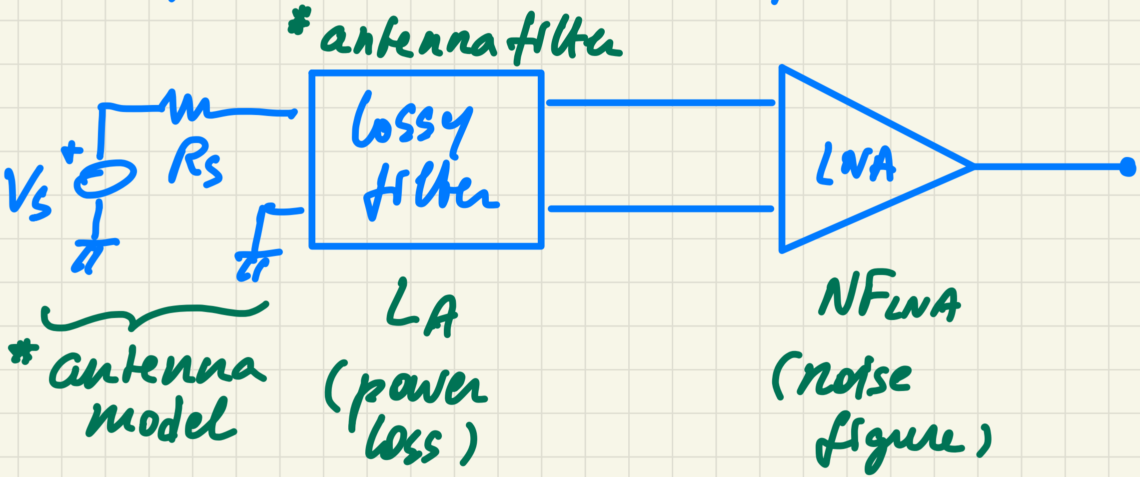
RF Circuit Design

L17

Example of NF of filter + LNA cascade



Total noise figure:

$$NF = NF_{filter} + \frac{NF_{LNA} - 1}{\underbrace{1/L_A}_{\text{av. power gain of stage 1}}} =$$

$$= L_A + L_A\left(NF_{LNA} - 1\right) =$$

$$= L_A \cdot NF_{LNA}$$

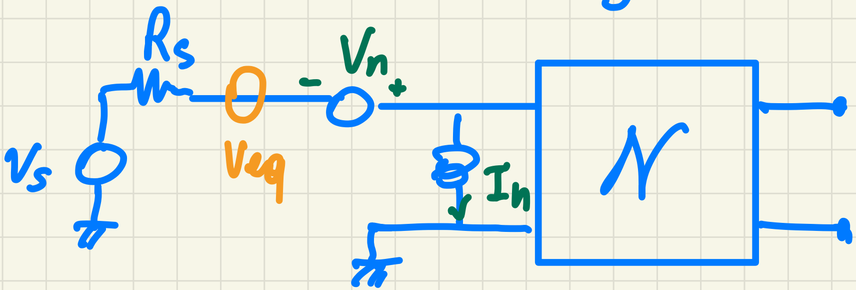
$\overset{dB}{\Rightarrow}$ $NF_{dB} = L_{A,dB} + NF_{LNA,dB}$

e.g. $L_A = 2\,dB$

$NF_{LNA} = 1.6\,dB$ $\Rightarrow$ $NF = 3.6\,dB$

Noise figure of the LNA is amplified by the losses of the previous passive filter

Noise matching



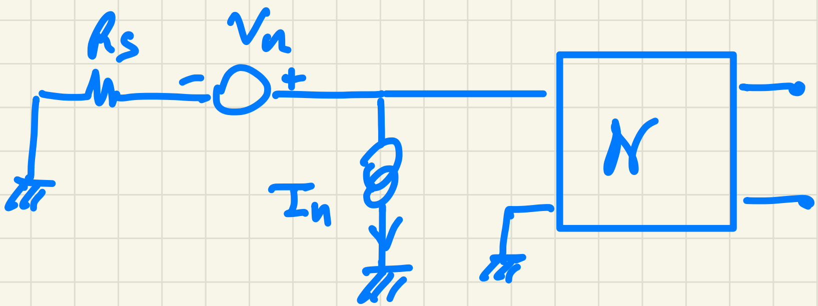
V_n, I_n input-ref. noise sources of N

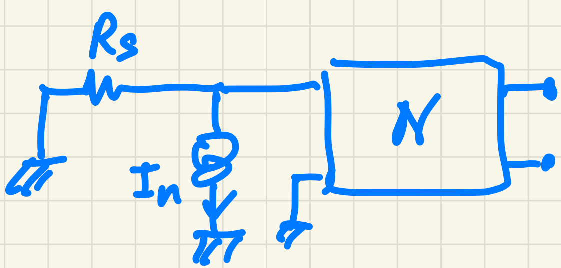
correlated (origin from the same physical noise source)

$$NF = 1 + \frac{\text{Network noise in } V_{eq}}{\text{Source noise in } V_{eq}} =$$

