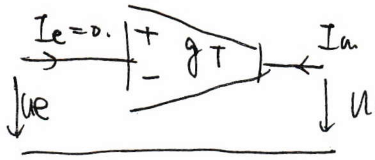
5. Transkonduktionsverstärker

5.1 Model.

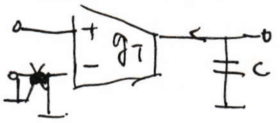


$I_a = g_T U_e$.

- 非线性
- I_a, I_e 有限
- 受频率影响

5.2 应用.

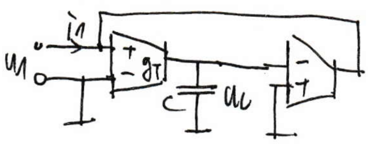
"GmC" Filter.



OTA: $\tau = \frac{C}{g_T}$

OPV: $\tau = RC$.

"回转器"



$U_C = \frac{1}{j\omega C} I_1$, $i = \frac{dQ}{dt} = C\frac{du}{dt} \Rightarrow I_1 = C \cdot s\, U_C$

$U_C = \frac{-g_T U_1}{sC}$ $I_1 = -g_T U_C$

$\Rightarrow Z_1 = U_1 / I_1 = \frac{sC}{|-g_T|\,|g_T|} = s \cdot \frac{C}{g_T^2}$.

用容器件变成电感.

5.3. Transistor als Elementar

双极管 $I_a = I_s \exp\left(\frac{U_e}{U_T}\right)$ $g_T = \frac{I_{aA}}{U_T}$

MOS. 可变电阻区.

$$I_D = \frac{\beta}{2}(U_{GS} - U_{th})^2 (1 + \lambda U_{DS})$$，厄立效应可以忽略

$$g_T = \sqrt{2\beta \cdot I_{DA}(1 + \lambda U_{DSA})} \approx \sqrt{2\beta I_{DA}} = g_m$$

恒流区.

$$I_a = I_D = \beta\left[(U_e - U_{th})U_{DS} - \frac{U_{DS}^2}{2}\right]$$

$$g_T = g_m = \beta \cdot U_{DSA}$$

问题(基本放大电路). 1. 非线性 2. T, 工艺. 3. 零点漂移

5.4. Schaltungsprinzipien

5.4.1 差分电路

$$I_a = I_1 - I_2 = I_0 \tanh\frac{U_e - I_a\frac{R_E}{2}}{2U_T}$$，当无 R_E 时. $g_T = \frac{\partial I_0}{\partial U_e}\Big|_{U_e=0} = \frac{I_0}{2U_T} = \frac{I_C}{U_T}$

求跨导. $F(I_a, U_a) = I_0 \tanh\frac{U_e - I_a\frac{R_E}{2}}{2U_T} - I_a = 0$.

小信号近似. $\tanh x \sim x$, $I_0 \cdot \frac{1}{2U_T} \cdot \left(U_e - I_a \cdot \frac{R_E}{2}\right) - I_a = 0$

$$\frac{I_0}{2U_T} dU_e - \left(\frac{I_0 R_E}{4U_T} + 1\right) dI_a = 0 \Rightarrow \frac{dI_a}{dU_e} = \frac{I_0}{2U_T} \cdot \frac{4U_T}{I_0 R_E + 4U_T} = \frac{2I_0}{I_0 R_E + 4U_T} = \frac{g_T}{1 + g_T \cdot \frac{R_E}{2}}$$

由 $\frac{A}{1+AF}$ 得. $AF = g_T \cdot \frac{R_E}{2}$，则为环路增益.

$$i_a = a_1 U_e + a_2 U_e^2 + a_3 U_e^3, \Rightarrow \begin{cases} a_1 = g_T / 1 + g_T \cdot \frac{R_E}{2} \\ a_2 = 0 \\ a_3 = -\frac{g_T'}{12 U_T^2}\left(1 - \frac{R_E}{2} g_T'\right)^3 \end{cases}$$ g_T' 即为 a_1.

