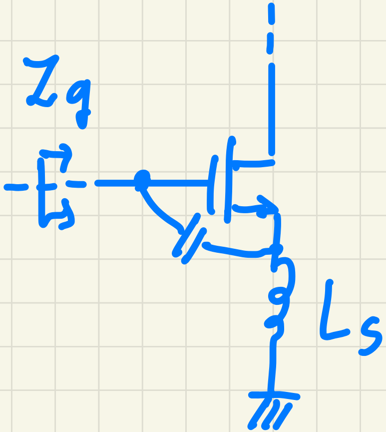
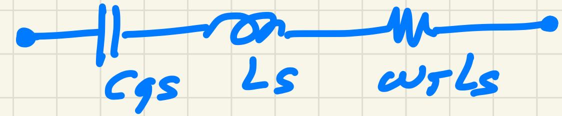
RF Circuit Design

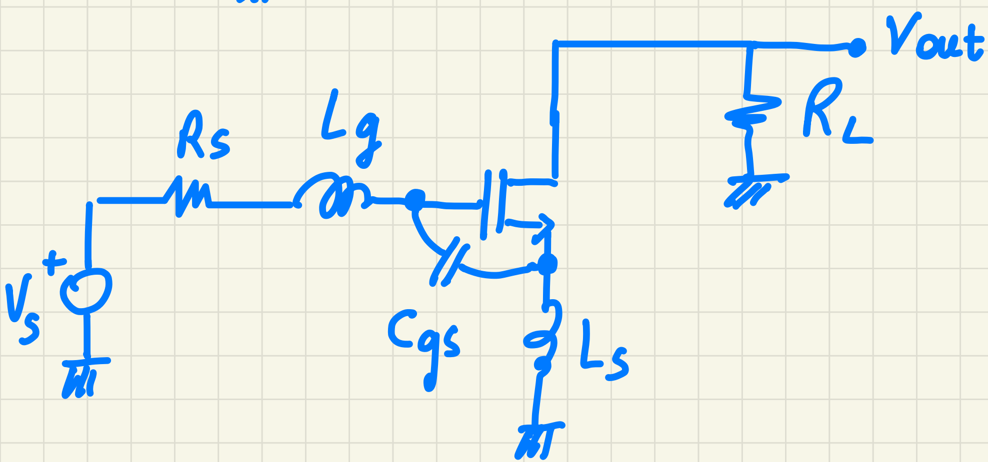
L19

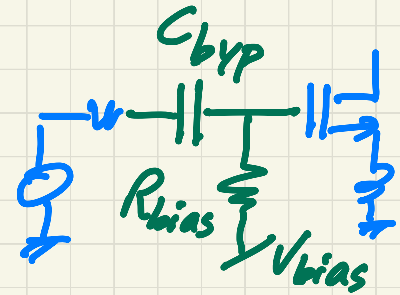
Inductive degeneration





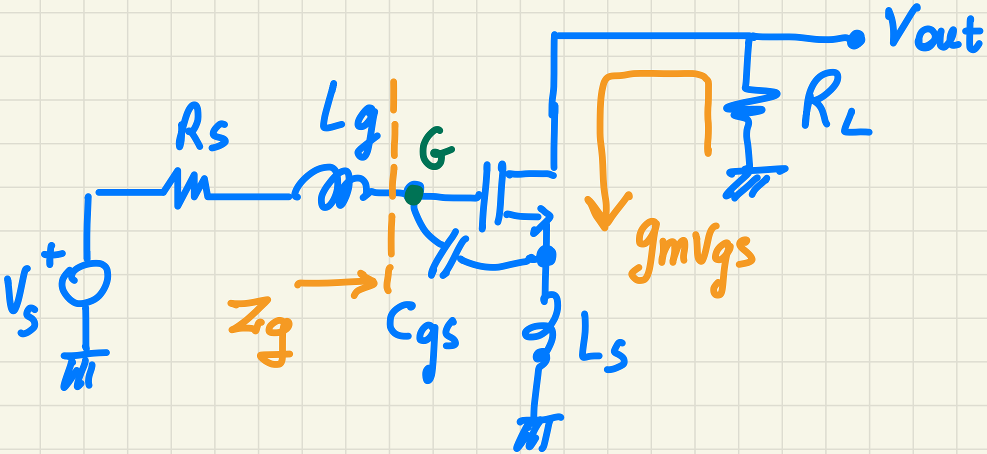
$$Z_g = \underbrace{\frac{1}{sC_{gs}} + sL_s}_{\text{resonator}} + \underbrace{\omega_T L_s}_{\text{equivalent resistance}}$$





"bias-tee"

