低雑音増幅回路

通信機器システムの要

雑音の評価

雑音の定式化

瞬時値での評価→困難（不可）

↓

統計的な評価

2乗平均値：$\overline{{v_n}^2} = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} {v_n}^2(t)dt$

複数の雑音源の取り扱い

$$\lim_{T\to\infty}\left[\frac{1}{T}\int_{-T/2}^{T/2}\{v_{n1}(t)+v_{n2}(t)\}^2 dt\right]$$

$$=\lim_{T\to\infty}\left[\frac{1}{T}\left\{\int_{-T/2}^{T/2}v_{n1}{}^2(t)+2v_{n1}(t)v_{n2}(t)+v_{n2}{}^2(t)dt\right\}\right]$$

$$=\overline{v_{n1}{}^2}+\lim_{T\to\infty}\frac{2}{T}\underline{\underline{\int_{-T/2}^{T/2}v_{n1}(t)v_{n2}(t)dt}}+\overline{v_{n2}{}^2}$$

$v_{n1}(t)$と$v_{n2}(t)$が全く独立：無相関

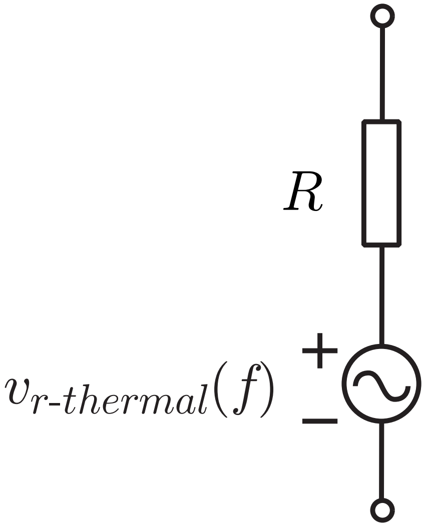
$$\int_0^{\tau}v_{n1}(t)v_{n2}(t)dt=0$$

雑音源を考慮した回路素子モデル

熱雑音，1/f雑音，ショット雑音

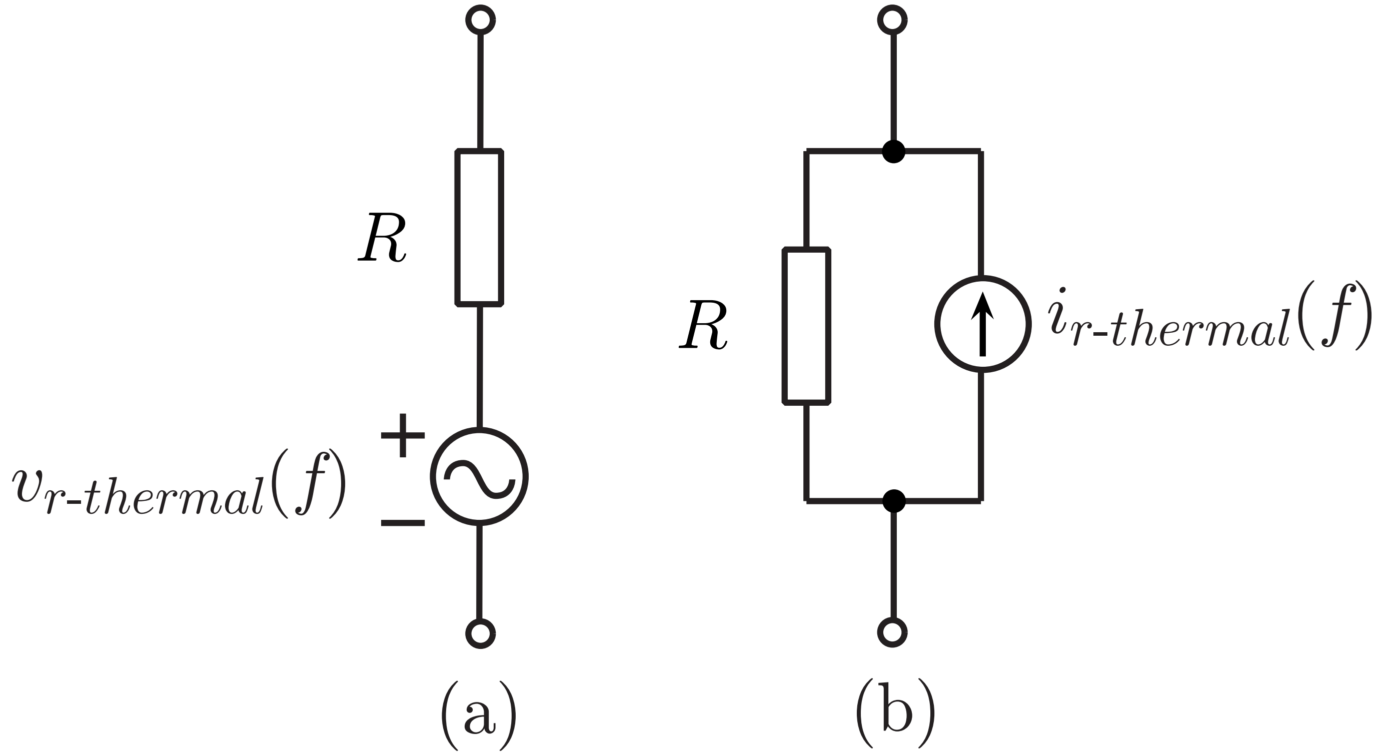
熱雑音：キャリアが移動する際のランダムな動きによって
生じる雑音

抵抗の熱雑音



$$\overline{v_{r-thermal}{}^2(f)} = 4kTR\,[\mathrm{V^2/Hz}]$$

問　「電源の等価性」の定理を用いて
下記に示す抵抗の等価回路の雑音を
表している電流源の値を求めよ.



$$\overline{v_{r-thermal}}^2(f)=4kTR[\mathrm{V^2/Hz}]$$

MOSトランジスタの熱雑音

キャリアがチャネルを通過する際に発生

$$\overline{v_{mos-thermal}^{\,2}} = 4kT\gamma_n \frac{1}{g_m}$$

$$\overline{i_{mos-thermal}^{\,2}} = 4kT\gamma_n g_m$$

$$\gamma_n \approx \frac{2}{3}$$ （最小線幅が短くなると増加）

バイポーラトランジスタの熱雑音

ベース広がり抵抗：$\overline{v_{b-thermal}(f)^2}=4kTr_b$

エミッタ抵抗，コレクタ・エミッタ間抵抗：仮想の抵抗

↓

熱雑音の発生無し

スペクトラム強度が一定：白色雑音

1/f雑音：シリコンの汚れや結晶欠陥によりキャリアが
捕らわれたり，捕らわれたキャリアが離されたりを
繰り返すというランダムな過程によって生じる雑音

直流電流がないと発生しない

$$\overline{{v_{mos-1/f}}^2(f)}=\frac{\alpha_{1/f}}{C_{OX}WLf}$$

$$\overline{{i_{b-1/f}}^2(f)}=\frac{K_{1/f}{I_B}^a}{f}$$

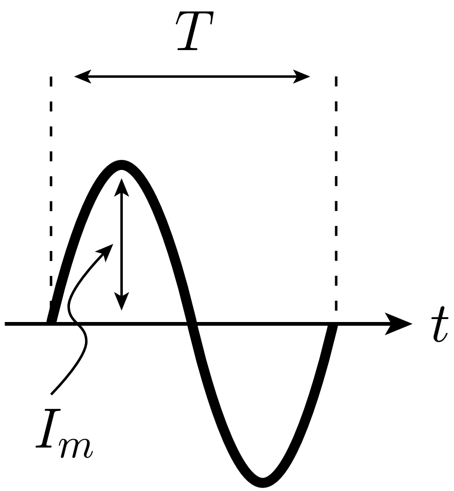
ショット雑音：

電流＝キャリアによる電流パルスの和の平均値

電流の平均値からの揺らぎ

$$\overline{i_{b-shot}^{\,2}}(f)=2qI_B$$

$$\overline{i_{c-shot}^{\,2}}(f)=2qI_C$$



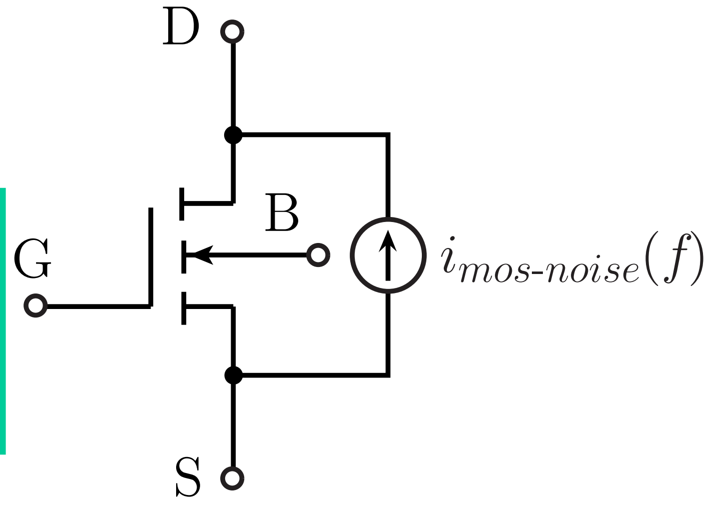
$$Q=\int_0^{T/2} I_m \sin(2\pi\frac{t}{T})=\frac{I_m T}{\pi}$$

1nA@1GHz→1.6×10^{-19}C×2個

雑音源を含むトランジスタモデル

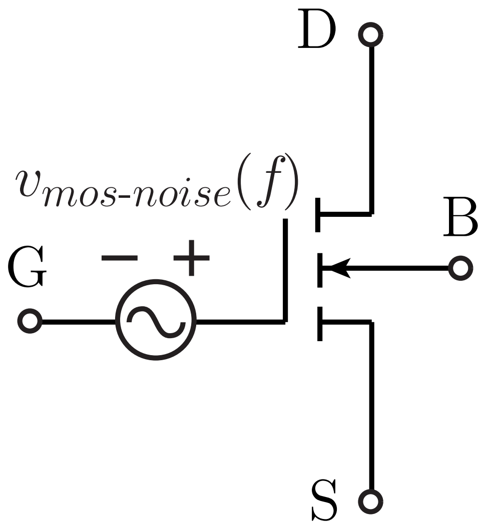
MOSトランジスタモデル

$$\overline{i_{mos-noise}^{\,2}(f)} = 4kT\gamma_n g_m + \frac{\alpha_{1/f}\, g_m^{\,2}}{C_{OX}WLf}$$



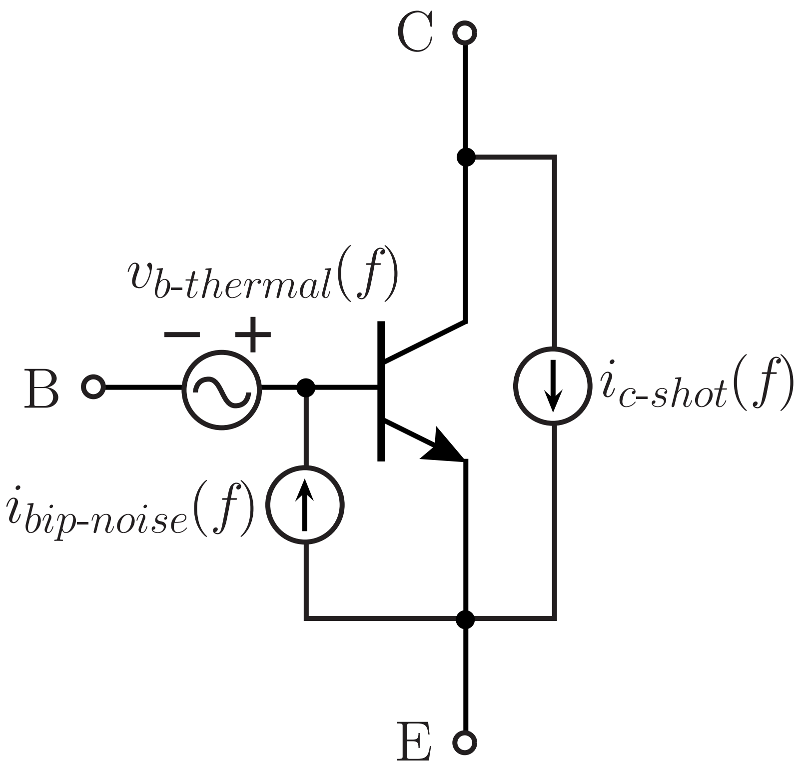
(a)

$$\overline{v_{mos-noise}^{\,2}(f)} = 4kT\gamma_n \frac{1}{g_m} + \frac{\alpha_{1/f}}{C_{OX}WLf}$$



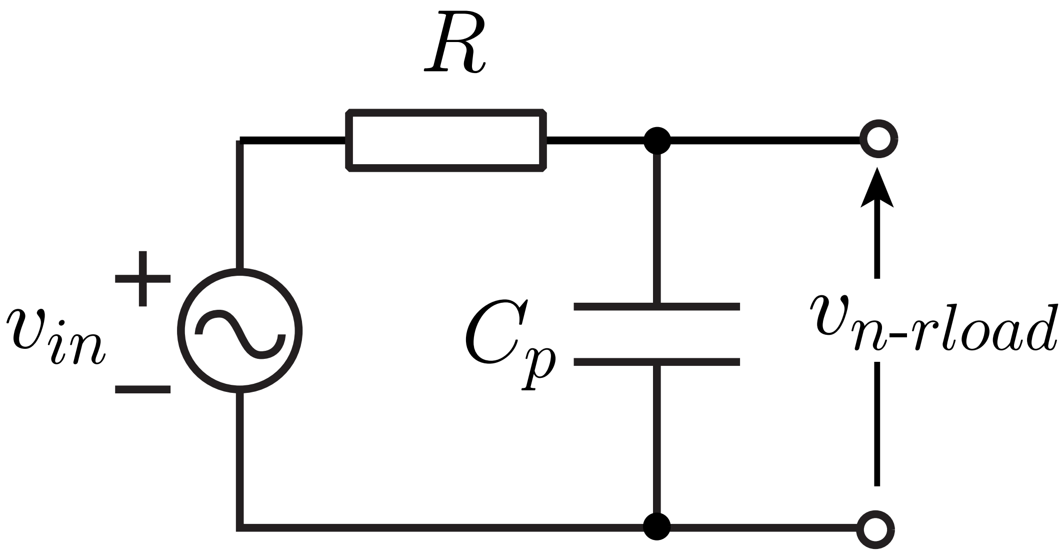
(b)