① $HP_3 = \frac{1}{4}\left|\frac{a_3}{a_1}\right| \hat{U}_e^2 = \frac{1}{48}\left(\frac{1}{1 + R_E \cdot \frac{g_T}{2}}\right)^3 \left(\frac{\hat{U}_e}{U_T}\right)^2$，闭环(有反馈)

② $HP_3 = \frac{1}{48}\left(\frac{\hat{U}_e}{U_T}\right)^2$，开环(无反馈)

$$\left(\frac{1}{1 + R_E \cdot \frac{g_T}{2}}\right) = (1 - R_E \cdot g'_T)$$

从①式. $R_E = \frac{2}{g_T'}\left[1 - \sqrt[3]{48 (HP_3) \left(\frac{\hat{U}_e}{U_T}\right)^{-2}}\right]$

从中解得 I_0，我们需要先推出 $R_E \cdot g_T'$，这样

$R_E \cdot g_T' = 2\left[1-\sqrt[3]{48 \cdot HD_3 \cdot \left(\frac{\hat{u}_e}{U_T}\right)^2}\right]$，着我先说从 HD_3 的式子看更清楚

由 $1+g_T\cdot\frac{R_E}{2}=\frac{g_T}{g_T'}$ $\Rightarrow$ $\cancel{g_T' + g_T \cdot \frac{1}{2} R_E \cdot g_T' = g_T}$. $1+\frac{R_E}{2}\cdot g_T=\frac{I_0}{2U_T g_T'}$

$$\Rightarrow I_0 = 2U_T \cdot g_T' \left(48 HD_3\right)^{-\frac{1}{3}} \left(\frac{\hat{u}_e}{U_T}\right)^{\frac{2}{3}}$$

5.4.2. CMOS跨导放大器

先推导一下. $I_a = I_a^+ - I_a^-$

$U_e = U_{gs1} - U_{gs2}$, $\quad I_a = \frac{\beta}{2}(U_{gs}-U_{th})^2 \Rightarrow U_{gs} = \sqrt{\frac{2\beta}{I_a}} + U_{th}$

$$= \sqrt{\frac{2\beta}{I_{a1}}} - \sqrt{\frac{2\beta}{I_{a2}}} = \frac{\frac{2\beta}{I_{a1}} - \frac{2\beta}{I_{a2}}}{\sqrt{\frac{2\beta}{I_{a1}}}+\sqrt{\frac{2\beta}{I_{a2}}}} = \frac{\frac{2\beta(I_{a2}-I_{a1})}{I_{a1}\cdot I_{a2}}}{\sqrt{2\beta}\left(\frac{1}{\sqrt{I_{a1}}}+\frac{1}{\sqrt{I_{a2}}}\right)} = \frac{\sqrt{2\beta}\,(I_{a2}-I_{a1})}{\left(\sqrt{I_{a1}}\cdot I_{a2} + I_{a1}\sqrt{I_{a2}}\right)}$$

暂时没解出来. 结果下面

$I_{a1}+I_{a2}=I_0$.

$\Rightarrow I_0 = I_{a1}+I_{a2} =$

$$I_{a2}-I_{a1} = \frac{1}{\sqrt{2\beta}}\cdot U_e \cdot \sqrt{I_{a1}I_{a2}}\,(I_{a1}+I_{a2})$$

$$= I_{a2}-I_{a1} = \frac{I_0}{\sqrt{2\beta}}\cdot U_e \cdot \frac{\beta}{2}\cdot [U_{gs1}-U_{th}][U_{gs2}-U_{th}]$$

$$\Rightarrow \sqrt{\beta I_0}\cdot U_e \cdot \sqrt{1-\frac{\beta}{4I_0}U_e^2}$$, $U_{eA}=0$. $I_{aA}=0$.

