrt{2I_QK_n-V_d^2K_n^2}}{2}$

$g_f=\left.\frac{di_{D2}}{\partial V_d}\right|_{V_d=0}=-\sqrt{\frac{I_QK_n}{2}}=-\frac{1}{2}g_m$ $A_d=-g_fR_{D2}=\frac{g_m}{2}R_{D2}$

$A_d, A_{cm}$, CMRR AC Analysis

(KCL at S): $(V_{cm}+\frac{V_d}{2}-V_S)g_{m1}+(V_{cm}-\frac{V_d}{2}-V_S)g_{m2}=\frac{V_S}{R_o}$

$\xrightarrow{g_m\text{ match}}$ $V_S=\frac{2V_{cm}}{\frac{1}{R_og_m}+2}$

$V_o=V_{D2}=-g_mV_{gs2}R_D=-g_mR_D(V_{cm}-\frac{V_d}{2}-V_S)$

$=-g_mR_D\left[\underbrace{V_{cm}\frac{1}{2g_mR_o+1}}_{A_{cm}}-\underbrace{\frac{V_d}{2}}_{A_d}\right]$ (one-sided output) $CMRR=\frac{1}{2}(2g_mR_o+1)$

(Two Sided Output)

$V_o=V_{D2}-V_{D1}=-g_m(V_2-V_S)R_{D2}-(-g_m(V_1-V_S)R_{D1})$

$\xrightarrow{(g_m, R_c\text{ match})}$ $A_d=g_mR_D$ $A_{cm}=0$

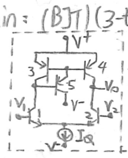
If $R_D$ mismatch ($R_{D1}-R_{D2}=2\Delta R$, $\frac{R_{D1}+R_{D2}}{2}=R_D$)

$A_{cm}=\frac{g_m(2\Delta R_D)(V_{cm}-V_S)}{(V_{cm})}=\frac{2g_m\Delta R_D}{2g_mR_o+1}\approx\frac{\Delta R_D}{R_o}$

$A_d=g_mR_D$ $CMRR\approx\frac{g_mR_DR_o}{\Delta R_D}$

If $g_m$ mismatch $A_{cm}=\frac{2\Delta g_mR_D}{2g_mR_o+1}$ $CMRR=\frac{1+2g_mR_o}{2\Delta g_m/g_m}$

To increase gain: Configure Diff-Amp with Active Load (BJT) (3-tran)

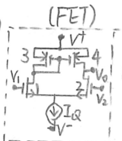


$I_{E5}=\frac{I_{C3}}{\beta}+\frac{I_{C4}}{\beta}$ to match $I_1=I_2$

$I_{B5}=\frac{I_{E5}}{1+\beta}\approx\frac{I_Q}{\beta(1+\beta)}(=I_o)$

$R_o=r_{o4}\|r_{o2}\|R_L$

(FET)



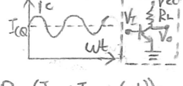
$R_o=r_{o4}\|r_{o2}\|R_L$

## § Output Stages (输出级) & Power Amplifier (功率放大器)

Emitter Follower (Common C): $A_i\gg1$, $A_v\approx1$

- maintain linearity (measured by Total Harmonic Distortion (THD, 总谐波失真))
- low $R_o$ (in terms of V)

• ClassA (甲类功放)



$P_Q=(I_{CQ}+I_{cp}\cos(\omega t))\cdot(V_{CQ}-V_{cp}\cos(\omega t))$

$\overline{P_Q}=I_{CQ}V_{CQ}-\frac{I_{cp}V_{cp}}{2}$ $\overline{P_S}=V_{CC}I_{CQ}$

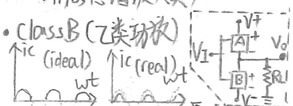
$\eta=\frac{\overline{P_L}}{\overline{P_S}}=\frac{I_{cp}V_{cp}/2}{V_{CC}I_{CQ}}$ $P_{LDC}=I_{CQ}(V_{CC}-V_{CQ})$

$\eta_{max}$: $V_{CQ}=\frac{V_{CC}}{2}$, $I_{cp}=I_{CQ}$, $V_{cp}=V_{CQ}$

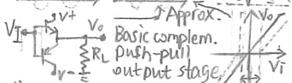
$\eta_{max}=\frac{I_{CQ}V_{CC}/4}{V_{CC}I_{CQ}}=25\%$

