Triodenbereich: $V_{DS} < V_{GS} - V_{th}$, $\underline{I_D} = \frac{W}{L} k_n \left(V_{GS} - V_{th} - \frac{1}{2} V_{DS}\right) V_{DS}$

$g_{DS} = \frac{W}{L} k_n (V_{GS} - V_{th})$ nur bei Transmission

$\underline{g_m} = \frac{W}{L} k_n V_{DS}$ p-MOS: $g_m = -k_p \frac{W}{L} V_{DS}$

Sättigung: $V_{DS} > V_{GS} - V_{th}$, $\underline{I_D} = \frac{1}{2} \frac{W}{L} k_n (V_{GS} - V_{th})^2$

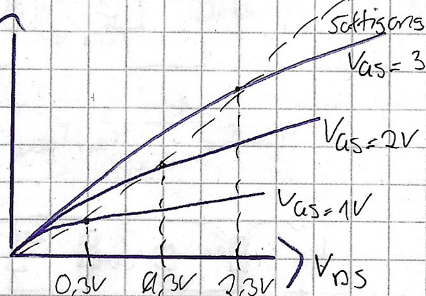
$\underline{g_m} = \frac{W}{L} k_n (V_{GS} - V_{th})$ $(k_n \Rightarrow -k_p)$

$\underline{g_{DS}} = \frac{1}{2} \frac{W}{L} k_n (V_{GS} - V_{th})^2 \lambda \frac{L_{min}}{L} = I_D \lambda \frac{L_{min}}{L}$ $(k_n = 5 k_p)$

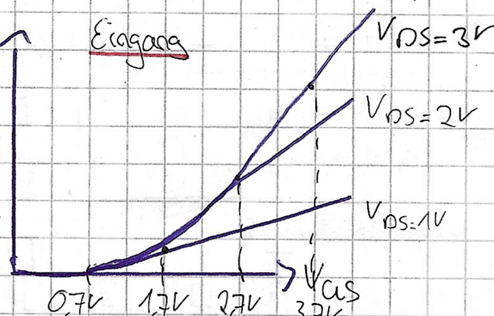
Unterschwell: $V_{GS} < V_{th}$, $\underline{I_D} = \frac{W}{L} I_{D,0} 10^{\frac{(V_{GS} - V_{th})}{S}} \left[1 - \exp\left(-\frac{V_{DS}}{kT/q}\right)\right]$

Kennlinien:

Ausgang:

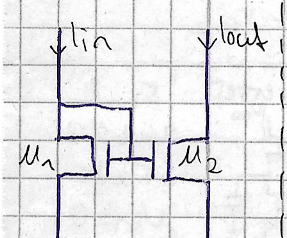


Eingang

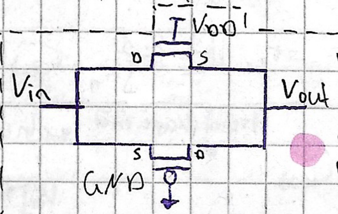


C: $I = j\omega C U$

L: $U = j\omega L I$



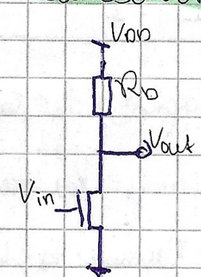
$\frac{I_{out}}{I_{in}} = \frac{(W/L)_2}{(W/L)_1}$



$V_{in} \approx V_{out} \Rightarrow$ lin. Bereich $(V_{DS} \approx 0)$

Für versch. V_{in}: Welcher ist On?

Sourceschaltung: Source auf Masse



$V_{out} = -g_m V_{in} \underbrace{\frac{r_{DS} R_D}{r_{DS} + R_D}}_{= (r_{DS} \| R_D) = r_{aus}}$

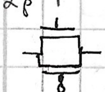
$\left(\approx -g_m V_{in} R_D \quad (r_{DS} \gg R_D)\right)$

