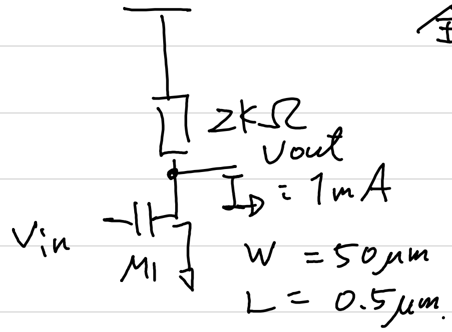
入力換算雑音電圧の導出 を目標とする。

問題(7.1)



左図で帯域幅を100 MHzとした時の
全入力換算熱雑音電圧は.

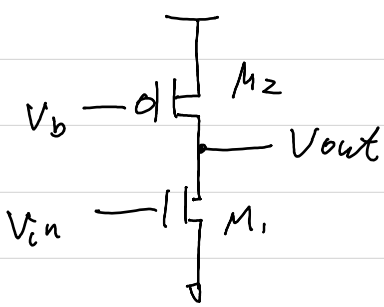
$$\overline{V_{out}^2} = 4kT\left(\frac{2}{3}g_{m1} + \frac{1}{R_D}\right)R_D^2$$

$|A_v| = g_{m1} R_D$ なので

1Hzあたりの $\overline{V_{n,in}^2}$ は

$$\overline{V_{n,in}^2} = 4kT\left(\frac{2}{3g_{m1}} + \frac{1}{g_{m1}^2 R_D}\right)$$

問題(7.2)



入力換算電圧は、

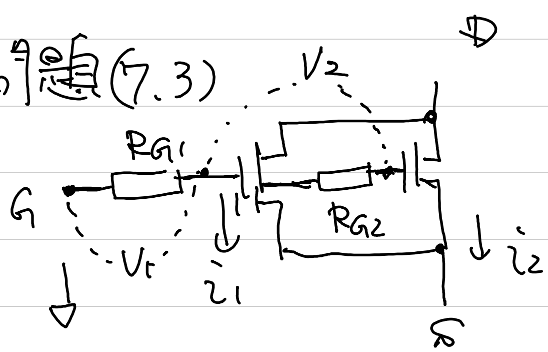
$$\overline{V_{n,in}^2} = 4kT\frac{2}{3}\frac{1}{g_{m1}}\left(1+\frac{g_{m2}}{g_{m1}}\right)$$

$(= r_0)$

∵ $R_D \approx \frac{1}{g_{m2}}$ なので

問題(7.1)の式に代入すれば良い。

問題(7.3)



$$R_G = R_{G1} + R_{G2} + \cdots$$

$$i_{total} = i_1 + i_2 + \cdots + i_n$$

$$= g_{m1}V_1 + g_{m2}(V_1+V_2) + \cdots$$

$$= \frac{g_m}{n}\{nV_1 + (n-1)V_2 + \cdots + V_n\}$$

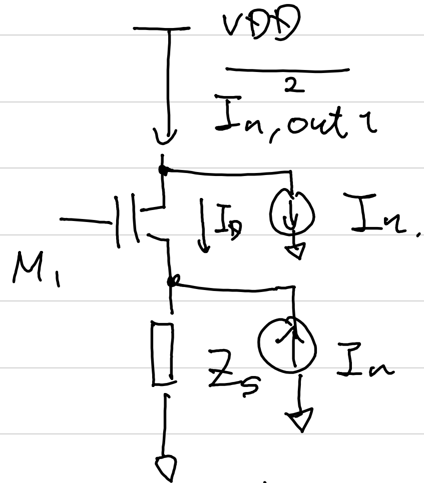
ここで $g_{m1} = g_{m2} = \frac{g_m}{n}$ とする。

$\overline{V_1^2} = \overline{V_2^2} = \cdots = \overline{V_n^2} = 4kT\frac{R_G}{n}$ とおくことで

$$i_{total} = 4kT\frac{R_G}{n}\left(\frac{g_m}{n}\right)^2\{n^2+(n-1)^2+\cdots+1\} \overset{n\to\infty}{\Longrightarrow} 4kT\left(\frac{R_G}{3}\right)g_m^2$$

(教) P.272 の補助定理.

問題(7.4)　左図の出力雑音電流を求める。



$$I_{n,out1} = I_D + I_n \quad \text{(KCL@drain)}$$

$$I_D = (-)\frac{Z_s}{\left(\frac{1}{g_{m1}} // r_{o1}\right) + Z_s} I_n$$

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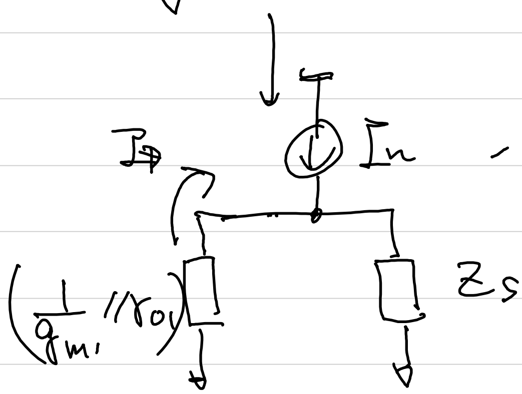
符号がマイナスなのに注意する.