Linear, but very low η

• ClassB (乙类功放)



Basic complem. push-pull output stage
基本互补推挽输出级



Dead Band

$\overline{P_{Qn}}=(V_{CC}-V_{cp}\cos(\omega t))I_{cp}\cos(\omega t)$ (when $I\geq0$)

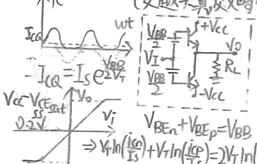
$\overline{P_{Qn}}=\frac{2V_{CC}I_{cp}}{2\pi}-\frac{V_{cp}I_{cp}}{4}$ $\overline{P_S}=V_{CC}I_{cp}\cos(\omega t)$ (half) $=\frac{2V_{CC}I_{cp}}{2\pi}$

$\eta=\frac{V_{cp}I_{cp}/4}{V_{CC}I_{cp}/\pi}=\frac{\pi V_{cp}}{4V_{CC}}$ $\eta_{max}$: $V_{CC}=V_{cp}$

$\eta_{max}\approx78.5\%$

Satisfactory η, but distortion (Dead band)

• Class AB (甲乙类功放)
combat crossover distortion (交越失真 交叉畸变)

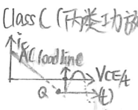


$I_{CQ}=I_Se^{\frac{V_{BB}}{2V_T}}$ $V_{BEn}+V_{BEp}=V_{BB}$

$\Rightarrow V_T\ln(\frac{i_{cn}}{I_S})+V_T\ln(\frac{i_{cp}}{I_S})=2V_T\ln\frac{I_{CQ}}{I_S}$

$\Rightarrow i_{cn}i_{cp}=I_{CQ}^2$ (const)

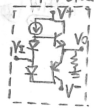
• Class C (丙类功放)



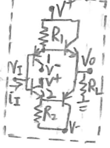
can provide larger P
$\eta>$ 78.5% → RF circuit

Advanced ClassAB Push-Pull

• With Diode Biasing:



• With input buffer transistor

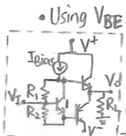


$i_o=\frac{V_o}{R_L}\approx\frac{V_I}{R_L}$

$i_I=\frac{(V_I-V_{BE})-V^-}{(1+\beta_n)R_2}-\frac{V^+-(V_I-V_{EB})}{(1+\beta_p)R_1}=\frac{2V_I-(V^++V^-)}{(1+\beta)R}$

$A_i=\frac{i_o}{i_I}=\frac{V_I(1+\beta)R}{R_L[2V_I-V^--V^+]}\xrightarrow{(V^-+V^+=0)}\frac{(1+\beta)R}{2R_L}$

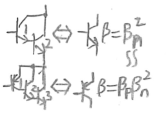
• Using $V_{BE}$ Multiplier:



$V_{BB}=V_{BE1}\left(1+\frac{R_1}{R_2}\right)$ Can be designed to yield required $V_{BB}$

$V_{BE1}=V_T\ln\left(\frac{I_{C1}}{I_S}\right)$ Avoid $V_{BB}$ change when $i_{Bn(p)}$ draw too much current

• Darlinton Pair (达灵顿对, 复合晶体管)



$\beta=\beta_n^2$ $\beta_p<\beta_n$ when in large power $R_{in}=(\beta_n+1)r_{\pi2}+r_{\pi1}$

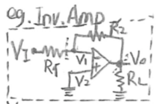
$\beta=\beta_p\beta_n^2$ $R_{in}=(\beta_n+1)\beta_pr_{\pi3}+\beta_pr_{\pi2}+r_{\pi1}$

§ Non-Ideal Effects in Op-Amp

- I/O limit: $V_{in}$, $V_0$, $i_0$
- Finite Open-Loop (OL) gain
- $R_i \neq \infty$, $R_0 \neq 0$
- Slew Rate (SR)
- Freq Response: Finite BW, $\varphi$ delay
- I/O offset Voltage
- Input bias current

