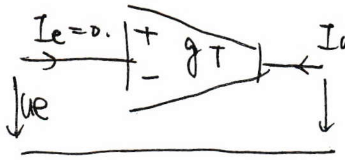
5. Transkonduktionsverstärker

5.1 Model.

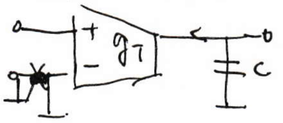


$I_a = g_T U_e$.

- 非线性.
- I_a, I_e 有限
- 受频率影响

5.2 应用.

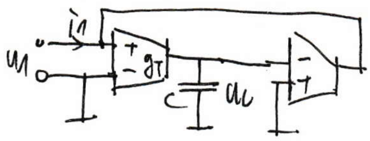
"GmC" Filter.



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

OPV: $\tau = RC$.

"回转器"



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

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

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

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

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

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

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

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

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

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

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

5.4.2. CMOS跨导放大器

先推导一下. $I_a = I_a^+ - I_a^-$

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

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

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

暂时没解出来
结果下方

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

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

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

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

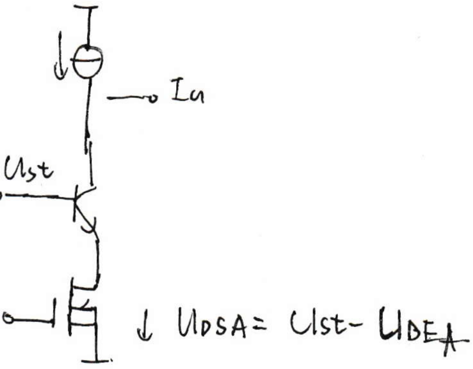
$I_a = a_1U_e + a_2U_e^2 + a_3U_e^3$

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

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

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

5.4.3. BiCMOS - Transkonduktanzverstärker

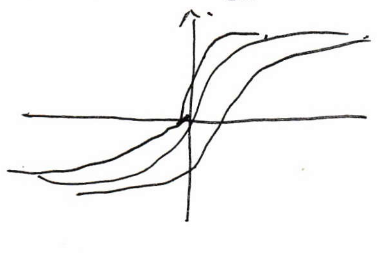


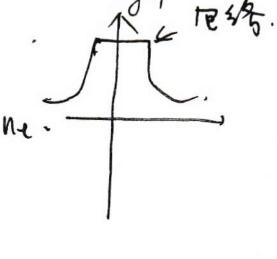
$\downarrow U_{DSA} = U_{st} - U_{BEA}$

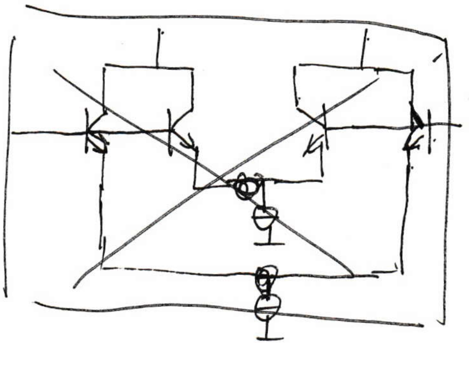
$I_D = \beta\left[(U_{GS}-U_{th})U_{DS}-\frac{U_{DS}^2}{2}\right]$

$g_m = \beta U_{DSA}$

5.4.4.







见笔记.
不同的管子相连.

~~从中解得 I_0、再问需率先推出 $R_E \cdot g_T'$. 这样~~

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

~~$I_0 =$~~

TK-01.

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

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

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

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

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

$$\boxed{\begin{aligned} &1-\frac{R_E}{2}\cdot g_T' = \left|\frac{1}{40}\right|^{\frac{1}{3}} \\ &R_E\cdot g_T = \left[1-\left(\frac{1}{10}\right)^{\frac{1}{3}}\right]\frac{2}{g_T'} \end{aligned}}$$

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

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

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

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

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

$g_{T(3)}' = 1.16\,\text{mS}$

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

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

TK-02.

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

$\hat{I}_a = g_T\,\hat{U}_e = \sqrt{\beta I_0}\cdot\hat{U}_e = 56.6\,\mu A$.

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) $I_5 + I_6 + 2nI_0 = I_0$

$0 \le I_5 + I_6 = (1-2nI_0) \le I_0$

$0 \le n \le 0.5$

TK-03 电路说明，可参见 Einstellungschaltung 的共模设置。在MOS负载中，放大倍数 $\approx -\frac{g_{m1}}{g_{m2}} = \sqrt{\frac{u_n(W/L)_1}{u_2(W/L)_2}}$，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，过驱动电压 $|V_{gsp}-U_{thp}|$ 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 $\rightarrow I_{T2} = \frac{1}{5}I_{T20} \rightarrow g_{m2} = \frac{1}{5}g_{m20}$，$V\uparrow$ ⑤x

(2) $V_1 = \frac{I_3 - I_4}{I_1 - I_2} = \frac{I_3 - I_4}{I_7 - I_6} = \frac{\sqrt{\beta_A \cdot I_0} \cdot U_Z \cdot \sqrt{1 - \frac{\beta_A}{4 I_0} \cdot U_Z^2}}{\sqrt{\beta_B \cdot I_{01}} \cdot U_Z \sqrt{1 - \frac{\beta_B}{4 \cdot I_{01}} U_Z^2}}$, $I_{01} = I_0 - 2n I_0$

$\beta_A \sim I_0$, $\beta_B \sim I_{01}$. $\frac{\beta_A}{\beta_B} = \frac{I_0}{I_{01}} = \frac{1}{1-2n} = V_1 \rightarrow n = \frac{1}{2}(1 - \frac{1}{V_1})$

3) $\boxed{V_1 = \frac{\sqrt{\beta_A I_0} \cdot U_Z \cdot \sqrt{1 - \frac{\beta_A}{4 I_0} U_Z^2}}{\sqrt{\beta_C I_0} \cdot U_e \sqrt{1 - \frac{\beta_C}{4 \cdot I_0} U_e^2}}}$

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

$\hat{I}_a = V_i \cdot g_T \, U_e = V_i \cdot \sqrt{\beta_c I_0} \cdot U_e$.

$\Rightarrow \beta_c = \frac{I_0}{(V_i \cdot \hat{U}_e)^2}$

$HD_3 = \frac{1}{32} \cdot \frac{1}{(V_1)^2} = \frac{1}{32} \cdot \frac{1}{(1-2n)^2}$

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

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

W/L $\beta = \frac{I_0}{(V_i \cdot U_e)^2} / K_P = 100$.

TK-04.

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

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

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

$\rightarrow \beta = 606.1 \frac{mA}{V^2} \rightarrow \frac{W}{L} = \beta / K_P = 6.06$

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

(3)

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

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

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

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

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

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

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

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

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

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

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

$\hat{I}_{a,max} = 72.7 mA$.

TK-05.

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

$= U_T \ln(\frac{I_C}{I_S}) + I_C \cdot R_E$.

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

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