Biasing scheme

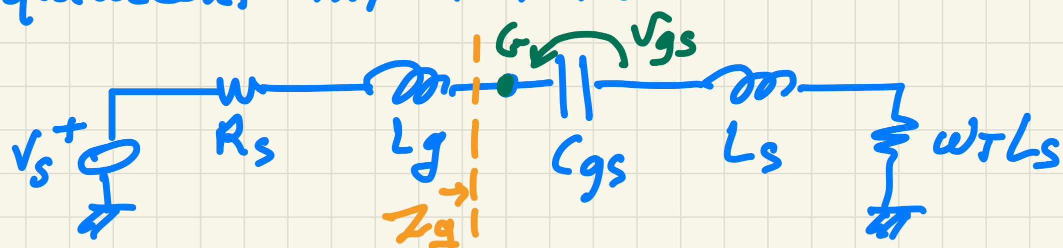


$$\omega_T = \frac{g_m}{C_{gs}}$$

Matching condition :

- $\omega_T L_s = R_s$
- $\omega_0 = \dfrac{1}{\sqrt{(L_g + L_s)\,C_{gs}}}$

Equivalent input network



$$\Rightarrow V_{gs} = Q \cdot V_s$$

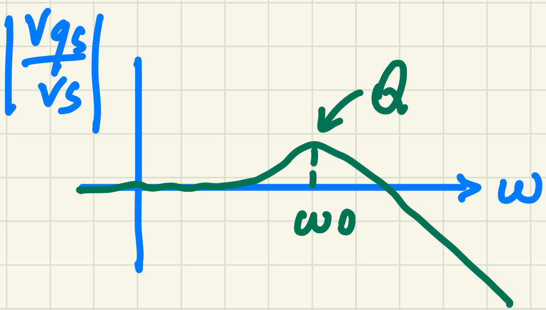
- Amplifier voltage gain:

at $\omega_0 = \frac{1}{\sqrt{(L_s+L_g)C_{gs}}}$

$$v_{out} = -g_m R_L v_{gs} = -g_m R_L \cdot Q \cdot v_s$$

$$Q = \frac{1}{\omega_0 C_{gs}(R_s + \omega_T L_s)} = \frac{1}{\omega_0 C_{gs} \cdot 2R_s}$$

matched



$\Downarrow$

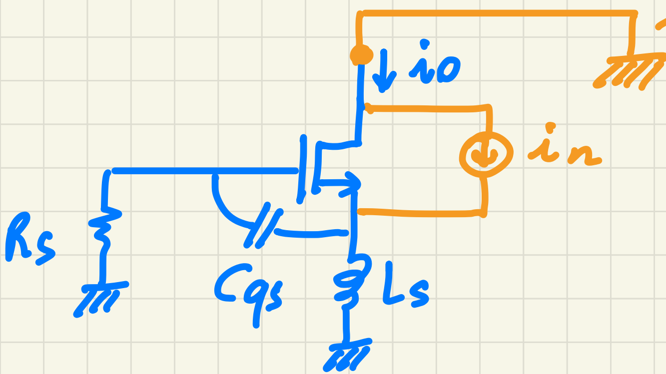
$$A_0 = \frac{v_{out}}{v_s} = -\underbrace{g_m R_L}_{\text{gain of CS topology}} \cdot \underbrace{Q}_{\text{gain of impedance transform. network}}$$

$$\Rightarrow A_0 = -\overset{\omega_T}{\overset{\parallel}{g_m}} R_L \cdot \frac{1}{\omega_0 C_{gs}\, 2R_s} = -\underbrace{\frac{\omega_T}{\omega_0}}_{\text{increasing factor}} \cdot \underbrace{\frac{R_L}{2R_s}}_{\text{gain of CG topology}}$$