上式より

$$I_{n,out1} = I_n\left(1 - \frac{Z_s}{\left(\frac{1}{g_{m1}} // r_{o1}\right) + Z_s}\right)$$

$$1 - \frac{Z_s}{Z_s + \frac{1}{\left(g_{m1} + \frac{1}{r_{o1}}\right)}}$$

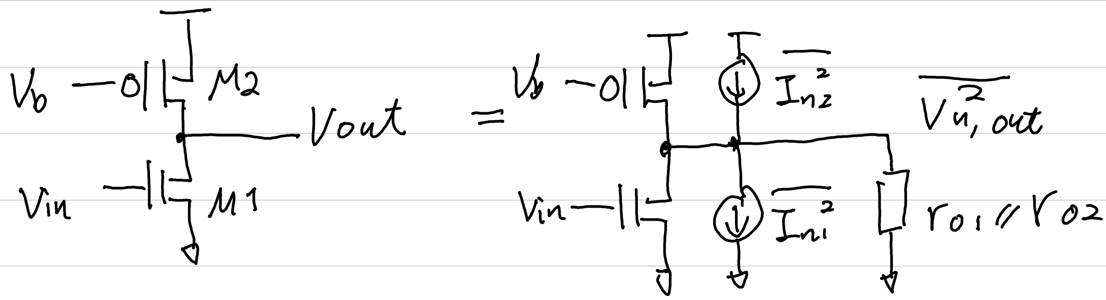
$\left(g_{m1} + \frac{1}{r_{o1}}\right)$ を A と置く.

$$\frac{Z_s \times A}{\left(Z_s + \frac{1}{A}\right)\times A} = \frac{AZ_s}{AZ_s + 1}$$

$$1 - \frac{AZ_s}{AZ_s+1} = \frac{AZ_s + 1 - AZ_s}{AZ_s+1} = \frac{1}{AZ_s+1}$$

∴ (7.54)の $I_{n,out1} = \dfrac{I_n}{Z_s\left(g_{m1} + 1/r_{o1}\right) + 1}$ が導出できる。

問題(7.5) 式[7.59]を求めるための回路は.



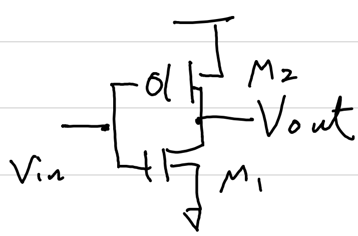
$$\overline{V_{n,out}^2} = 4kT\left(\frac{2}{3}g_{m1}+\frac{2}{3}g_{m2}\right)(r_{o1}\|r_{o2})^2$$

$A_v = g_{m1}\cdot(r_{o1}\|r_{o2})$ で割って

$$\overline{V_{n,in}^2} = 4kT\left(\frac{2}{3g_{m1}}+\frac{2}{3}\frac{g_{m2}}{g_{m1}^2}\right) \quad \cdots\cdots [7.59]$$

M2は電流源なので g_{m2} を最小にしなければならない.

次に以下の回路の入力換算雑音電圧を求める。



回路の利得は $|A_v| = (g_{m1}+g_{m2})(r_{o1}\|r_{o2})$

と与えられる

$$\overline{V_{n,out}^2} = 4kT\frac{2}{3}(g_{m1}+g_{m2})(r_{o1}\|r_{o2})^2$$

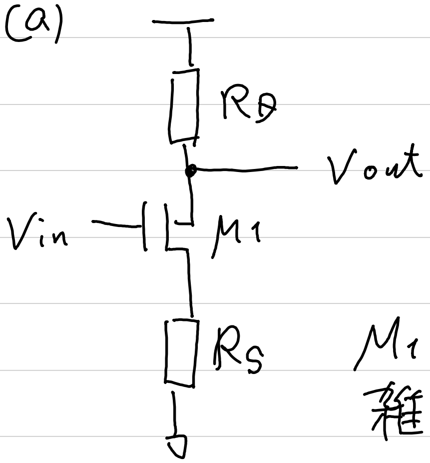
は先程と同じ.

$$\therefore \quad \overline{V_{n,in}^2} = \frac{\overline{V_{n,out}^2}}{|A_v^2|} = 4kT\frac{2}{3}\left(\frac{1}{g_{m1}+g_{m2}}\right)$$ となる.

従って g_{m2} の増加に対して inverterでは雑音が減少し.
ソース接地では雑音が増加する。

問題(7.6)

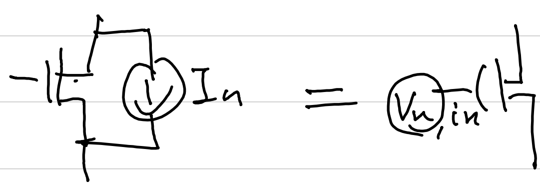
(a)



回路の利得は $|A_v| = \dfrac{g_{m1}R_D}{1+g_{m1}R_S}$

(3.57)参照。

M_1の雑音は補助定理によって
雑音電流をゲート電圧に換算し、



$\left(\overline{V_{n,in}^2} = 4kT\dfrac{2}{3}\dfrac{1}{g_{m1}}\right)$

かつ回路の利得を乗ずることで

$\overline{V_{n,out,M_1}^2} = 4kT\dfrac{2}{3}\dfrac{1}{g_{m1}}A_v^2$ となる。

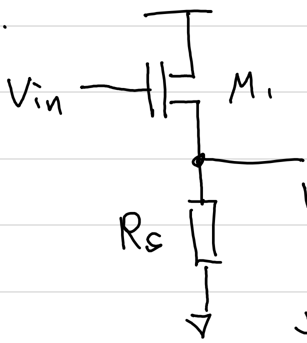
R_Dの雑音は
$\overline{V_{n,out,R}^2} = 4kTR_D$.

