transformer 变压器 (subtitle transform)

$V_{out1} = -g_{m1}V_{in1}R_{out1}$, $V_{out2} = -g_{m2}V_{in2}R_{out2}$

两个串联：$V_{out2} = [-g_{m1}(R_{out1}\|R_{out1})V_{in1}](-g_{m2})R_{out2}$

计算方法：直接求出 V_i 再联接

如何求 R_{in1}, g_{m1}, R_{out1}：g_{m1}：将 V_{out1} 接地，V_{in1} 一侧接入 test voltage，求 $i_{out}/V_{test} = g_m$

$g_{m1} = \frac{i_{out}}{V_{out}}$

如何求 R_{out1}：将 V_{in1} 侧接地，V_{out1} 接入 test voltage，求 $\frac{V_{out1}}{i_{out1}} = R_{out}$

如何求 R_{in}：将 V_{out1} 侧什么也不做，在 V_{in} 侧接入一枚 test voltage，求 $\frac{V_{test}}{i_{in}} = R_{in1}$

$\frac{V_{test}}{i_{in}} = R_{in}$（另一侧什么都不做！）

Common Source, Resistive load (电阻负载)

$\lambda=0$ $\Gamma=0$ $A_v = -g_m R_D$

$\lambda\neq0$ $\Gamma\neq0$ $A_v = -g_m(R_D\|R_o)$

（λ 影响 r_o，λ 影响 g_{mb}）

small signal model

R_o：$\lambda\neq0$ 存在

g_{mb}：$\Gamma\neq0$ 存在

如何画 small-signal model：(pair 不适用)

⊥：短路 —⊖— 断路 —⊖—：短路

Common Source, Diode Load

方法：求出 R_{in2}，相当于并联入电路（求法在上面）

g_{ds} 是斜率

small-signal model

当 $\lambda=0$, $\Gamma\neq0$（已忽略 r_{o1}, r_{o2} 元）：$R_{in2} = \frac{1}{g_{m2}+g_{mb2}}$, $A_v = -g_{m1}\cdot\frac{1}{(g_{m2}+g_{mb2})}$

当 $\lambda\neq0$, $\Gamma\neq0$：$R_{in2} = \frac{1}{g_{m2}}\|\frac{1}{g_{mb2}}\|r_{o2}$（相当于并联）

$A_v = -g_{m1}(r_{o1}\|R_{in2}) = -g_{m1}(\frac{1}{g_{m2}}\|\frac{1}{g_{mb2}}\|r_{o2}\|r_{o1})$

$A_v = \frac{V_{out}}{V_{in}} = -g_{m1}(\frac{1}{g_{m2}}\|r_{o1}\|r_{o2}) \approx \frac{-g_{m1}}{g_{m2}}$（上面为 P，下面为 n）（$\lambda\neq0$）

I_1, I_2 相直流!!!

远大于 $= \frac{\sqrt{\mu_n C_{ox}(W/L)_1 I_1}}{\sqrt{\mu_p C_{ox}(W/L)_2 I_2}} = \frac{(V_{SG2}-V_{TH2})}{(V_{SG1}-V_{TH1})}$

（此时假设 MOS 都是饱和的）

缺点 (1) gain 一定为 10 $(W/L)_1/(W/L)_2$ 为 100，不成比例

若直流 $I_5 = \frac{3}{4}I_1$，则 $A_v = \frac{-g_{m1}}{g_{m2}} = \sqrt{\frac{2\mu_n C_{ox}(W/L)_1 I_{D1}}{2\mu_p C_{ox}(W/L)_2 I_{D2}}} = \sqrt{\frac{4\mu_n(W/L)_1}{4\mu_p(W/L)_2}}$

$= 4(V_{SG2}-V_{TH2})/(V_{GS1}-V_{TH1})$

Common source, current source load

$R_{in2} = r_{o2}$（注意上面是 P-mos）（$\lambda\neq\Gamma\neq0$）

$A_v = -g_{m1}(r_{o1}\|r_{o2})$

Common-Source with source degradation

求 $G_m \approx \frac{-g_{m1}r_{o1}}{R_S + r_{o1} + (g_{m1}+g_{mb1})r_{o1}R_S}$（若 $(g_{m1}+g_{mb1})r_{o1}R_S \gg r_{o1}$ and R_S）