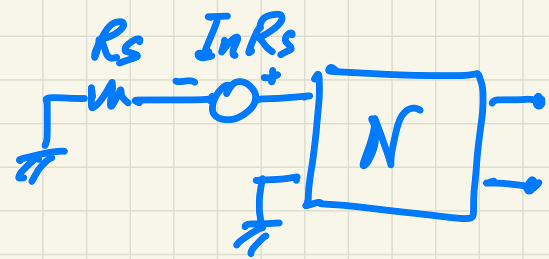
$$= 1 + \frac{\overline{(V_n + I_n R_s)^2}}{4kTR_s} \approx 1 + \frac{\overline{V_n^2} + \overline{I_n^2} R_s^2}{4kTR_s}$$

Hyp. V_n, I_n uncorrelated (approximation)





$\equiv$



$$\Rightarrow \quad NF = 1 + \frac{\overline{V_n^2}}{4kTR_S} + \frac{\overline{I_n^2}}{\frac{4kT}{R_S}}$$

Network voltage noise

source voltage noise

Network current noise

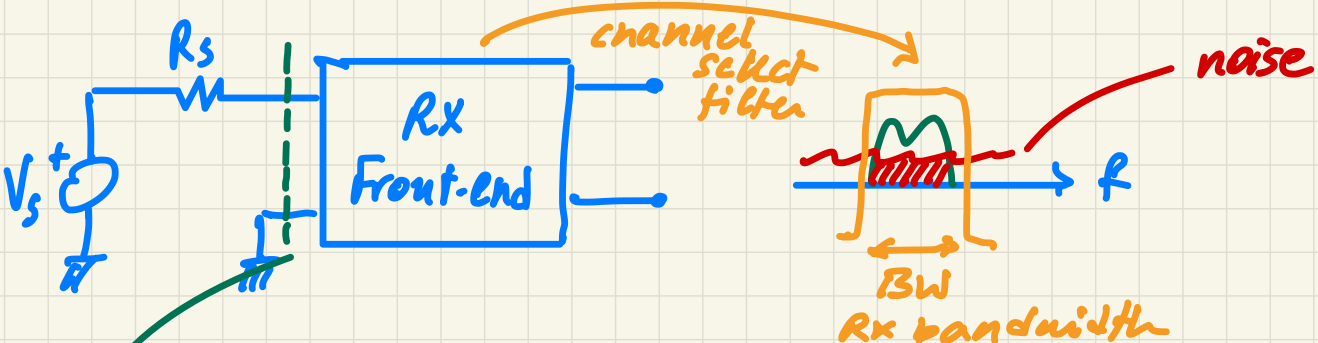
Source current noise

NF has a term decreasing with R_S
and a term increasing with R_S
$\Rightarrow$ an NF_{min} exists for an opt. R_S

$$\frac{\partial N}{\partial R_S} = 0 \quad \Rightarrow \quad R_{S,opt} = \sqrt{\frac{\overline{V_n^2}}{\overline{I_n^2}}}$$

RX sensitivity and Dynamic Range

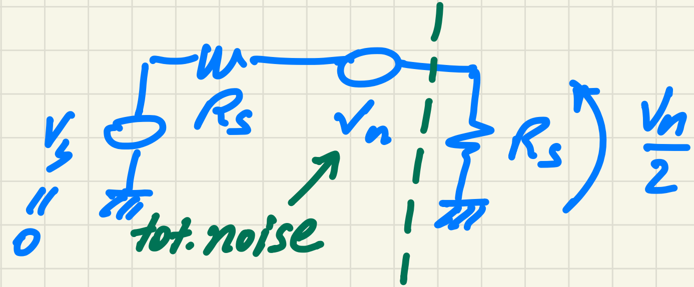
RX sensitivity = min. detectable signal (SNR = SNRmin)