Effect of $A_{OL}$ to: $A_{CL}$, $R_{of}$ $R_{if}$

eg. Inv. Amp



$$\begin{cases} \frac{V_0}{R_L} + \frac{V_0-(-A_{OL}V_1)}{R_0} + \frac{V_0-V_1}{R_2} = 0 \\ i_1 = \frac{V_1}{R_i} + \frac{V_1-V_0}{R_2} \end{cases} \Rightarrow V_0 = \frac{\left(\frac{1}{R_2}-\frac{A_{OL}}{R_0}\right)V_1}{\frac{1}{R_L}+\frac{1}{R_0}+\frac{1}{R_2}}$$

$$\Downarrow$$

$$\frac{1}{R_{if}} = \frac{i_1}{V_I} = \frac{1}{R_i} + \frac{1}{R_2}\left(\frac{\frac{1}{R_L}+\frac{1}{R_0}+\frac{A_{OL}}{R_0}}{\frac{1}{R_L}+\frac{1}{R_0}+\frac{1}{R_2}}\right)$$

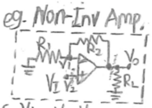
$$\begin{cases} \frac{V_I-V_1}{R_1} = \frac{V_1-V_0}{R_2} \\ V_0 = -A_{OL}V_1 \end{cases} \Rightarrow A_{CL} = \frac{-\frac{R_2}{R_1}}{1+\frac{1}{A_{OL}}\left(1+\frac{R_2}{R_1}\right)}$$

$$\begin{cases} I_0 = \frac{V_0-A_{OL}(-V_1)}{R_0} + \frac{V_0}{R_1+R_2} \\ V_1 = \frac{R_1}{R_1+R_2}V_0 \end{cases} \Downarrow$$

$$\frac{1}{R_{of}} = \frac{I_0}{V_0} = \left(\frac{1}{R_0} + \frac{1}{R_1+R_2} + \frac{A_{OL}R_1}{R_0(R_1+R_2)}\right)$$

$R_{if} \to 0$ as $A_{OL} \to \infty$ ($V_1$ virtual GND)

eg. Non-Inv Amp.

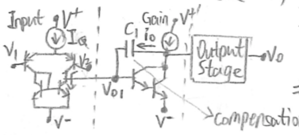


$$\begin{cases} \frac{V_0}{R_L} + \frac{V_0-A_{OL}V_d}{R_0} + \frac{V_0-V_1}{R_2} = 0 \\ V_d = i_I R_i = V_I - V_1 \\ i_I = \frac{V_1}{R_1} + \frac{V_1-V_0}{R_2} = \frac{V_I-V_1}{R_i} \end{cases} \Rightarrow R_{if} = \frac{V_I}{i_I} \approx \frac{R_i(1+A_{OL})+R_2\left(1+\frac{R_i}{R_1}\right)}{1+\frac{R_2}{R_1}}$$

$$\begin{cases} -\frac{V_1}{R_1} = \frac{V_1-V_0}{R_2} \Rightarrow V_1 = V_I - \frac{V_0}{A_{OL}} \\ V_0 = A_{OL}(V_I - V_1) \end{cases}$$

$$\Rightarrow A_{CL} = \frac{V_0}{V_I} = \frac{\frac{1}{R_2}+\frac{1}{R_1}}{\frac{1}{R_1A_{OL}}+\frac{1}{R_2A_{OL}}+\frac{1}{R_2}}$$

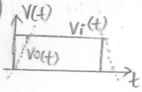
Limited Slew Rate (SR, 变化率)

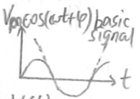


In case a step input $V_I = \pm V\varepsilon(t)$ ($V > 120mV$)

$i_0 \approx \pm I_Q$ $\quad i_0 = C_1\frac{d(V_0-V_{01})}{dt} \approx C_1\frac{dV_0}{dt} \approx I_Q$

$\Rightarrow SR = \left(\frac{dV_0}{dt}\right)_{max} \approx \frac{I_Q}{C_1} \propto \frac{1}{R_{eq}C_1} \propto f_{PD} \propto f_T$ $\quad R_{eq} \propto \frac{1}{R_{odiff}R_{igain}}$





$V_{po}\cos(\omega t+\varphi)$ basic signal

$SR = \frac{dV_0(t)}{dt} = \omega V_{po}\sin(\omega t+\varphi)$

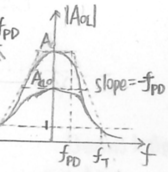
$\Rightarrow SR = \omega_{max}V_{po}$

Freq. Response

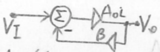
For Op-Amp: $F_T = A_0 f_{PD}$

$A_{OL}(f) = \frac{A_0}{1+j\frac{f}{f_{PD}}}$

$\varphi_{OL}(f) = \arctan\left(-\frac{f}{f_{PD}}\right)$



1st order feedback (OpAmp)