バイポーラトランジスタモデル



$$\overline{i_{bip-noise}{}^{2}(f)} = \frac{K_{1/f} I_{B}{}^{a}}{f} + 2qI_{B}$$

雑音解析の例(抵抗が発生する雑音)

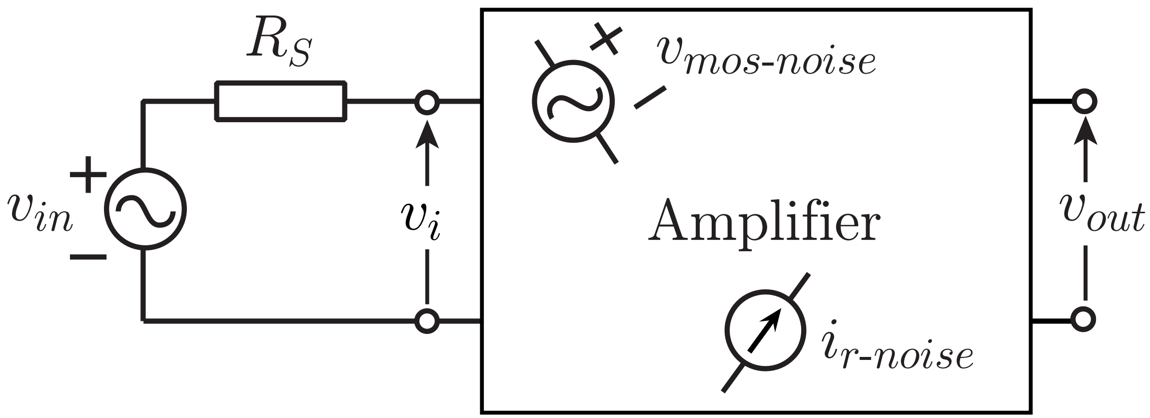


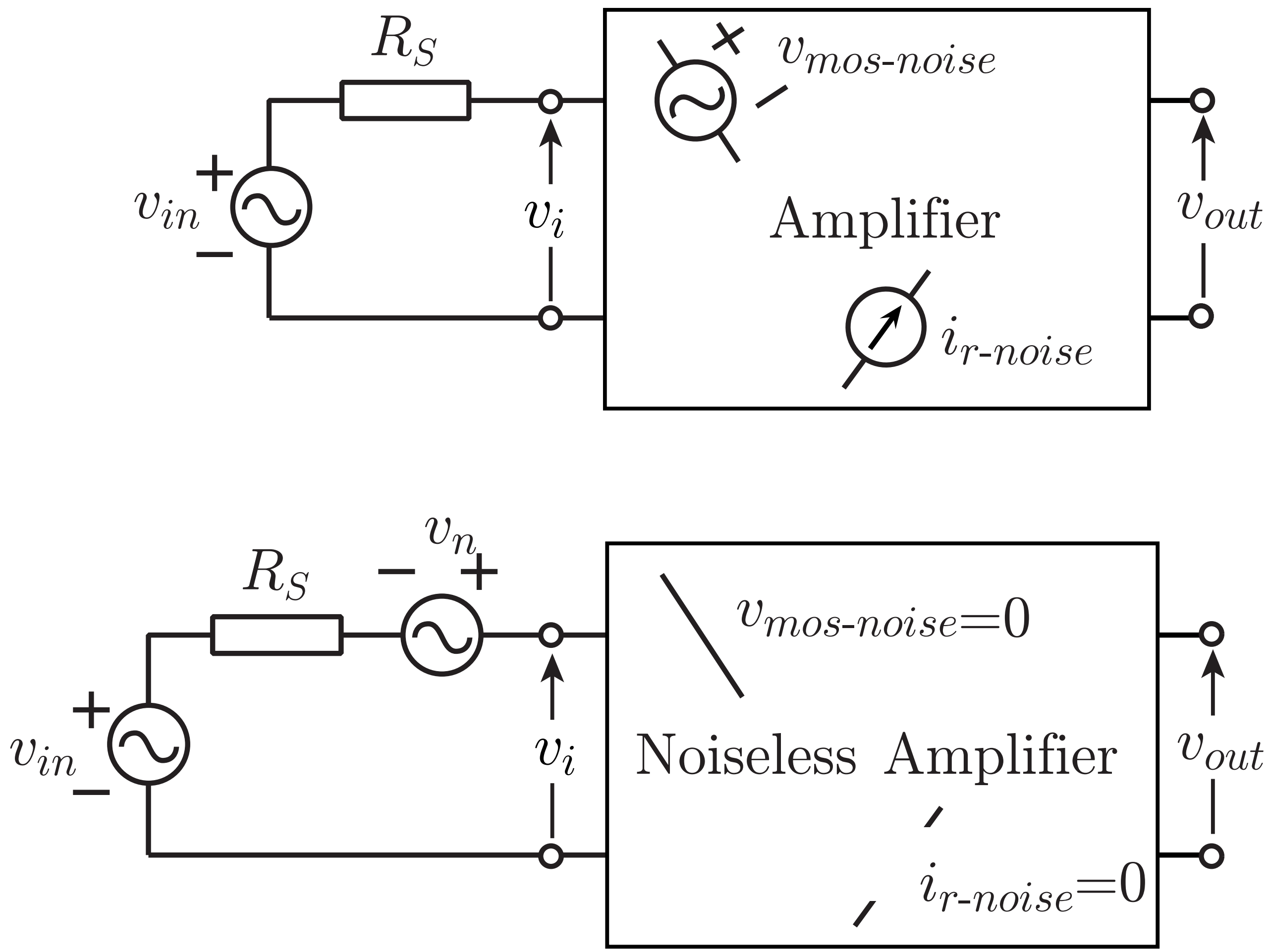
問１　上の回路の伝達関数$T_{rload}(s)$=$\dfrac{v_{n-rload}}{v_{in}}$を求めよ.

問２　$\overline{v_{n-rload}}^{2}=\displaystyle\int_0^{\infty}\left|T_{rload}(j\omega)\right|^2\frac{4kTR}{2\pi}d\omega$を求めよ.

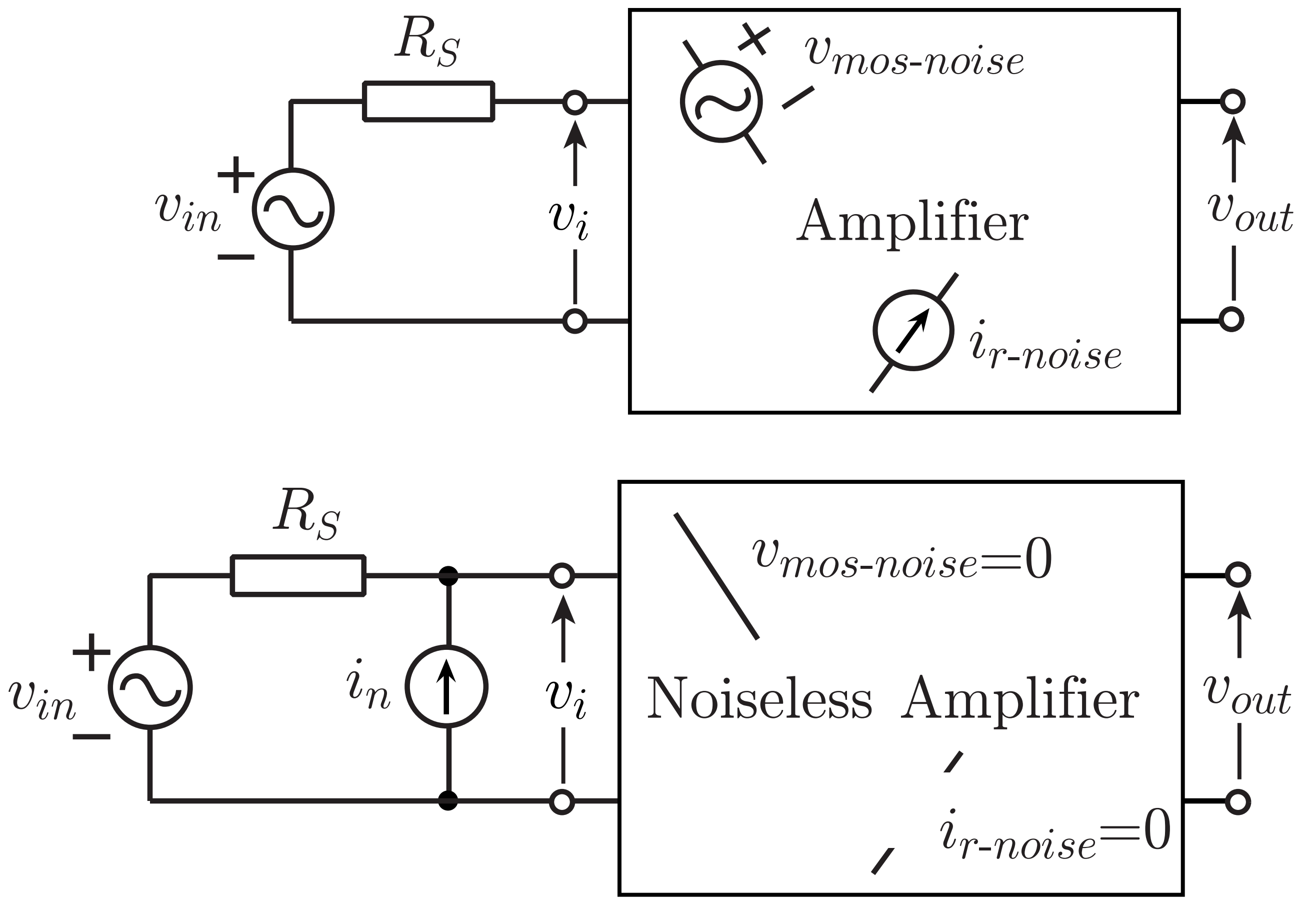
増幅回路と雑音

増幅回路内部で発生する
雑音の等価表現



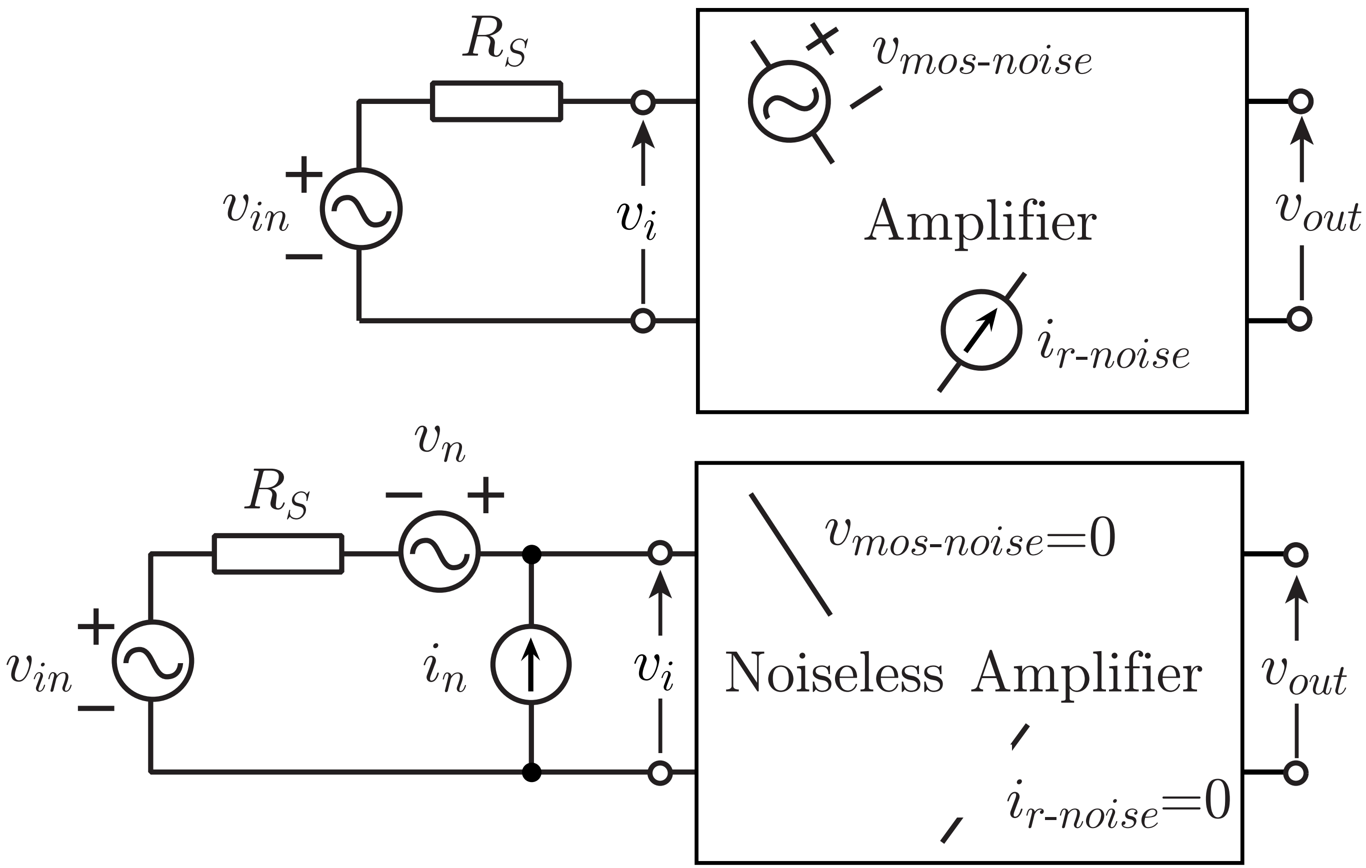


$R_S=\infty$のとき矛盾



R_S
$v_{mos\text{-}noise}$
v_{in}
v_i
Amplifier
v_{out}
$i_{r\text{-}noise}$
R_S
$v_{mos\text{-}noise}=0$
v_{in}
i_n
v_i
Noiseless Amplifier
v_{out}
$i_{r\text{-}noise}=0$