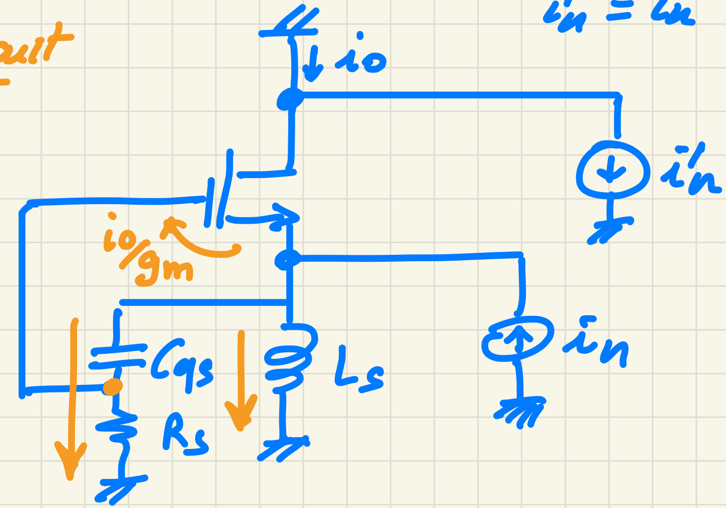
matched

- **Noise figure : MOSFET noise**

$i'_n = i_n$



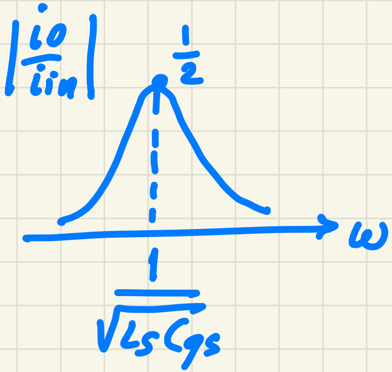
$\Longrightarrow$



$$i_n + i_o = \underbrace{-\frac{i_o}{g_m}\cdot sC_{gs}}_{\text{current in } C_{gs}} + \underbrace{\frac{-\frac{i_o}{g_m}\cdot sC_{gs}\cdot R_s - \frac{i_o}{g_m}}{sL_s}}_{\text{current in } L_s};$$

$$i_o\left(1 + \frac{sC_{gs}}{g_m} + \frac{R_sC_{gs}}{g_mL_s} + \frac{1}{sg_mL_s}\right) = -i_n$$

- $$\frac{i_o}{i_n} = -\frac{s\, g_m/C_{gs}}{s^2 + s\left(\frac{g_m}{C_{gs}} + \frac{R_s}{L_s}\right) + \frac{1}{L_s C_{gs}}}$$

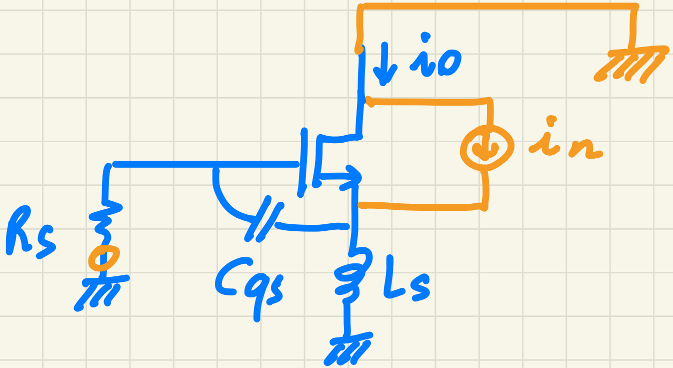


$$\left.\frac{i_o}{i_{in}}\right|_{\text{at resonance}} = -\frac{\cancel{j\omega_0}\, g_m/C_{gs}}{\cancel{j\omega_0}\left(\frac{g_m}{C_{gs}} + \frac{R_s}{L_s}\right)} =$$

$$= -\frac{\omega_T L_s}{\omega_T L_s + R_s} \underset{\text{input matching}}{=} -\frac{1}{2}$$

- $$\frac{i_o}{i_n'} = 1$$

$\Rightarrow$ superposition: $i_n = i_n'$ $\qquad \left.\frac{i_o}{i_n}\right|_{\text{at res.}} = -\frac{1}{2} + 1 = \frac{1}{2}$



NF component

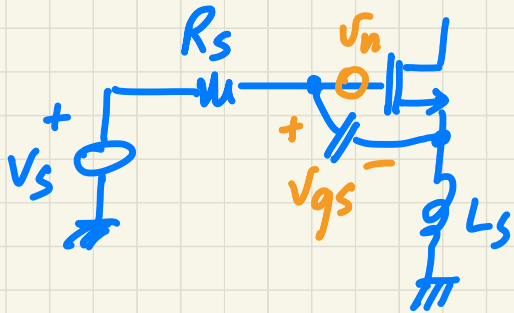
$$\frac{\cancel{4kT}\,\dfrac{\gamma}{\alpha}\,\cancel{g_m}\cdot\overbrace{\dfrac{1}{\cancel{4}}}^{\left|\frac{i_o}{i_n}\right|^2}}{\cancel{4kTR_s}\cdot\dfrac{g_m^{\cancel{2}}}{\underbrace{\omega_0^2\, C_{gs}^2\cdot \cancel{4}R_s^{\cancel{2}}}_{(g_m\cdot Q)^2}}} =$$

$$= \frac{\gamma}{\alpha}\cdot\frac{R_s\,\omega_0^2\,C_{gs}^2}{g_m} = \frac{\gamma}{\alpha}\cdot\frac{\omega_0}{\omega_T}\cdot\underbrace{\omega_0 C_{gs} R_s}_{1/Q_L} =$$

$$= \frac{\gamma}{\alpha}\cdot\frac{\omega_0}{\omega_T}\cdot\frac{1}{Q_L}$$

quality factor of Zg netw.
(in matching conditions)

$$\Rightarrow \quad NF = 1 + \overbrace{\underbrace{\frac{\gamma}{\alpha}}_{\text{term in CG or shunt-feedb. topologies}} \cdot \underbrace{\frac{\omega_0}{\omega_T} \cdot \frac{1}{Q_L}}_{\text{reduction factor}}}^{\text{MOS noise}} + \overbrace{\underbrace{\frac{4R_S}{R_L}}_{\text{term in CG top.}} \cdot \underbrace{\left(\frac{\omega_0}{\omega_T}\right)^2}_{\text{reduct. factor}}}^{R_L \text{ noise}}$$