$R_{out} = [R_S + r_{o1} + (g_{m1}+g_{mb1})r_{o1}R_S]\|R_D \approx R_D$（当 $(g_{m1}+g_{mb1})r_{o1}R_S \gg R_D$）

$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_D}{R_S}$

当 $\lambda=\Gamma=0$：$G_m = \frac{1}{1/g_{m1}+1/g_{m2}}$, $R_{out} = R_D$

R_D 提成 ideal current source：$R_D = +\infty$

Source Follower 相当于 Common gate

$\lambda=0$ $\Gamma\neq0$（无 Γ）：$A_v = \frac{g_m R_S}{1+(g_m+g_{mb})R_S} \approx \frac{1}{1+\eta}$

$\lambda\neq\Gamma\neq0$ $G_m = g_m$ $R_{out} = r_{o1}\|R_{o2}\|(\frac{1}{g_m+g_{mb}})$

$A_v = \frac{g_m r_{o1}R_S}{r_{o1}+R_S+(g_m+g_{mb})r_{o1}R_S} \approx \frac{1}{1+\eta}$

（当 $(g_m+g_{mb})r_{o1}R_S \gg r_{o1}$（或 R_S））

理想电流源 current source

（只能近似求）

线性

slope ≈ 1

饱和 $A_v = \frac{g_m}{g_m+g_{mb}} = \frac{1}{1+\eta}$

（$\lambda=0$, $\Gamma\neq0$ 情况）

非理想电流源 current source

（$\lambda\neq\Gamma\neq0$）

$g_m = g_{m1}$ $R_{out} = r_{o1}\|r_{o2}\|(\frac{1}{g_{m1}+g_{mb1}})$

$A_v = \frac{g_{m1}r_{o1}r_{o2}}{r_{o1}+r_{o2}+(g_m+g_{mb})r_{o1}r_{o2}} = g_m R_{out}$

上下输入版图且全为 P-mos

$\lambda\neq\Gamma\neq0$ $G_m = g_{m1}$ $R_{out} = r_{o1}\|r_{o2}\|\frac{1}{g_{m1}}$

$A_v = (g_{m1}r_{o1}r_{o2})/(r_{o1}+r_{o2}+g_{m1}r_{o1}r_{o2})$

Common-Gate 常 gate 值

关闭

（$\lambda=0$, $\Gamma\neq0$）$A_v = R_D g_m(1+\eta)$

饱合

$G_m = \frac{(g_m+g_{mb})r_o+1}{r_o+R_S+(g_m+g_{mb})r_oR_S}$

$R_{out} = R_D\|[r_o+R_S+(g_m+g_{mb})r_oR_S]$

$A_v = \frac{[(g_m+g_{mb})r_o+1]R_D}{r_o+R_S+(g_m+g_{mb})r_oR_S+R_D} \approx R_D g_m(1+\eta)$（当 $R_S=0$, $r_o=\infty$）

$R_D=0 \Rightarrow R_{in} = r_o\|1/g_m\|1/g_{mb}$, $R_D=\infty \Rightarrow R_{in}=\infty$

Transconductance Gain：输出 small-signal 电压与输入 i_{in} 之比

$G_m = -g_{m1}r_{o1}/(r_{o1}+(r_{o2}\|\frac{1}{g_{m2}+g_{mb2}}))$

$R_{out} = [r_{o1}+r_{o2}+(g_{m2}+g_{mb2})r_{o2}r_{o1}]\|R_D$

$A_v = G_m R_{out}$

$G_m = \frac{-g_{m1}r_{o1}}{r_{o1}+(r_{o2}\|\frac{1}{g_{m2}+g_{mb2}})}$

$R_{out} = r_{o1}+r_{o2}+(g_{m2}+g_{mb2})r_{o1}r_{o2}$

$G_m = -g_{m1}\frac{r_{o1}}{r_{o1}+(r_{o2}\|1/(g_{m2}+g_{mb2}))}$

$R_{out} = [r_{o1}+r_{o3}+(g_{m2}+g_{mb2})r_{o1}r_{o2}]\|[r_{o3}+r_{o4}+(g_{m3}+g_{mb3})r_{o3}r_{o4}]$