$4kTR_S$ が A_v倍に増幅される
と考える。

R_Sの寄与は $\overline{V_{n,out,R_S}^2} = \boxed{4kT\dfrac{1}{R_S}\left(\dfrac{R_S}{\frac{1}{g_{m1}}+R_S}\right)^2 R_D^2}$

∴ $\overline{V_{n,in}^2} = \dfrac{\overline{V_{n,out}^2}}{|A_v|^2} = 4kT\dfrac{2}{3}\dfrac{1}{g_{m1}} + 4kTR_S$
$+ 4kTR_D\left(\dfrac{1+g_{m1}R_S}{g_{m1}R_D}\right)^2$

(b).

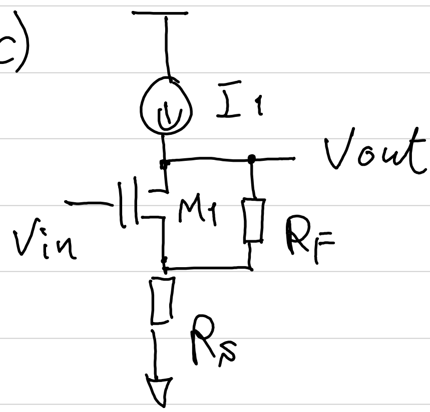


$$|A_v| = g_m \cdot \left(\frac{1}{g_{m1}} /\!/ R_s\right)$$

$$\overline{V_{n,out}^2} = \left(4kT\frac{2}{3}g_m + 4kT\frac{1}{R_s}\right)\left(\frac{1}{g_m} /\!/ R_s\right)^2$$

$$\therefore \overline{V_{n,in}^2} = \frac{\overline{V_{n,out}^2}}{|A_v|^2} = 4kT\frac{2}{3}\frac{1}{g_m} + 4kT\frac{1}{g_m^2 R_s}$$

(c)

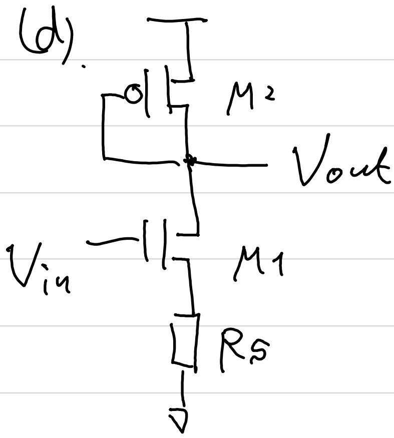


$$|A_v| = \frac{g_m}{1 + \left(g_m + \frac{1}{R_F}\right)R_s} \cdot R_{out}$$

(これは (a) の $|A_v|$ の分母と同じ)

$$R_{out} = R_s + (1 + g_m R_s) R_F.$$

(d).



$$|A_v| = \frac{g_{m1}}{1 + g_{m1} \cdot R_s} \cdot R_{out}$$

(教) (3.51) 参照.

$$R_{out} = \frac{1}{g_{m2}}$$

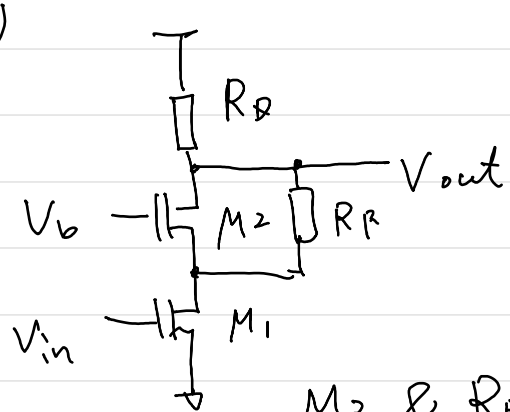
$$\overline{V_{n,out}^2} = 4kT\frac{2}{3}g_{m2}R_{out}^2 + 4kT\frac{2}{3}\frac{1}{g_{m1}}|A_v|^2 + 4kT\frac{1}{R_s}\left(\frac{R_s}{\frac{1}{g_{m1}} + R_s}\right)^2 R_{out}^2$$

前の(a)と同じ

M1の寄与 $\overline{V_{n1}^2} = \frac{\overline{I_{n1}^2}}{g_{m1}^2} = 4kT\left(\frac{2}{3}g_{m1}\right)/g_{m1}^2$

これが $|A_v|$ される で考える.

e)



$|A_v| = g_{m1} R_D$.

$\overline{V_{n,out}^2} = \left(4kT\frac{2}{3}g_{m1} + 4kT\frac{1}{R_D}\right)R_D^2$

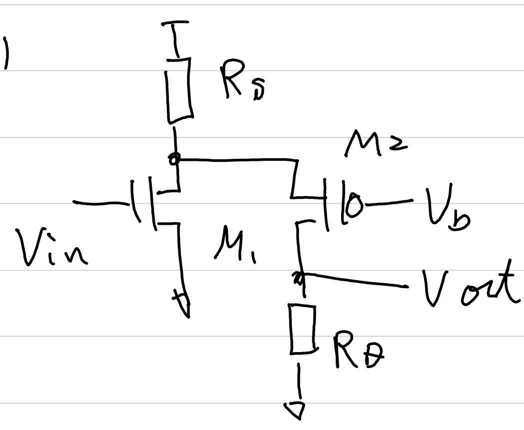
M_2 & R_F は（カスコード段は）noise に寄与しない。点に注意

$r_{o1} = \infty$.