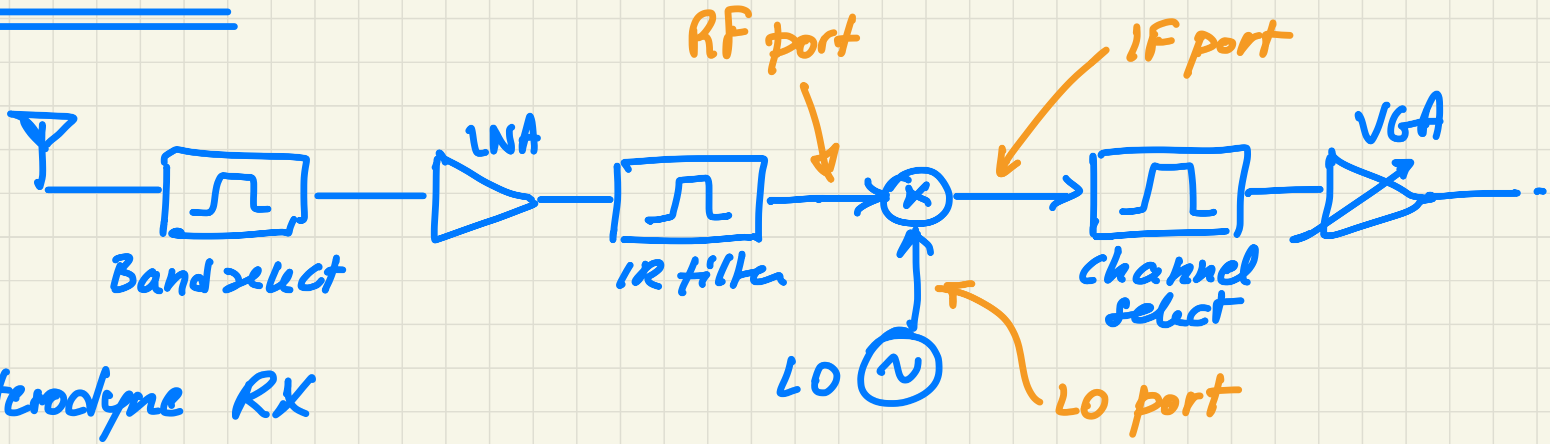


$Q_L \nearrow \quad Q \nearrow$

larger v_{gs} signal compared to v_n (equivalent MOSFET noise)

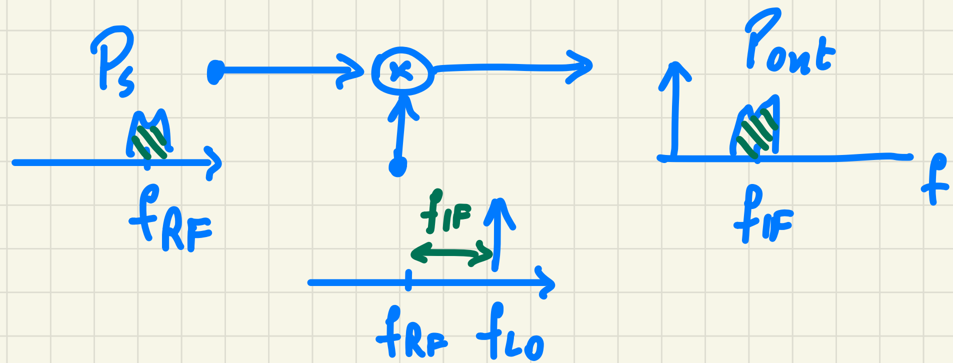
→ narrowband input matching

Mixers

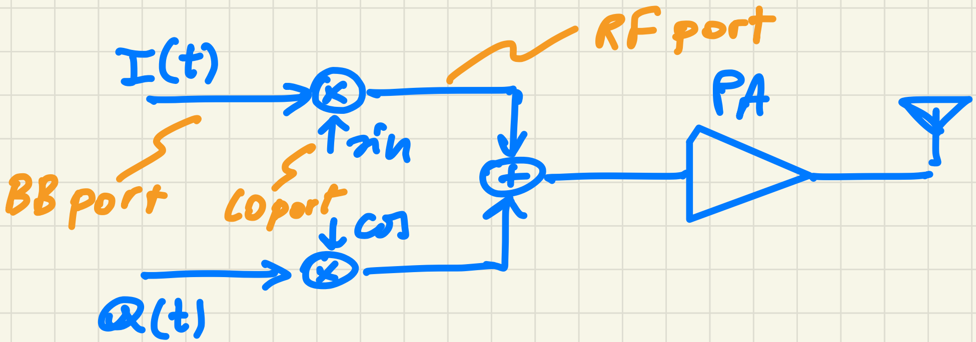


Heterodyne RX

Mixer is used as a DOWN-converter



Direct-conversion TX



Mixer is used as an up-converter

Specifications :