$A_v = G_m R_{out}$

$G_m = -g_{m1}\frac{(r_{o1}\|r_{o2})}{(r_{o1}\|r_{o3})+(r_{o2}\|\frac{1}{g_{m2}+g_{mb2}})}$

$R_{out} = [(r_{o1}\|r_{o3})+r_{o2}+(g_{m2}+g_{mb2})r_{o2}(r_{o1}\|r_{o3})]\|R_D$

$A_v = G_m R_{out}$

方法：一次关闭一个电源，

$V_{out1,1} = \frac{R_D}{1/g_{m1}+1/g_{m2}}V_{in1}$

$V_{out1,1} = \frac{-R_D}{1/g_{m1}+1/g_{m2}}V_{in1}$

$V_{out2,2} = \frac{-R_D}{1/g_{m1}+1/g_{m2}}V_{in2}$

$V_{out1,2} = \frac{R_D}{1/g_{m1}+1/g_{m2}}V_{in2}$

由于 V_{in1} 导致 $V_{out1}-V_{out2} = \frac{-2R_D}{1/g_{m1}+1/g_{m2}}V_{in1}$

由于 V_{in2} 导致 $V_{out1}-V_{out2} = \frac{2R_D}{1/g_{m1}+1/g_{m2}}$

（g_{m1}, g_{m2} 由直流引发，若 $W/L_1 = 2/1$, $W/L_2 = 2/1$ 则 $g_{m1} = 2g_{m2}$）

fully symmetric Method：方法为将

Half-Circuit Method：

（两侧分别）分析然后两侧相减

此图 $V_{out1} = -g_m(R_D\|r_o)\frac{V_d}{2}$ $V_{out2} = -g_m(R_D\|r_o)\frac{-V_d}{2}$

$A_{DM} = \frac{V_{out1}-V_{out2}}{V_{in1}-V_{in2}} = \frac{V_{out1}-V_{out2}}{V_d} = -g_m(R_D\|r_o)$

若 fully symmetric $A_{CM-DM}=0$, CMRR = +∞

如何求 A_{DCM}？ $A_{CM} = V_{out1,2}/V_{incm}$（common）

$R_{in1}+R_{in2} = \frac{R}{2}$

$M_1+M_2 = (g_{m1}+g_{m2})V_{in1}$

$R_{SS} \| \frac{r_o}{2}$

$A_{CM} = -\frac{2g_m\frac{r_o}{2}}{[R_{SS}+\frac{r_o}{2}+(2g_m+2g_{mb})\frac{r_o}{2}R_{SS}]}$

$\cdot\frac{[R_{SS}+\frac{r_o}{2}+(2g_m+2g_{mb})\frac{r_o}{2}R_{SS}]\frac{R_D}{2}}{[R_{SS}+\frac{r_o}{2}+(2g_m+2g_{mb})\frac{r_o}{2}R_{SS}]+\frac{R_D}{2}}$

（上面：$V_{out1} = -R_D V_{in1}/(1/g_m+(1/g_{m2}\|R_{SS}))$

$V_{out2} = (R_{SS}R_D/R_{SS}+\frac{1}{g_{m2}})V_{in1}/(1/g_{m1}+(1/g_{m2}\|R_{SS}))$

$V_{out1}-V_{out2} = \frac{-(g_{m1}+2R_{SS}g_{m1}g_{m2}R_D)V_{in1}}{+(g_{m1}+g_{m2})R_{SS}}V_{in1}$

（与之前结合）$= (V_{in1}-V_{in2})\times\frac{V_{in1}}{V_{in1}}$ 与

Current Mirror (直流)

若 $\lambda=0$, $I_{out} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(\frac{R_2}{R_1+R_2}V_{DD}-V_{TH})^2$