$r_{ein} = R_G \approx \infty$

$g_{ds,n} = \frac{W_n}{L_n} k_n (V_{DD} - V_{in} - V_{th})$

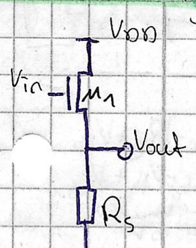
$g_{ds,p} = \frac{W_p}{L_p} k_p (|-V_{in}| - |V_{th,p}|)$

für



Sätt.: $g_m = \frac{2 I_{in}}{V_{GS} - V_{th}}$

Drainschaltung: Drain auf festem Potential



$\frac{V_{out}}{V_{in}} = \frac{g_m}{g_m + \frac{1}{r_{DS}} + \frac{1}{R_S}}$

$\approx 1 \quad \left(g_m \gg \frac{1}{r_{DS}}, \frac{1}{R_D}\right)$

$r_{out} \approx \frac{1}{g_{m_1}}$ (Knotengleichung)

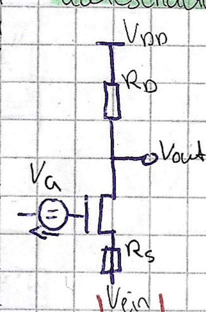
$r_{out} = \left(\frac{1}{g_m} \| R_S\right)$

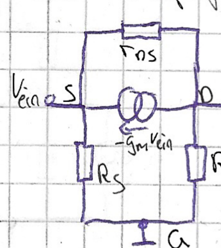
$r_{ein} = R_G \approx \infty$

siehe Rückseite ↗

(mit aktiver Last: $r_{out} = r_{DS1} \| r_{DS2} \| \frac{1}{g_{m_{21}}}$)

Gateschaltung: Gate auf festem Potential



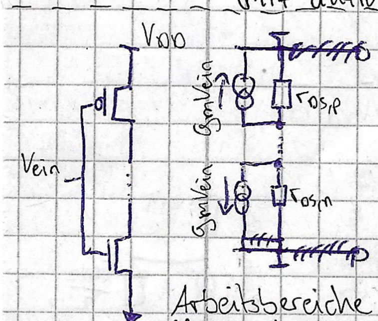


$r_{ein} \approx \frac{1}{g_m}$

$r_{aus} \approx R_D$

$r_{out} = (R_D \| r_{DS})$

$\frac{V_{out}}{V_{ein}} \approx g_m (R_D \| r_{DS}) = g_m \frac{R_D r_{DS}}{R_D + r_{DS}} \quad (\approx g_m R_D)$



Arbeitsbereiche unterscheiden!

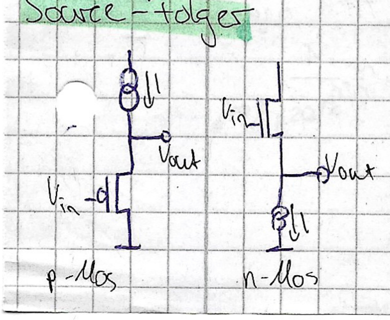
Frequenzen: $\phi(A(\omega)) = \arctan\left(\frac{\mathrm{Im}(A(\omega))}{\mathrm{Re}(A(\omega))}\right)$ ← Phase

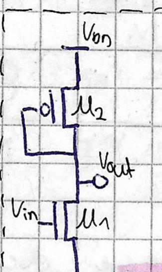
$A(\omega) = \frac{V_{out}}{V_{in}}$

~~Bandbreit~~ Verstärkungs-Bandbreite-Produkt

... ist definiert durch die Frequenz $f_0 \left(= \frac{\omega_0}{2\pi}\right)$, bei der $A(\omega_0) = 1$ ist.

Source-Folger





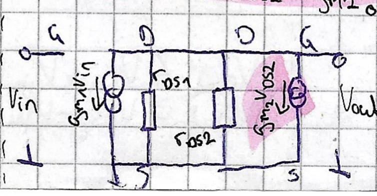
$V_{out} = V_{DD} - |V_{GS2}|$

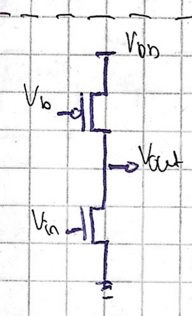
$\frac{V_{out}}{V_{in}} = -g_{m_1} \left(r_{DS1} \| r_{DS2} \| \frac{1}{g_{m_2}}\right)$

$\approx -\frac{g_{m_1}}{g_{m_2}} \quad \left(\frac{1}{g_{m_2}} \gg \ldots\right)$