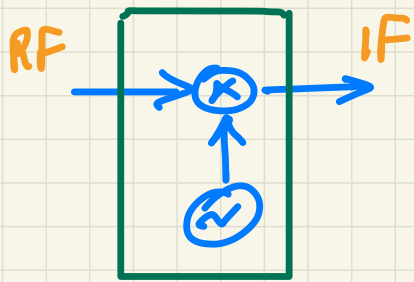
- Conversion gain :

case of down convers.

$$G \triangleq \frac{P_{out}}{P_s}$$

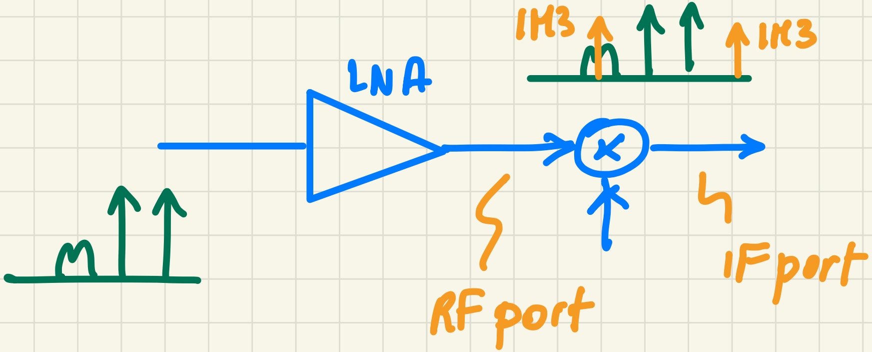
P_{out}: power at f_{IF}

P_s: power at f_{RF}



- linearity : signal at RF port is linearly transferred to IF port

IIP_3 mixer



Both IP_3 of LNA and IP_3 of mixer matter

- Noise : NF_{mixer}

LNA gain is limited (case RX)

- Feedthroughs : unwanted signal transfers from one to another port

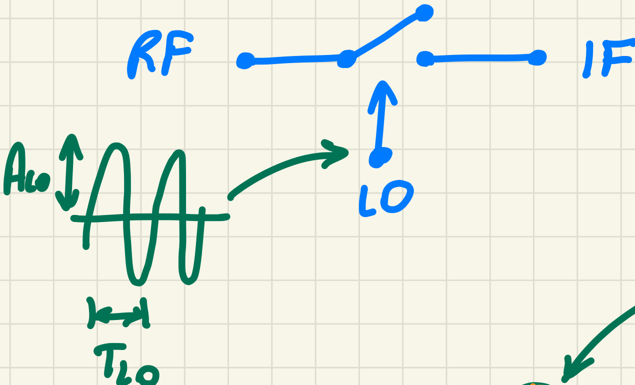
e.g.

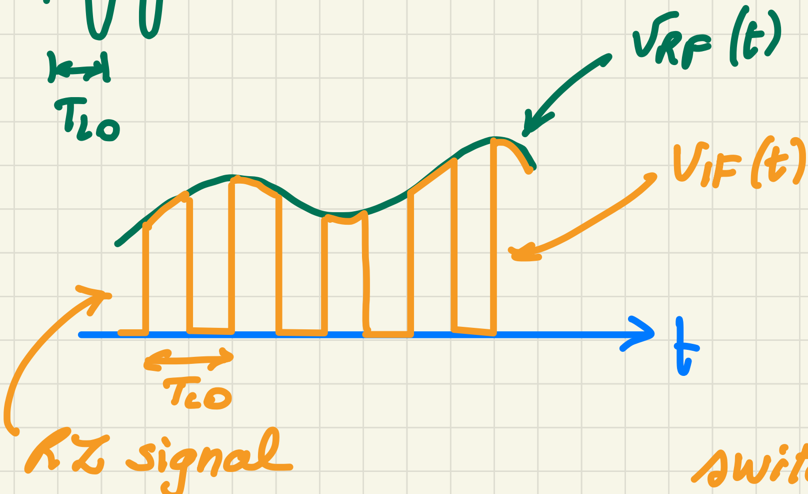
LO - to - RF

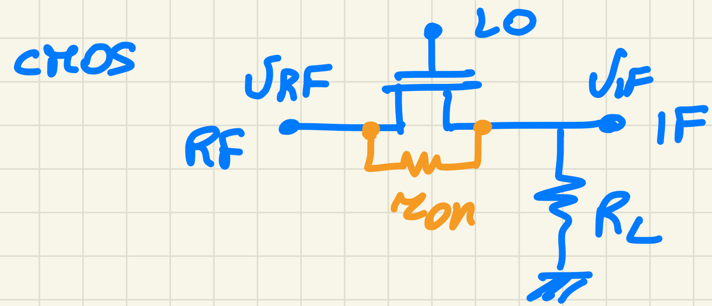
LO - to - IF

RF - to - IF → signal at RF input leaks into IF output : at IF port there is a signal component at f_{RF} (case RX)