$\overline{V_{n,in}^2} = \frac{\overline{V_{n,out}^2}}{|A_v|^2} = 4kT\left(\frac{2}{3}\frac{1}{g_{m1}} + \frac{1}{g_{m1}^2 R_D}\right)$

$r_{o1} = \frac{1}{g_{m1}} \sim \frac{1}{\lambda I_D}$

f)



$|A_v| = g_{m1}\underbrace{\left(\frac{g_{m2}R_S}{1+g_{m2}R_S}\right)}_{\text{カスコードの増幅率}}R_D$.

note : $\frac{R_S}{\frac{1}{g_{m2}}+R_S} = \frac{g_{m2}R_S}{1+g_{m2}R_S}$

$\overline{V_{n,out}^2} = \Big[\underbrace{4kT\frac{1}{R_D}}_{R_Dの寄与} + \underbrace{4kT\frac{2}{3}\frac{1}{g_{m2}}\left(\frac{g_{m2}}{1+g_{m2}R_S}\right)^2}_{\text{カスコードの寄与}} +$ $\left(\frac{2}{3}\frac{|A_v|^2}{g_{m1}}\right)$

$\underbrace{4kT\frac{2}{3}\frac{1}{g_{m1}}\left(\frac{g_{m1}R_S}{\frac{1}{g_{m2}}+R_S}\right)^2}_{M_1の寄与} + \underbrace{4kT\frac{1}{R_S}\left(\frac{R_S}{\frac{1}{g_{m2}}+R_S}\right)^2}_{R_Sの寄与}\Big]R_D^2$

$$\overline{V_{n,in}^2} = \frac{\overline{V_{n,out}^2}}{|A_v|^2} = 4kT\left[\frac{2}{3}\frac{1}{g_{m1}} + \frac{2}{3}\frac{1}{g_{m2}}\cdot\frac{1}{(g_{m1}R_S)^2} + \frac{1}{g_{m1}^2 R_S} + \frac{1}{g_{m1}^2 R_D}\left(\frac{1+g_{m2}R_S}{g_{m2}R_S}\right)^2\right] =$$

※[ ]内の カスコード段の寄与もM1の寄与と同様に

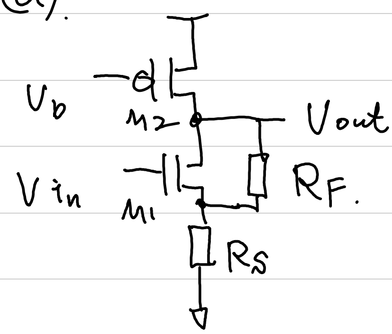
$$\underbrace{\left(\frac{g_{m2}}{1+g_{m2}R_2}\right)}_{|A_v|}\cdot R_S$$ から $\frac{2}{3 g_{m2}}|A_v|^2$ を

用いて

$$4kT\frac{2}{3}\frac{1}{g_{m2}}\left(\frac{g_{m2}}{1+g_{m2}R_S}\right)^2$$ と求まる

問題(7.7) 入力換算熱雑音電圧を求める。($\lambda=\gamma=0$を仮定)

(a).



左図は問題(7.6)の(c)と同じなので

$$|A_v| = \frac{g_{m1} R_{out}}{1+\left(g_{m1}+\frac{1}{R_F}\right) R_S}$$

$$R_{out} = R_S + (1+g_{m1}R_S)R_F.$$

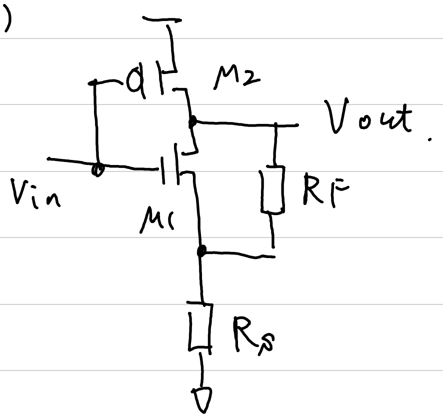
$$\overline{V_{n,out}^2} = \Bigg[\underbrace{4kT\frac{2}{3}\frac{g_{m1}}{\left(1+\left(g_{m1}+\frac{1}{R_F}\right)R_S\right)^2}}_{M_1\text{の寄与}} + \underbrace{\frac{4kT\frac{1}{R_F}}{\left(1+\left(g_{m1}+\frac{1}{R_F}\right)R_S\right)^2}}_{R_F\text{の寄与}}$$

$$+ \underbrace{\frac{4kT\frac{1}{R_S}\cdot R_S^2}{\left(R_S+\frac{1}{g_{m1}}/\!/R_F\right)^2}}_{R_S\text{の寄与}} + \underbrace{4kT\frac{2}{3}g_{m2}}_{M_2\text{の寄与}}\Bigg]\cdot R_{out}^2$$

$$\therefore \overline{V_{n,in}^2} = \frac{\overline{V_{n,out}^2}}{|A_v|^2}$$

$$= 4kT\left[\frac{2}{3}\frac{1}{g_{m1}} + \frac{1}{g_{m1}^2 R_F} + R_S\left(1+\frac{1}{g_{m1}R_F}\right)^2 + \frac{2}{3}g_{m2}\left(\frac{1+\left(g_{m1}+\frac{1}{R_F}\right)R_S}{g_{m1}}\right)^2\right] //$$