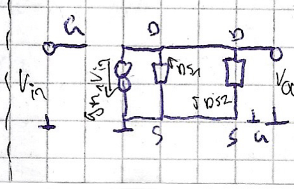
$r_{out} = \left(r_{DS1} \| r_{DS2} \| \frac{1}{g_{m_2}}\right) \approx \frac{1}{g_{m_2}}$

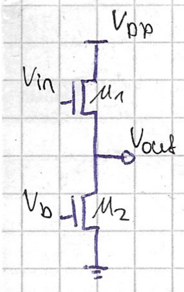
aber: $g_{m_2} V_{DS2} \Rightarrow \frac{1}{g_{m_2}}$ V





$\frac{V_{out}}{V_{in}} = -g_m \underbrace{(r_{DS1} \| r_{DS2})}_{= r_{out}}$



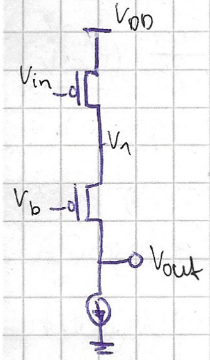


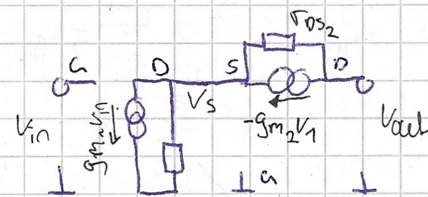
$V_{out} = g_{m1}(V_{in}-V_{out})(r_{DS1}\|r_{DS2})$

$= \frac{g_{m1}(r_{DS1}\|r_{DS2})}{1+g_{m1}(r_{DS1}\|r_{DS2})} \approx 1$

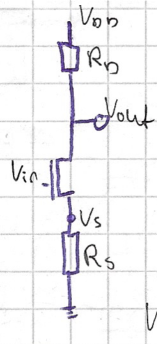
$r_{out} = \frac{V_X}{I_X} = \frac{r_{DS1}\|r_{DS2}}{1+g_{m1}(r_{DS1}\|r_{DS2})} \approx \frac{1}{g_{m1}}$

$(r_{out} = r_{DS1}\|r_{DS2}\|\frac{1}{g_{m1}})$



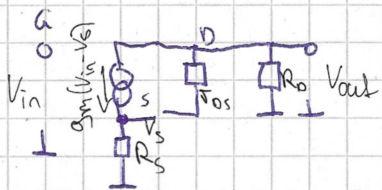


$r_{out} = \; '' \; \approx g_{m2} r_{DS2} r_{DS1}$ $(R_D=\infty, R_S=r_{DS1})$



$\frac{V_{out}}{V_{in}} = -\frac{g_m r_{DS} R_D}{r_{DS}+R_D+R_S(1+g_m r_{DS})}$

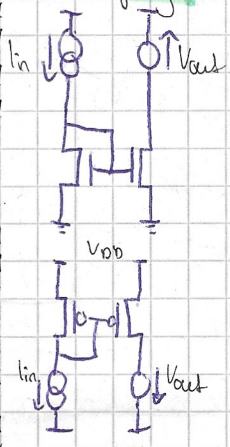
$\approx -\frac{g_m R_D}{1+g_m R_S}$

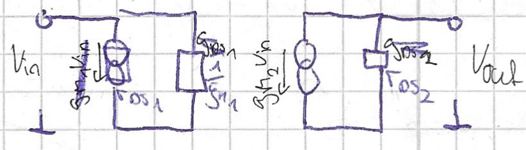


$r_{out} = R_D \| (g_m r_{DS} R_S + r_D + R_D)$

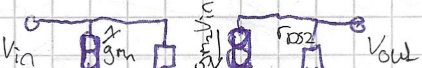
$\approx R_D \quad (R_D \ll \dots)$

Stromspiegel



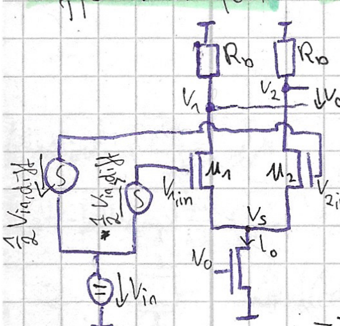


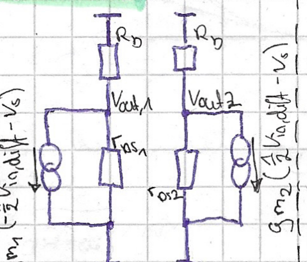
$r_{ein} = \frac{1}{g_{m1}+g_{DS1}} = \frac{1}{g_{m1}}$, $r_{out} = \frac{1}{g_{DS2}}$