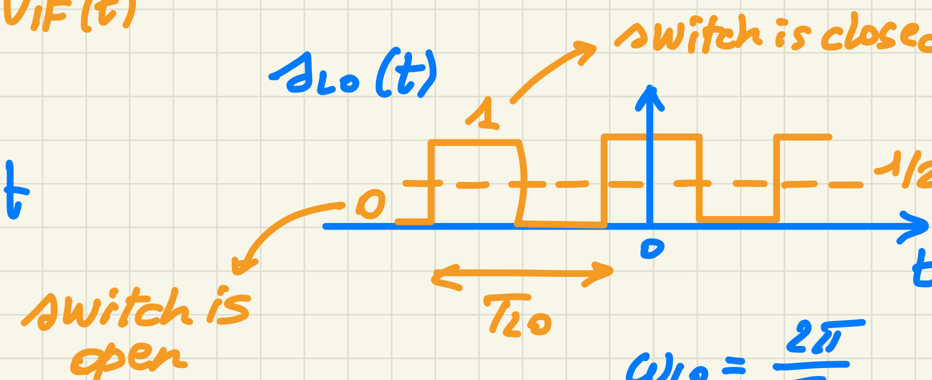
Passive Return-to-Zero (RZ) mixer







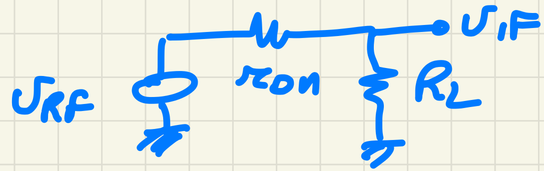
Define a function:

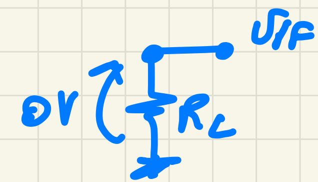


$$\omega_{LO} = \frac{2\pi}{T_{LO}}$$

$$\Rightarrow \quad v_{IF}(t) \simeq \frac{R_L}{R_L + r_{on}} \cdot s_{LO}(t) \cdot v_{RF}(t)$$

constant r_{on} (indipendent on MOSFET biasing over time)





$\Rightarrow$ LTV system (ideally if r_{on} is constant)

$$v_{IF}(t) \simeq \frac{R_L}{R_L + r_{on}} \cdot \Big[\underbrace{\frac{1}{2}}_{\text{RF-to-IF feedthrough}} + \underbrace{\frac{2}{\pi} \cos \omega_{LO} t}_{\text{wanted frequency conversion}} + 0 \cdot t \Big] \cdot v_{RF}(t)$$

at $3\omega_{LO}$, $5\omega_{LO}$

50% duty cycle $s_{LO}(t)$ square wave function

Hyp: $v_{RF}(t) = A\cos\omega_{RF} t$

RF-to-IF

$$\Rightarrow \quad v_{IF}(t) = \frac{R_L}{R_L + r_{on}} \cdot \Big[\frac{A}{2}\cos\omega_{RF} t \; +$$

wanted signal at ω_{IF}

$$+ \frac{1}{\cancel{2}} \cdot A \cdot \frac{\cancel{2}}{\pi} \cdot \cos(\omega_{LO} - \omega_{RF}) t$$

$$+ \frac{1}{\cancel{2}} \cdot A \cdot \frac{\cancel{2}}{\pi} \cos(\omega_{LO} + \omega_{RF}) t$$

$$+ \; o.t. \Big]$$

$\Downarrow$

- Conversion voltage gain: $A_V = \dfrac{V_{IF}(\overbrace{\omega_{LO} - \omega_{RF}}^{\omega_{IF}})}{V_{RF}(\omega_{RF})} = \dfrac{1}{\pi} \cdot \dfrac{R_L}{R_L + r_{on}}$

max. conv. gain $\rightarrow \dfrac{1}{\pi}$

$\rightarrow \sim -10\,dB$

- linearity : r_{on} depends on V_{gs} $\Rightarrow$ on $V_{RF}(t)$

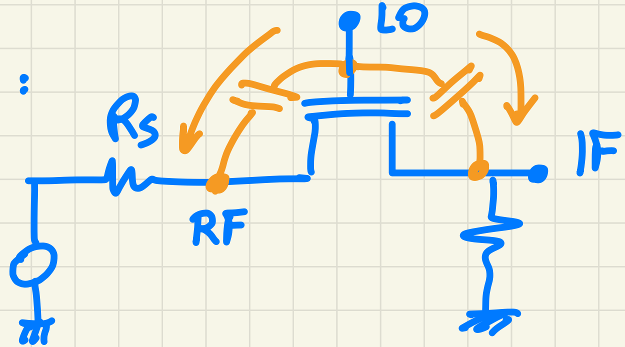
  $\Rightarrow$ nonlinearity

  Mixer linearity $\nearrow$ $\left\{\begin{array}{l}\text{Tx gate} \\ r_{on} \ll R_L\end{array}\right.$