$R_S=0$のとき矛盾

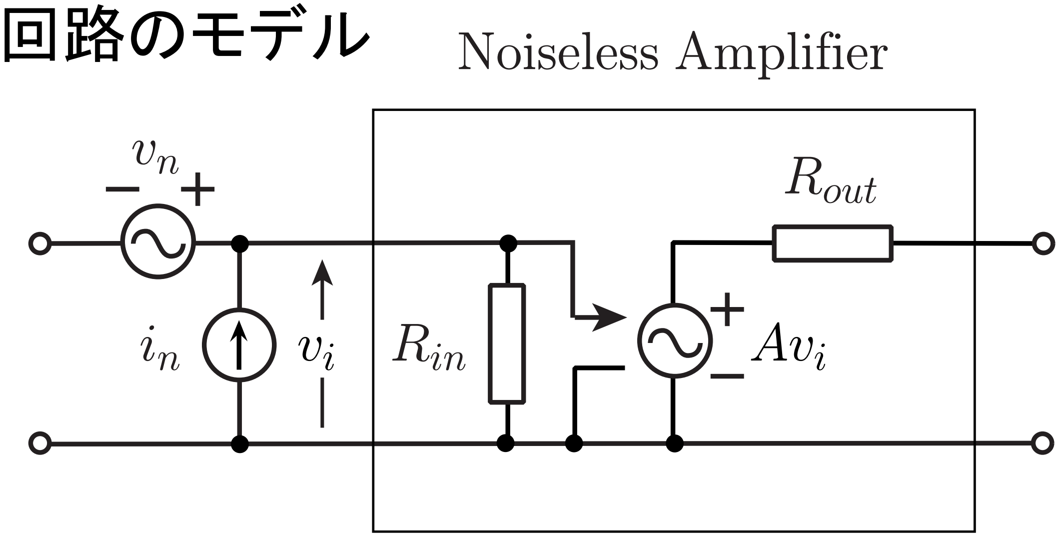


任意のR_Sについて矛盾無し

導出方法:テブナンの定理を拡張

雑音係数と雑音指数

増幅回路のモデル



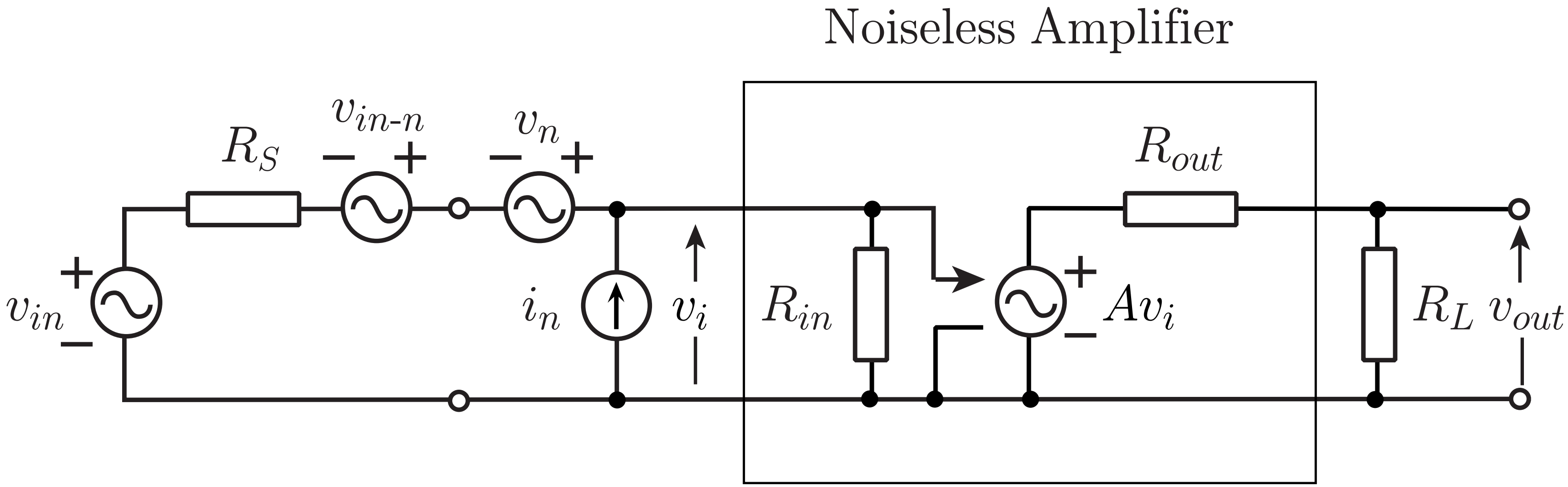
A：増幅回路の電圧利得

R_{in}: 増幅回路の入力インピーダンス

R_{out}: 増幅回路の出力インピーダンス

v_n: 増幅回路の入力換算雑音電圧

i_n: 増幅回路の入力換算雑音電流

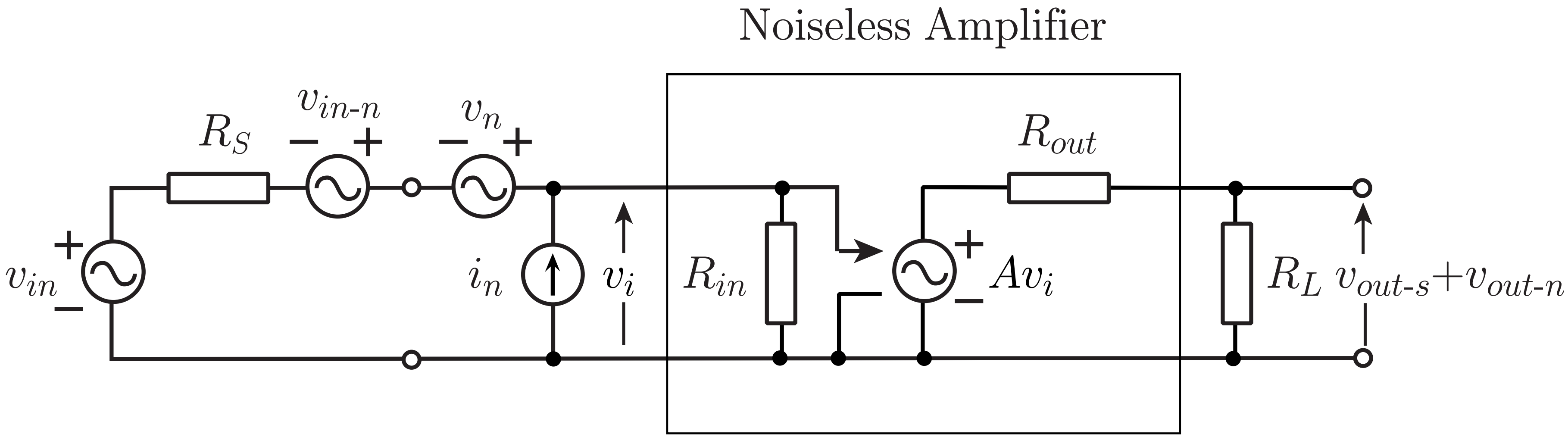


v_{in}: 入力電圧信号

R_S: 信号源抵抗

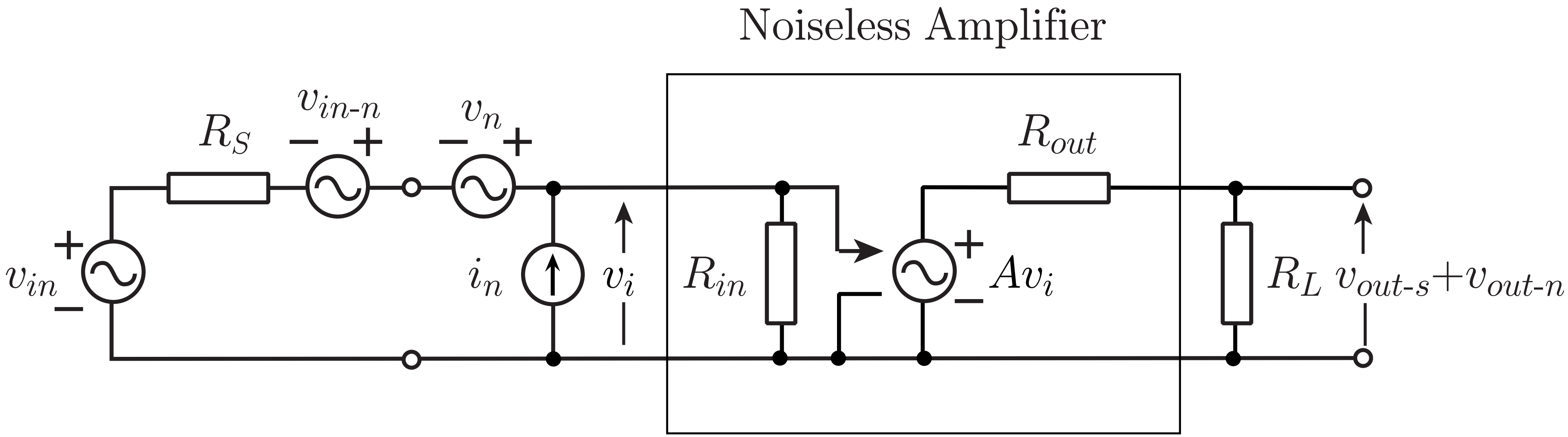
v_{in-n}: 入力信号に加わる雑音電圧

R_L: 負荷抵抗



入力における信号対雑音比：$SNR_{in}=\dfrac{\overline{v_{in}^{2}}}{\overline{v_{in-n}^{2}}}$

出力における信号対雑音比：$SNR_{out}=\dfrac{\overline{v_{out-s}^{2}}}{\overline{v_{out-n}^{2}}}$

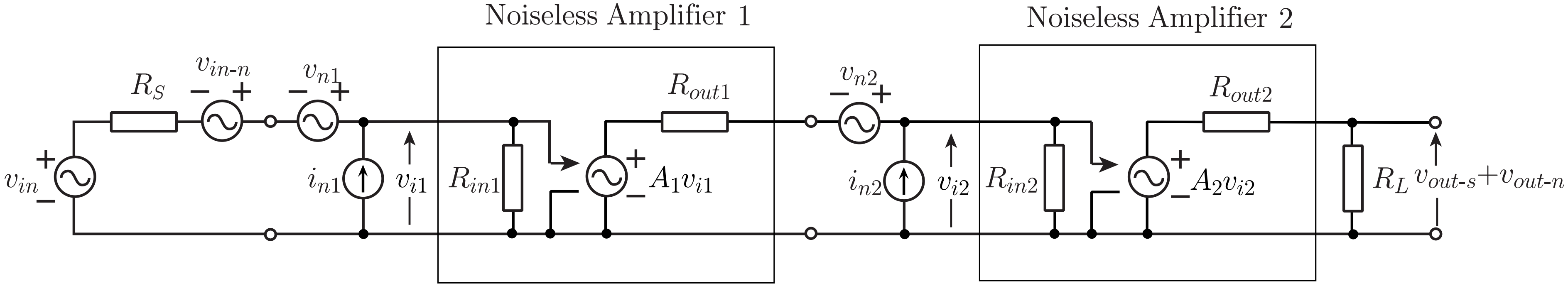


雑音係数：$F=\dfrac{SNR_{in}}{SNR_{out}}$

雑音指数：$NF=10\log F$

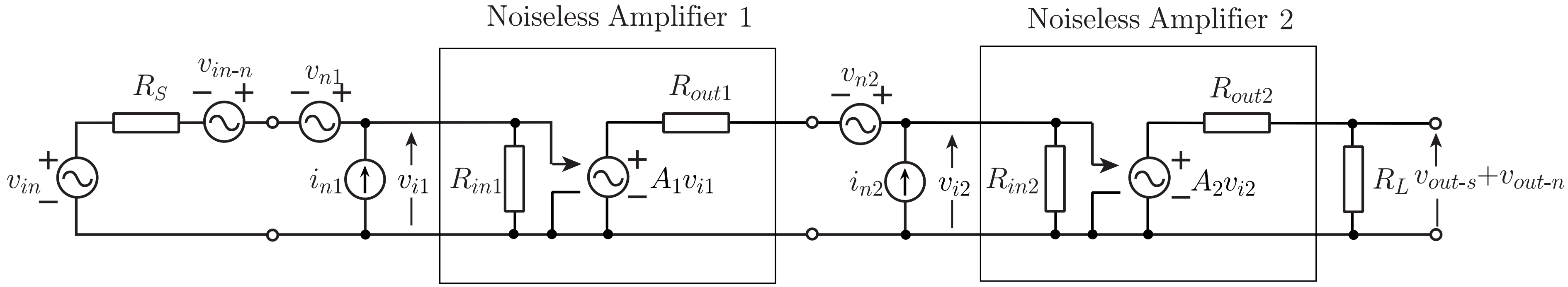
問　上の増幅回路の雑音係数を求めよ.