$r_{in} = r_{DS1}\|\frac{1}{g_{m1}} \approx \frac{1}{g_{m1}}$ $\quad r_{out} = r_{DS2}$

Differenzstufen: Diff-Verstärker





$\rightarrow V_S = 0$

$V_{out,diff} = V_{2out} - V_{1out} \Rightarrow \frac{V_{out,diff}}{V_{in,diff}} = -g_m(R_D\|r_{DS1})$

treibt Kapazität

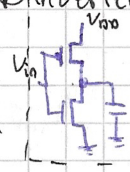
Verzögerung: $t_d \sim r_{DS} C_{Load}$

$P_{dynamic} = V_{dd}^2 \cdot f_{clock} \cdot C_{Load} = \frac{1}{t_d} \cdot V_{dd}^2 \cdot C_{Load}$

$E = P_{dynamic} \cdot t_d = V_{dd}^2 \cdot C_{Load}$

$\frac{E_1}{E_2} < 0 \rightarrow E_1 < E_2$

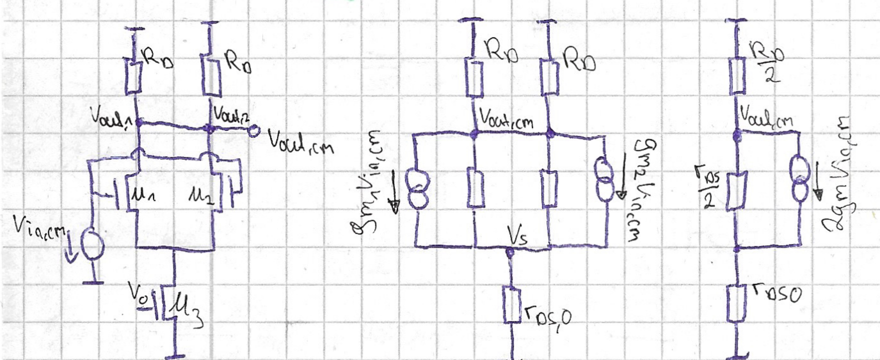
Inverter



r_{in}: $V_{out} \neq 0$

r_{out}: $V_{in} = 0$

Gleichtaktverstärker

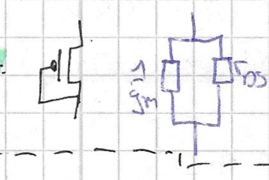


$\frac{V_{out}}{V_{in}}$ = siehe oben

$V_{OS} = V_{in2} - V_{in1} = V_{th1} - V_{th2}$

$= -\frac{R_D}{2r_{ds3}}$ (auch bei P-MOS)

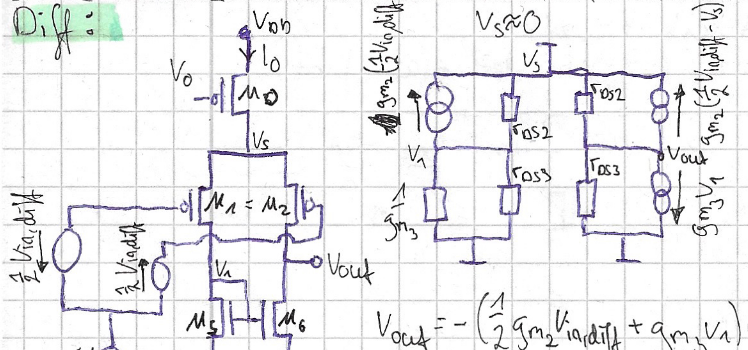
Diodenlast:



$V_{in} \le V_{DD} - |R_D| + V_{th}$

$V_{in} \ge V_{GS0} - V_{th0} + V_{GS1}$ über I_0?