  $\Downarrow$

  Large parasitic cap. $\Leftarrow$ large MOSFETS

- Feedthrough :

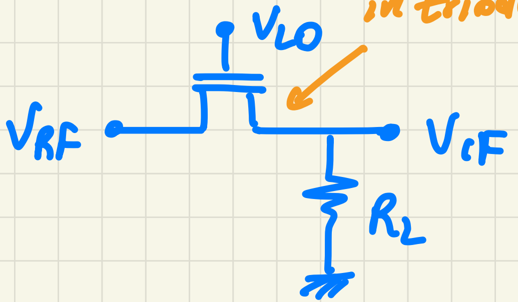


LO-to-IF
LO-to-RF

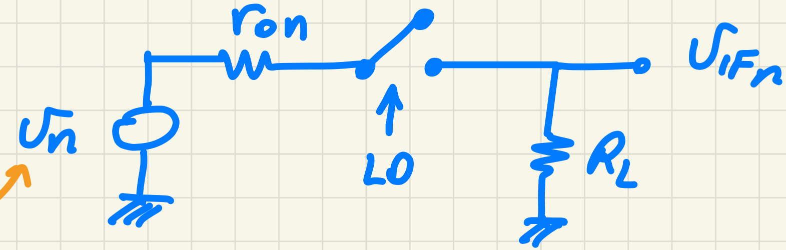
Linearity $\xleftrightarrow{\text{trade-off}}$ Feedthrough

- **Noise in mixers** :

in triode when on



– **MOSFET noise** :



MOSFET noise

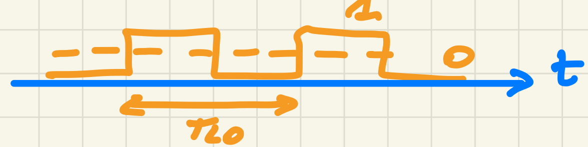
$$PSD^{SSB} = 4KT\,r_{on}$$

$$v_{IF_n}(t) = v_n(t)\cdot s_{LO}(t)\cdot\frac{R_L}{R_L+r_{on}} \qquad (LTV)$$

$$\Downarrow$$

$$PSD^{DSB}_{v_{IF}}(f) = \underbrace{PSD^{DSB}_n(f)}_{2kTr_{on}} * \underbrace{\left|S_{LO}(f)\right|^2}_{\downarrow}\cdot\left(\frac{R_L}{R_L+r_{on}}\right)^2$$

$s_{LO}(t)$

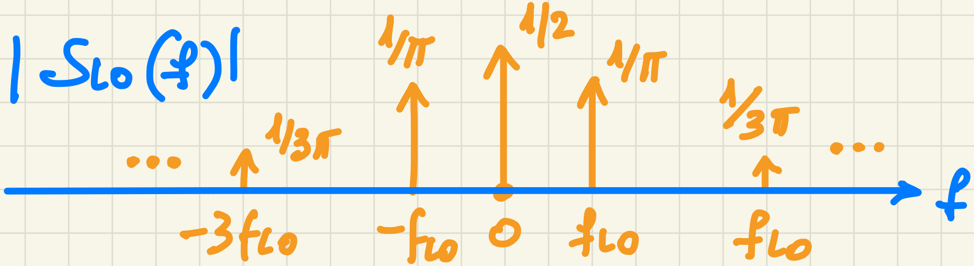


$c_0 = 1/2$

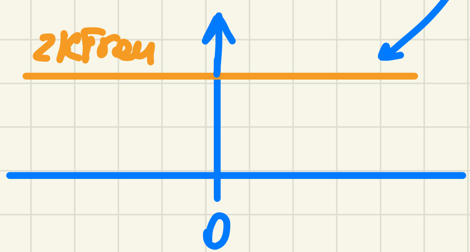
$c_1 = c_{-1} = 1/\pi$

$\vdots$

$|S_{LO}(f)|$



$$\Rightarrow PSD_{v_{IF}}^{DSB}(f) = 2kTr_{on} * \sum_{k=-\infty}^{\infty} |c_k|^2 \delta(f - k f_{LO}) \cdot \left(\frac{R_L}{R_L + r_{on}}\right)^2$$



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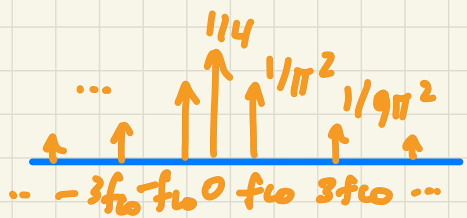