縦続接続型システムの評価



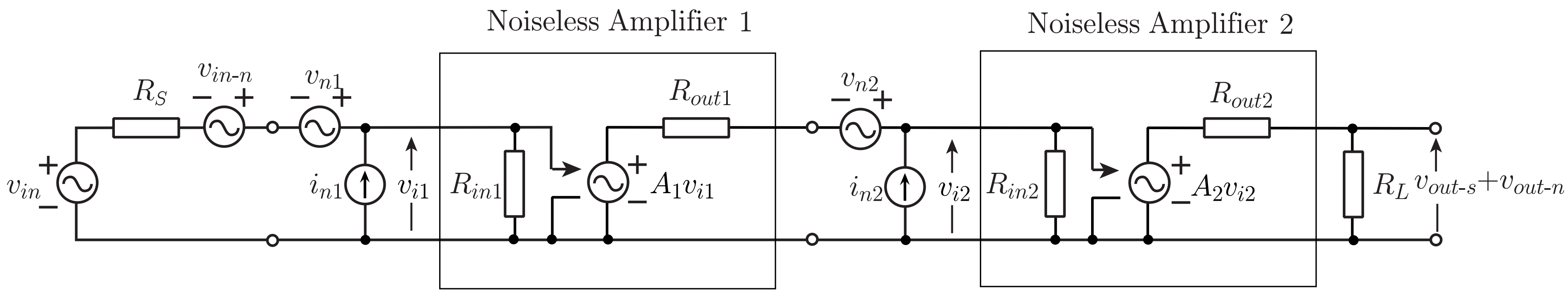
$$F_{total}=\frac{\dfrac{\overline{v_{in}^{\;2}}}{\overline{v_{in-n}^{\;2}}}}{\dfrac{(A_{total}v_{in})^2}{\overline{v_{out-n}^{\;2}}}}=\frac{\overline{v_{out-n}^{\;2}}}{A_{total}^{\;2}\,\overline{v_{in-n}^{\;2}}}$$

$$A_{total}=\frac{R_{in1}}{R_S+R_{in1}}\times A_1\times\frac{R_{in2}}{R_{out1}+R_{in2}}\times A_2\times\frac{R_L}{R_{out2}+R_L}$$



$$\overline{v_{in1-n}^{\;2}} = \overline{\left(\frac{R_{in1}}{R_S+R_{in1}} v_{n1} + \left(R_S // R_{in1}\right) i_{n1}\right)^2} + \left(\frac{R_{in1}}{R_S+R_{in1}}\right)^2 \overline{v_{in-n}^{\;2}}$$

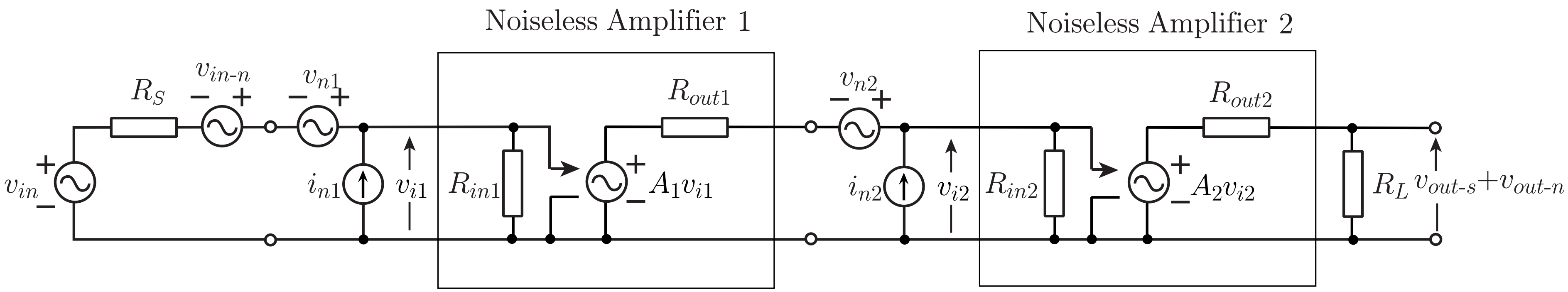
$$\overline{v_{in2-n}^{\;2}} = \overline{\left\{\frac{R_{in2}}{R_{out1}+R_{in2}} v_{n2} + \left(R_{out1} // R_{in2}\right) i_{n2}\right\}^2} + \left(\frac{A_1 R_{in2}}{R_{out1}+R_{in2}}\right)^2 \overline{v_{in1-n}^{\;2}}$$



$$F_{total}=\frac{\overline{v_{out-n}{}^2}}{A_{total}{}^2\,\overline{v_{in-n}{}^2}}$$

$$A_{total}=\left(\frac{A_1 R_{in1}}{R_S+R_{in1}}\right)\left(\frac{A_2 R_{in2}}{R_{out1}+R_{in2}}\right)\left(\frac{R_L}{R_{out2}+R_L}\right)$$

$$\overline{v_{out-n}{}^2}=\frac{A_2{}^2 R_L{}^2\,\overline{v_{in2-n}{}^2}}{(R_{out2}+R_L)^2}$$

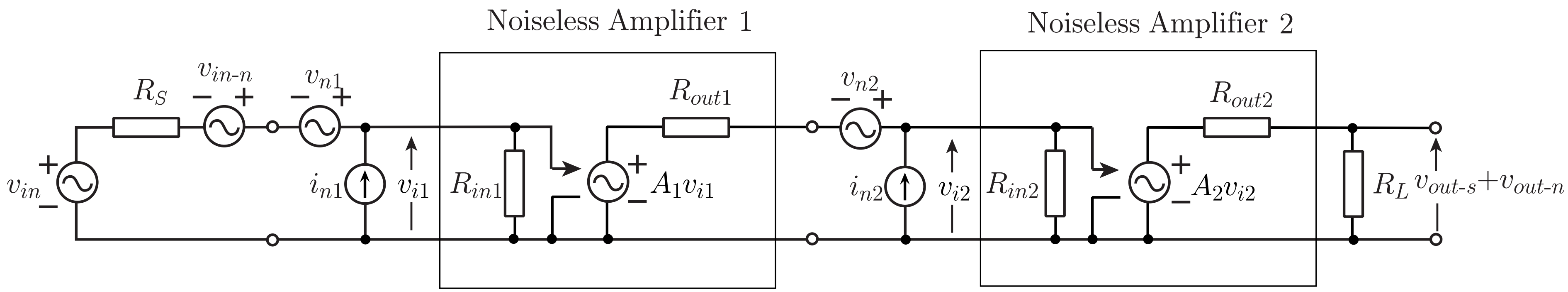


$$F_{total}=\frac{\overline{(v_{n1}+R_S i_{n1})^2}+\overline{v_{in-n}{}^2}}{\overline{v_{in-n}{}^2}}$$

$$+\frac{\overline{(v_{n2}+R_{out1} i_{n2})^2}}{A_1{}^2}\times\frac{1}{\left(\frac{R_{in1}}{R_S+R_{in1}}\right)^2\overline{v_{in-n}{}^2}}$$

$$F=1+\frac{\overline{(v_n+R_S i_n)^2}}{\overline{v_{in-n}{}^2}}$$

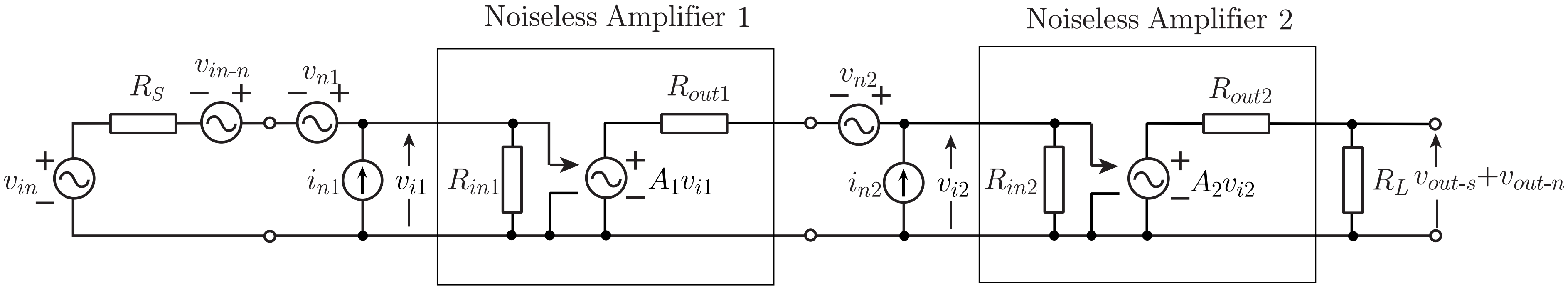
$\overline{v_{in-n}{}^2}=4kTR_S$: 抵抗$R_S$の熱雑音



$$F_{total}=F_1+\frac{\overline{\left(v_{n2}+R_{out1}i_{n2}\right)^2}}{A_1{}^2}\times\frac{1}{\left(\frac{R_{in1}}{R_S+R_{in1}}\right)^2 4kTR_S}$$

$$=F_1+\frac{\overline{\left(v_{n2}+R_{out1}i_{n2}\right)^2}}{4kTR_{out1}}\times\frac{1}{A_1{}^2\frac{R_S}{R_{out}}\left(\frac{R_{in1}}{R_S+R_{in1}}\right)^2}$$

$$F=1+\frac{\overline{\left(v_n+R_S i_n\right)^2}}{\overline{v_{in-n}}^2}$$



$$\text{有効電力利得}=\frac{\text{出力から取り出し可能な電力の最大値}}{\text{入力から取り出し可能な電力の最大値}}$$

$$A_{p1}=\frac{\dfrac{\left(A_1\dfrac{R_{in1}}{R_S+R_{in1}}v_{in}\right)^2}{4R_{out1}}}{\dfrac{{v_{in}}^2}{4R_S}}=\left(A_1\frac{R_{in1}}{R_S+R_{in1}}\right)^2\frac{R_S}{R_{out1}}$$

$$F_{total}=F_1+\frac{F_{2,R_{out1}}-1}{A_{p1}}$$

$$F_{total} = F_1 + \frac{F_{2,R_{out1}} - 1}{A_{p1}}$$

一般化 (Friisの式，フリスの式)

$$F_{total} = 1 + (F_1 - 1) + \frac{F_{2,R_{out1}} - 1}{A_{p1}} + \frac{F_{3,R_{out2}} - 1}{A_{p1} A_{p2}} + \cdots + \frac{F_{m,R_{outm-1}} - 1}{A_{p1} A_{p2} \ldots A_{pm-1}}$$