(b)



$$|A_v| = \left(g_{m2} + \frac{g_{m1}}{1+(g_{m1}+\frac{1}{R_F})R_S} \right) \cdot R_{out}$$

g_{m2}：M2からの寄与

$\frac{g_{m1}}{1+(g_{m1}+\frac{1}{R_F})R_S}$：M1からの寄与　前ページ(a)の式と同じ

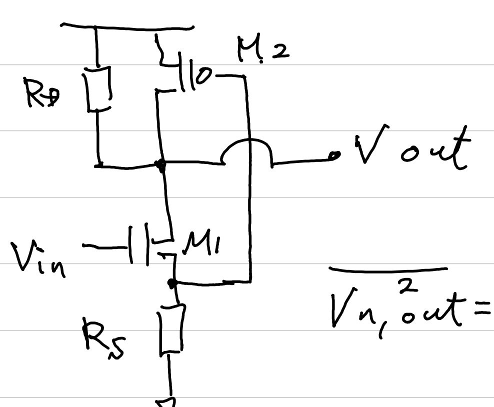
$$R_{out} = R_S + (1+g_{m1}R_S)R_F$$

$$\overline{V_{n,out}^2} = \left[\frac{4kT\frac{2}{3}g_{m1}}{(1+(g_{m1}+\frac{1}{R_F})R_S)^2} + \frac{4kT\frac{1}{R_F}}{(1+(g_{m1}+\frac{1}{R_F})R_S)^2} + \frac{4kT\frac{1}{R_S}\cdot R_S^2}{(R_S+\frac{1}{g_{m1}}/\!/R_F)^2} + 4kT\frac{2}{3}g_{m2} \right] \cdot R_{out}^2$$

↑ この式は前ページと全く同じ.

(難)

(c)



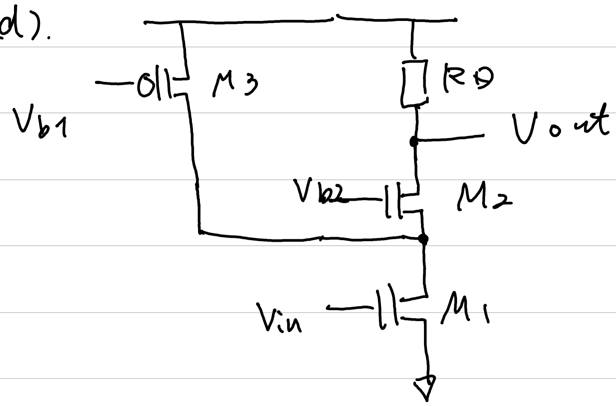
$$|A_v| = \left(\frac{g_{m1}}{1+g_{m1}R_S} \right) (1+g_{m2}R_S)R_D$$

(宿) これの導出.

$$\overline{V_{n,out}^2} = 4kTR_D + 4kT\frac{2}{3}g_{m2}R_D^{2} + 4kT\frac{2}{3}\frac{1}{g_{m1}}|A_v|^2 + 4kT\frac{1}{R_S}\left[\frac{R_S}{\frac{1}{g_{m1}}+R_S} - \frac{\frac{1}{g_{m1}}R_S}{\frac{1}{g_{m1}}+R_S} \cdot g_{m2} \right]^2 \cdot R_D^2$$

(宿) これの導出.

(d).



$$|A_v| = g_{m1} R_D.$$

$$\overline{V_{n,out}^2} = \left[4kT\frac{1}{R_D} + 4kT\frac{2}{3}g_{m3} + 4kT\frac{2}{3}g_{m1}\right] R_D^2$$

M2はノイズには寄与しない。$\because$ r_{o1}と$r_{o3} = \infty$

$$r_{o1} = \frac{1}{g_{m1}}$$

$$\overline{V_{n,in}^2} = \frac{\overline{|V_{n,out}^2|}}{|A_v|^2} = 4kT\left[\frac{2}{3}\frac{1}{g_{m1}} + \frac{2}{3}\frac{g_{m3}}{g_{m1}^2} + \frac{1}{g_{m1}^2 R_D}\right]$$

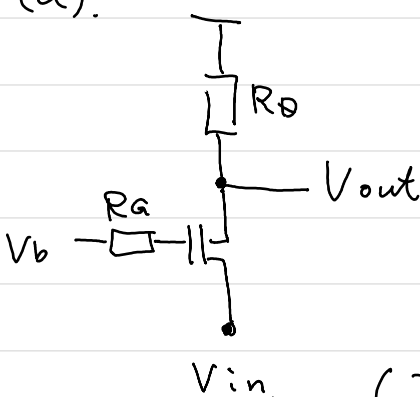
カスコード段はノイズに寄与しない！

(教) §7.4.4の議論を参照.

=

問題(7.8) 入力換算電圧の導出

(a).



$$|A_v| = g_{m1} R_D.$$

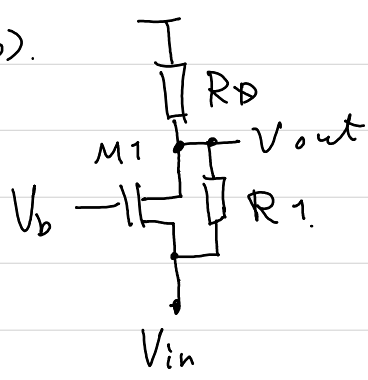
$$\overline{V_{n,out}^2} = \left[4kT\frac{1}{R_D} + 4kT\frac{2}{3}g_{m1} + 4kT R_G g_{m1}^2\right] R_D^2$$

(入力を短絡して出力端で観測されるノイズ)

一方入力を開放して出力端で観測される熱雑音電流は $\overline{I_{n,out}^2} = \frac{4kT}{R_D}$

この電流が入力にそのまま換算されて $\overline{I_{n,in}^2} = \frac{4kT}{R_D}$ となる。

(b).