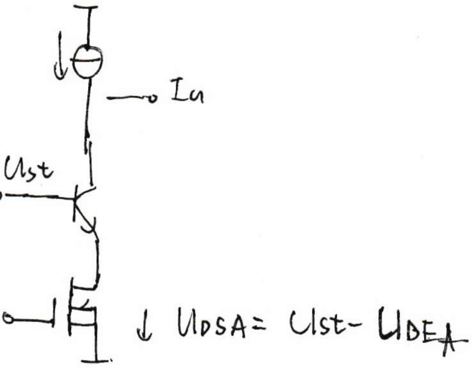
$I_a = a_1 U_e + a_2 U_e^2 + a_3 U_e^3$

$\rightarrow a_1 = g_T = \sqrt{\beta I_0}$ $\qquad HD_3 = \frac{1}{4}\left|\frac{a_3}{a_1}\right|\hat{u}_e^2 = \frac{1}{32}\frac{\beta}{I_0}\hat{u}_e^2$, $g_T = \sqrt{\beta_0 I_0}$

$a_2 = 0$ $\qquad I_0 = g_T\cdot \hat{u}_e\sqrt{\frac{1}{32 HD_3}}$. $\beta = \frac{g_T}{\hat{u}_e}\sqrt{32 HD_3}$

$a_3 = -\frac{1}{8}\frac{\beta^{\frac{3}{2}}}{\sqrt{I_0}}$

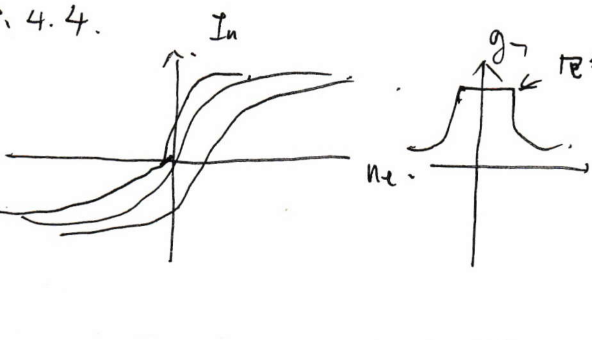
5.4.3. BiCMOS – Transkonduktanzverstärker

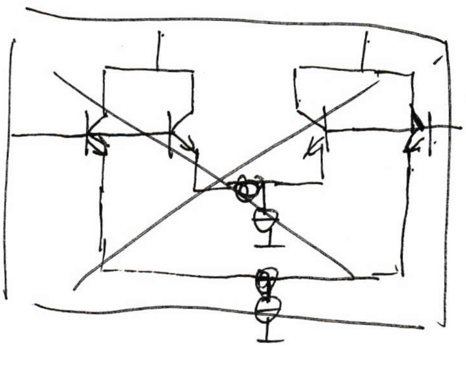


$I_D = \beta\left[(U_{GS}-U_{th})U_{DS} - \frac{U_{DS}^2}{2}\right]$

$g_n = \beta U_{DSA}$

5.4.4.





见笔记.
不同的管子相连.

~~从中解得 I_0，再...带... $R_E \cdot g_T'$ 选样~~

~~$1 + g_T \cdot \frac{R_E}{2} = g_T / g_T' = \frac{I_0 / 2U_T}{g_T'}$~~

~~$I_0 =$~~

TK-01.

1.) $g_T = \frac{I_{CA}}{U_T} = \frac{I_0}{2U_T} = 1.92\,mS$

$~~I_{CA} = g_T~~ \hat{U}_e \Rightarrow \hat{U}_e = U_T = 26\,mV$

$HD_3 = \frac{1}{48}(1)^3 \cdot 1^2 = \frac{1}{48}$

2). $HD_3' = \frac{1}{48}\left(1 - \frac{R_E}{2} \cdot g_T'\right)^3 \left(\frac{\hat{U}_e}{U_T}\right)^3 = \frac{1}{480}$

~~$R_E \cdot g_T' = \frac{}{48}$~~

$$\boxed{\begin{aligned} 1 - \frac{R_E}{2} \cdot g_T' &= \left|\frac{1}{10}\right|^{\frac{1}{3}} \\ R_E \cdot \cancel{g_T} &= \left[1 - \left(\frac{1}{10}\right)^{\frac{1}{3}}\right] \frac{2}{g_T'} \end{aligned}}$$

$\Rightarrow 1 - \frac{R_E}{2} \cdot g_T' = 1 - \frac{R_E}{2} \cdot \frac{g_T}{1 + g_T \cdot \frac{R_E}{2}} = \frac{1}{1 + g_T \cdot \frac{R_E}{2}}$