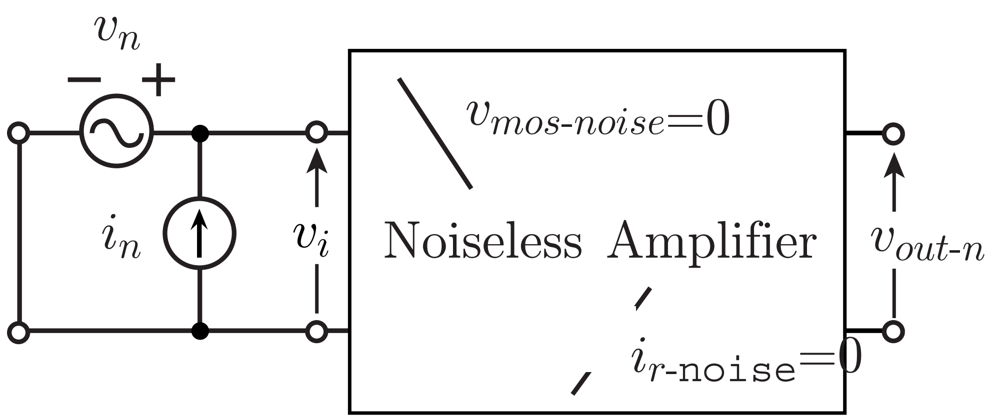
低雑音増幅回路の設計

増幅回路の出力雑音のみ考慮

v_nの求め方

$$v_n = \frac{v_N}{A}$$

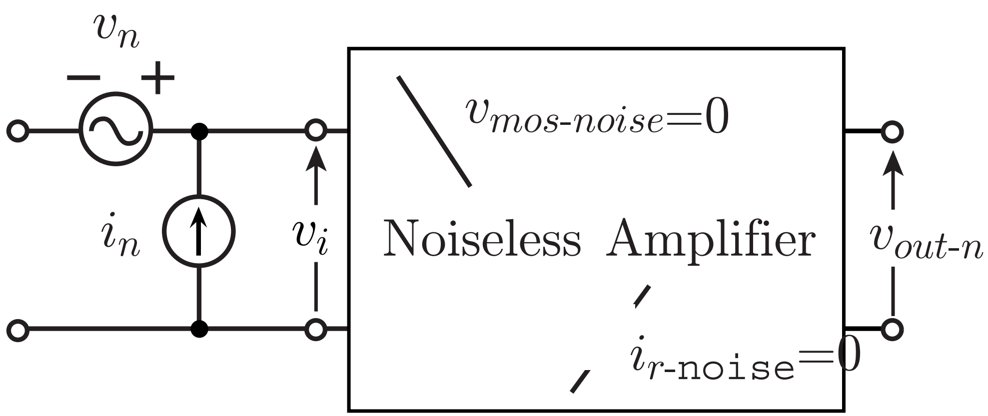
A：電圧利得



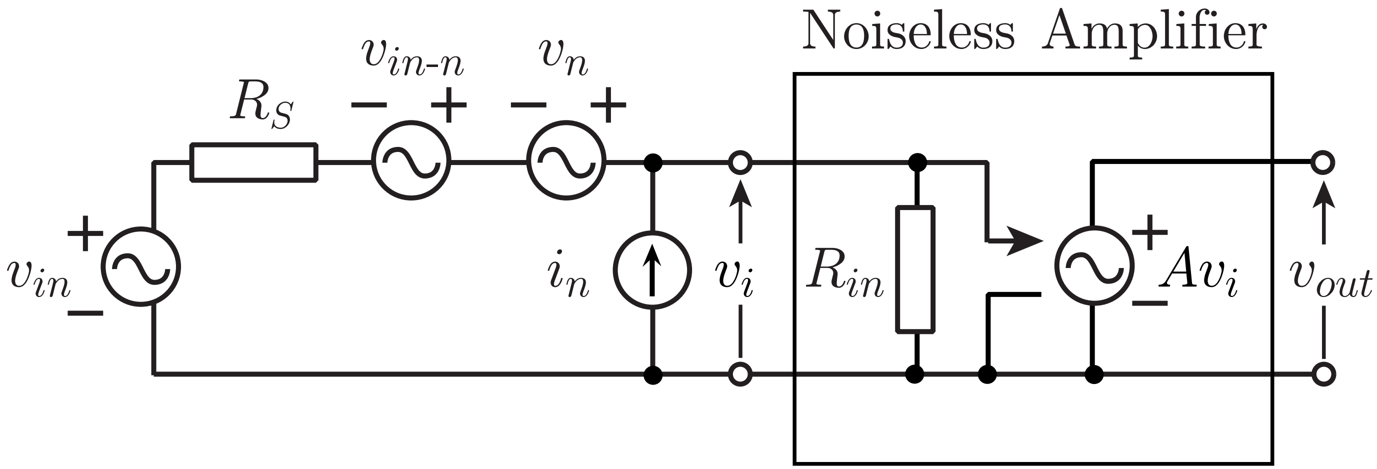
i_nの求め方

$$i_n = \frac{v_N}{Z_T}$$

Z_T: 伝達インピーダンス

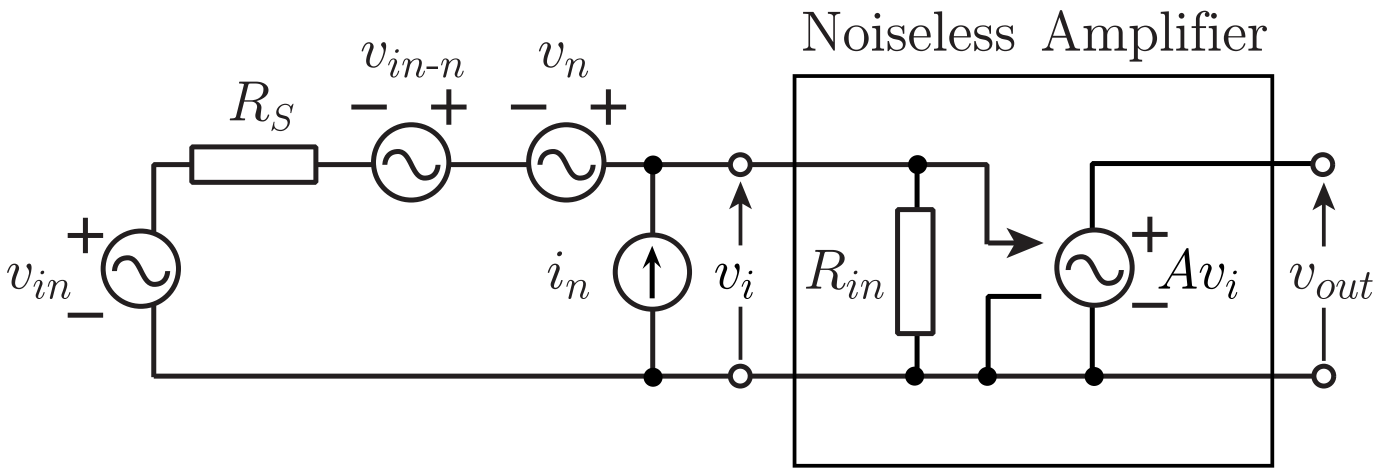


雑音整合



$$\overline{v_{in-n}}^{2}=4kTR_S$$

$$v_S=\frac{AR_{in}}{R_S+R_{in}}v_{in}$$



v_{in-n}とv_n，　v_{in-n}とi_nは無相関

v_nとi_nは相関有り

$$\overline{{v_{out-n}}^2}=\frac{A^2{R_{in}}^2}{\left|R_S+R_{in}\right|^2}\left\{\overline{{v_{in-n}}^2}+\overline{\left(v_n+R_S i_n\right)^2}\right\}$$

$$\overline{e_n^{\,2}} = 4kTR_S \qquad v_S = \frac{AR_{in}}{R_S + R_{in}} v_{in}$$

$$\overline{v_{out-n}^{\,2}} = \frac{A^2 R_{in}^{\,2}}{\left|R_S + R_{in}\right|^2} \left\{ \overline{v_{in-n}^{\,2}} + \overline{(v_n + R_S i_n)^2} \right\}$$

$$SNR_{in} = \frac{\overline{v_{in}^{\,2}}}{\overline{v_{in-n}^{\,2}}}$$

$$SNR_{out} = \frac{\overline{v_{out-s}^{\,2}}}{\overline{v_{out-n}^{\,2}}} = \frac{\overline{v_{in}^{\,2}}}{\overline{v_{in-n}^{\,2}} + \left(\overline{v_n + R_S i_n^{\,2}}\right)^2}$$

$$F = \frac{SNR_{in}}{SNR_{out}} = \frac{\overline{v_{in-n}^{\,2}} + \overline{(v_n + R_S i_n)^2}}{\overline{v_{in-n}^{\,2}}} = 1 + \frac{\overline{(v_n + R_S i_n)^2}}{4kTR_S}$$

$$F=1+\frac{\overline{(v_n+R_S i_n)^2}}{4kTR_S}=1+\frac{\overline{\left(\frac{v_n}{\sqrt{R_S}}+\sqrt{R_S}\,i_n\right)^2}}{4kT}$$