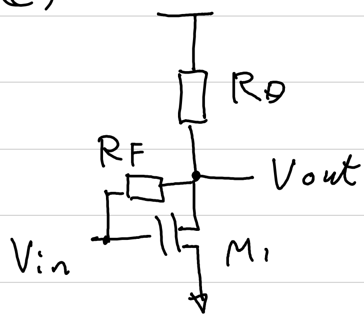


$$|A_v| = \left(g_{m1} + \frac{1}{R_1}\right)(R_1 \parallel R_D)$$

$$\overline{V_{n,out}^2} = \left[4kT\frac{1}{R_D} + 4kT\frac{1}{R_1} + 4kT\frac{2}{3}g_{m1}\right] \times (R_1 \parallel R_D)^2$$

$$\overline{V_{n,in}^2} = \frac{\overline{V_{n,out}^2}}{|A_v|^2} = 4kT\left(\frac{1}{g_{m1}+\frac{1}{R_1}}\right)^2\left[\frac{2}{3}g_{m1} + \frac{1}{R_1} + \frac{1}{R_D}\right] =$$

(c)



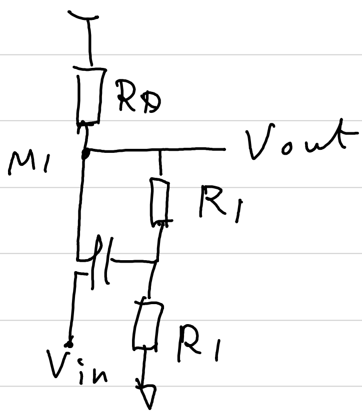
$$A_v = \left(-g_{m1} + \frac{1}{R_F}\right)(R_F /\!/ R_D)$$

$$\overline{V_{n,out}^2} = 4kT\left(\frac{1}{R_F} + \frac{1}{R_D} + \frac{2}{3}g_{m1}\right) \times (R_F /\!/ R_D)^2$$

$$\overline{V_{n,in}^2} = \frac{\overline{V_{n,out}^2}}{|A_v|^2} = 4kT\left(\frac{1}{-g_{m1} + \frac{1}{R_F}}\right)^2\left[\frac{2}{3}g_{m1} + \frac{1}{R_F} + \frac{1}{R_D}\right]$$

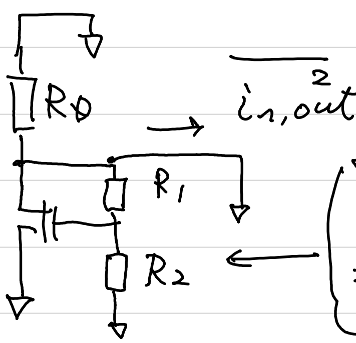
難

(d)



→

入力を短絡して得られる雑音電流



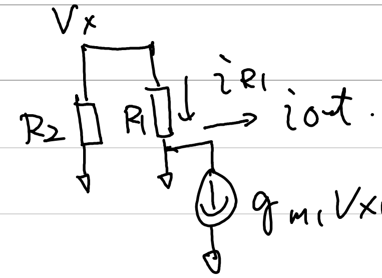
M1でR_1, R_2に流れる電流ノイズが増幅されるというイメージ

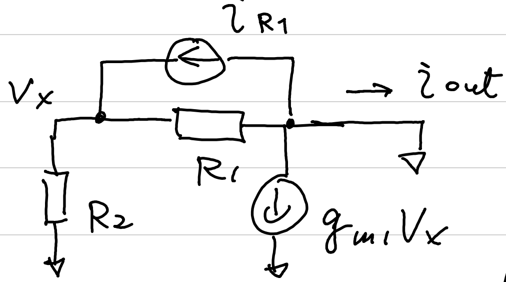
$$\overline{i_{n,out}^2} = 4kT\frac{1}{R_D} + 4kT\frac{2}{3}g_{m1} + \overline{i_{noiseR1}^2} + \overline{i_{noiseR2}^2}$$

$$\overline{i_{noiseR1}^2} = 4kT\frac{1}{R_1}|A_{I,R1}|^2$$

$$\overline{i_{noiseR2}^2} = 4kT\frac{1}{R_2}|A_{I,R2}|^2$$

次に $A_{I,R1}$ を求める.





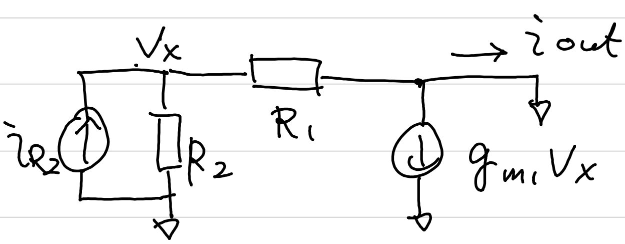
$$A_{I,R_1} = \frac{i_{out}}{i_{R_1}}$$

$$= -\left[1+(R_1/\!/R_2)\left(g_{m1}-\frac{1}{R_1}\right)\right]$$

~~($i_{out} = -(i_{R1} + g_{m1}V_x)$ ここの計算.~~

~~$i_{R1} = \frac{V_x}{R_2}$ $\longrightarrow$ $1+g_{m1}R_2$)~~

次に A_{I,R_2} を求める



$$A_{I,R_2} = \frac{i_{out}}{i_{R2}}$$

$$= \left[\frac{R_2}{R_1+R_2} - g_{m1}(R_1/\!/R_2)\right]$$

$$\therefore\ \overline{i_{n,out}^2} = 4kT\frac{1}{R_D} + 4kT\frac{2}{3}\cdot g_{m1} +$$

$$4kT\frac{1}{R_1}\left(1+(R_1/\!/R_2)\left(g_{m1}-\frac{1}{R_1}\right)\right)^2 +$$

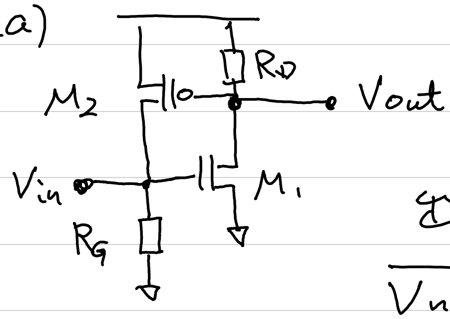
$$4kT\frac{1}{R_2}\left[\frac{R_2}{R_1+R_2} - g_{m1}(R_1/\!/R_2)\right]^2$$

$$\overline{V_{n,in}^2} = \frac{\overline{i_{n,out}^2}}{g_{m1}^2}$$

Razavi 演習　　　　　　　　　　　　23・01・11

問題7.9　入力換算電圧の計算（$\lambda=\gamma=0$とする）

(a)