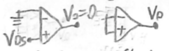


$A_{OL}(V_I - \beta V_0) = V_0$

$\Rightarrow A_{CL} = \frac{V_0}{V_i} = \frac{A_{OL}}{1+\beta A_{OL}} \overset{\beta A_{OL} \gg 1}{\approx} \frac{1}{\beta}$

$$A_{CL}(f) = \frac{A_0/(1+j\frac{f}{f_{PD}})}{1+\beta A_0/(1+j\frac{f}{f_{PD}})} = \frac{A_0}{1+j\frac{f}{f_{PD}}+\beta A_0} = \frac{A_0/(1+\beta A_0)}{1+j\frac{f}{f_{PD}(1+\beta A_0)}} = \frac{A_{CL0}}{1+j\frac{f A_{CL0}}{f_{PD}A_0}}$$

Offset Voltage (DC)



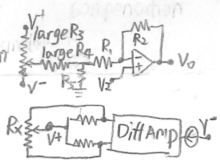
in/out put offset

Source of input offset

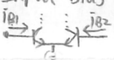
- (Diff-Amp) $\begin{cases} Q_1Q_2 \text{ (or } Q_3Q_4\text{) mismatch} \\ M_1M_2 \text{ (or } M_3M_4\text{) mismatch} \end{cases}$
- Input offset current $I_{OS}$

compensation

- Ext. OS compensation Network
- (Int.) OS NULL Terminal



Input Bias Current



If every thing match: $i_{B1} = i_{B2}$ $\begin{cases} nA \sim \mu A \text{ (BJT)} \\ \sim pA \text{ (FET)} \end{cases}$

else $|i_{B1} - i_{B2}| = I_{OS} \neq 0$

$\Downarrow$

lead to Offset voltage

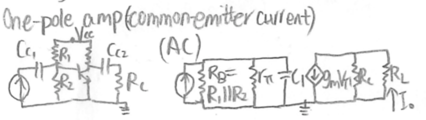
eg.

$V_{OS} = \pm I_{OS}R_2$

compensation:

§ Stability

One-pole amp (common-emitter current)



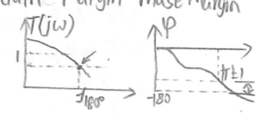
$I_0 = \left(\frac{R_C}{R_C+R_L}\right)g_mV_\pi$

$V_\pi = I_i\left[R_\pi \| \left(\frac{1}{sC_1}\right)\right]$

$A_i = g_mR_\pi\left(\frac{R_C}{R_C+R_L}\right)\left(\frac{1}{1+sR_\pi C_1}\right)$

$\frac{A_{i0}}{1+j\frac{f}{f_1}} \Rightarrow \frac{A_{i0}}{\sqrt{1+\left(\frac{f}{f_1}\right)^2}} \angle -\arctan\left(\frac{f}{f_1}\right)$

Gain Margin Phase Margin

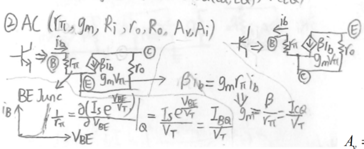


Freq Compensation:

Add a small PP to drop the gain (<1 before $f_{180°}$)

L7 BJT Analysis: ① DC ($I_{BQ}$ (CQ, EQ), $V_{CEQ}$)

② AC ($r_\pi$, $g_m$, $R_i$, $r_o$, $R_o$, $A_v$, $A_i$)



$\beta i_b = g_m r_\pi i_b$ $\Downarrow$ $g_m = \frac{\beta}{r_\pi} = \frac{I_{CQ}}{V_T}$

BE Junc

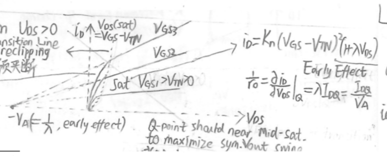
$\frac{1}{r_\pi} = \frac{\partial\left(I_S e^{\frac{V_{BE}}{V_T}}\right)}{\partial V_{BE}}\Bigg|_Q = \frac{I_S e^{\frac{V_{BE}}{V_T}}}{V_T} = \frac{I_{BQ}}{V_T}$

$\uparrow$ $d_{N\text{-}ch}\uparrow$. $I_D$ forms when $V_{DS} > 0$

non-sat.