$\left(\frac{1}{1 + g_T \cdot \frac{R_E}{2}}\right)^3 = \left|\frac{1}{10}\right|^{\frac{1}{3}}$ $\quad R_E \Rightarrow \frac{2\sqrt[3]{10} - 2}{g_T}$

$R_E = \cancel{2.43}\ 1.28\,k\Omega$

$g_T' = \frac{g_T}{1 + g_T \cdot \frac{R_E}{2}} = 0.\cancel{576}\ 892\,mS$

3) $g_{T(3)} = 2 g_T = 3.84\,mS$

$g'_{T(3)} = 1.16\,mS$

$g_T' = \frac{g_T}{1 + g_T \cdot \frac{R_E}{2}} = \frac{1}{\frac{1}{g_T} \cdot \frac{R_E}{2}}$

$\lim_{g_T \to \infty} g_T' = \frac{2}{R_E} = 1.67\,mS \Rightarrow HD_3 = \frac{1}{48}\left(1 - \frac{R_E}{2} \cdot g_T'\right)^3 \left|\frac{\hat{U}_e}{U_T}\right|^2 = 0.00585 < \frac{1}{480}$

TK-02.

1) $HD_3 = \frac{1}{32} \cdot \frac{\beta}{I_0} \cdot \hat{U}_e^2 \rightarrow \beta = 51.2\,\frac{mA}{V^2}$

$\hat{I}_A = g_T \hat{U}_e = \sqrt{\beta I_0} \cdot \hat{U}_e = 56.6\,mA$

2). $g_T = \sqrt{\beta I_0} \rightarrow \beta = \frac{g_T^2}{I_0} \rightarrow HD_3 = \frac{1}{32} \cdot \frac{g_T^2}{I_0^2} \hat{U}_e^2$, verringert um Faktor 4

TK-03.

1) $I_5 + I_6 + 2n I_0 = I_0$

$0 \le I_5 + I_6 = (1 - 2n I_0) \le I_0$

$0 \le n \le 0.5$

TK-03 电路说明，可参见 Einstellungschaltung 的共模设置。在 MOS 负载中，放大倍数 $\approx -\frac{g_{m1}}{g_{m2}} = \sqrt{\frac{\mu_n (W/L)_1}{\mu_p (W/L)_2}}$，若扩大增益，则 $(W/L)_2$ 应减小，而 $g_{m2}\downarrow$ X 点的共模电平会下降，使驱动晶体管 $|V_{gsp} - U_{thp}|$ 会增大，而在两侧并联电流源后，减小了第二级 MOS 管的电流，从而在不改变长宽比的情况下降低了 g_m，例如 $n=0.4$ 时 $\rightarrow I_{T2} = \frac{1}{5} I_{T20} \rightarrow g_{m2} = \frac{1}{5} g_{m20}$，V↑ 5x

(2) $V_{\hat{1}} = \frac{I_3 - I_4}{I_1 - I_2} = \frac{I_3 - I_4}{I_5 - I_6} = \frac{\sqrt{\beta_A \cdot I_0} \cdot U_Z \cdot \sqrt{1 - \frac{\beta_A}{4 I_0} U_Z^2}}{\sqrt{\beta_B \cdot I_{01}} \cdot U_Z \sqrt{1 - \frac{\beta_B}{4 \cdot I_{01}} U_Z^2}}$, $I_{01} = I_0 - 2n I_0$

$\beta_A \sim I_0$, $\beta_B \sim I_{01}$. $\frac{\beta_A}{\beta_B} = \frac{I_0}{I_{01}} = \frac{1}{1-2n} = V_{\hat{1}} \rightarrow n = \frac{1}{2}\left(1 - \frac{1}{V_{\hat{1}}}\right)$

3) $\boxed{V_{\hat{1}} = \frac{\sqrt{\beta_A I_0} \cdot U_Z \cdot \sqrt{1 - \frac{\beta_A}{4 I_0} U_Z^2}}{\sqrt{\beta_C I_0} \cdot U_e \sqrt{1 - \frac{\beta_C}{4 \cdot I_0} U_e^2}}}$

Kleinsignal $\longrightarrow$ $g_T = \sqrt{\beta \cdot I_0}$.