$|A_v| = g_{m1} R_D$

出力端での雑音電圧は

$$\overline{V_{n,out}^2} = 4kT\left(R_D + \frac{2}{3} g_{m1} R_D^2\right)$$

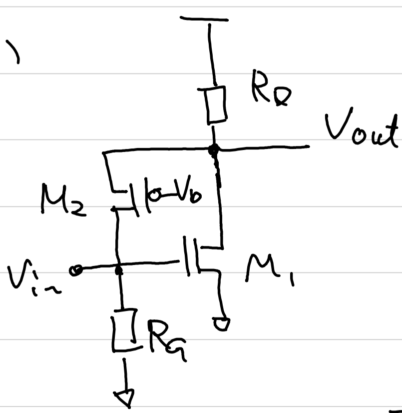
従って入力換算電圧は $\overline{V_{n,in}^2} = 4kT\left(\frac{1}{g_{m1}^2 R_D} + \frac{2}{3 g_{m1}}\right)$

一方入力換算電流は回路の入力インピーダンスR_Gに対して同じ出力雑音電圧を生じるので

$$\overline{I_{n,in}^2} = 4kT\left(\frac{R_D}{R_G^2} + \frac{2}{3} g_{m1} \frac{R_D^2}{R_G^2}\right)$$ である

$$\left(R_G^2 \cdot \overline{I_{n,in}^2} = \overline{V_{n,out}^2} \right)$$

(b)



出力端での雑音電圧は

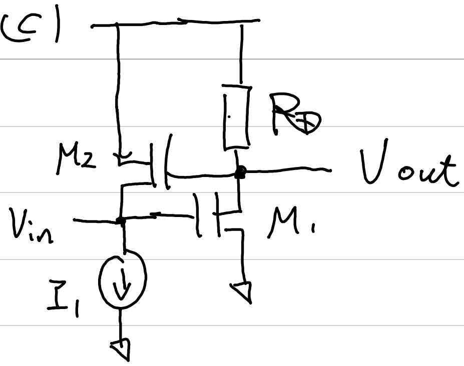
$$|A_v| = g_{m1}\left(R_D \parallel \frac{1}{g_{m2}}\right)$$

$$\overline{V_{n,out}^2} = 4kT\left(\frac{1}{R_D} + \frac{2}{3} g_{m1} + \frac{2}{3} g_{m2}\right)\left(R_D \parallel \frac{1}{g_{m2}}\right)^2$$

$$\overline{V_{n,in}^2} = \frac{\overline{V_{n,out}^2}}{|A_v|^2}$$ で求まる。

（$\frac{2}{3} g_{m1} + \frac{2}{3} g_{m2}$：トランジスタ2つの換算電流）

(c)



M2 は Vout がゲートにつながっているので
ゲインには影響しない (a)と同じ

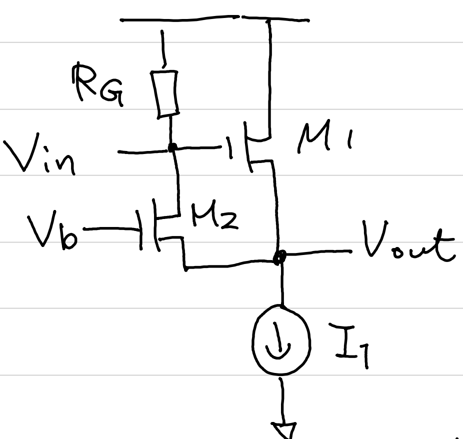
$$|A_v| = g_{m1} R_D$$

$$\overline{V_{n,out}^2} = 4kT\left(\frac{2}{3} g_{m1} + \frac{1}{R_D}\right) R_D^2$$

なので

$$\overline{V_{n,in}^2} = \frac{\overline{V_{n,out}^2}}{|A_v|^2} = 4kT\left(\frac{2}{3}\frac{1}{g_{m1}} + \frac{1}{g_{m1}^2 R_D}\right)$$

(d) (誤植)



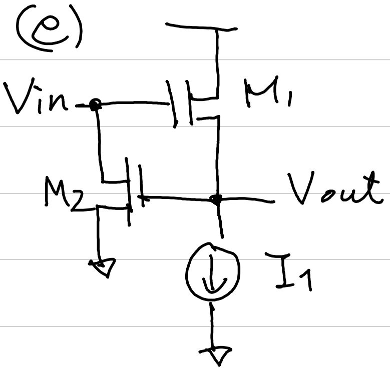
$$|A_v| = \frac{g_{m1}}{g_{m1} + g_{m2}} \quad \left(R_{out} = \frac{1}{g_{m1} + g_{m2}}\right.$$ トランスコンダクタンスは g_{m1})

$$\overline{V_{n,out}^2} = 4kT\left(\frac{2}{3} g_{m1} + \frac{2}{3} g_{m2}\right) \times \left(\frac{1}{g_{m1} + g_{m2}}\right)^2$$

おさらい

$$R_{out} = \left(\frac{1}{g_{m1}} \,/\!/\, \frac{1}{g_{m2}}\right) = \frac{1}{g_{m1} + g_{m2}}$$

(e)



ソースフォロワなので $|A_v| = 1$

$$\overline{V_{n,in}^2} = \overline{V_{n,out}^2} = 4kT \frac{2}{3 g_{m1}}$$

M2 は何の意味があるのか？
ゲートがVoutにつながっている時は出力雑音には
影響しない.