$I_{ref} = \frac{1}{2}\mu_n C_{ox}(\frac{W}{L})_1(V_A-V_{TH})^2$

$I_{out} = \frac{1}{2}\mu_n C_{ox}(\frac{W}{L})_2(V_A-V_{TH})^2$

若 $\lambda=0$ $I_{out} = \frac{(W/L)_2}{(W/L)_1}I_{ref}$

$I_{out} = \frac{(W/L)_2}{(W/L)_1}\frac{(W/L)_4}{(W/L)_3}I_{ref}$

（看成）

$V_A = -V_{in}g_{m1}(r_{o1}\|r_{o2}\|\frac{1}{g_{m2}})$

$V_{out} = -V_A g_{m3}(R_L\|r_{o3})$

$\frac{V_{out}}{V_{in}} = g_{m1}(r_{o1}\|r_{o2}\|\frac{1}{g_{m2}})g_{m3}(R_L\|r_{o3})$

$\frac{V_{out}}{V_{in}} = g_m(\frac{W_1}{W_2}R_L)$

Active Current Mirror ($g_{m3} \gg r_{o1}, r_{o2}, r_{o3}, r_{o4}$)

V_{in} 上升，M_1 下降，M_1 的电流上升，M_2 的电流下降 ⇒ 由此 V_{out} 会上升（因为 M_3 的阻抗较大），$\frac{V_{out}}{V_{in}}$ 会余弦率为正

V_{out} 大致 fully symmetric

求 R_{out}

求 GM

$A_{CM-DM} = \frac{V_{out1}-V_{out2}}{V_{in1}+V_{in2}}$

$A_{DM} = \frac{V_{out1}-V_{out2}}{\frac{V_d}{2}-(-\frac{V_d}{2})}$

$= \frac{V_{out1}-V_{out2}}{V_{in1}-V_{in2}} = \frac{V_{out1}-V_{out2}}{V_{incm}}$

$A_{CM} = \frac{(V_{out1}+V_{out2})/2}{(V_{incm1}+V_{in2})/2} = \frac{V_{out1,2}}{V_{in,cm}}$（fd）

$CMRR = |\frac{A_{DM}}{A_{CM-DM}}| \to \infty$

fully sym　fully-sym, 0.

如何求 A_{DCM}

在 $V_{out1} = V_{out2}$（gain 最大）

V_{out2}, V_{out1}, $V_{in1}-V_{in2}$, $V_{out1}-V_{out2}$

Non-fully symmetric：superposition

Fully symmetric：half circuit method

$A_{CM} \approx \frac{-2g_{m12}\frac{r_{o12}}{2}(\frac{1}{2g_{m34}}\|\frac{r_{o34}}{2})}{R_{SS}+\frac{r_{o12}}{2}+(2g_{m1,2}+2g_{mb2})\frac{r_{o12}}{2}R_{SS}+(\frac{1}{2g_{m34}}\|\frac{r_{o34}}{2})} \approx \frac{-1}{2g_{m34}R_{SS}}$

$CMRR = g_{m1,2}(r_{o2}\|r_{o4})2g_{m34}R_{SS}$

$A_v = g_m R_{out} = g_{m12}(r_{o2}\|r_{o4})$

$i_x = 2\frac{r_{o12}}{2r_{o12}+(\frac{1}{g_{m3}}\|r_{o3})}+\frac{V_x}{r_{o4}}$

（$i_x = i_1+i_2+i_3$）

原因：$i_4 = V_3 g_{m4}$

$V_3 = i_1\cdot(\frac{1}{g_{m3}}\|r_{o3})$ ⇒ $i_4 \approx i_1$

$R_{out} = \frac{V_{out}}{i_x} \approx (r_{o2}\|r_{o4})$

$i_1 = i_2$, $i_1 = -i_3$

$R_{in} = (\frac{1}{g_{m3}}\|r_{o3})$ 很小

∴ i_{out} 只与 M_1, M_2 有关

$i_{out} = g_{m12}(\frac{V_d}{2})$

⇒ $G_m = g_{m1,2}$