$\hat{I}_a = V_{\hat{1}} \cdot g_T \cdot U_e = V_{\hat{1}} \cdot \sqrt{\beta_c \cdot I_0} \cdot U_e$.

$\Rightarrow \beta_C = \frac{I_0}{|V_{\hat{1}} \cdot \hat{U}_e|^2}$

$HD_3 = \frac{1}{32} \cdot \frac{1}{|V_{\hat{1}}|^2} = \frac{1}{32} \cdot \frac{1}{|1-2n|^2}$

4) $n = \frac{1}{2}\left(1 - \frac{1}{2}\right) = \frac{1}{4}$

$HD_3 = \frac{1}{32} \cdot \frac{1}{4} = \frac{1}{128}$

W/L $\beta = \frac{I_0}{|V_{\hat{1}} \cdot U_e|^2} / K_P = 100$.

TK-04.

1) $\boxed{\begin{array}{l} 0 \le U_{GS} - U_{DS} \le U_{th} \quad (U_{GS} > U_{DS}) \\ 0 \le U_e - (U_0 - U_{DEA}) \le U_{th} \\ U_e + U_{DEA} - U_{th} \le U_0 \le U_e + U_{DEA} \end{array}}$

$U_0 = U_{BEA} + U_{DSA} = 1.1\,V$.

$I_0 = I_D = \beta\left[(U_e - U_{th}) \cdot U_{DSA} - U_{DS}^2/2\right]$

$\rightarrow \beta = 606\,\mu \frac{A}{V^2} \rightarrow \frac{W}{L} = \beta / K_P = 6.06$

(2). $g_T = \frac{dI_a}{dU_e} = \frac{dI_D}{dU_e} = \beta(U_0 - U_{BEA}) = 182\,\mu A/V$. $g_T \sim U_D$

(3)

a_1 $g_T = \frac{dI_a}{dU_e} = \left|\frac{-F(I_a)}{F(U_e)}\right|^{-1} = \left(-\frac{I_a \cdot \frac{-R_E}{U_T} - 1}{I_a \cdot \frac{1}{U_T}}\right)^{-1}$

$= \left|\frac{1 + g_m \cdot R_E}{g_m}\right|^{-1} = \frac{g_m}{1 + g_m R_E}$.

(4) $U_e \geq U_{BE} - U_{th} - U_0\,V$

$U_e \geq U_0 + U_{th} - U_{DE}\,V$

$U_{e,min} = 1.1\,V$

$\hat{U}_{e,max} = 0.4\,V$

$\hat{I}_{a,max} = 72.7\,\mu A$

$a_2 = \frac{1}{2} \cdot \frac{(1+g_m R_E)\, g_m' \cdot g_m - g_m' R_E \cdot g_m}{|1 + g_m R_E|^2} = \frac{g_m'}{|1 + g_m R_E|^2}$

$g_m = \frac{I_a}{U_T} \Rightarrow g_m' = \frac{1}{U_T} \cdot \frac{g_m}{1 + g_m R_E} = \frac{1}{2U_T} \cdot \frac{g_m}{|1 + g_m R_E|^3}$

$a_3 = \frac{1}{3} \cdot a_2' = \frac{1}{6 \cdot U_T^2} \cdot \frac{g_m}{|1 + g_m U_E|^5} \cdot (1 - 2g_m \cdot U_E)$

TK-05.

$U_e = U_{BE} + I_c \cdot R_E$.

$= U_T \ln\left(\frac{I_c}{I_S}\right) + I_c \cdot R_E$.

$U_e = U_{BE} + I_s \exp\left(\frac{U_{BE}}{U_T}\right) \cdot R_E$.

$\rightarrow 0 = I_s \exp\left(\frac{U_e - R_E \cdot I_a}{U_T}\right) - I_a$

wenn $1 - 2g_m \cdot R_E = 0$.

$g_m = \frac{1}{2R_E} = \frac{I_0}{U_T} \Rightarrow I_0 = \frac{U_T}{2R_E}$ 时

上面只是一种做法. 也可以先算 $U_e = b_1 i_a + b_2 i_a^2 + b_3 i_a^3$ 再导出 a_1, a_2, a_3, 推荐对 g_m 求导比较快.