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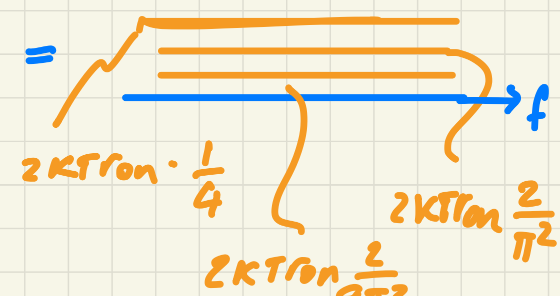
SPECTRUM FOLDING

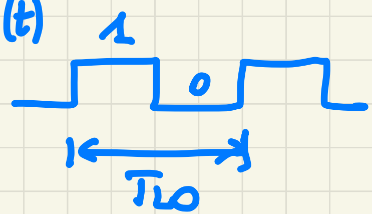


$$\Rightarrow \quad PSD_{v_{IF}}^{DSB} = 2kT\,r_{on} \cdot \underbrace{\sum_{k=-\infty}^{+\infty} |c_k|^2}_{\text{Power of } s_{LO}(t)} \cdot \left(\frac{R_L}{R_L + r_{on}}\right)^2$$

Parseval's theor.: $\displaystyle\int_{-\infty}^{+\infty} |S_{LO}(f)|^2\,df = \frac{1}{T_{LO}} \int_0^{T_{LO}} |s_{LO}(t)|^2\,dt$

$$\Downarrow$$

$s_{LO}^2(t)$

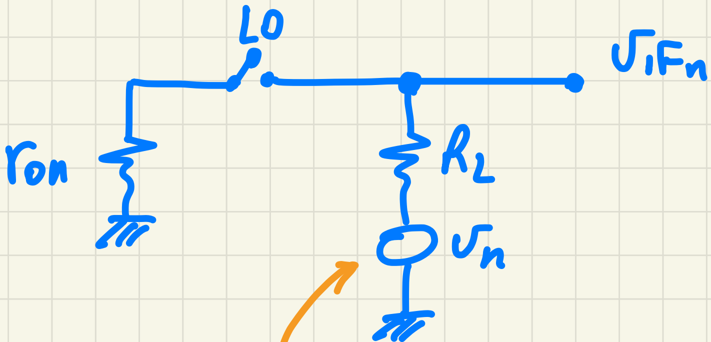


$$\sum_{k=-\infty}^{+\infty} |c_k|^2 = \frac{1}{\cancel{T_{LO}}} \cdot \frac{\cancel{T_{LO}}}{2} \cdot 1 = \frac{1}{2}$$

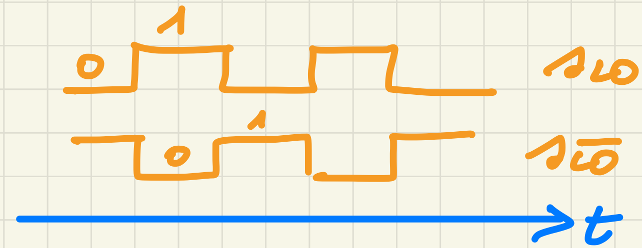
$$\Rightarrow \quad PSD_{v_{IF}}^{DSB} = \cancel{2}kT\,r_{on} \cdot \frac{1}{\cancel{2}} \cdot \left(\frac{R_L}{R_L + r_{on}}\right)^2$$

Intuitively: v_n is transferred to v_{IF} for half of the time $\Rightarrow$ PSD weighted by 1/2

– R_L noise :



$PSD^{SSB} = 4kTR_L$



weight 1/2

$$v_{IF_n}(t) = \underbrace{v_n(t)\cdot s_{LO}(t)\cdot \frac{r_{on}}{r_{on}+R_L}}_{\text{when switch is closed}} + \underbrace{v_n(t)\cdot s_{\overline{LO}}(t)}_{\text{when switch is open}}$$

DSB $2kTR_L$

$$PSD^{DSB}_{V_{IF}} = \cancel{2}kTR_L \cdot \frac{1}{\cancel{2}} \cdot \left(\frac{r_{on}}{r_{on}+R_L}\right)^2 + \cancel{2}kTR_L \cdot \frac{1}{\cancel{2}}$$

$$\Rightarrow \underbrace{PSD^{SSB}_{V_{IF_n}}}_{\text{total PSD including both MOS and } R_L \text{ noise}} = \underbrace{2KT r_{on} \cdot \left(\frac{R_L}{R_L + r_{on}}\right)^2}_{\text{MOSFET noise}} + \underbrace{2KTR_L \cdot \left(\frac{r_{on}}{R_L + r_{on}}\right)^2}_{R_L \text{ noise}} + \overbrace{2KTR_L}$$

$$= \underbrace{2KT \cdot (r_{on} // R_L)} + \underbrace{2KTR_L}$$

Intuitive explanation

when switch is closed

when switch is open