$P_{s,av(min)}$ sensitivity

$$SNR_{min} = \frac{P_{s,av(min)}}{P_{n,av}}$$

$$\frac{P_{n,av}}{\Delta f} = \frac{\frac{\overline{v_n^2}}{R_s}\cdot\frac{1}{4}}{\Delta f} =$$



$$= \frac{\cancel{4}kT\cancel{R_s}\cdot NF_{Rx}}{\cancel{4}\cancel{R_s}} = \Leftarrow \quad \frac{\overline{v_n^2}}{\Delta f} = 4kTR_s\cdot NF_{Rx}$$

$$= \underbrace{kT}_{\text{available power density of the source noise}} \cdot NF_{Rx}$$

$$\Rightarrow P_{n,av} = kT\cdot NF_{Rx}\cdot BW \Rightarrow SNR = \frac{P_{s,av,min}}{kT\cdot NF_{Rx}\cdot BW}$$

$$\Rightarrow P_{s,ar\,min} = \underbrace{KT}_{} \cdot NF_{Rx} \cdot SNR_{min} \cdot BW$$

$$KT \simeq 4 \cdot 10^{-21}\ \text{J} \quad \text{at } 25° \text{ temperature}$$

$$\Rightarrow 10 \log_{10} KT = -204\ \text{dBW/Hz} =$$

$$= \boxed{-174\ \text{dBm/Hz}}$$

$$\xrightarrow{\text{dB}} \underset{\substack{\text{sensitivity}\\ \text{in dBm}}}{P_{s,ar\,min}} = -174\ \frac{\text{dBm}}{\text{Hz}} + NF_{Rx}\big|_{dB} + SNR_{min}\big|_{dB} +$$

$$+ 10 \log(BW)$$

e.g. GSM handset :

- sensitivity $P_S = -100\,\text{dBm}$
- $BW = 200\,\text{KHz}$
- $SNR_{min} = 9\,\text{dB}$

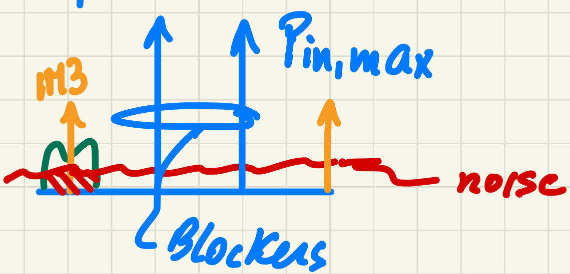
$2\cdot 10^5 \Rightarrow 3+50$

$$\Rightarrow NF_{Rx} = P_S + 174 - SNR_{min} - 10\log(BW) =$$

$$= -100 + 174 - 9 - 53 =$$

$$= -162 + 174 = 12\,\text{dB}$$

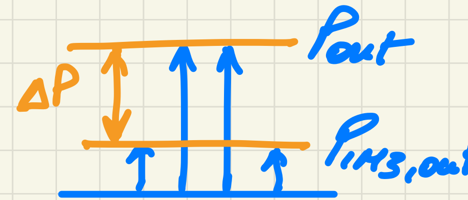
Dynamic Range



SFDR spurious free dynamic range

$$SFDR_{dB} = \underbrace{P_{in,max}}_{\text{input power of the two tones such that IM3 power equals noise power}} - \underbrace{P_{in,min}}_{\text{sensitivity level}}$$

$$\underbrace{P_{IIP_3\,dBm} = P_{in} + \frac{\Delta P}{2}}$$



$$G_{A\,dB} = P_{out} - P_{in}$$

$$\Downarrow$$

$$P_{IIP_3} = P_{in} + \frac{P_{out} - P_{IM3,out}}{2} =$$

$$= P_{in} + \frac{P_{in} + \cancel{G_A} - \left(P_{IM3,in} + \cancel{G_A}\right)}{2} =$$