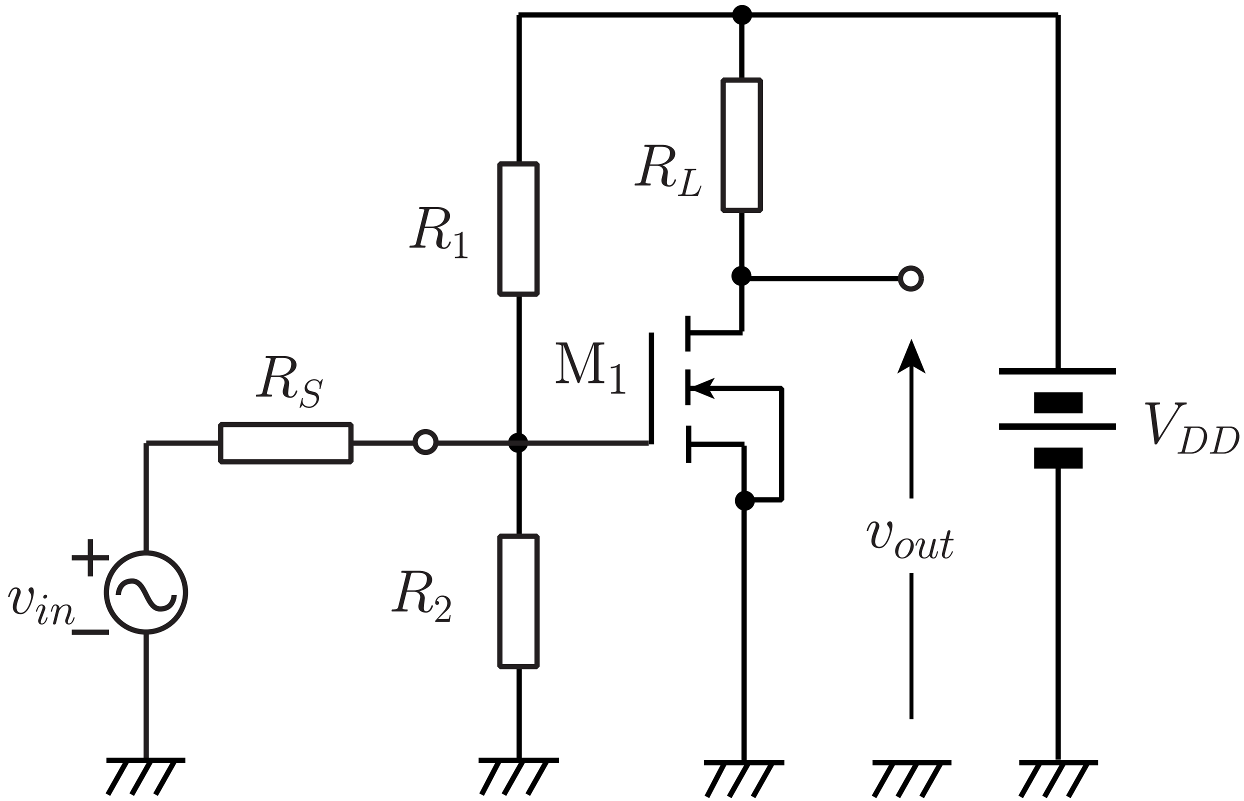
相加・相乗平均の定理　$a+b\geq 2\sqrt{ab}$

$\frac{v_n}{\sqrt{R_S}}=\sqrt{R_S}\,i_n$のとき$F$が最小

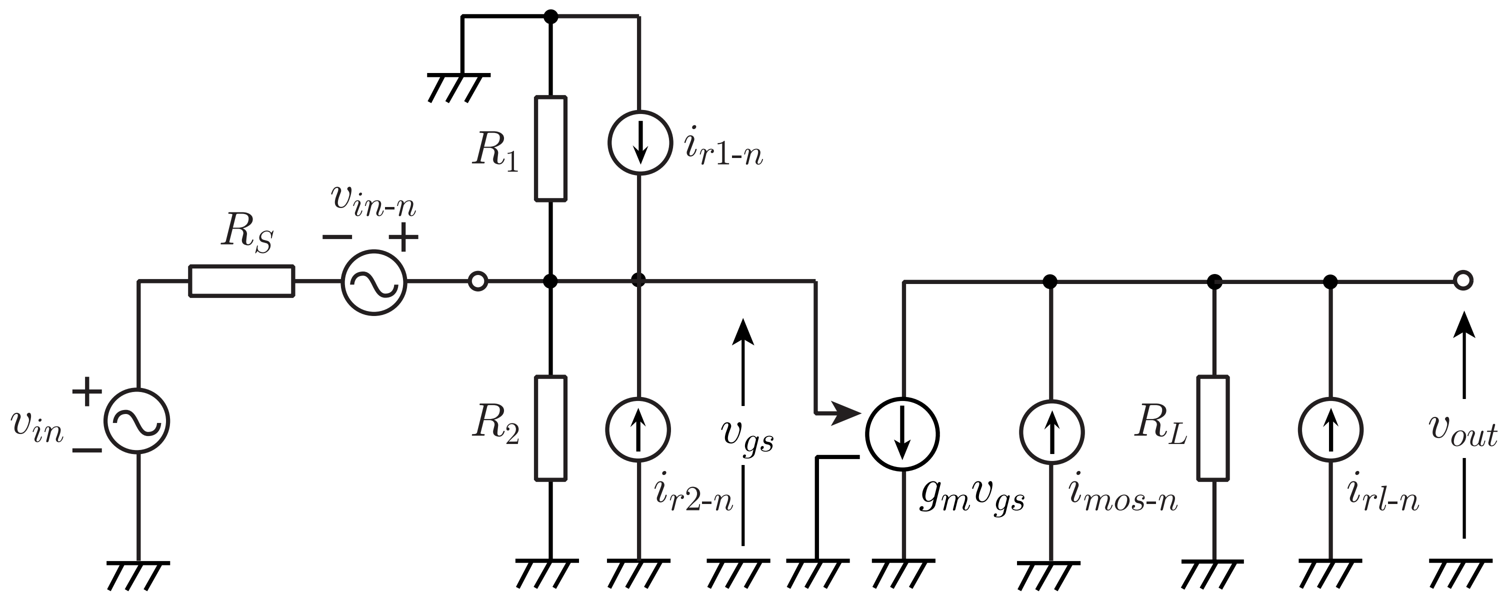
$$\boxed{R_S=\frac{v_n}{i_n}}$$

実際の増幅回路の雑音解析例

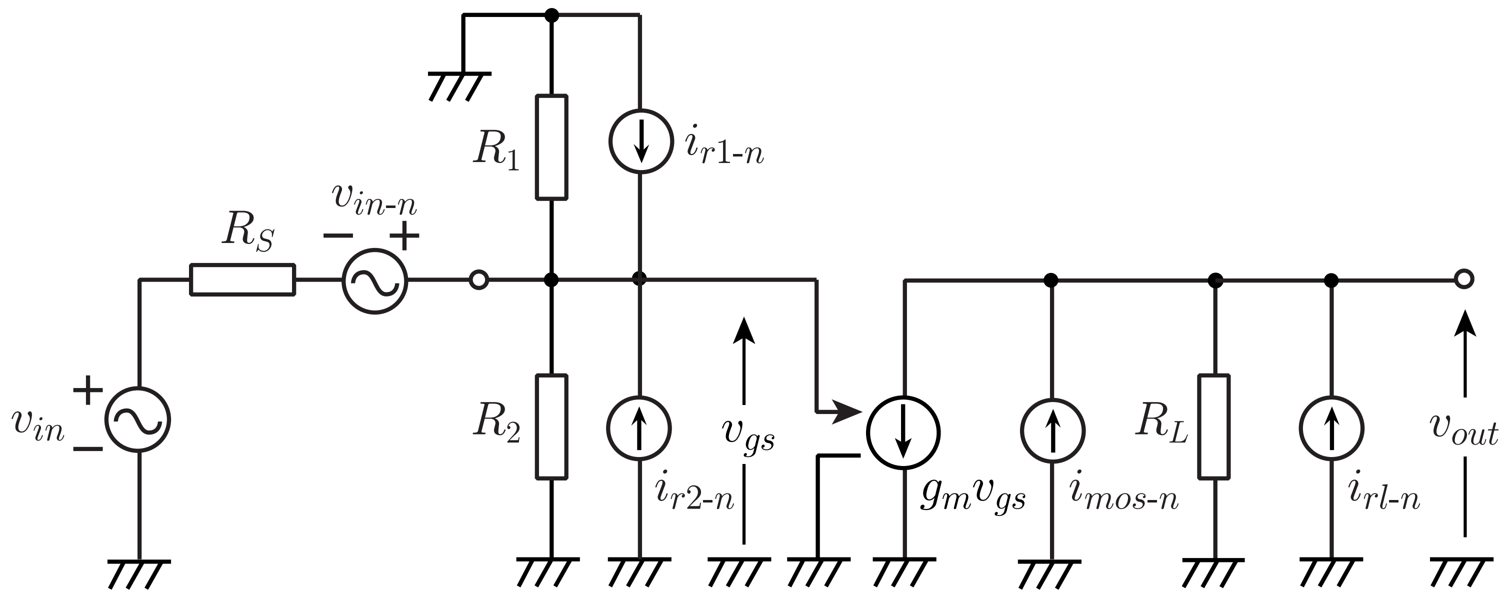
ソース接地増幅回路



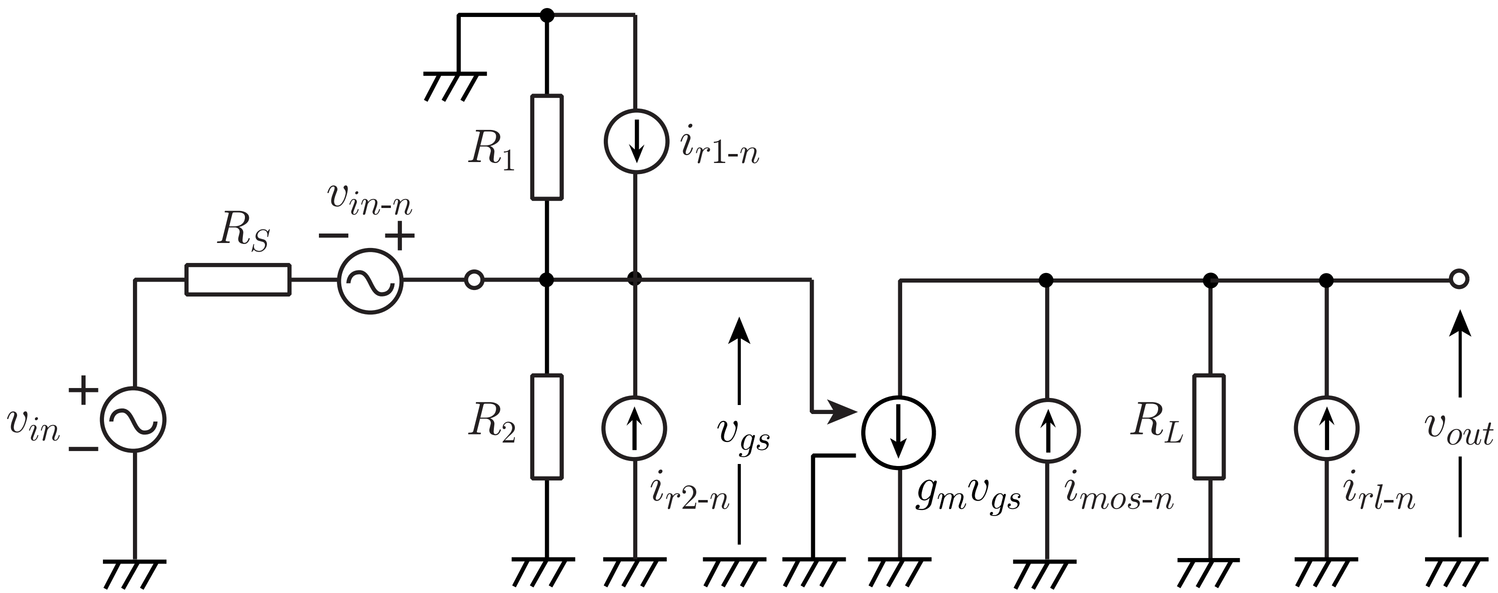
ソース接地増幅回路の小信号モデル



$$\overline{v_{o\text{-}n1}^{\,2}} = R_L^{\,2}\left(\overline{i_{rl\text{-}n}^{\,2}} + \overline{i_{mos\text{-}n}^{\,2}}\right)$$



$$\overline{v_{o\text{-}n2}}^2 = \left(g_m R_L \frac{R_1 R_2 R_S}{R_1 R_2 + R_2 R_S + R_S R_1} \right)^2 \left(\overline{i_{r1\text{-}n}}^2 + \overline{i_{r2\text{-}n}}^2 \right)$$



$$\overline{v_{o\text{-}n3}}^2 = \left(g_m R_L \frac{R_1 R_2}{R_1 R_2 + R_2 R_S + R_S R_1} \right)^2 \overline{v_{in-n}}^2$$

$$\overline{v_{out-n}^{2}} = \overline{v_{o\text{-}n1}^{2}} + \overline{v_{o\text{-}n2}^{2}} + \overline{v_{o\text{-}n3}^{2}}$$

$$= R_L^{2}(\overline{i_{rl-n}^{2}} + \overline{i_{mos-n}^{2}})$$

$$+ \left(g_m R_L \frac{R_1 R_2 R_S}{R_1 R_2 + R_2 R_S + R_S R_1} \right)^2 (\overline{i_{r1\text{-}n}^{2}} + \overline{i_{r2\text{-}n}^{2}})$$

$$+ \left(g_m R_L \frac{R_1 R_2 R_S}{R_1 R_2 + R_2 R_S + R_S R_1} \right)^2 \overline{v_{in-n}^{2}}$$

$$\overline{v_{out-s}^{2}} = \left(g_m R_L \frac{R_1 R_2}{R_1 R_2 + R_2 R_S + R_S R_1} \right)^2 \overline{v_{in}^{2}}$$

$$SNR_{in} = \frac{\overline{v_{in}^{2}}}{\overline{v_{in-n}^{2}}}$$

$$\overline{v_{out-n}^{2}}=\overline{v_{o\text{-}n1}^{2}}+\overline{v_{o\text{-}n2}^{2}}+\overline{v_{o\text{-}n3}^{2}}$$

$$\overline{v_{out-s}^{2}}=\left(g_m R_L \frac{R_1 R_2}{R_1 R_2+R_2 R_S+R_S R_1}\right)^2 \overline{v_{in}^{2}}$$

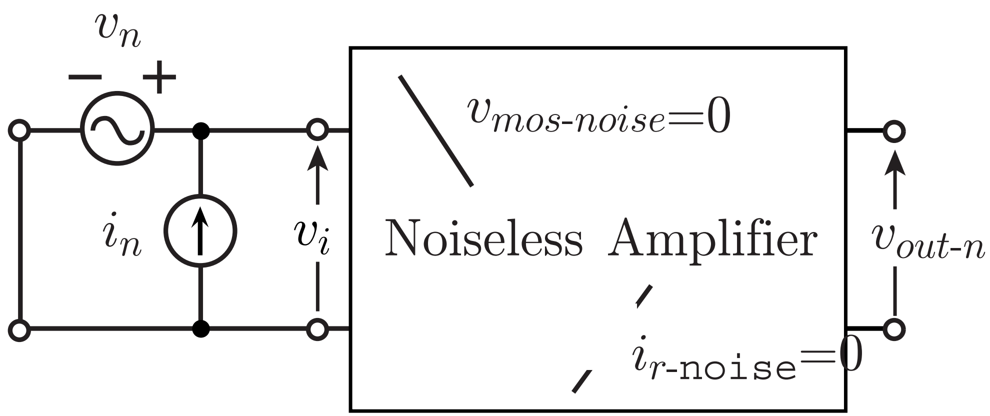
$$SNR_{in}=\frac{\overline{v_{in}^{2}}}{\overline{v_{in-n}^{2}}} \qquad v_{in-n}^{2}=4kTR_S$$

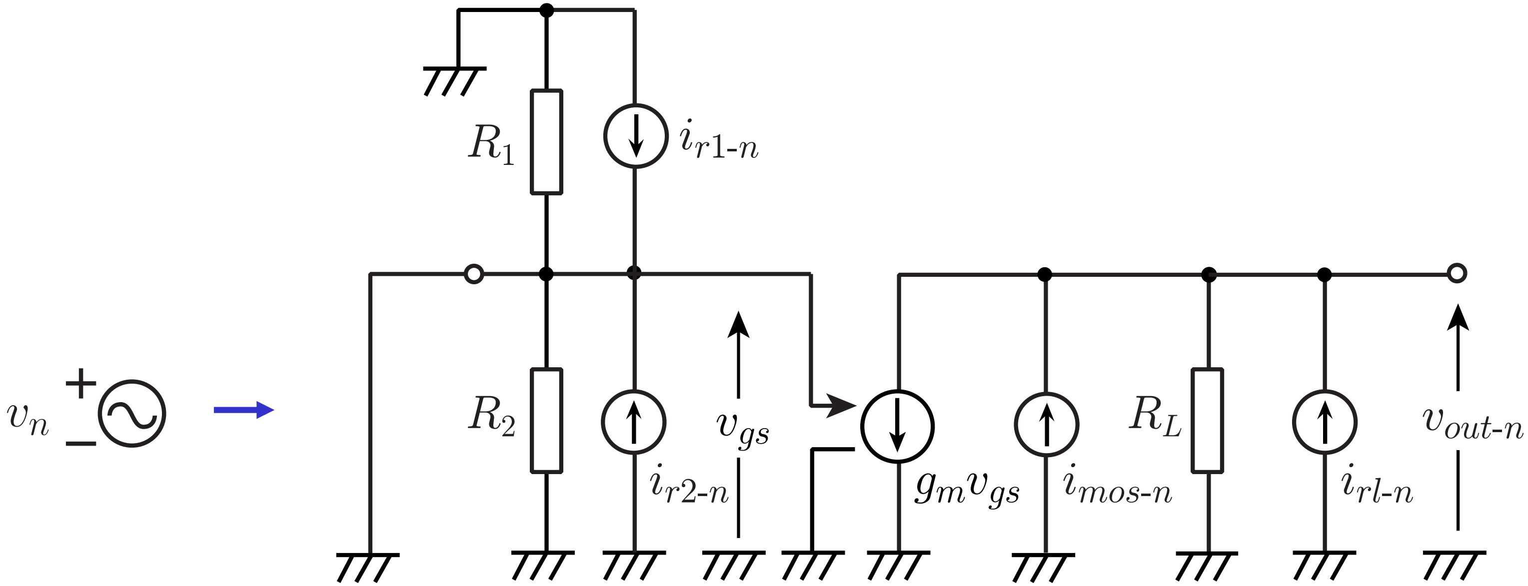
$$F=\frac{SNR_{in}}{SNR_{out}}$$

$$=1+\frac{1}{4kTR_S}\left\{\left(\frac{R_1 R_2+R_2 R_S+R_S R_1}{g_m R_1 R_2}\right)^2 (\overline{i_{rl\text{-}n}^{2}}+\overline{i_{mos\text{-}n}^{2}})\right.$$

$$\left.+R_S^2(\overline{i_{r1\text{-}n}^{2}}+\overline{i_{r2\text{-}n}^{2}})\right\}$$