$i_D = K_n[2(V_{GS}-V_{TN})V_{DS} - V_{DS}^2]$

$[K_n] = A/V^2$



$i_D = K_n(V_{GS}-V_{TN})^2(1+\lambda V_{DS})$

Early Effect

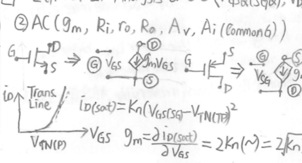
$\frac{1}{r_o} = \frac{\partial i_D}{\partial V_{DS}}\Big|_Q = \lambda I_{DQ} = \frac{I_{DQ}}{V_A}$

$-V_A = -\frac{1}{\lambda}$, early effect

Q-point should near Mid-sat. to maximize sym. Vout swing

L9 IGMOSFET Analysis ① DC ($V_{GSQ(SGQ)}$, $V_{DSQ(SDQ)}$, $I_{DQ}$)

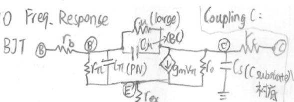
② AC ($g_m$, $R_i$, $r_o$, $R_o$, $A_v$, $A_i$ (CommonG))



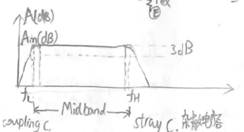
$i_{D(sat)} = K_n(V_{GS(SG)} - V_{TN(TP)})^2$

$g_m = \frac{\partial i_{D(sat)}}{\partial V_{GS}} = 2K_n(\sim) = 2\sqrt{K_nI_{DQ}}$

40 Freq. Response BJT



Coupling C:



coupling C. bypass C.

stray C. 杂散电容

transistor C. 晶体管电容

The open-loop voltage gain of an amplifier is given by $A_v = \frac{10^4}{\left(1+j\frac{f}{5\times10^3}\right)^2\left(1+j\frac{f}{5\times10^5}\right)}$

(a) Assuming the feedback transfer function is not a function of frequency, determine the frequency at which the phase of the loop gain is 180 degrees. (b) At what value of $\beta$ will the feedback amplifier become unstable? (c) Using the value of $\beta$ found in part (b), what is the low-frequency closed-loop gain? (d) Is the closed-loop feedback system stable for smaller or larger values of $\beta$?

(a) $\phi = -2\tan^{-1}\left(\frac{f}{5\times10^3}\right) - \tan^{-1}\left(\frac{f}{5\times10^5}\right)$

At $f_{180} = 7.1\times10^4$ Hz, $\phi \cong -180°$

(b) $|T| = 1 = \frac{\beta(10^4)}{\left[1+\left(\frac{7.1\times10^4}{5\times10^3}\right)^2\right]\sqrt{1+\left(\frac{7.1\times10^4}{5\times10^5}\right)^2}}$

$1 = \frac{\beta(10^4)}{(202.64)(1.01)} \Rightarrow \beta = 0.0205$

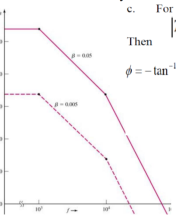
(c) $A_{vf}(0) = \frac{10^4}{1+(0.0205)(10^4)} = 48.54$

(d) Smaller

A three-pole feedback amplifier has a loop gain given by

$T(f) = \frac{\beta(10^4)}{\left(1+j\frac{f}{10^3}\right)\left(1+j\frac{f}{10^4}\right)\left(1+j\frac{f}{10^5}\right)}$

Sketch Bode plots of the loop gain magnitude and phase for: (a) $\beta = 0.005$, and (b) $\beta = 0.05$ (c) Is the system stable or unstable in each case? If the system is stable, what is the phase margin?



c. For $\beta = 0.005$,

$|T(f)| = 1$ (0 dB) at $f \approx 2.10\times10^4$ Hz

Then

$\phi = -\tan^{-1}\left(\frac{2.10\times10^4}{10^3}\right) - \tan^{-1}\left(\frac{2.10\times10^4}{10^4}\right) - \tan^{-1}\left(\frac{2.10\times10^4}{10^5}\right)$

$= -87.27 - 64.54 - 11.86$

or

$\phi = -163.7$

System is stable.