$$= \frac{3}{2} P_{in} - \frac{1}{2} P_{IM3,in}$$

input-referred level of IM3 products

IM3 = noise level

$$P_{IIP_3} = \frac{3}{2} P_{in,\,max} - \frac{1}{2} P_n$$

input-referred level of noise

$$\Rightarrow \quad P_{in,max}(dBm) = \frac{2P_{IIP3} + P_n}{3}$$

$SNR_{min} =$

$= P_{in,min} - P_n$

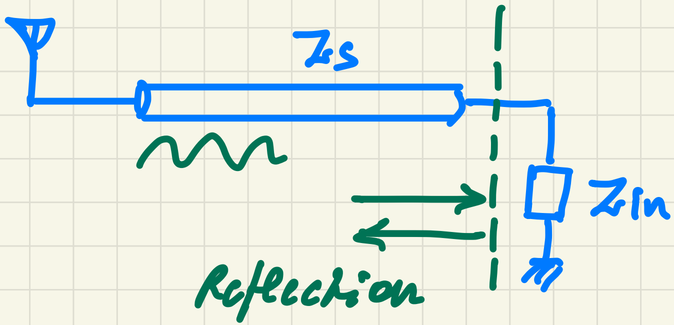
$$SFDR = P_{in,max} - P_{in,min} =$$

$$= \frac{2}{3}P_{IIP3} + \frac{1}{3}P_n - (P_n + SNR_{min}) =$$

$$= \frac{2}{3}P_{IIP3} - \frac{2}{3}P_n - SNR_{min} =$$

$$= \frac{2}{3}(P_{IIP3} - P_n) - SNR_{min}$$

Scattering Parameters or S-parameters



Reflection coefficient

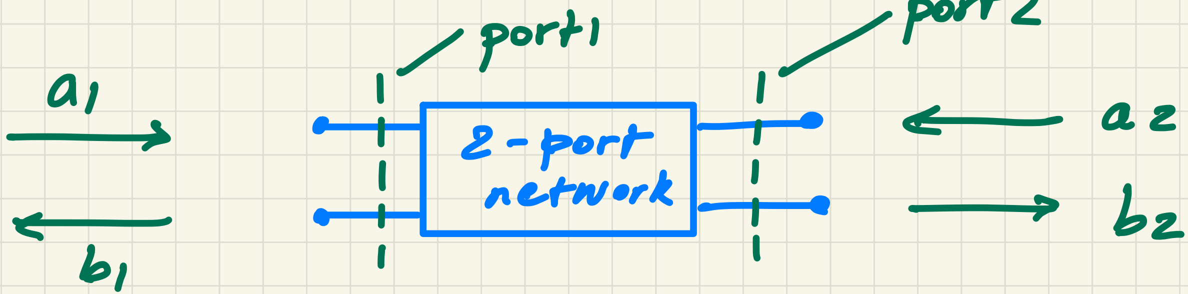
$$\Gamma = \frac{P_{reflected}}{P_{incident}}$$

$$\Gamma = \left| \frac{Z_{in} - Z_S}{Z_{in} + Z_S} \right|^2$$

only if $Z_{in} = Z_S$: $\Gamma = 0$
no reflection ("termination" is matched to the characteristic impedance of the line)

$$P_{ref} = \Gamma \cdot P_{inc}$$

Extension to 2-port networks



a_1 is incident power wave at port 1

b_1 is reflected power wave " " "

scattering or S param

$$\begin{cases} b_1 = S_{11} \cdot a_1 + S_{12}\, a_2 \\ b_2 = S_{21}\, a_1 + S_{22}\, a_2 \end{cases}$$

$$\begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix}$$

capital "S"

$$S_{11} = \frac{b_1}{a_1}$$

$$s_{11} = \frac{V_1^-}{V_1^+}\Bigg|_{\underbrace{V_2^+=0}_{\text{matched load at port 2}}} \Rightarrow S_{11} \text{ is the reflection coefficient at port 1 with matched port 2}$$

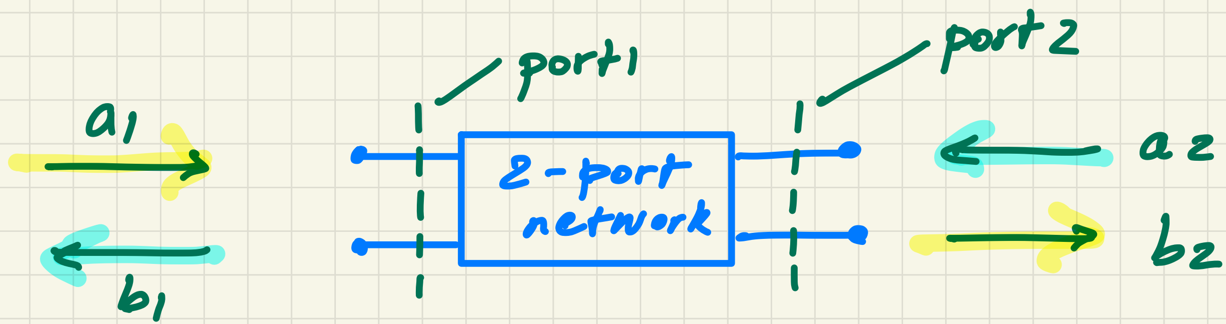
small "s"