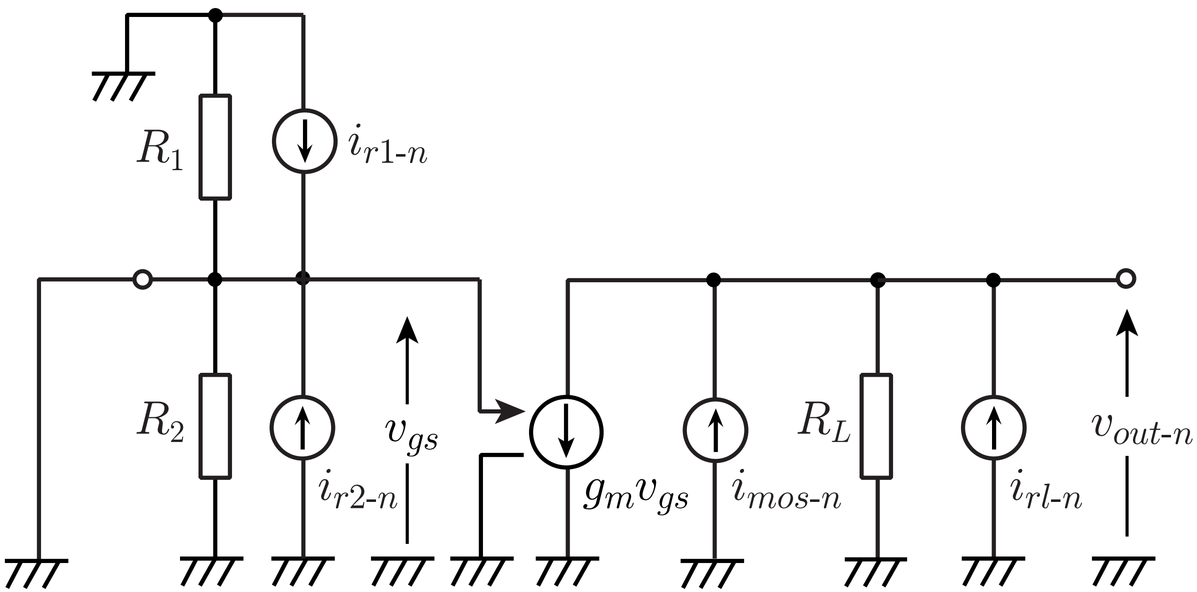
v_nの求め方





$$A=\frac{v_{out}}{v_n}=-g_m R_L$$

$$v_n=\frac{v_{out-n}}{A}$$

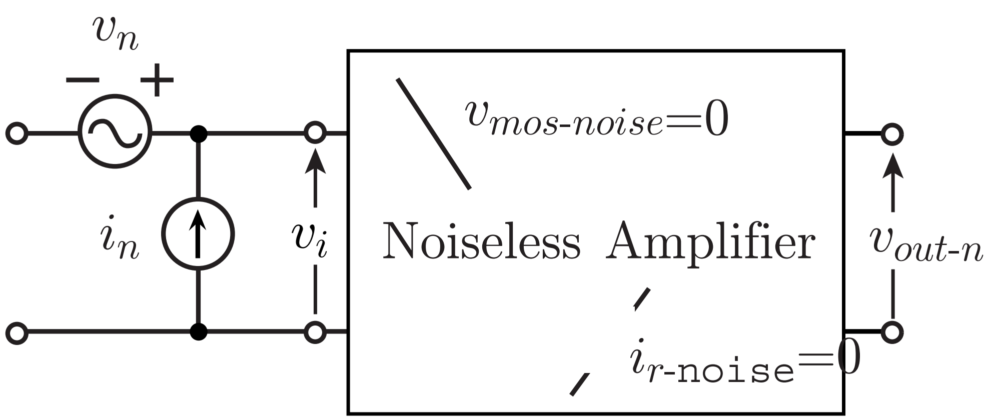


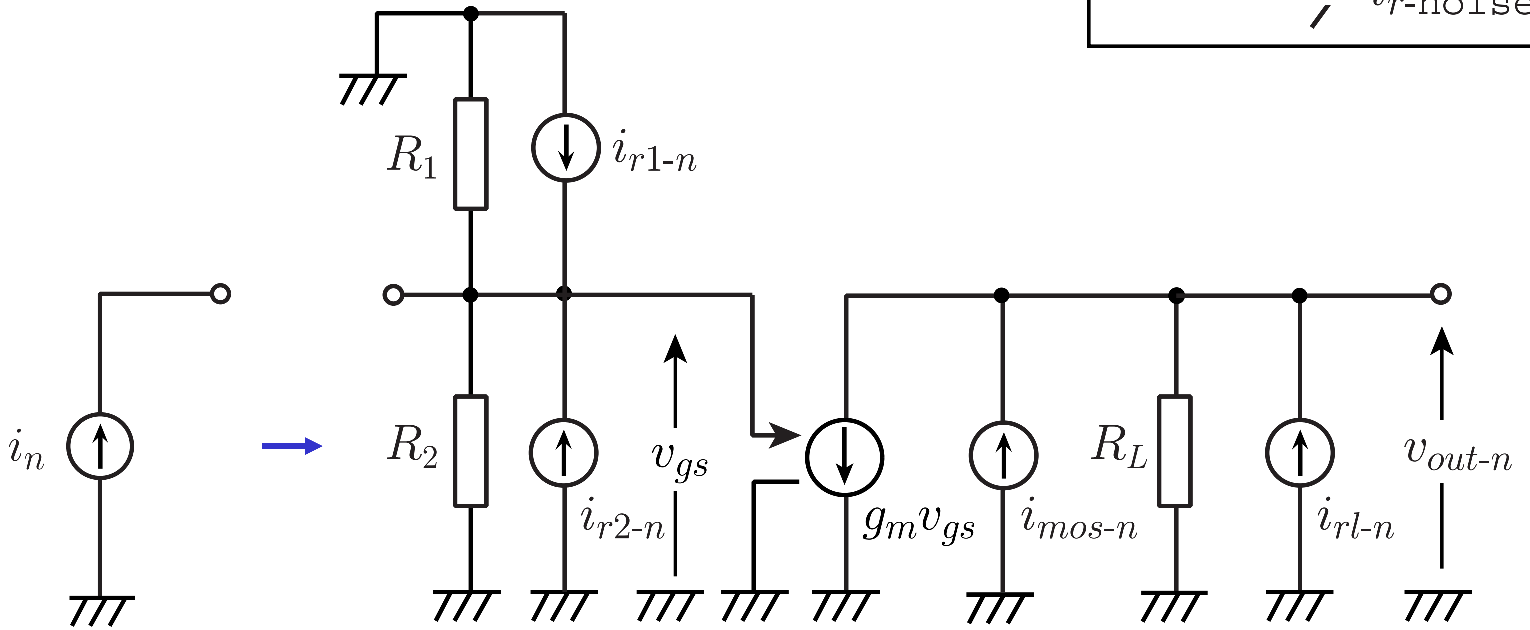
$$v_{out-n} = R_L\left(i_{rl\text{-}n} + i_{mos\text{-}n}\right)$$

$$A = \frac{v_{out}}{v_n} = -g_m R_L$$

$$v_n = -\frac{i_{rl\text{-}n} + i_{mos\text{-}n}}{g_m}$$

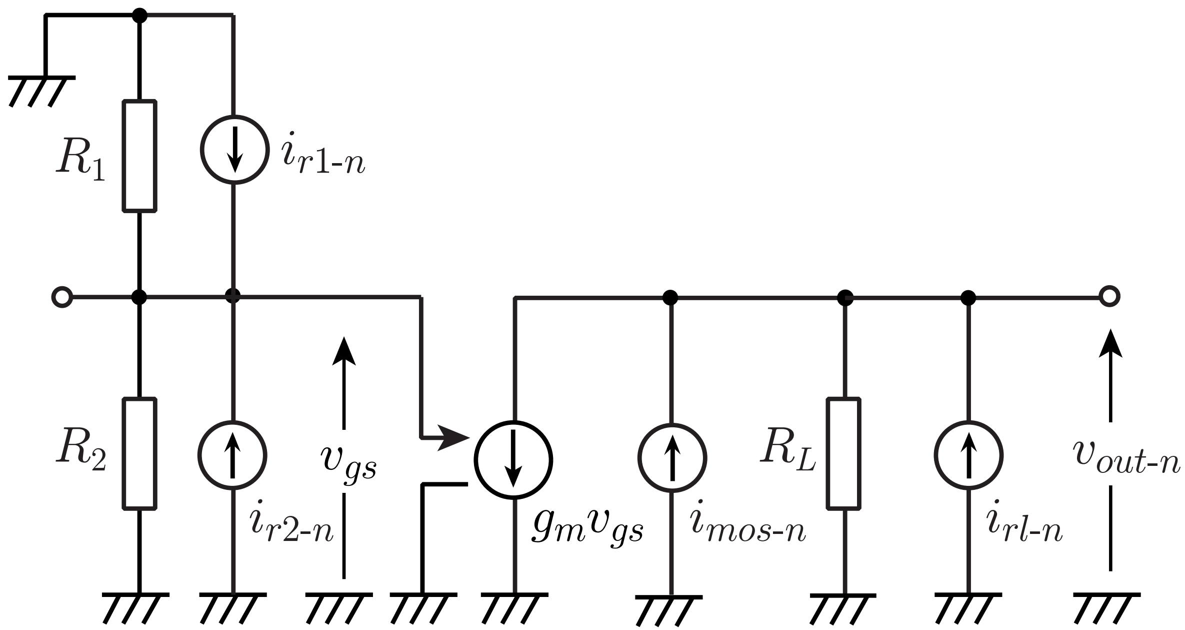
i_nの求め方





$$Z_T = -g_m R_L \frac{R_1 R_2}{R_1 + R_2}$$

$$i_n = \frac{v_{out-n}}{Z_T}$$

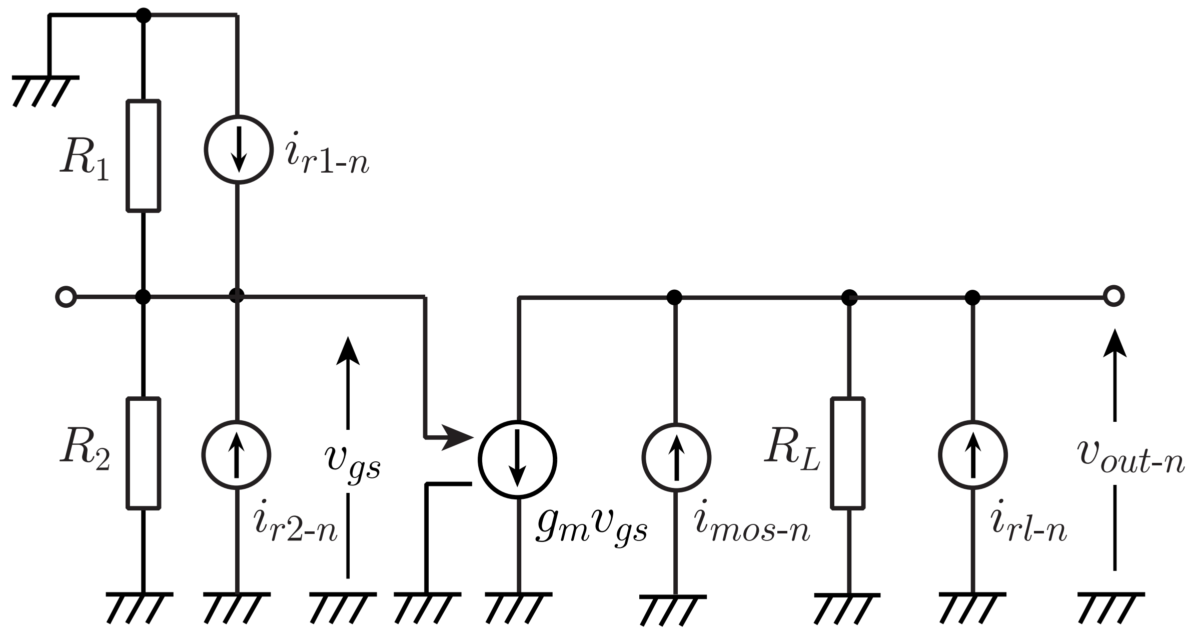


$$v_{o\text{-}n1} = R_L\left(i_{rl\text{-}n} + i_{mos\text{-}n}\right)$$

$$v_{o\text{-}n2} = -g_m R_L \frac{R_1 R_2}{R_2 + R_1}\left(i_{r1\text{-}n} + i_{r2\text{-}n}\right)$$

$$v_{out-n} = v_{o\text{-}n1} + v_{o\text{-}n2}$$

$$v_{out-n} = R_L\left(i_{rl-n} + i_{mos-n}\right) - g_m R_L \frac{R_1 R_2}{R_2 + R_1}\left(i_{r1\text{-}n} + i_{r2\text{-}n}\right)$$



$$i_n = \frac{v_{out-n}}{Z_T}$$

$$Z_T = -g_m R_L \frac{R_1 R_2}{R_2 + R_1}$$

$$i_n = -\frac{R_1 + R_2}{g_m R_1 R_2}\left(i_{rl-n} + i_{mos-n}\right) + i_{r1\text{-}n} + i_{r2\text{-}n}$$

$$v_n = -\frac{i_{rl\text{-}n} + i_{mos\text{-}n}}{g_m}$$

$$i_n = -\frac{R_1 + R_2}{g_m R_1 R_2}\left(i_{rl-n} + i_{mos-n}\right) + i_{r1\text{-}n} + i_{r2\text{-}n}$$

$F = 1 + \dfrac{\overline{\left(v_n + R_S i_n\right)^2}}{4kTR_S}$なので，まず$v_n + R_S i_n$を求める

$$v_n + R_S i_n = -\frac{i_{rl-n} + i_{mos-n}}{g_m} - \frac{R_S\left(R_1 + R_2\right)}{g_m R_1 R_2}\left(i_{rl-n} + i_{mos-n}\right)$$

$$+ R_S\left(i_{r1\text{-}n} + i_{r2\text{-}n}\right)$$

$$v_n + R_S i_n = -\frac{i_{rl-n} + i_{mos-n}}{g_m} - \frac{R_S\left(R_1 + R_2\right)}{g_m R_1 R_2}\left(i_{rl-n} + i_{mos-n}\right)$$
$$+ R_S\left(i_{r1\text{-}n} + i_{r2\text{-}n}\right)$$

これより $F = 1 + \frac{\overline{\left(v_n + R_S i_n\right)^2}}{4kTR_S}$ は

$$F = 1 + \frac{1}{4kTR_S}\left\{\left(\frac{R_1R_2 + R_2R_S + R_SR_1}{g_m R_1 R_2}\right)^2 \left(\overline{i_{rl\text{-}n}^{\ 2}} + \overline{i_{mos\text{-}n}^{\ 2}}\right)\right.$$
$$\left. + R_S^{\ 2}\left(\overline{i_{r1\text{-}n}^{\ 2}} + \overline{i_{r2\text{-}n}^{\ 2}}\right)\right\}$$

低雑音増幅回路の設計

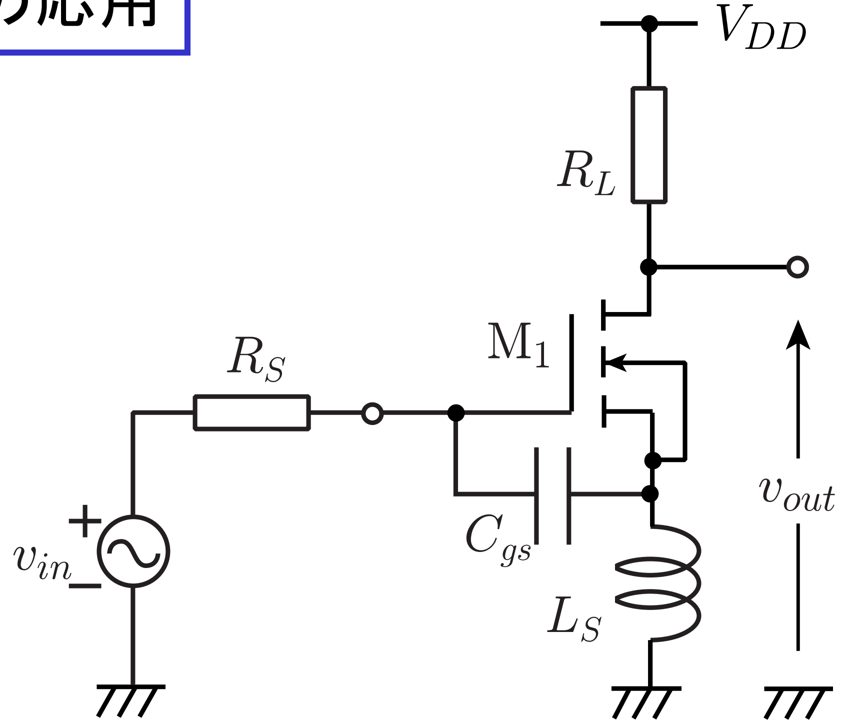
通信機器用低雑音増幅回路

高周波(数GHz)