A feedback system has an amplifier with a low-frequency open-loop gain of $5\times10^4$ and has poles at $10^3$ Hz, $10^5$ Hz, and $10^7$ Hz. (a) Determine the frequency $f_{180}$ at which the phase of the loop gain is 180 degrees. (b) Determine the feedback transfer function $\beta$ for which the phase margin of the system is 45°. (c) Using the results of part (b), determine the low-frequency closed-loop gain.

(a) $\phi = -\tan^{-1}\left(\frac{f}{10^3}\right) - \tan^{-1}\left(\frac{f}{10^5}\right) - \tan^{-1}\left(\frac{f}{10^7}\right)$

At $f_{180} = 10^6$ Hz, $\phi \cong -180°$

(b) $\phi = -135° = -\tan\left(\frac{f_{135}}{10^3}\right) - \tan^{-1}\left(\frac{f_{135}}{10^5}\right) - \tan^{-1}\left(\frac{f_{135}}{10^7}\right)$

$f_{135} \cong 10^5$ Hz

$|T(f_{135})| = 1 = \frac{\beta(5\times10^4)}{\sqrt{1+\left(\frac{10^5}{10^3}\right)^2}\sqrt{1+\left(\frac{10^5}{10^5}\right)^2}\sqrt{1+\left(\frac{10^5}{10^7}\right)^2}}$

$1 = \frac{\beta(5\times10^4)}{(100)(1.414)(1)} \Rightarrow \beta = 2.83\times10^{-3}$

c) $A_{vf}(0) = \frac{5\times10^4}{1+(2.83\times10^{-3})(5\times10^4)} = 351$

The open-loop amplifier of a feedback system has its first two poles at $f_{P1}$ = 1 MHz and $f_{P2}$ = 10 MHz, and has a low-frequency open-loop gain of $|A_o|$ = 100 dB. (a) A dominant pole is to be added such that the closed-loop amplifier with a low-frequency gain of 20 has a phase margin of 45 degrees. What is the dominant pole frequency? (b) If the feedback transfer function from part (a) is increased such that the closed-loop low-frequency gain is 5, determine the phase margin of the amplifier.

(a) $A_o = 100$ dB $\Rightarrow A_o = 10^5$

$20 = \frac{10^5}{1+(10^5)\beta} \Rightarrow \beta = 0.04999$

$T = \frac{(0.04999)(10^5)}{\left(1+j\frac{f}{f_{PD}}\right)\left(1+j\frac{f}{10^6}\right)\left(1+j\frac{f}{10^7}\right)}$

Phase Margin $= 45° \Rightarrow \phi = -135°$

$-135 = -\tan^{-1}\frac{f}{f_{PD}} - \tan^{-1}\frac{f}{10^6} - \tan^{-1}\frac{f}{10^7}$

$f \approx 10^6$ Hz

$|T| = 1 = \frac{(0.04999)(10^5)}{\sqrt{1+\left(\frac{10^6}{f_{PD}}\right)^2}\sqrt{1+\left(\frac{10^6}{10^6}\right)^2}\sqrt{1+\left(\frac{10^6}{10^7}\right)^2}}$

$1 = \frac{(0.04999)(10^5)}{\sqrt{1+\left(\frac{10^6}{f_{PD}}\right)^2}(1.414)(1.005)}$

$\frac{10^6}{f_{PD}} = \frac{(0.04999)(10^5)}{(1.414)(1.005)}$

$f_{PD} = 2.84$ Hz

(b) $5 = \frac{10^5}{1+(10^5)\beta} \Rightarrow \beta = 0.19999$

$|T| = 1 = \frac{(0.19999)(10^5)}{\sqrt{1+\left(\frac{f}{284}\right)^2}\sqrt{1+\left(\frac{f}{10^6}\right)^2}\sqrt{1+\left(\frac{f}{10^7}\right)^2}}$

$f = 2.25\times10^6$ Hz

$\phi = -\tan^{-1}\left(\frac{2.25\times10^6}{284}\right) - \tan^{-1}\left(\frac{2.25\times10^6}{10^6}\right) - \tan^{-1}\left(\frac{2.25\times10^6}{10^7}\right)$

$= -89.99 - 66.04 - 12.68$

$\phi = -168.7$

Phase Margin $= 180 - 168.7 = 11.3°$