Input return loss : $RL_{in} = 10 \log_{10} \frac{1}{|s_{11}^2|} = -20 \log_{10}\{s_{11}\}$

Output return loss : $RL_{out} = -20 \log_{10}\{s_{22}\}$

Forward gain $20 \cdot \log\{s_{21}\}$

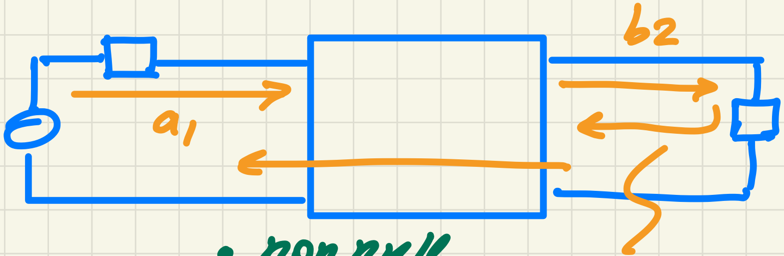
Reverse isolation $-20 \log\{s_{12}\}$



$$S_{21} = \frac{b_2}{a_1}$$

$$S_{12} = \frac{b_1}{a_2}$$

capital "s"



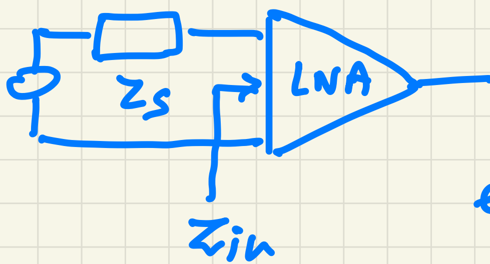
- non-matched load $\Rightarrow$ stability issues

- non null reverse gain

reflection of non matched load

Low-Noise Amplifiers (LNAs)

- Low noise (NF noise figure)
- Large gain (G_A or S_{21} power gain)
- input matching (Return loss $1/S_{11}$)



$$S_{11} = \left| \frac{Z_{in} - Z_s}{Z_{in} + Z_s} \right|^2$$

e.g. $Z_s = 50\,\Omega$

$Z_{in} = 40\,\Omega$

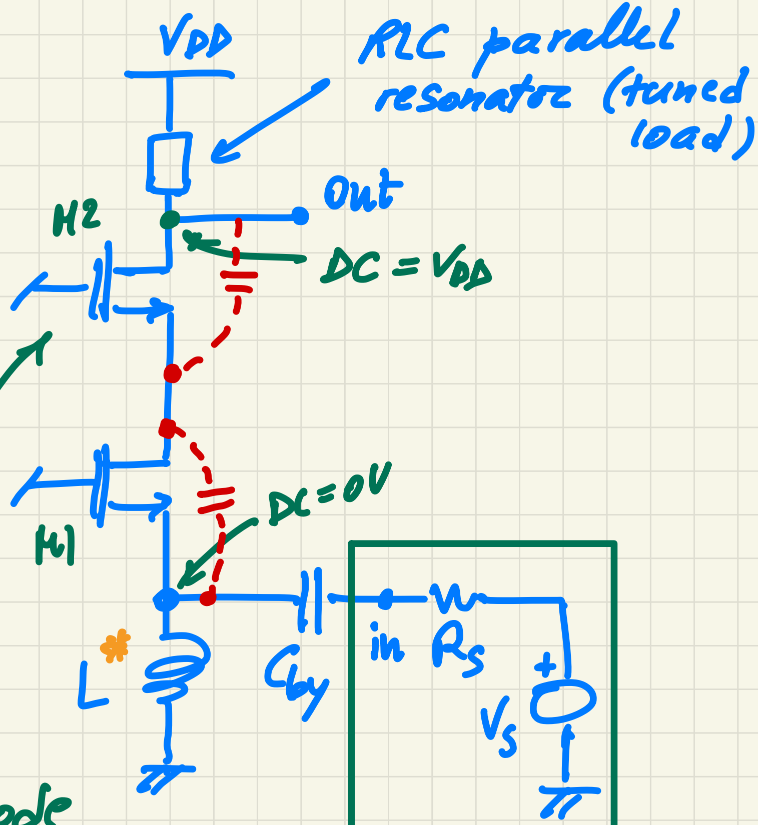
typ. $S_{11} = -10\,dB$ is acceptable

$P_{ref} = 0.1 \cdot P_{inc}$ (loss of 10%)