Diff:



$V_{out} = -(\frac{1}{2} g_{m2} V_{in,diff} + g_{m3} V_1)(r_{DS2}\|r_{DS3})$

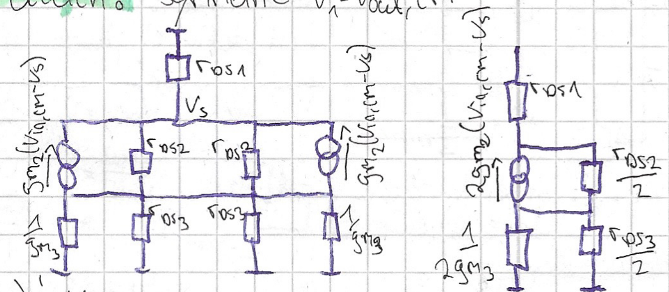
$= -g_{m2} V_{in,diff}(r_{DS2}\|r_{DS5})$

Für Sättigung: $V_{in} \le V_{DD} - |V_{GS1}| - |V_{GS0}| + V_{th}$

$V_{in} \ge V_{GS5} - V_{th}$

Gleich:

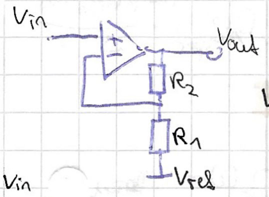
Symmetrie $V_1 = V_{out,cm}$



$\frac{V_{out,cm}}{V_{in,cm}}$ = siehe oben $\approx -\frac{1}{2 r_{DS1} g_{m3}}$

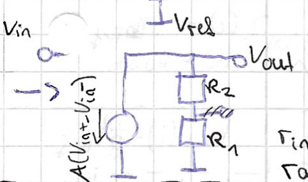
$V_{out} \le V_{in} + V_{th}$

$V_{out} \ge V_{GS6} - V_{th}$



$$\frac{V_{out}-V_{ref}}{V_{in}-V_{ref}} = 1+\frac{R_2}{R_1}$$

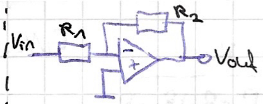
$V_{out} = A(V_{in^+} - V_{in^-})$



Nicht invert. Verstärker

$r_{in} = \infty$

$r_{aus} = 0$



$$\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}$$

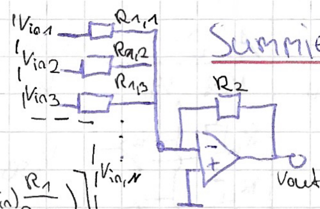
$$V_{out} = A\left[0-\left(V_{ein}+(V_{out}-V_{ein})\frac{R_1}{R_1+R_2}\right)\right]$$

$r_{in} = R_1$

$r_{aus} = 0$

Invertierend Verstärker

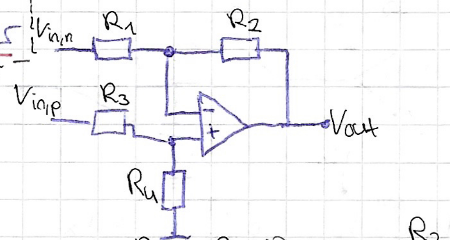
Instrumentenverstärker siehe AB



Summierer

$$V_{out} = -\sum_{k=1}^{N} V_{in,k}\frac{R_2}{R_{1,k}}$$

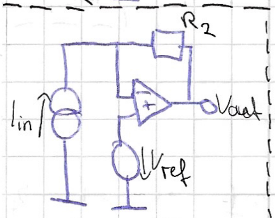
$r_{ein,k} = R_{1,k}$



$$V_{out} = V_{in,p}\frac{R_4}{R_4+R_3}\cdot\frac{R_1+R_2}{R_1} - V_{in,n}\frac{R_2}{R_1}$$