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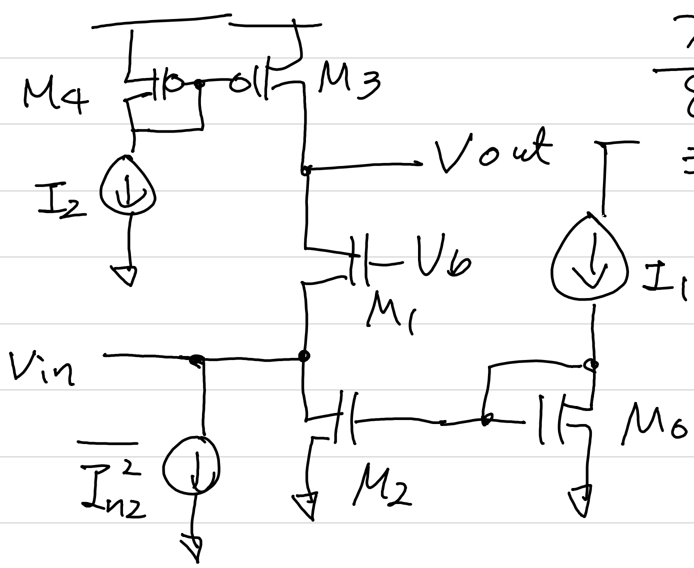
問題7.10 入力換算 1/f 雑音電圧の計算



入力端をグランドに接地して出力端における 1/f 雑音を求める。
(寄与はM1, M3, M4)

$$\overline{V_{n,out}^2} = \frac{1}{C_{ox} f}\left(\frac{K_n g_{m1}^2}{W_1 L_1} + \frac{K_p g_{m3}^2}{W_3 L_3} + \frac{K_p g_{m3}^2}{W_4 L_4}\right)(r_{o1} /\!/ r_{o3})^2$$

$|A_v| = (g_{m1} + g_{mb1})(r_{o1} /\!/ r_{o3})$ なので

$$\overline{V_{n,in}^2} = \frac{1}{C_{ox} f}\left[\frac{g_{m1}^2 K_n}{(W_1 L_1)} + \frac{g_{m3}^2 K_p}{(W_3 L_3)} + \frac{g_{m3}^2 K_p}{(W_4 L_4)}\right]\frac{1}{(g_{m1} + g_{mb1})^2}$$

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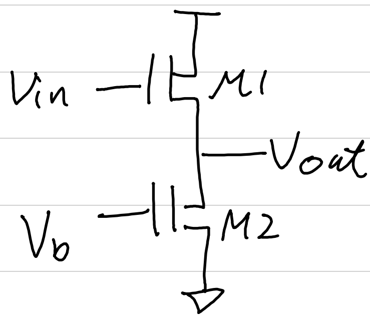
問題7.11 ソースフォロワの入力換算 1/f 雑音電圧の計算



$|A_v| = g_{m1} R_{out}$, p.88参照

$R_{out} = \left(\frac{1}{g_{m1}} // \frac{1}{g_{mb1}} // r_{o1} // r_{o2} \right)$ チャネル長変調

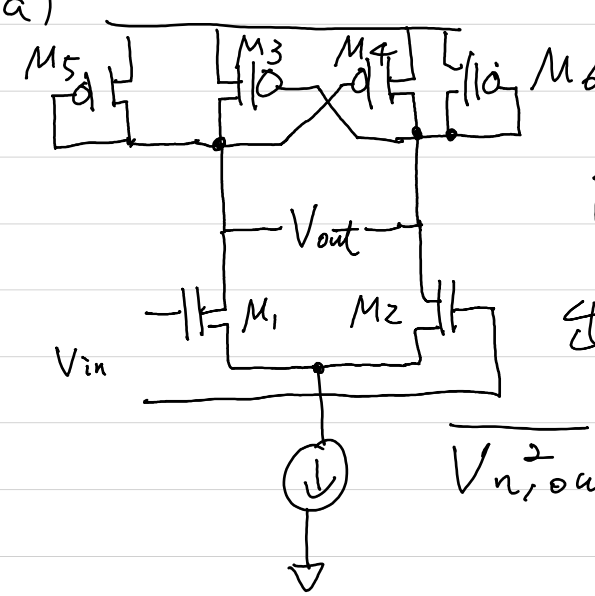
出力端における 1/f 雑音電圧は

$$\overline{V_{n,out}^2} = \frac{k_n}{C_{ox} f} \left(\frac{g_{m1}^2}{W_1 L_1} + \frac{g_{m2}^2}{W_2 L_2} \right) R_{out}^2$$

$$\therefore \overline{V_{n,in}^2} = \frac{k_n}{C_{ox} f} \left(\frac{1}{W_1 L_1} + \frac{g_{m2}^2}{W_2 L_2 g_{m1}^2} \right)$$

問題7.12 入力換算熱雑音電圧の計算

(a)



$g_{m3,4} = 0.5 g_{m5,6}$ とする

回路の利得は $|A_v| = g_{m1} R_{out}$

出力端で観測される雑音電圧は

$$\overline{V_{n,out}^2} = 4kT \frac{2}{3} (g_{m1} + g_{m2} + g_{m3} + \cdots g_{m6}) \times R_{out}^2$$

$$\therefore \overline{V_{n,in}^2} = 4kT \frac{2}{3} \left(\frac{2}{g_{m1}} + \frac{3 g_{m5}}{g_{m1}^2} \right)$$