$$\Rightarrow S_{11} = 20 \log \left| \frac{40-50}{40+50} \right| = -20\,dB$$

- linearity (IIP3 intercept point) because of block

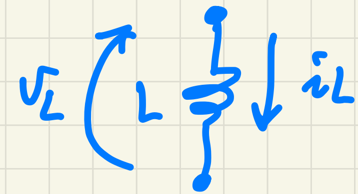
Common - gate topology



cascode
typ used to
improve Reverse isolation

* Choke inductor

$$\frac{di_L}{dt} = \frac{v_L}{L}$$

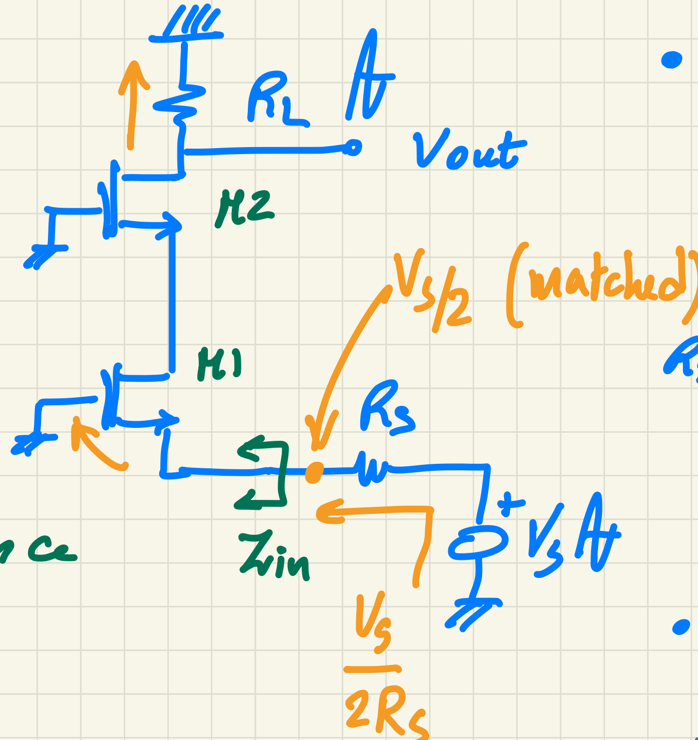


$$L \to \infty$$

$$\Rightarrow \frac{di_L}{dt} \to 0$$

$$\Rightarrow i_L \to \text{constant}$$

Sufficiently large ind. is used as a current generator at center frequency f_0 At



input impedance

$$Z_{in} \simeq \frac{1}{g_{m1}}$$

neglecting r_{o1}

neglecting C_{gs1}, C_{ds1}, C_{sb1}

- Matching condition

$$g_{m1} = \frac{1}{R_s}$$

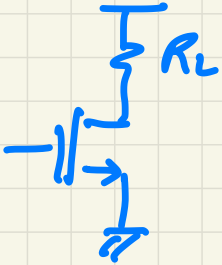
$R_s = 50\,\Omega$:

$$g_m = 20\,mS$$

- Voltage gain

match

$$A_0 = \frac{V_{out}}{V_s} = \frac{V_s/2R_s \cdot R_L}{V_s} = \frac{R_L}{2R_s}$$



$$g_m R_L = \frac{2I}{V_{ov}} \cdot R_L = \frac{2V_{R_L}}{V_{ov}}$$

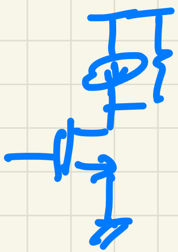
e.g. $f_0 = 1\,GHz$ $L = 1\,nH$
$Q = 10$
$\Rightarrow R_L = 62.8\,\Omega$

$R_s = 50\,\Omega$

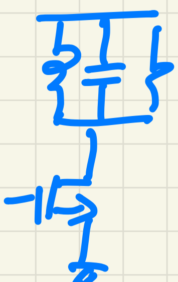
$$\Rightarrow A_0 \doteq \frac{R_L}{2R_s} = 1 \div 10$$

$\Downarrow$

$0 \div 20\,dB$



$$g_m r_o = \dots$$



$$R_L = \omega_0 L Q \Leftarrow Q = \frac{R_L}{\omega_0 L}$$

$g_m R_L$ at RF $R_L \approx 100 \div 1000\,\Omega$