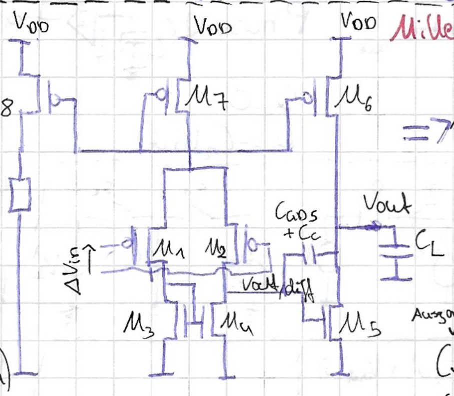
Differenzverstärker

Mit Spannungsfolgern am Eingang $r_{in} \to \infty$

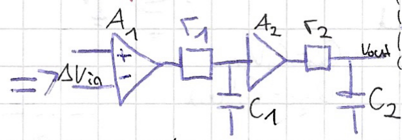


$V_{out} = V_{ref} - I_{in}R_2$

Miller-Op



$$\frac{V_{out,diff}}{V_{in}} = -g_{m1}(r_{DS2}\|r_{DS4})$$



$$f_1 = \frac{1}{2\pi r_1 C_1},\quad r_1 = (r_{DS2}\|r_{DS4})$$

$$A_1 = \frac{V_{out}}{V_{out,diff}} = -g_{m5}(r_{DS5}\|r_{DS6})$$

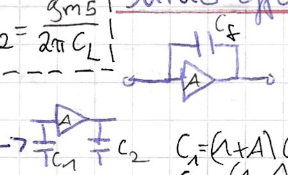
Ausgangs Verstärkung

$C_x = C_1 = (C_{GD5}+C_C)(1+A)$

$C_{out} = C_L + C_2$

$$f_2 = \frac{g_{m5}}{2\pi C_L}$$

Millers Effekt



$C_1 = (1+A)C_F$

$C_2 = (1+\frac{1}{A})C_F$

$$A(f) = \frac{A_0}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})}$$

$$A_0 = A_1\cdot A_2 = g_{m2}(r_{DS2}\|r_{DS4})\,g_{m5}(r_{DS5}\|r_{DS6})$$

Verstärkung: $G = 80\,dB = 20\log(x) \Rightarrow x = 10^4$

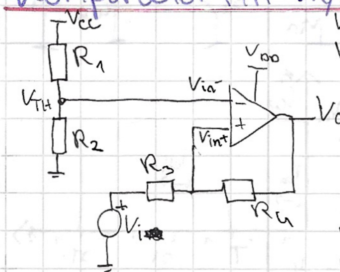
Phasenreserve bei $A=0$

BW bis f_1

Bei $V_i < V_L$ ist $V_{i+} = V_H$ $\Rightarrow V_H = V_{CC}\frac{R_3+R_4}{R_4}\cdot\frac{R_2}{R_1+R_2}$

Bei $V_i > V_H$ ist $V_{i+} = V_L$ $\Rightarrow V_L = V_{CC}\frac{R_2}{R_2+R_3}\left(1+\frac{R_3}{R_4}\right) - \frac{R_3}{R_4}V_{CC}$

Komperator mit Hysterese



$V_{in} < V_L \to V_o = 0$

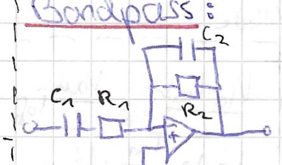
$V_{in} > V_H \to V_o = V_{CC}$

$V_{HYS} = V_H - V_L = \frac{R_3}{R_4}V_{CC}$

A Eingangsverstärkung:
$A > -g_{m2}(r_{DS2}\|r_{DS4})$

Komperator: V_{TH} meist zw. V_L & V_H

Bandpass:



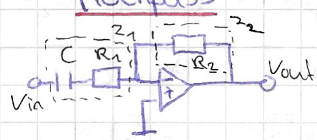
$$H(j\omega) = \frac{R_2}{R_1}\cdot\frac{-j\omega R_1C_1}{1+j\omega R_1C_1}\cdot\frac{1}{1+j\omega R_2C_2}$$

$$= A_0\frac{-j\frac{\omega}{\omega_1}}{(1+j\frac{\omega}{\omega_1})(1+j\frac{\omega}{\omega_2})}$$