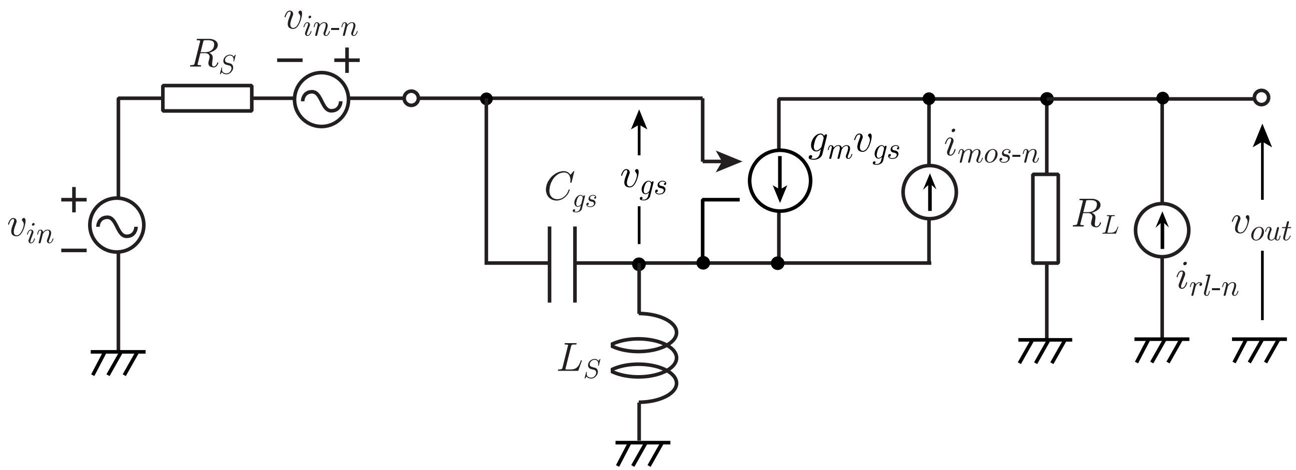
狭帯域

LC共振特性の応用

LC共振特性の応用

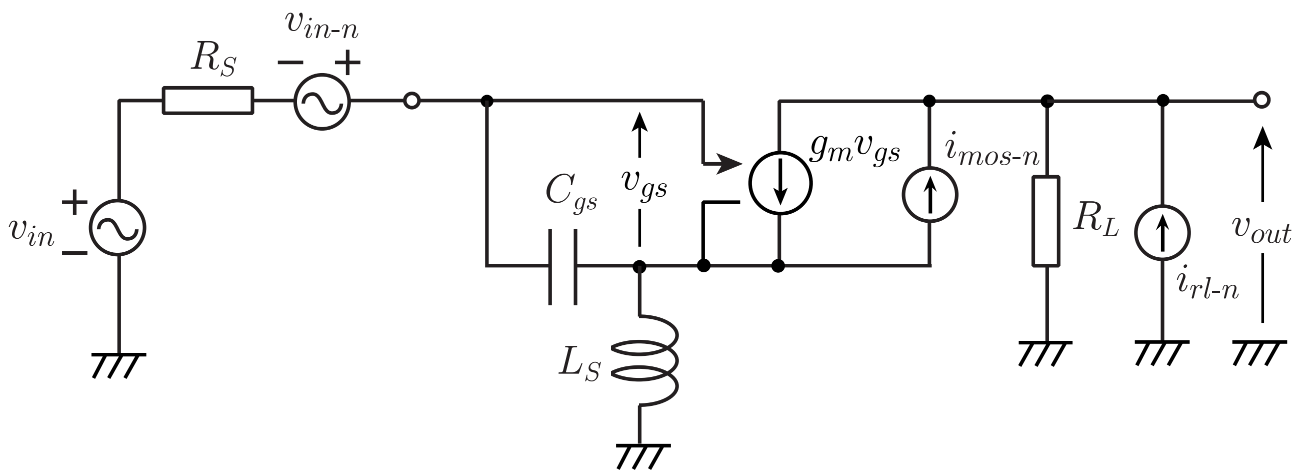


V_{DD}
R_L
M_1
R_S
v_{in}
C_{gs}
L_S
v_{out}

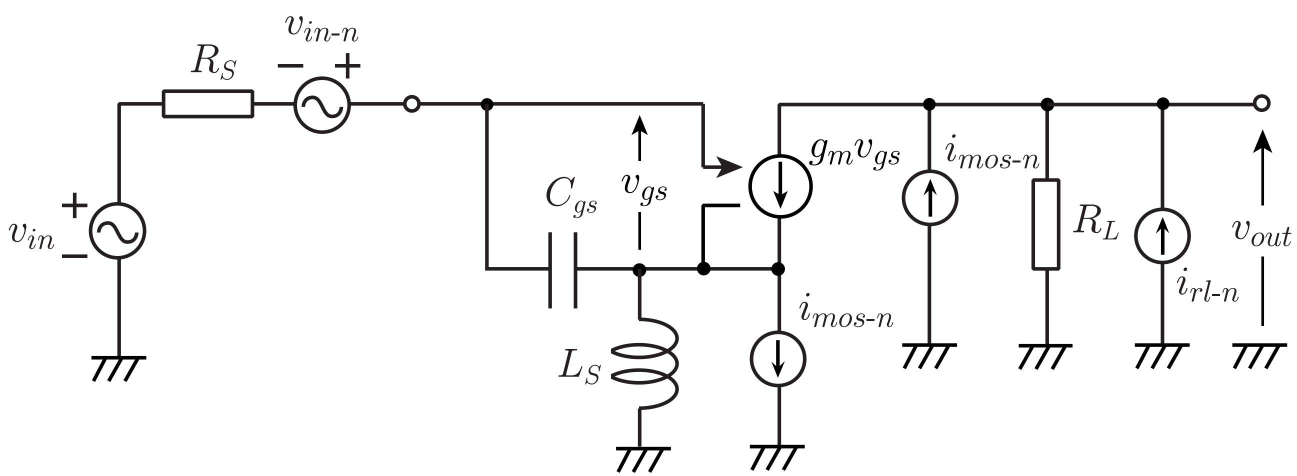


$v_{in\text{-}n}$
R_S
v_{in}
C_{gs}
v_{gs}
$g_m v_{gs}$
$i_{mos\text{-}n}$
R_L
$i_{rl\text{-}n}$
v_{out}
L_S

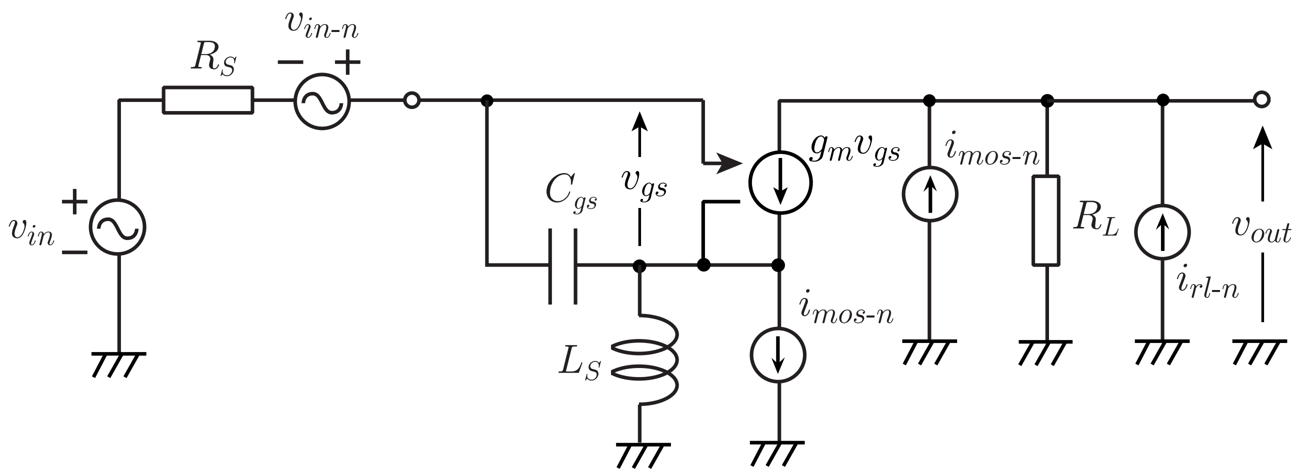
電流源の等価変換



$v_{in\text{-}n}$
R_S
v_{in}
C_{gs}
v_{gs}
$g_m v_{gs}$
$i_{mos\text{-}n}$
R_L
v_{out}
$i_{rl\text{-}n}$
L_S



$v_{in\text{-}n}$
R_S
v_{in}
C_{gs}
v_{gs}
$g_m v_{gs}$
$i_{mos\text{-}n}$
R_L
v_{out}
$i_{rl\text{-}n}$
$i_{mos\text{-}n}$
L_S



$$v_{out-n}=R_L i_{rl\text{-}n}+R_L\left(1-\frac{sL_S g_m}{1+sL_S g_m+s^2 L_S C_{gs}}\right)i_{mos\text{-}n}$$

$$A=\frac{-g_m R_L}{1+sL_S g_m+s^2 L_S C_{gs}} \qquad Z_T=-\frac{g_m}{sC_{gs}}R_L$$

$$v_{out-n}=R_L i_{rl\text{-}n}+R_L\left(1-\frac{sL_S g_m}{1+sL_S g_m+s^2 L_S C_{gs}}\right)i_{mos\text{-}n}$$

$$A=\frac{-g_m R_L}{1+sL_S g_m+s^2 L_S C_{gs}} \qquad Z_T=-\frac{g_m}{sC_{gs}}R_L$$

$$v_n=\frac{1+sL_S g_m+s^2 L_S C_{gs}}{-g_m}\left\{i_{rl\text{-}n}+\left(1-\frac{sL_s g_m}{1+sL_S g_m+s^2 L_S C_{gs}}\right)i_{mos\text{-}n}\right\}$$

$$i_n=\frac{sC_{gs}}{-g_m}\left\{i_{rl\text{-}n}+\left(1-\frac{sL_S g_m}{1+sL_S g_m+s^2 L_S C_{gs}}\right)i_{mos\text{-}n}\right\}$$

$$v_n =$$

$$\frac{1+sL_S g_m + s^2 L_S C_{gs}}{-g_m}\left\{ i_{rl\text{-}n} + \left(1 - \frac{sL_s g_m}{1+sL_S g_m + s^2 L_S C_{gs}}\right) i_{mos\text{-}n} \right\}$$

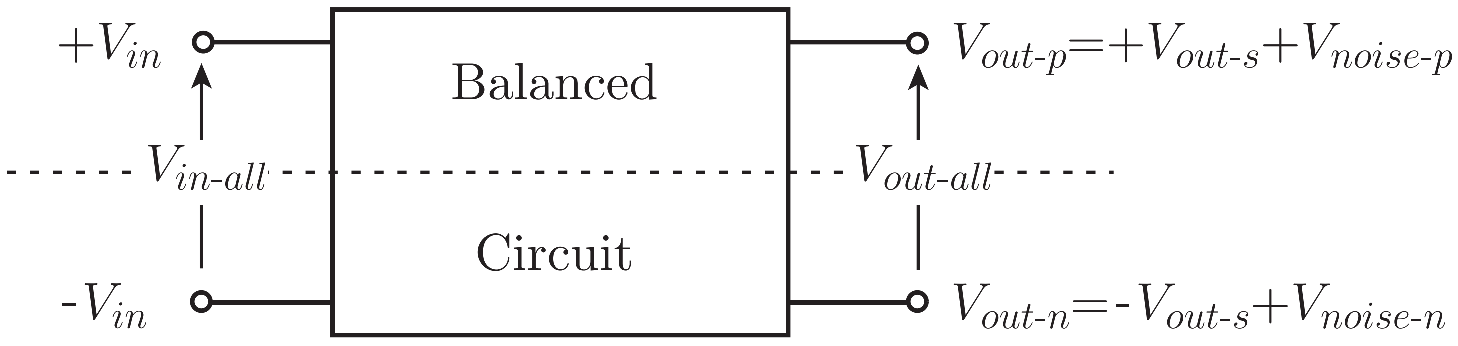
$$i_n = \frac{sC_{gs}}{-g_m}\left\{ i_{rl\text{-}n} + \left(1 - \frac{sL_S g_m}{1+sL_S g_m + s^2 L_S C_{gs}}\right) i_{mos\text{-}n} \right\}$$

$$\frac{v_n}{i_n} = \frac{1+sL_S g_m + s^2 L_S C_{gs}}{sC_{gs}}$$

$$\frac{1+sL_S g_m + s^2 L_S C_{gs}}{sC_{gs}} = R_S$$

$f = \frac{1}{2\pi}\sqrt{\frac{1}{L_S C_{gs}}}$のとき$\frac{L_S g_m}{C_{gs}}$の純抵抗

平衡型構成による雑音の低減？



Symmetry Structure

$$V_{noise\text{-}d}=\frac{V_{noise\text{-}p}-V_{noise\text{-}n}}{2}$$

$$V_{noise\text{-}p}=+V_{noise\text{-}d}+V_{noise\text{-}c}$$

$$V_{noise\text{-}c}=\frac{V_{noise\text{-}p}+V_{noise\text{-}n}}{2}$$

$$V_{noise\text{-}n}=-V_{noise\text{-}d}+V_{noise\text{-}c}$$

$$V_{out\text{-}all}=V_{out\text{-}p}-V_{out\text{-}n}=2V_{out\text{-}s}+2V_{noise\text{-}d}$$

不平衡型回路のSNR

$$V_{out} = V_{out\text{-}s} + V_{noise}$$

$$\lim_{T\to\infty}\frac{1}{T}\int_0^T {V_{out\text{-}s}}^2 dt = \overline{V_{out\text{-}s}}^2 \qquad \lim_{T\to\infty}\frac{1}{T}\int_0^T {V_{noise}}^2 dt = \overline{V_{noise}}^2$$

$$SNR_{imbal} = \frac{\overline{V_{out\text{-}s}}^2}{\overline{V_{noise}}^2}$$

平衡型回路のSNR

$$V_{out\text{-}all}=V_{out\text{-}p}-V_{out\text{-}n}=2(V_{out\text{-}s}+V_{noise\text{-}d})$$

$$\lim_{T\to\infty}\frac{1}{T}\int_0^T V_{out\text{-}s}{}^2 dt=\overline{V_{out\text{-}s}}^2$$

$$\overline{V_{noise\text{-}d}}^2=\lim_{T\to\infty}\frac{1}{T}\int_0^T V_{noise\text{-}d}{}^2 dt=\lim_{T\to\infty}\frac{1}{T}\int_0^T V_{noise\text{-}c}{}^2 dt=\frac{1}{2}\overline{V_{noise}}^2$$

SNRの改善： $SNR_{bal}=\dfrac{\overline{V_{out\text{-}s}}^2}{\overline{V_{noise\text{-}d}}^2}=2\dfrac{\overline{V_{out\text{-}s}}^2}{\overline{V_{noise}}^2}$

ただし，回路規模は2倍