$\omega_1 = \frac{1}{R_1C_1}$ $\quad\omega_2 = \frac{1}{R_2C_2}$

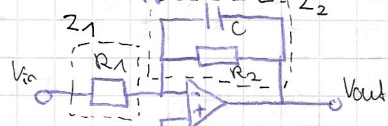
$|H(j\omega)| = A_0 = \frac{R_2}{R_1}$

Hochpass

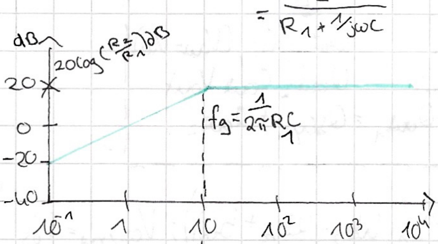


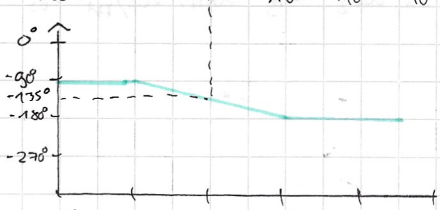
$$\frac{V_{aus}}{V_{in}} = H(j\omega) = -\frac{Z_2(j\omega)}{Z_1(j\omega)} = \frac{-R_2}{R_1+1/j\omega C}$$

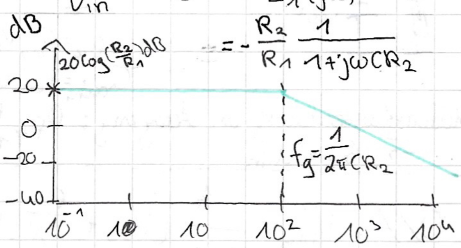
Tiefpass

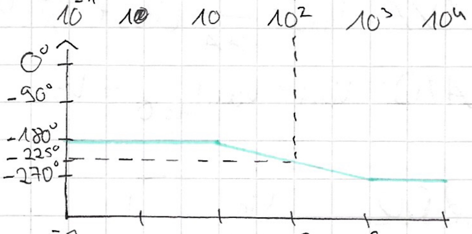


$$\frac{V_{aus}}{V_{in}} = H(j\omega) = -\frac{Z_2(j\omega)}{Z_1(j\omega)} = -\frac{R_2}{R_1}\cdot\frac{1}{1+j\omega CR_2}$$









Wenn kein „-" in $H(j\omega)$, dann Phase um 180° nach oben verschieben

Allgemein Verstärker:

$A \to \infty$: $V_{out} = A\cdot V_{in}$

A endlich: $V_{out} = A(V_{in+} - V_{in-})$

Offset: $V_{out} = V_{out}|_{V_{os}=0} + V_{out}|_{V_{in}=0}$

$$H(j\omega) = -\frac{R_2}{R_1}\cdot\frac{1}{1+(\frac{1}{\omega R_1C})^2}\left(1-\frac{j}{\omega R_1C}\right)$$

$$|H(j\omega)| = \frac{R_2}{R_1}\cdot\frac{1}{\sqrt{1+(\frac{1}{\omega R_1C})^2}}$$

$$\varphi(H(j\omega)) = -180° + \arctan\left(\frac{1}{\omega CR_1}\right)$$

$$H(j\omega) = -\frac{R_2}{R_1}\cdot\frac{1}{1+(\omega CR)^2}(1-j\omega CR_2)$$

$$|H(j\omega)| = \frac{R_2}{R_1}\cdot\frac{1}{\sqrt{1+(\omega CR)^2}}$$

$$\varphi(H(j\omega)) = -180° + \arctan(-\omega CR_2)$$

Invertierender Verstärker mit Offset:

$A \to \infty$: $V_{out} = -\frac{R_2}{R_1}V_{in} + \left(1+\frac{R_2}{R_1}\right)V_{os}$

$$A \text{ endlich: } V_{out} = -\left(\frac{R_2}{R_1}\right)\frac{1}{1+\frac{1}{A}(1+\frac{R_2}{R_1})}V_{in} + \left(1+\frac{R_2}{R_1}\right)\frac{1}{1+\frac{1}{A}(1+\frac{R_2}{R_1})}V_{os}$$

Rail-to-Rail: $V_{out,max} \widehat{=}$ Versorgungsspannung

Miller Op: Wenn als Spannungsfolger:

$V_{in} \le V_{DD} - |V_{GS7}| - |V_{GS1}| + V_{th}$ $\qquad V_{out} \ge V_{GS5} - V_{th}$

$V_{in} \ge V_{GS3} - V_{th}$ $\qquad V_{out} \le V_{DD} - |V_{GS6}| + V_{th}$

$R_L > \frac{V_{out}}{I_{D6}}$ $\qquad V_{in} \overset{!}{=} V_{out}$